Doctoral Dissertation
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The resource efficiency in sustainable production system

Monitoring consumption, reducing waste, and reusing them as raw materials

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Summary

Manufacturing activities are responsible for a large consumption of the virgin resources and the production of wastes that could jeopardize the environment. Sustainable production systems should allow the monitoring of both the economic and the environmental performance, not only within the same production system but they should also take into consideration the external stakeholders. In fact, zero waste production is not achievable by an individual company in an efficient way, while the waste of a stakeholder can be the raw materials for another through the Industrial Symbiosis (IS). However, the IS may increase the complexity of the whole production system, where data about value-added and non-value-added activities must be collected and updated along the time. A single company could belong to several IS networks (ISNs) to exploit its various wastes, thus making the whole production system a complex network of interconnected processes.

The first part of the dissertation proposes a new method to formalize value-added (production) and non-value-added (storage, transport) activities. The proposed method aims to capture technical and environmental performance of the activities, by representing them in a way suitable both for the pen and paper analyses and for the use in accordance with the principles of the Industry 4.0 in complex production systems. The dissertation introduces two application cases: (i) it has been used in combination with Material Flow Cost Accounting and Stream Mapping approaches; (ii) it has been included in a Decision Support System and used in combination with mathematical programming approach and modules for the automatic update of data.

The second part of the dissertation focuses on the perspective of the individual firms to support them in the development of a strategy to reduce the production of waste, by increasing the value create and exploiting the remaining ones through potential IS. In this dissertation, IS is considered as a part of the comprehensive strategy to improve resource efficiency rather than a stand-alone approach. The focus is on the preliminary assessment phase of IS emergence, where the individual companies consider IS and the adoption of other technologies and operational changes concurrently to outline the best strategy. A methodology to support the individual companies in the definition of the strategy to improve resource efficiency has been developed, by including in it the relevant factors that can affect the IS emergence such as technical feasibility, economic viability, and energy and environmental policies.

The third part of the dissertation investigates the tools and methods to reduce the implementation costs of the proposed methodology within companies and the preliminary evaluation of the potential stakeholders to be involved in ISN. A Decision Support System (DSS) has been developed to reduce the implementation costs of the methodology in terms of time, effort, and knowledge, which may be limited resources especially in SMEs, thus hindering the actual spread of the sustainability culture in production systems. Then, the characteristics of the stakeholders belonging to a ISN, characterized by significant initial investments, are analyzed to support the individual companies in evaluating the potential benefits achievable by joining it. A Commitment Keeping Mechanism based on the Payback Period has been proposed to improve the robustness of the ISN and foreseen, before the negotiation phase, its potential benefits for the individual companies. Furthermore, the potential use of the Commitment Keeping Mechanism is investigated to reduce the propagation of production uncertainties of a stakeholder through the whole production network, by decoupling the current production system from the several ISNs to which a company can join.

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Introduction

Sustainable development is becoming crucial for stakeholders from many sectors ([285]; [30]) to achieve and support competitive advantage ([237]; [178]). Companies not pursuing sustainable development may incur higher costs [122] thus losing competitive advantage [42]. The economic growth should become socially sustainable and respectful of the environment, and one of the possible ways is measuring the achieved goals according to the Triple Bottom Line (TBL), i.e., social, environmental, and economic sustainability [123]. However, achieving positive results on all the three dimensions of TBL often requires different approaches in different application fields [11]. Radical changes are required in manufacturing systems [236], business models ([101]; [191]) and top management ([22]; [294]). Sustainable development disrupts both strategic ([245]; [253]) and operational levels in supply chains [40]. Eco-innovation is often considered as the practical way for the transition towards a sustainable development condition, then it fostered by many national and supranational institutions (e.g., [195]; [65]; [66]).

Pursuing Eco-innovation is promising but complex due to its emerging twofold nature: it must be born within the individual companies, but it must progressively involve the surrounding stakeholders. Sustainability is a matter of culture [21], indeed; but zero-waste production cannot be achieved efficiently by a single company [208]. Therefore, companies must invest in their capacity to reconfigure and extend their competencies according to sustainable development, i.e., sustainable development must be treated as a dynamic capability ([11], [214]). In fact, technological innovation and the circular economy paradigm alone are not decisive for the transition towards sustainable development ([232], [3]). Company cooperation and technological improvement reach together important results including the improvement of resource efficiency, which may be decisive in operational, economic, and environmental terms [24]. Resource efficiency has several definitions [241], which link abundance/scarcity of some resources with their market prices [76] i.e., the increase in value created from the same resources. Resource efficiency has been identified as the triggering factor of three among the most famous Eco-Industrial Parks: Kalundborg in Denmark [146], Kwinana and Gladstone, in Australia [270].

This PhD thesis proposes a comprehensive approach to support the transition towards the sustainable development, by focusing on the economic and environmental dimensions. New manufacturing processes can reduce the amount of used raw materials for unit of finished product, a part of the produced waste may be avoided while the remaining part may be exchanged with other companies or processes able to use it as raw material. Due to the complexity of such a comprehensive approach to improve the creation of economic and environmental value, all the potential benefits of the manufacturing revolution of Industry 4.0 have to be exploited. In the implementation of the approach proposed in this thesis, companies, even those with limited resources such as SMEs, can benefit of Industry 4.0 paradigm in several activities, e.g., the concurrent and real-time assessment of economic and environmental performances of manufacturing systems, data collection, and data exploitation through Decision Support Systems. The theoretical framework is based on Industrial Ecology and Circular Economy paradigm to propose a methodology able to support both Eco-innovation process and sustainable development capabilities of companies. The distinctive characteristic of the followed approach is the combination of system improvement solutions with the development of a cooperative network of companies where the waste are exchanged to be used as raw material.

The Istituto Italiano di Tecnologia funded and supported this research work providing data and information from the European Project ENGICOIN, 2018, where new technologies are developed and improved to produce added value chemical products from wasted carbon dioxide. This collaboration led to the development of a case study for the methodology and the analyses proposed during this PhD.

Overview of the thesis

The dissertation is organized in 5 parts: this unnumbered introductory part presents the theoretical background common to all the next parts, the aims of the thesis, and the followed methodology. Each one of the 3 central parts (from I to III) specifically focuses in a certain topic that remains crucial, and assumed given, for the subsequent ones. The last part (Part IV) concludes this thesis. Each part introduces the state of the art relevant for the topic addressed to keep it close to the contribution that this thesis provide to it.

Part I is focused on tools and methodologies to analyze and represent value creation and resource efficiency performance of systems. It highlights the pivotal role of resources into value creation process, and it is composed by chapters from 1 to 4. Chapter 1 reviews the state of the art of methods and tools available for both value and resource efficiency analysis, then it addresses the new challenges for these tools. In Chapter 2, a new formalization method, which integrates Multi-Layer

Stream Mapping with a combination of Material Flow Analysis and Enterprise Input-Output (MEIO-SM), is proposed together with its application into the value creation process analysis of the case study InnovaEcoFood. Chapter 3 introduces the EngiCOIN project and the company Acea Pinerolese, then it focuses on the synergies of the MEIO-SM (introduced in Chapter 2) with Industry 4.0 paradigm for automatic update of the formalization, to finally apply MEIO-SM in its mixed deterministic-stochastic version to Acea Pinerolese. Finally, Chapter 4 summarizes and concludes Part I.

Part II addresses the Eco-innovation process within the individual company. A novel comprehensive and holistic methodology is proposed to support the single companies in the continuous pursue of Eco-innovation. Generally, eco-innovative approaches are oriented to one dimension of Eco-innovation at a time: product, process, or organizational, although holistic approaches can bring better results in economic-environmental terms. The proposed methodology includes Industrial Symbiosis (IS) in the overall strategy to improve resource efficiency, by reducing waste production and inefficiencies, and exploiting the remaining part of waste to create value through IS. The methodology fully exploits the MEIO formalization tool to model the processes of the system. A mathematical programming model represents the physical systems and, through the exploitation of processes modeled with MEIO approach, provides managerial insights about both the technologies useful for improving productivity through waste reduction and the other technologies to exploit the remaining wastes via IS network. Part II presents in Chapter 5 a methodology to lead individual companies through the Eco-innovation process. The methodology is based on the concurrent evaluation of IS opportunities and system improvements. In Chapter 6, the methodology is applied to Acea Pinerolese case study by exploiting EngiCOIN technologies. Chapter 7 summarizes the insights and concludes Part II.

Part III investigates the internal perspective of the firm about the proposed tools and how to design the Eco-Industrial Park and Supply Chain to ensure stability to the entire network; hence, Part III keeps to maintain the focus on the single company, but it considers interactions with other potential partners. It aims to investigate the presence of potential barriers and drivers, caused by specific characteristics of the potential partners, of the network opportunities identified in Part II. The objective is identifying the best opportunities of network development by aiming to anticipate the emergence of opportunistic behaviors in some of them. Part III proposes an initial state of the art of design and mechanism tools to increase network resilience, and coordinate company behaviors, beyond the tools devoted to support companies in the Eco-innovation process. It collects chapters from 8 to 10. In Chapter 8, the digital tools able to support companies in resource efficiency are introduced, then followed by the Decision Support Tool developed for the case of

Acea Pinerolese. Chapter 9 introduces the commitment keeping mechanisms concept and the mathematical model to identify the fairest allocation of investments and contributions. Chapter 10 highlights the results of this Part, by summarizing all the contents.

Finally, Part IV puts together the managerial insights from Part I to Part III, the benefits of Eco-innovation methodology and how it changes when IS opportunities are considered. Chapter 11 is dedicated to the discussion of both managerial insights and mathematical representations. Chapter 12 summarizes the scientific and industrial contribution of this PhD thesis, highlighting the new research questions for the scientific community and concluding this document.

Theoretical background

The last forty years have been characterized by an increasing awareness of the human negative impacts over the environment. This growing awareness has triggered a profound reflection on the entire sustainability of the economic value created in terms of human and natural capital. New economic paradigms and research fields have emerged to investigate barriers and drivers to guide economic activities in the transition to sustainable development worldwide.

Sustainable Development

Sustainable development (SD), i.e., the consideration of environmental and social dimensions together with economic growth to measure the development of human activities, is traced back to the centuries. Campos-Filho et al. [41] highlight one of the ancient regenerative activities, i.e., tree direct seeding described, was already introduced by John Evelyn's essay of 1662 [84] to limit the effects of the over-exploitation of timber, while Hahn and Knoke [121] recall Von Carlowitz [277] and his Sylvicultura oeconomica of the 1713. However, SD starts to spread in modern time in 1960s, when three different topics arise: (i) the use of common resources to satisfy individual interest while jeopardizing those of all the others (the tragedy of commons of Garrett [104]); (ii) the dangerous effects on environment and biodiversity (the negative effects of pesticides supported by Carson [45]); (iii) the awareness of limited amount of resources for all the human needs (the concept of "spaceship Earth" [34]). In 1972, the club of Rome pointed out the impossibility of infinite growth in a world of limited resources through the publication of the report "Limits to Growth" in collaboration with the Massachusetts Institute of Technology [185]. Since the oil crisis of 1973, the relevance of the dependence on limited resources became an issue common to the entire world. In 1980, the United Nations adopted the "World Charter for Nature" based on five principles used to judge every actions affecting environment [282]. In 1987, the most famous definition of SD has been diffused by the United Nations World Commission on Environment and Development through the report "Our common future" also known as "Brundtland Report" from the name of the president of the commission:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

SD initiates to be intended as a goal of socially inclusive and environmentally sustainable economic growth. In 1993, the Agenda21, which is the action plan to achieve a worldwide SD by 21^{st} century, was published by the UN Conference on Environment and Development, also known as Rio Summit [268]. In 2000, the Millenium Development Goals, eight goals for SD alongside the Agenda21, were defined by the Millenium Summit of the United Nations [267] and fixed for 2015. Rio Summit were supported from Rio+10 (World Summit on Sustainable Development (Earth Summit 2002)) and Rio+20 (United Nations Conference on Sustainable Development). In 2015, new goals of sustainability have been set for the 2030 during UN Sustainable Development Summit in 2015, and they are the 17 Sustainable Development Goals (SDGs), in Figure 1, which define the Agenda 2030 [195]. From 2015, many national and supranational institutions are supporting programs to foster SD, also through the spread of circular economy [65].

Figure 1: The 17 Sustainable Development Goals defined by Agenda 2030.

Circular economy and Industrial Ecology have a crucial role in this field, and they represent the essential bases for approaching the SD. This section presents the state of the art of Circular Economy (CE), Industrial Ecology (IE), and SD together with their implications for company activities.

The Circular Economy

Circular Economy (CE) paradigm is mainly intended as a way to lead economic prosperity through recycling, reuse and resource reduction [155]. Even though SD was not among the factors that determined CE conceptualization [155], its intrinsic characteristics have direct and positive effects on it. Nowadays, the relationship among SD and CE has been widely recognized and made explicit, by underlining especially the characteristics of regenerative system, waste reduction and resource efficiency improvement ([107]; [175]). CE does not focus specifically on network of companies instead of stand-alone companies; however, it has a relevant influence in Supply Chain Management (SCM), especially for the implementation of 6Rs networks (i.e., Reduction, Reuse, Recycling, Recover, Redesign, Re-manufacture) ([116]; [16]). The goals of stakeholders within a SC and an Eco-Industrial Park (EIP), i.e., a network of Industrial Symbioses, are different, and this difference affects the emergence of different strengths and weaknesses of SC and EIP. Stakeholders of a SC are all oriented to the satisfaction of the same customers' needs, while in an EIP there is an exchange of waste to achieve a greater overall resource efficiency [240]. However, SCs and EIPs can lead a company towards two opposed directions, by forcing it to make a decision. Furthermore, Figure 2 shows that there is a hierarchical preference of actions to reduce the overall environmental impacts [141], however, according to the competencies of the involved SCs, SC could be oriented to other actions.

*As a minimum, waste should be disposed at a "controlled dump," which includes site selection, controlled access, and where practical, compaction of waste. Incineration requires a complimentary sanitary landfill, as bottom ash, non-combustibles and by-passed waste needs to be landfilled.

Figure 2: The hierarchical preference of actions to improve environmental performance [141].

Eco-innovation

Eco-innovation is assuming a crucial role in the achievement of SD targets. In the last decade, Eco-innovation is attracting the attention of scholars, practitioners, institutions, and companies because it helps to improve economic and environmental performances [39] and it can lead to cost savings through the improvement of corporate image, production efficiency, organizational capabilities [73]. Eco-innovation may help companies to achieve competitive advantage [71] by leading to larger advantages than non-eco innovation [26]. In fact, a sustainable business model is a key factor for achieving the competitive advantage, and it cannot neglect the sustainable operations [182]. Furthermore, it is determinant for the transition towards CE in many ways and fields ([71]; [72]). For this reason, Eco-innovation has been defined in a deliberately broad way by the Eco-Innovation Observatory of European Union [197]:

> "(It is the) introduction of any new or significantly improved product (good or service), process, organizational change or marketing solution that reduces the use of natural resources (including materials, energy, water and land) and decreases the release of harmful substances across the whole life-cycle."

Three levels of Eco-innovation have been proposed to separately refer to different scopes: (a) macro, (b) meso, and (c) micro level ([53]; [71]) At macro level, the research focuses on regional performance through the development of indexes to measure the advancement in Eco-innovation [53] and Eco-efficiency [184]. At meso level, the research addresses the environmental effects of the innovation on networks of companies to drive policies and regulation [205], whilst, at micro level, it focuses on the individual companies.

From the micro level point of view, the research results fragmented [126] due to its pervasive effect. In fact, Eco-innovation influences the performances of the companies at any level, from the strategical management to the operational one, and in any business function, from the production and the new product development functions, up to the interactions with the other companies. Therefore, at micro level, Eco-innovation is commonly identified through its three dimensions:

1. **process Eco-innovation**, the adoption of new technologies and the changes in the manufacturing chains that allow to achieve a better environmental performance;
2. **product Eco-innovation**, the development of new products that are more environmental friendly in the whole life cycle, e.g., by designing them for the disassembly and recycle;
3. **organizational Eco-innovation**, any changes within the company structure or the manufacturing chain that facilitate the pursue of process and product Eco-innovation.

These dimensions are often individually addressed, even though, to be effectively pursuit, Eco-innovation should be concurrently treated along all the three dimensions by using holistic approaches [55]. Organizational Eco-innovation facilitates the adoption of product and process Eco-innovation, whilst they altogether impact on business performance. Furthermore, organizational Eco-innovation lowers the barriers, favoring the continuous improvement brought about by the Eco-innovation process [55]. Organizational Eco-innovation is assuming an increasing importance also because it is spreading the necessity of multi-stakeholder approach. Multi-stakeholder approach helps to increase the efficient use of resources [168], and, also, within the same company, the interactions among professionals from different departments can lead the product Eco-innovation ([150]; [286]).

Industrial Symbiosis

Industrial Symbiosis (IS) comes from Industrial Ecology, and it is a relationship between companies or processes where wastes are exchanged to be used as raw materials. Industrial Ecology (IE) is pivotal for the transition towards a regenerative CE ([72]; [228]), due to its focus on material exchanged flows between environmental and anthropological ecosystems [117]. IS is in continuous evolution [31], but it remains a source of competitive advantage [135]. Originally, IS was considered relevant only to increase resource efficiency by using waste as a raw material [102]. Later, IS demonstrated to be effective as a tool for fostering eco-innovation-based company networks [172], and as a way to lead entities to gain a greater collective benefit ([57]; [56]). Entities exchanging wastes through IS form an EIP.

The path towards SD cannot neglect CE and resource efficiency, of which IS is one of the major drivers ([248]; [81]). However, IS is struggling to widespread through the industries and practitioners ([110]; [139]; [186]). Inhibiting factors acts at different scale level, and they also change with the evolution of IS from its preliminary state (identification) to its implementation, maturity and the final disruption [288]. Literature has been focused for more than a decade on removing barriers to IS emergence and development, by supporting it through new tools, and analyses of both networks and behaviors of initiators and tenants. Many tools have been proposed mainly focused on three areas: (a) the identification of opportunities of resource exchange (Input-Output Matching tools), (b) modeling aggregation scheme of several stakeholders (Stakeholder Processes tools) and (c) analysis of sources and sinks of resources and wastes (Materials Budgeting tools) [57]. ICT tools, mainly oriented to IS identification and/or IS assessment, have been developed to facilitate companies in designing and implementing IS by their own. ICT tools based on IS identification usually cover three areas: (i) New Process Discovery, (ii) Input-Output Matching and (iii) Case Study Mimicking [118]. Each one of them has a different focus, i.e., (i) it is mainly oriented to new technologies to create value from waste adoption, (ii) it aims to provide tools to analysis and model real system to facilitate the identification of opportunities for IS; finally, (iii) it tries to replicate successful cases of IS. The three areas are sorted in a descending order of effort required to develop IS: in (i) new technologies are required and larger investments are likely necessary, in (ii) the management of the complex network of stakeholders' resource flows and their cooperation are crucial, whilst (iii) can lead to an IS easier implementation thanks to the application of best practices studied in other IS. These three points have been addressed by several research projects to overcome the 7 barriers to the diffusion of IS, identified by [112]:

1. **Lack of commitment to sustainable development.** Several reasons affect the lack of commitment of companies in SD, and more specifically in IS. Even into one of the most successful EIP, i.e., Kalundborg, the commitment to the IS is limited and the recurring reason is the investment allocation. Investments for IS, and SD, are bounded to their economic return by limiting the commitment of companies [269].

2. **Lack of information sharing.** Confidentiality reasons and technological issues limit the sharing of information data through the network, affecting the IS performance [91] and emergence [98].

3. **Lack of cooperation and trust.** Cooperation is fundamental for IS; in fact, network resilience and robustness are relevant issue. Operational performance of companies can be damaged by opportunistic behaviors [206], increasing normative bureaucracy [149] and, lack of commitment of partners [48].

4. **Technical infeasibility.** Some IS projects require the introduction of emergent technologies to find a way to use some wastes as raw materials [75]. However, these technologies could not be enough performant [14], or the paces of manufacturing systems could not be compatible with their efficient adoption [129]. In that case, IS emergence or development could be limited by endemic causes of a specific region or industrial field.

5. **Uncertainty in environmental legislation.** Environmental and energy legislation change rapidly, and companies are worried about not being able to recoup the investment [206].

6. **The lack of awareness from communities.** IS is tightly connected to the local community where it is settled. Local authorities are increasing the attention to the exploitation of local wastes and resources [9]; however, the interaction between individual companies and local needs is a widespread difficulty [120].

7. **Economic infeasibility.** IS must be able to address also economic sustainability [289] to be effectively a driver of competitive advantage [99], tax reduction [96], and resource efficiency [180]. However, economic feasibility depends on the entire network [48], the available technologies [75], the commitment and power of partners [128] and much more. Often, it is difficult

for companies to have a realistic idea of economic feasibility a priori, which is one of the main drivers of IS emergence [192].

MAESTRI project dealt with them by proposing a library of IS case studies and several KPIs and methods to analyze systems and identify opportunities for IS [19]. The EPOS' methodology has a funnel approach to implement IS through the improvement of commitment, cooperation and trust of involved companies in Humber region [51]. Blueprint methodology is mainly focused on overcome trust and cooperation barriers through a safe preliminary exchange of data among companies to assess opportunities for IS [52].

Resource efficiency, like the most of the aspects of SD, has a twofold nature: it should be born within the individual company; however, to be effectively pursuit, it must necessarily involve the entire local community, i.e., the aggregated demand of products and production of wastes of households and economic sectors. Zero waste production systems are not economic sustainable within an individual company [208], and also in IS there is no guarantee of zero waste [138]. Furthermore, CE and technological innovation are crucial but non-sufficient clauses to achieve SD ([3]; [232]). SD is a dynamic capability, and dynamic capabilities must be supported from their emergence to their continuous improvement within companies. Also, IS needs the development of its own dynamic capabilities, which involve six aspects according to [140]:

1. having dedicated team for specific waste streams;
2. leveraging on cross-functional knowledge;
3. better time management;
4. creating employee engagement for IS;
5. creating networks in anticipation of new waste streams;
6. ability to replicate good sales team for waste streams.

There are many studies in literature focusing on both the community characteristic of resource efficiency and the one individual, but no one, at author's knowledge, addresses resource efficiency by considering its twofold nature although it is crucial to support companies in this path. Furthermore, a comprehensive approach to support diffusion of IS must address also the environmental and economic context where the companies are settled [188]. The economic context must take into consideration that, nowadays, individual companies are part of networks whose the complexity of requirements is increasing to respond to the needs of resilience, stability and competitiveness. In fact, the competition moved from the single companies to the entire SCs [74], and the new paradigm to achieve better performance is the Reconfigurable Supply Chain [80]. Hence, IS development must be compatible, flexible, and dynamic over time to adapt to the general need of the respective SCs.

Aims of the thesis

This PhD dissertation explicitly aims to bring its contribution to some of the SDGs through its various tools and approaches proposed. SDG 9, i.e. "Industry, innovation and infrastructure" is central all over the thesis since the topic of Eco-innovation and its impacts on both the economic and environmental performances of the companies is the common leitmotiv. SDG 12, i.e. "Responsible consumption and production" is embodied by the resource efficiency concept, where waste are reduced, and they are exchanged with stakeholders able to reuse them as raw materials. Minor contributions are provided to SDG 7, "Affordable and clean energy", and SDG 17, i.e. "Partnerships for the goals". A Waste-To-Energy Supply Chain has been used as case study to improve the value created from waste and reduce the emissions; at the same time industrial partnerships to improve the reuse of waste and by-products and reduce the extraction of virgin resources, especially those not renewable, is fostered.

The thesis aims to propose a comprehensive approach to enhance resource efficiency in manufacturing companies, especially SMEs, which have limited resources in terms of knowledge and investment availability. IS is crucial for the comprehensive approach, thus the thesis addresses the seven IS barriers by considering concurrently the three main areas of research previously identified , i.e., (i) evaluate the adoption of new technologies enabling new IS, (ii) manage the complex network, and (iii) lower the barriers to IS development and diffusion. Figure 3 underlines the three-dimensional approach of this PhD thesis to the resource efficiency.

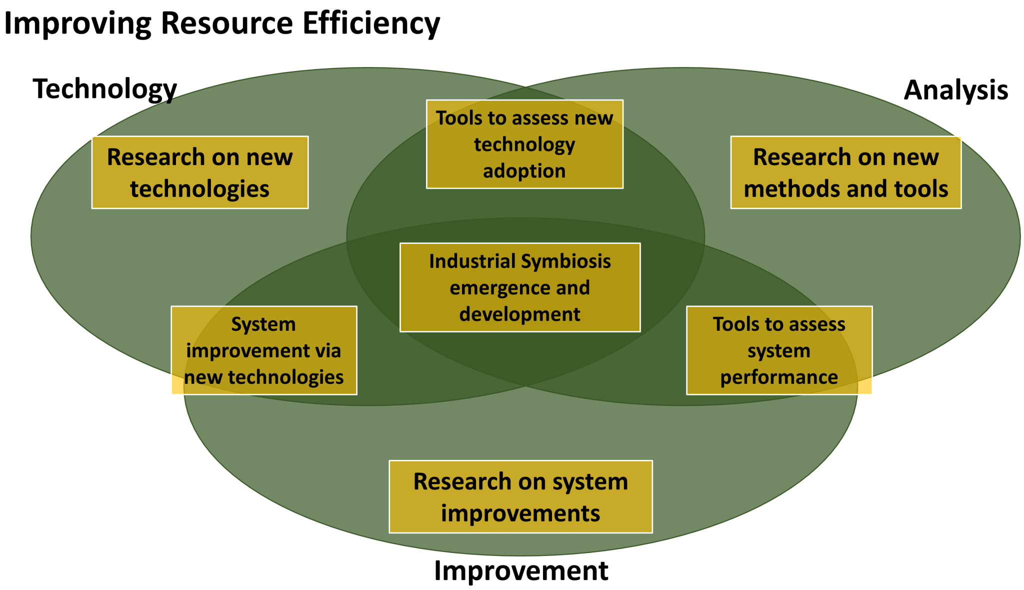


Figure 3: The three main research domains of resource efficiency improvement addressed.

Figure 3 sheds a light on the pivotal role covered by the intersection of the aforementioned Technology-Analysis-Improvement around which the entire thesis work is centered. This thesis addresses IS emergence and development by taking into consideration all of the three highlighted domains. In the literature, there are six steps to implement IS: (1) preliminary assessment, (2) engage business, (3) find synergy opportunities, (4) determine feasibility, (5) implement transactions, and (6) documentation [293]. However, companies approaching resource efficiency through IS for the first time need a wide and simultaneous of perspective on all the required phases to implement it. Furthermore, sometimes the retroactive assessment of these steps is not efficient nor effective as the simultaneous consideration. New technologies are fundamental both for IS development and for SD; in fact, the most recent studies have been showing how positively SD is affected by the integration of sustainable value analysis with new technology assessment [87]. Moreover, new technology assessment is carried out by private companies as part of technology forecasting and road-mapping activities, thus the individual companies themselves cannot be overlooked. New technologies can be applied not only within IS but also for the improvement of production systems, and the convenience in opting for one solution rather than the other or a combination of both depends on the specific context where the focal company is. Hence, IS development is one of the alternatives that must be considered together with the others [229]. IS becomes part of the comprehensive strategy of a company to enhance resource efficiency. Finally, a well-rounded and comprehensive approach to resource efficiency should integrate also tools and methods able to support companies in both the practical implementation of the strategies and in the analysis of potential benefits and arising risks. Therefore, Part I proposes a method to support the concurrent analysis of value creation and economic, technical, and environmental performance of manufacturing systems. Part II introduces the comprehensive approach and Part III focuses on Decision Support System and analysis to support both the practical implementation of the approach and the analysis of potential benefits and arising risks.

This research is strongly linked with the economic sectors to favorite the diffusion of sustainable manufacturing processes by providing their adoption through the Eco-innovation process of companies. Hence, a special attention is given to the twofold nature of resource efficiency to foster the development of dynamic capabilities of individual companies, while helping them to the understanding of strategies for combining system improvement and IS opportunities. SD is the objective, resource efficiency is the target, and IS is one of the key players of the Technology-Analysis-Improvement approach. Barriers and drivers of IS (previously listed in subsection Industrial Symbiosis) are the same barriers and drivers of this research and with them it must be confronted. This document neglects the second and the sixth barrier of the seven identified by [112], i.e., "Lack of information sharing" and "Awareness of local communities". All the others are central for this research; more specifically, "Lack of commitment to sustainable development", "Technical infeasibility", and "Economic infeasibility" are the main targets of the thesis. Uncertainty in environmental legislation is deepened in a specific chapter of Part II due to its relevance not only for the SD but also for the robustness of networks and technology adoption. Part III deals with the "Lack of cooperation and trust" within the proposed approach. Addressing "Lack of commitment to sustainable development", "Technical infeasibility", and "Economic infeasibility" means to take into consideration the process of value creation from waste. To overcome the barrier of limited investments in SD it is necessary increasing the amount of value created to raise the bar. However, both the waste and byproducts reduction and the recovery through the exchange not always lead to a sufficient creation of value to close the resource loops. Value creation is particularly jeopardized especially in those cases where resource waste has no value, there is no cost for their disposal in the environment, and large investments are required to achieve the end-of-waste condition. This research fosters companies to collect data about any resource disposed in the environment, in any case. Later, IS opportunities and options for system improvement will be assessed to increase created value. Furthermore, the role of new SCs, i.e., those stemming from IS networks, is investigated to produce and supply new products via waste an by-products exploitation. The integration of IS and SCs, by ensuring technical feasibility, is able to increase the aggregated value creation and stimulate the commitment in SD. New crucial issues emerge when SC and EIP are concurrently designed because proper network design and network robustness are sources of competitive advantage ([115];[46]).

Methodology

The initial literature review showed the multidisciplinary aspect of the resource efficiency enhancement in manufacturing systems. In fact, it cannot be achieved either through the alone company cooperation or the technological advancement, but it depends on both of them and also the economic, cultural, and normative context. The entire literature review has been separated through the three central parts of the thesis to focus on the state of the art of the specific topic addressed, even though all the parts are intertwined.

The qualitative approach has been followed to develop the proposed quantitative tools and methods, and to define the comprehensive approach to improve resource efficiency and analysis the arising risks and the potential benefit. This work is based on the assumption of realism because the data exploited, the knowledge, and the final results are intertwined with economic, cultural, and social context, then they may not be universally shared, even though the relationships among factors are studied on the international literature. The abductive approach has been followed in each part of the thesis, by alternating the inductive development of methods and methodologies, on the basis of the state of the art, and the deductive approach in deriving insights from the application of case study methodology. The thesis fosters the resource efficiency improvement in manufacturing systems, by providing tools and practical methodologies to support companies in improve their economic and environmental performance. Two methodologies have been followed in different parts of the thesis to meet: (i) the need of developing the comprehensive approach and the supporting tools, and (ii) validate their effectiveness. The action research methodology has been applied to develop the methods and tools for modeling the manufacturing systems to control and improve their economic, technical, and environmental performance. The case study approach has been used to finally test, improve and then validate the proposed tools and the methodology.

The action research methodology has been applied by iteratively develop and test the methods, tools and the methodology developed, by collecting the feedback of the company and the other stakeholder involved in the several projects. Their initial frameworks come from the state of the art, the initial implementation is proposed to the research partners and, through the interaction with them, tools, methods and methodology have been improved. Then, the case study methodology has been applied in different cases to deduce insights about their effectiveness in the resource efficiency improvement. The single parts of the thesis provide deeper information on the reason of the selection of the case study, the collection of data, and the specific methodology used.

Part I

Value creation and resource efficiency: tools and methods for analysis and modeling

Chapter 1

State of the art and new challenges in value creation analysis

The improvement of resource efficiency requires tools to analyze and model current and future use of resources whether they are raw materials, consumables, water, air, or energy. Moreover, the constraint of economic feasibility for both the focal companies and the other involved in the network requires the analysis of a further element: the created value.

1.1 Value creation, sustainable development, and current manufacturing paradigms

Value and added-value are largely discussed in the literature and their definitions change from a field to another [69]. The general definition of value as "what buyers are willing to pay" [215] can be sophisticated by introducing the required resources for the production of goods, i.e., the value concept can be referred as the ratio between the satisfaction of functional requirements and the amount of resources used to meet customers' requirements [224]. Hence, value analysis can be normally used to increase product value and/or cut costs [224]. Commonly, the value creation process is intended as a linear flow (a stream) crossing all the activities until the delivery of the final product [215] to the customer; hence, its analysis is said "value stream analysis". Value stream analysis allows to identify waste within the system, i.e., those activities ancillary to production system that customers do not want to pay for [5]. Lean Management aims to reduce waste and non-added value burdens within companies to make them performing and reactive ([199]; [61]). Generally, Lean Management identifies 8 types of waste: (1) defects, (2) inventory, (3) motion, (4) overprocessing, (5) overproduction, (6) transportation, (7) waiting and (8) waste of human potential [199]. The most famous tool to identify sources of waste is the Value Stream Mapping (VSM) [5]. It is able to identify activities that contribute to the form, fit or function of the product that customer need. The efficiency of these activities must be improved, while the others, which do not provide the contribution to the product or service, should be avoided or limited ([37];[244]). Thanks to its general approach, it is widely used to improve performance in many industrial fields and applications also different from the production control such as, service organizations [250], in cruise ship design [224], facility layout design [159].

VSM has been improved in these decades to deal also with the future states of the system and their sources of waste [221], and incorporate risk management [275]. However, the new industrial revolution, i.e., Industry 4.0 (I4.0), is introducing new technologies and paradigms, which are disrupting methodologies and tools to manage operations ([90];[200]) and value creation ([194]), paving the way to new paths for pursuing sustainable development [89]. However, the interactions with Lean principles, whether positive and negative, are not completely clear yet [231]. In some cases, new technologies can improve the effectiveness of some principles of Lean [230]. Tortorella et al., [264] highlights that the adoption of new technologies should be driven by the pursuit of Lean principles; however, they underlined the difficulties of Lean approach to deal with the increasing amount of data and system complexities. The risk of using new tools in obsolete way exists, by precluding new paradigms [156] and struggling to achieve better results in sustainable development. In fact, the large potential of I4.0 and digitization could positively affect only few principles of Lean Manufacturing, i.e., Just-in-Time and Jidoka, while one of the most neglected is waste reduction [226]. For example, VSM is struggling to include the information about all the used resources and the outcomes of its application depend on the arbitrary choice of the flow unit for the analysis [244]. Recently, also value chain model is becoming inappropriate to represent the value creation process in current production systems. Daaboul et al. identify three main limitations of considering production systems as a chain ([68]):

1. value considers only financial dimension as the turnover of the costs of activities;
2. activities are modeled in a specific and sequential order;
3. interactions between activities (both within the production system, and external such as supply chain partners) and their effects on created value are neglected.

The value creation networks are more complex than linear chains [5]. Furthermore, they are affected by trends and seasonality of several industrial fields with potential disruptive effects on economic and environmental performance, and they must be analyzable from many points of view rather than in sequential way as if they were a chains. Furthermore, any networks of companies need approaches exploiting and supporting digitization and I4.0 to achieve reconfigurability [32] and flexibility [281]. For this reason, synergies and compatibility of the tools of the Lean Manufacturing with digitization and I4.0 have been gaining scholars' interest. The various tools of Lean Manufacturing are useful for cost-based activities; however, [5] argued that the main issue is the lack of a formalism to objectively decompose processes in elementary unities to be managed. The lack of formalism explains why most of the tools and methodologies neglect the idea of open system architecture and standardized Computer Integrated Manufacturing modules supporting the 'plug and play' approach [5], fundamental for I4.0 framework. The new production system complexity is fostering the use of simulation, where the word "simulation" is used in the broadest sense of the term according to [63]:

> "Simulation modeling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system."

There is an increasing interest in combining Lean and simulation techniques [111]. Simulation is becoming relevant also for the investigation of new technologies, processes, and system layout [193]. Daaboul et al. propose the value network analysis through Discrete Event Simulation (DES) [68], Agyapong-Kodua et al. propose an enhancement of VSM through DES and system dynamic combination [5].

1.2 Environmental performance mapping tools

Tools and methods to map and analyze environmental performance are generally focused on the use of resources, their origins, and how they will be disposed at their end-of-life. These three steps can be considered the interface between the industrial and the environmental ecosystems. All the actions to mitigate the environmental impacts are in this interface. The three goals are: (i) the reduction of non-renewable resource extraction (such as fossil resources); (ii) avoiding pollutant emissions or waste with a secular path of degradation; and (iii) return to the environment substances capable of regenerating environmental resources production. These three goals are achievable through the cooperation of several stakeholders specialized in different phases of the resource transformation process. The whole resource transformation process aims to extend as much as possible the life-cycle duration of resources, at least up to the complete reuse of polluting waste. Figure 1.1 shows the resource transformation process through several actors involved in the so called 6Rs (recover, reuse, repair, remanufacturing, redesign, recycle)([16];[116]).

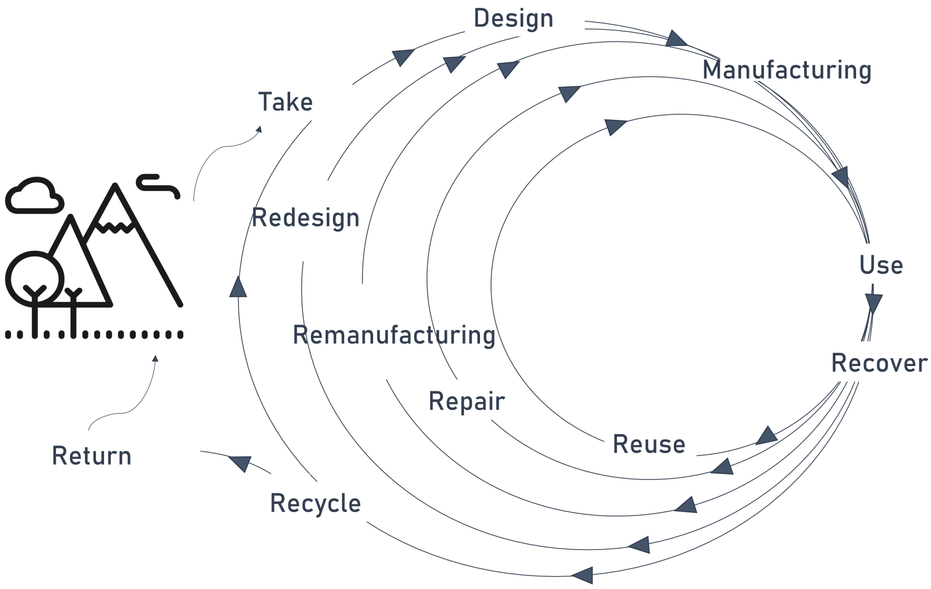


Figure 1.1: The 6Rs in circular and regenerative economy.

Stakeholders' interactions and exchange points between industrial and environmental ecosystem are pivotal for environmental performance analysis. Hence, tools to analyze and represent systems are mainly focused on resource flows and resources used or produced by transformation processes.

Input-Output models. Leontief in 1951 [167] introduced Input-Output models to study the American economy through resource flows among economic sectors. Input-Output analysis provides tables (namely, Input-Output tables) where rows are source sectors and columns are sink sectors. Products produced by sector in row i are absorbed by sectors in columns, according to their requirements. Table 1.1 shows the classic example of interactions between agriculture and industry. Agriculture provides products, which are partially used for supporting the production itself (row 1, column 1) and partially offered to the industrial sector for feeding workforce, for example (row 1, column 2). Accordingly, Industry provides products for supporting Agriculture (row 2, column 1), e.g., tools, and those for supporting its own production (row 2, column 2). The third column shows the total production for a resource, while the third row shows the requirements of each sector, usually expressed as amount of required money. The ratio between the resource x required and the total amount of resource y produced can be used to compare different systems, as it were such a type of resource productivity.

	Agriculture	**Industry**	**Total**
Agriculture (wheat kg)	40	60	100
Industry (iron kg)	40	40	80
Total (€*kg)	40*p_{wheat}+40*p_{iron}	60*p_{wheat}+40*p_{iron}	100*p_{wheat}+80*p_{iron}

Table 1.1: The IO table for a two-sector economy.

Input-Output tables have been extended to include also waste production and abatement activities [166]. Enterprise Input-Output (EIO) has been introduced to model and analyze the interactions among processes within a company [7]. Table 1.2 shows the application of IO tables to enterprise through a numerical example with four manufacturing processes (A, B, B', C), 2 intermediate products (P1, P2), 3 types of waste (W1, W2, W3), 1 finished product (FP), and 4 raw materials (RM1, RM2, RM3, RM4). Process B' uses imported intermediate products. The columns of the matrix represent the manufacturing processes and the last column is the total final demand, or the amount produced/consumed. The matrix is divided in four parts: (i) manufacturing processes outputs; (ii) imported finished or semi-finished products; (iii) materials and energy; (iv) byproducts and waste. In (i) rows are manufacturing processes, and the output of a process is the input of another. In (ii) there are production processes provided with imported finished products. In (iii) rows are the various raw material required and energy source such as gas or power. In (iv) the rows are waste and byproducts produced by processes (in columns).

		Process A	**Process B**	**Process B'**	**Process C**	**Total Demand/ Consumption/ Production**
(i)	**A (q. P1)**	500	-250		-250	
	B (q. P2)		100		-100	
	C (q. FP)				400	400
(ii)	**B' (q. P2)**			100	-100	
(iii)	**RM1 (kWh)**	-20	-50		-50	-120
	RM2 (kg)	-20	-30			-50
	RM3 (kg)		-10			-10
	RM4 (l)				-30	-30
(iv)	**W1 (kg)**	20	50		20	90
	W2 (kg)		30			30
	W3 (kg)		40		40	80

Table 1.2: EIO for a manufacturing system with 4 production processes.

EIO tables have been used to analyze and represents the exchange of resources within complex systems (e.g., supply chains [8]), and usually applied in combination with other techniques, e.g., agent-based simulation, which exploit its system representation [289].

Material flow approaches. Material Flow Analysis (MFA) statically describes the flows of resources (or substances, [133]), which are both used and produced by companies or processes (e.g., [247]). It can deal with parameter uncertainty (e.g., [43]) and the conditions of limited information [238]. MFA tracks resources and energy from their introduction into the system to the sales or disposal point [227]. Figure 1.2 shows the application of MFA in a Waste-To-Energy (WTE) Supply Chain (SC) through a Sankey Diagram, where biogas produced from waste is burnt in Combined Heat and Power (CHP) to produce power and heat for self-consumption and market demand. Fossil methane can be purchased to produce extra heat via boilers. MFA application highlights resource sources, production and disposal, by shedding a light on all the resources involved in a manufacturing process, usually neglected to favor the tracking of the finished product. Figures 1.2 and 1.3 report the results of an analysis oriented to determine the role of the resource within the production system of a WTE-SC sited in Piedmont, Italy (the name is omitted for confidentiality reasons). Then, the economic value of the waste has been assessed with the Material Flow Cost Accounting introduced later.

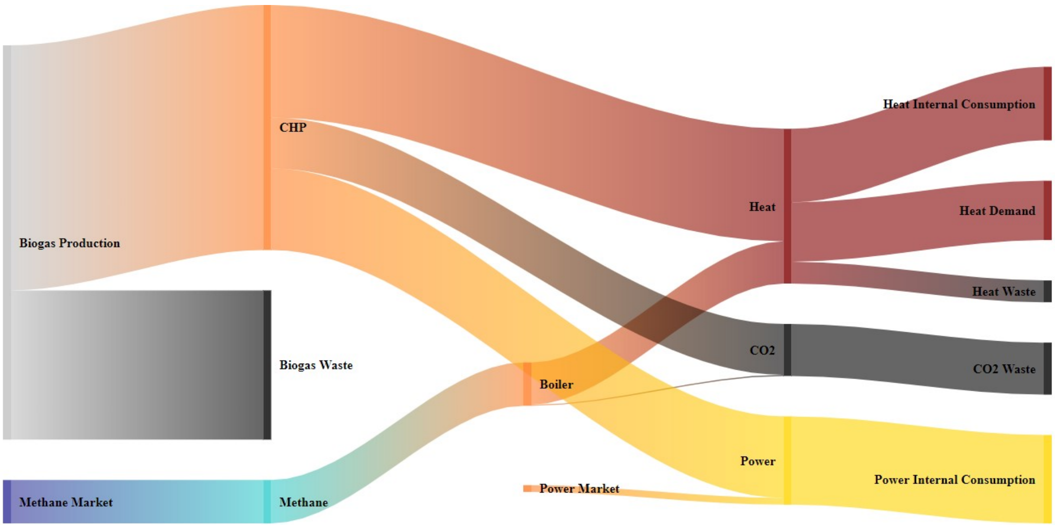


Figure 1.2: Sankey Diagram of Material Flow Analysis in a Waste-To-Energy Supply Chain.

Material Flow Cost Accounting (MFCA) approach starts from MFA and goes deep into the economic value of resources by separately considering material flows, services, economic indicators and energy consumption ([77]; [145]; [1]). MFCA is focused on resource management [223], by reducing waste and scraps [173] and improving productivity [202]. It underlines the contribution of each specific resource to value creation and when a resource is disposed as a waste, it represents a cost. In fact, waste disposal has some clear costs such as environmental taxes, disposal taxes, and the variable costs connected with the disposal activities. However, MFCA allocates part of the operational costs of the process source of waste also to waste rather than only to process outputs, e.g., CHP in figure 1.3 has several operational cost of maintenance and resource consumption, which usually are allocated to power and heat produced; MFCA spreads them also on the produced carbon dioxide (CO_2). Figure 1.3 shows the application of the MFCA to the previous example. This Sankey Diagram provides economic information of resource use: the internal consumption is an avoided cost, while external demand is a direct revenue, market purchases are direct costs. Wastes (biogas and CO_2) are an environmental costs, and a missed revenues due to poor resource efficiency. Figure 1.3b shows the same example with the introduction of two processes: biomethane purification to use biomethane rather than direct use of biogas; biofuel production from the produced biomethane. The resource efficiency increases as much as the profit per Nm^3 exploited, biogas is completely converted in biomethane or in CO_2, and CO_2 remains the only waste. Furthermore, the market purchase of power increases, however, fossil methane purchase is eliminated, and demand for biofuel and biomethane emerges.

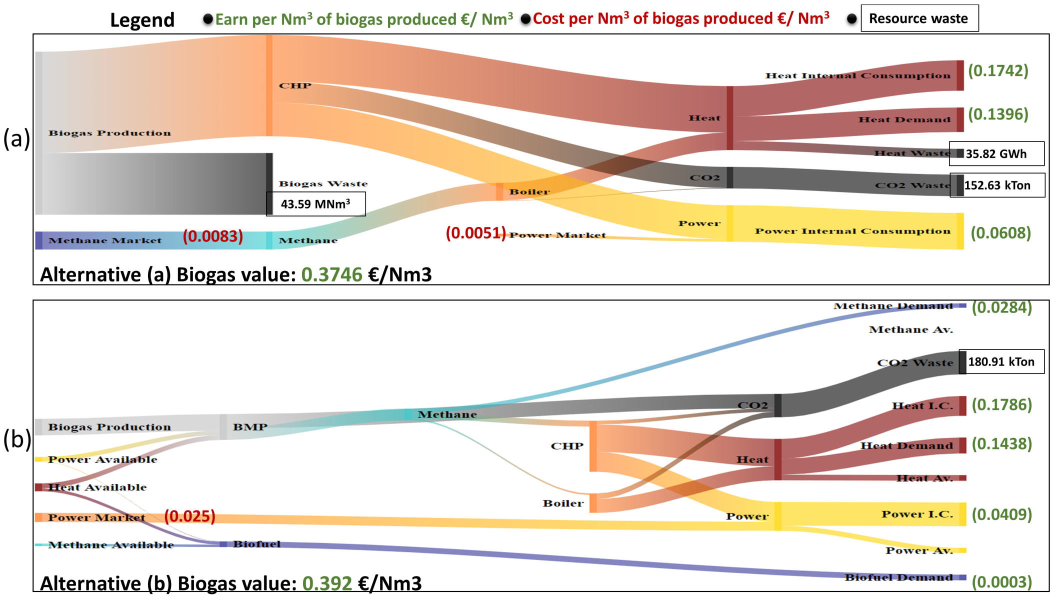


Figure 1.3: Sankey Diagram of Material Flow Analysis in a Waste-To-Energy Supply Chain.

MFCA allows the analysis and the representation of complex resource flows, by leading the identification of sources of missed revenues, poor resource efficiency exploitation and sources of waste. Hence, a deep economic perception of the costs of waste helps to foster accurate alternative identification to support economic and environmental sustainability. Four different cost streams are considered: (i) Material costs; (ii) Energy costs; (iii) System costs; and (iv) Waste management costs [255]. In the proposed analysis, it is shown the amount of wasted resources instead of their costs, which requires further assumptions. In fact, several techniques to evaluate waste costs exist identifying them as both fixed and variable costs [85], and they are evolving over time [278], e.g., from missed revenues it could be extended with manufacturing scrap [152], environmental taxes, disposal costs. The four types of costs are assessed in each activity of production, stocking or transportation, which are called Quantity Centres (QCs) [119]. In figure 1.3 they are: (i) biogas production, (ii) CHP, (iii) boilers, (iv) BMP, (v) biofuel production.

VSM-based: the Multi-Layer Stream Mapping approach. Stark et al. defined the four scope areas of sustainable manufacturing [251]:

1. Manufacturing technologies, which involves process and equipment;
2. Product lifecycles, product and design centered;
3. Value creation networks;
4. Global manufacturing impacts under social, economical and environmental dimension.

The fours areas are strictly interconnected although they involve different disciplines, and the actions, which involve more than an area, have larger effects on economic, environmental and social value creation. For this reason, the main current research questions, which drive the transition to the I4.0 manufacturing paradigm, cover mainly the intersections between different areas [176]. Some of the technologies of I4.0 are able to drive the transition towards sustainable development [176] and recent holistic concepts, such as MAESTRI Total Efficient Framework (MTEF), are exploiting this synergy. MTEF is a four-dimension paradigm involving: (i) Efficiency framework; IoT platform; Management system and IS [20]. It drives the analysis of production system productivity and the eco-efficiency of the whole value chain. On one hand, EcoPROSYS provides information about economic performance and the environmental impacts of the activities involved. EcoPROSYS is based on Environmental Performance Evaluation (EPE), Life Cycle Assessment (LCA) and cost and value assessment. On the other hand, the process efficiency is analyzed through a new methodology based on VSM, i.e., the

Multi-Layer Stream Mapping (MSM). MSM is a methodology to evaluate the resource efficiency of production systems, by following the lean principles of waste and value [138]. MSM extends the set of resources considered from the dimension of time, which is the classic resource considered by VSM, to all the raw materials, consumables and sources of energy involved in a process, by providing more accurate measures of process efficiency. Furthermore, the waste identification is introduced as opportunity for IS identification and then IS development through I4.0 technologies, which can help to overcome barriers of CE spreading in manufacturing ([252]; [160]). The MSM exploits the development of KPIs to evaluate processes and technologies, following the easiness of communication of Lean. KPI approach allows further extensions of MSM, e.g., technology selection according to environmental and economic dimensions [114]. MSM can be combined with MFCA to lead resource efficiency improvement [222] and life cycle approach, such as LCA and LCC to perform value analysis over the eco-efficiency of processes considering the whole lifecycle of resources involved and the respective costs [49].

1.3 New Challenges

The MSM overcomes the limitation of VSM in catching the aspect of processes linked with the resource consumption, so that waste assumes a more comprehensive meaning by considering also resource efficiency together with process efficiency and the added-value activities. Furthermore, MSM can lead more efficiently the adoption of new technologies to adopt I4.0 paradigm. Its integration with lifecycle tools and material flow analysis is crucial for comparing different technologies according to the TBL, while KPI approach facilitates the continuous monitoring of economic and environmental performance. However, two limitations to its adoption for concurrent exploitation of IS and system improvement, which is the aim of this thesis, still remain:

1. It does not have a structured and unique formalism to represent systems and their interactions, especially in a dynamic way;
2. It is value-chain oriented instead of value-network oriented where many processes are tightly interconnected, influenced by each other, and whose performances change over time following trends, seasonality and variability propagation.

Furthermore, several approaches are not suitable for SMEs, for example the application of LCA-based approaches is limited by knowledge and economic availability and its outcomes could be unhelpful for them [127]. SMEs are deeply affected by poor resource efficiency, which causes poor economic and environmental performances, and their scarce ability to provide raw materials exposes them to price volatility [105]. Hence, they would take large benefit from a strong belonging to networks of companies; however, they result the type of companies, which are struggling to create strong SCs [105] and IS partnerships [186]. For this reason, the focus on IS identification and IS development is crucial and it cannot be neglected, suggesting that more efforts must be done for identifying tools able to analyze, model and implement solutions oriented to complex manufacturing networks. Moreover, I4.0 is an opportunity because it supports the emergence of networks based on IS, thanks to IoT and the application of data-driven approach such as mathematical modeling and optimization [266]. In fact, network performance, in particular the networks involving also IS, can be assessed only if the data gap is filled and appropriate tools are used [81].

1.3.1 Discussion

The Multi-layer Enterprise Input-Output approach is based on the Multi-Layer Stream Mapping and the combination of Enterprise Input-Output and Material Flow Analysis. It aims to reconcile the value creation analysis based on the system performance evaluation and resource efficiency analysis devoted to the identification of sources and sinks of materials within the system. However, all the new tools and methods oriented to manufacturing systems must take into consideration the new industrial revolution of Industry 4.0 and digitization, since they are disrupting the production paradigms by introducing new technologies. The most diffused approaches based on Lean principles are struggling to identify their clear roles in the new industrial revolution, by showing the lack of formalization methods. MEIO is a formalization approach to represent production, inventory and transport activities, i.e., both value-added and not-value added activities, of a system. It is based on two tables: (i) Resource-Process and (ii) Process Parameters. Both tables can be based on data collected during an analysis and further continuously updated through data gathering systems. MEIO formalization is a flexible approach to be used in combination with Value Stream Mapping (MEIO-SM) to assess value creation and with even more complex approaches to define the digital twin of the system and to lead to changes to improve value creation via simulation and mathematical programming approaches.

Several IT approaches collect data and match them thanks to collaboration platforms to support IS identification and emergence [144]. However, technical, logistic and regulatory issues can make an IS unsustainable [81]; hence, economic and environmental sustainability must be measured by considering the specific conditions of each IS. MEIO formalization allows the representation of activity performances along both economic and environmental sustainability, then it can be crucial for leading accurate analyses and development of more complex tools and methods, but based on a more effective and lean formalization.

Chapter 2

Multi-layer Enterprise Input-Output Stream Mapping

The proposed system formalization has to be able to manage and organize data in order to identify and model economic, technical and environmental characteristics of involved processes. Furthermore, it must provide all the information required by mathematical models for system simulation and optimization, by ensuring the opportunity of autonomous update through system sensors. Part of this thesis is dedicated to the development and application of the Multi-layer Enterprise Input-Output Stream Mapping (MEIO-SM), which is based on the combination of Material Flow Analysis and Enterprise Input-Output with Multi-layer Stream Mapping.

2.1 The MEIO approach for system formalization

The two core subjects required to formalize the system through MEIO approach are (i) resources and (ii) processes. Economic and environmental performance is represented through the concurrent consideration of (i) and (ii).

Resources. Resources are identified following the MFA principles [209]:

1. identify the unit of analysis;
2. ensure material and energy balances.

The first one determines how deep is the resource analysis, e.g., it is possible to consider water flows (bottles in case of product industries) or molecules of hydrogen and oxygen, or even more specifically, dissolved toxic substances. After deciding the unit of analysis for all the involved resources entering (exiting) into (from) the system, they must be tracked through all the production and stocking activities until they go out from the boundaries of the system, by ensuring the conservation of material and energy and even including new types of resources (or assembled and disassembled pieces in the case of product industries) produced and or absorbed.

Processes. According to the MSM approach, all the processes are identified in terms of resource efficiency and productivity. Resource efficiency is intended as the consumption of each resource (raw materials, energy, and consumables) per unit of resource (product) produced. MEIO approach addresses productivity in a way as comprehensive as possible, by including in it both economic and efficiency characteristics such as maintenance costs and time stops, setups, failures and variability in production time. Here, processes are intended as manufacturing, stocking and transportation process when considered by the case of application. Processes are connected to each other through resources according to the EIO where the output of a process is the input of another. Each process specifies, for each resource involved, the amount of required and produced resources, by considering also waste, by-products, energy and the eventual remaining amount of the same input resources at the end of the process. For example, transports and inventories probably do not reduce the involved raw materials, while they use power or convert fuel in CO_2. Conversely, if a raw material at the end of a process has the same quality as the initial state and there are processes to recover, store, and reuse it, then it can be expressed as an output of the same resource. Else, in all the other cases, it becomes a waste (when it is not used) or a new raw material if used in other processes. Figure 2.1 shows an example: in a process of biscuit packaging there are biscuits and empty packs as input, while the outputs are packs of biscuits and broken biscuits. There are three cases: (a) blue arrow, crumbs are reused as input of packaging process to be packed together with new biscuits; hence, they remain an output of the same resource (eventually, a new process to recover crumbs and convey them to the packaging process is added); (b) gray arrow, crumbs are disposed so they are classified as waste; (c) green arrow, crumbs are used to produce a cream, so they are a new raw material for another process.

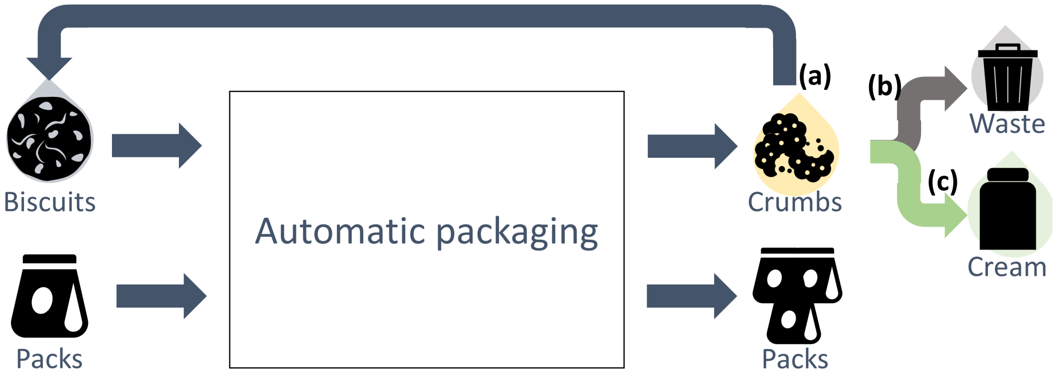


Figure 2.1: Classification of the remaining amount of raw material after a process: (a) the same input raw material, if it can be reused as it is; (b) waste, when it is disposed; (c) other raw material when it is used for other products.

MEIO approach is mainly based on two kinds of tables:(i) Resource-Process (RP) MEIO table, and (i) Process Parameters (PP) MEIO table. PP MEIO table has a flexible structure to adapt to the other tools used in combination with MEIO. For example, in the case of mathematical programming optimization model, productivity can be expressed in amount of product per unit of time, subtracting the time required for maintenance, setup and failures; operation costs can be represented as money per unit of time. Conversely, in the case of DES approach, costs and setup, failures and maintenance can be provided through their stochastic distributions to model the several events according to their frequency. MEIO formalization approach guarantees the sufficient flexibility to fit the different availability of system data. Moreover, the collected data are suitable to the use of different analysis tools and they can be collected and updated in autonomous way through system sensors.

Table 2.1 shows an example of RP MEIO table applied to a process industry manufacturing system composed of: two production process (P1, P2), two warehouses (W1, W2), a transportation process through truck (T1), three source of energy (power, heat, and fuel), a consumable (C1), three raw materials (RM1, RM2, and RM3), a finished product (FP1), three among waste and byproducts (RW1, RW2, and RW3). Processes are on columns, while all the resources are displayed in rows. The amount of both required input and the produced output, for each process, are expressed in the form "input/output". P1 uses RM1 (1 liter) and RM2 (2 kg) to produce RM3 (1 kg) and 2 liters of C1, it is powered through 0.5 kWh of power and heated with 2 kWh of heat, of which 0.5 kWh is recovered within the process, and 1.0 kWh is wasted (RW3). Stocking RM3 in W1 requires power (0.1 kWh) and heat (0.1 kWh), while the storage in W2 is less efficient due to 0.3 kWh requirement of power. Transport T1 requires 1.5 kWh of power (fuel) to transport 1 kg of RM3, which is partially degraded (it arrives 0.99 kg), by producing (for each kg of RM3 transported for each distance unit) 0.5 kg of CO_2 (RW1) and waste 1.5 kWh of heat. P2 produces 0.5 unit of FP1 with 1 kg of RM3, 0.5 liter of RM1, 1 liter of C1, 1 kWh of power and heat, plus 1 kg of waste RW2, which is a mixture non recoverable of RM1, RM3 and C1. Of course, chemical composition and equation to transform mass, density and energy required by processes are used to guarantee mass and energy balance.

	P1	**W1**	**T1**	**W2**	**P2**
RM1 (l)	1/0	0/0	0/0	0/0	0.5/0
RM2 (kg)	2/0	0/0	0/0	0/0	0/0
RM3 (kg)	0/1	1/1	1/0.99	1/1	1/0
FP1 (unit)	0/0	0/0	0/0	0/0	0/0.5
Power (kWh)	0.5/0	0.1/0	0/0	0.3/0	1/0
Heat (kWh)	2/0.5	0.1/0	0/0	0.1/0	1/0
Fuel (kWh)	0/0	0/0	1.5/0	0/0	0/0
C1 (l)	0.2/0	0/0	0/0	0/0	1/0
RW1 (kg)	0/0	0/0	0/0.5	0/0	0/0
RW2 (kg)	0/0	0/0	0/0	0/0	0/1
RW3 (kWh)	0/1.0	0/0	0/1.5	0/0	0/0

Table 2.1: An example of Resource-Process MEIO table to represent a system with 2 production processes, a transport and two warehouses.

Separately, productivity information and parameters are provide, including: (i) production, stocking and transportation unit capacity; (ii) investment cost for the adoption of an extra unit; (iii) eventual operation cost per unit capacity; (iv) available quantity of machines, warehouses, trucks and other. They can be provided as a numeric parameters or stochastic distributions in the case of hourly production, for example. Table 2.2 shows the deterministic number of machines (for P1 and P2), warehouses (for W1 and W2) and trucks (for T1); unit capacity for each one; investment cost for an extra machine, warehouse and truck; operation costs; distances among processes. The middle score highlights when a row is not applicable to a specific column, or a connection between two processes does not exist.

	P1	**W1**	**T1**	**W2**	**P2**
Production capacity (amount*machine/hour)	10	-	-	-	20
Transportation capacity (kg*truck)	-	-	100	-	-
Inventory capacity (kg*warehouse)	-	50	-	30	-
Unit investment cost (k€/unit)	300	50	25	30	500
Production cost (€/amount)	0.5	-	-	-	1.5
Inventory cost (€*day/kg)	-	0.5	-	0.2	-
Transport cost (€/kg))	-	-	2	-	-
Available machines/warehouses/trucks	2	1	3	1	1
P1 distance (km)	0	0	-	-	-
W1 distance (km)	0	0	0	10	-
T1 distance (km)	-	0	0	0	-
W2 distance (km)	-	10	0	0	0
P2 distance (km)	-	-	-	0	0

Table 2.2: Process Parameters MEIO table to provide productivity information and operation parameters for processes, warehouses and transports.

2.2 Mathematical aspects of MEIO formalization

EIO formalization tool links the outputs of a process with their inputs, thus a mathematical function indicates the output quantity r_i of i of a process given the absorbed quantity r_j of raw material j, and vice-versa. Generally, in other approaches the main finished product is the dependent variable of the function, while the input is the independent variable, thus all the raw materials have their function to link them with the same output. In other cases, e.g., EIO, the finished product is assumed as independent variable to define the amount of input required. MEIO approach does not assume the main finished product as dependent variable in all the cases. MEIO aims to enhance interactions with digital approaches such as mathematical optimization models for quick decision making and simulation models, beyond the pen and paper approaches, then the mathematical functions connecting raw materials with output should be properly defined. The solution of optimization models requires to make the used range of the orders of magnitude of all the different parameters as close to one as possible to avoid issues linked to the numerical precision of the machines; hence, the choices of both the units of measure and the independent variable are led by this criterion. These choices can be critical; in fact, MEIO method, when implemented within high digitized CPPS, may deal with many resources whose used amount ranges from few mg/ml, e.g. concentration of substances in fluids, to several tons, e.g., the mixture for finished products in process industry. The following example in Table 2.3 shows four resources (R1, R2, R3, R4), with different orders of magnitude, which are all reported in the second column, involved in the same process; each one of the resources is iteratively used to normalize the others, in column from 3 to 6. Hence, column free reports the order of magnitude of all the resources divided by the order of magnitude of resource R1; column 4 uses R2 to divide all the orders of magnitude, and so on. The columns from 3 to 6 are equivalent representation of the same process; however the absolute distance of the order of magnitude used from the single unit is different. The absolute distance from the single unit, which has to be minimized to reduce numerical errors due to the precision of the computers and algorithms, is reported in the last row.

	Order of Magnitude	Process 1 alternative 1	Process 1 alternative 2	Process 1 alternative 3	Process 1 alternative 4
R1	10	1	0,1	0,001	0,000001
R2	100	10	1	0,01	0,00001
R3	10000	1000	100	1	0,001
R4	10000000	1000000	100000	1000	1
Absolute distance	-	6	5	3	6

Table 2.3: Four alternative procedures of normalization, applied to the same process, and their absolute distance from the unit.

Hence, the units of measure are fixed, thus all the activities of the system use the same ones for the same resources, while the dependent variables to describe the functions between resources change from an activity to the other, according to the resources involved and their quantities. MEIO exploits two different approaches, i.e., that one deterministic and the stochastic one, to estimate, update, and save the mathematical functions in order to improve the compatibility with both the systems where the functions come from data-driven approaches and those where the functions are given a priori, e.g., from design parameters. Furthermore, two levels of approximation can be used and the choice between the two should be driven by the computation budget required; therefore, for quasi real-time update a higher level of approximation can be more suitable, especially in complex systems with many activities and resources. Figure 2.2 shows the two different approaches with the two levels of approximation applied to the same process. The formalization of the function between dependent and independent variable can be deterministic (Figure 2.2a and 2.2b), thus coming from a priori information or interpolation of few data; or stochastic (Figure2.2c and 2.2d) for data-driven approaches. Therefore, two outputs/inputs can be connected from a deterministic function or a stochastic distribution. The level of approximation indicates whether the approach followed tries to represent all the different states of the single activity (Figure 2.2a and c) or if a function is used to approximate the behavior in the entire space (Figure 2.2b and d). Often, the lowest level of approximation requires stepwise functions/stochastic distributions to properly model the behavior of the process in different states such as the warm-up period, the maximum capacity, and the suggested pace of work; while the higher level of approximation can use the same linear function to approximate the entire space of performance.

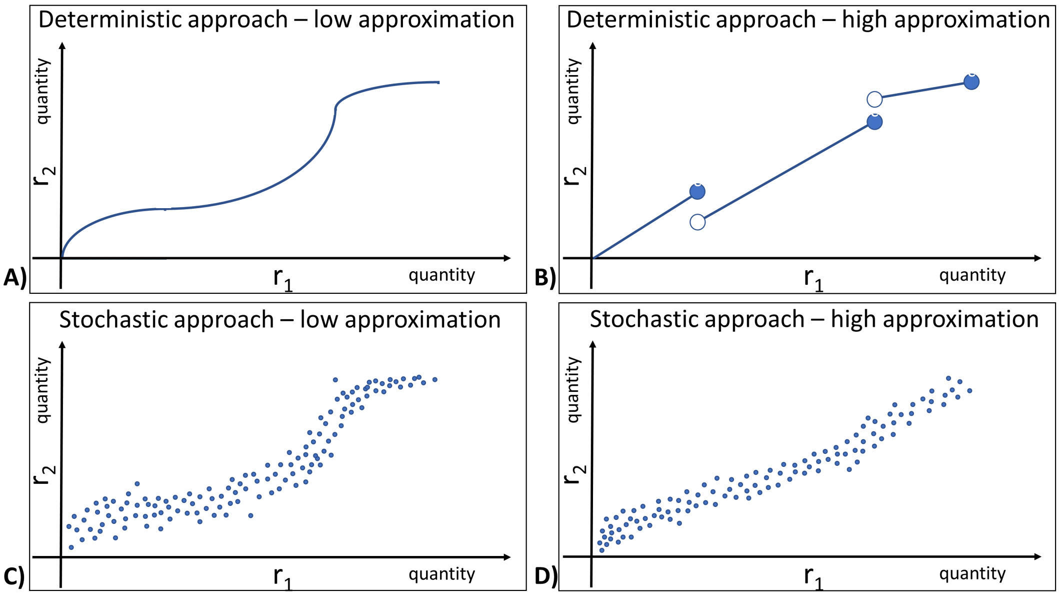


Figure 2.2: Four alternatives to represent the mathematical function that connects the consumption/production of two resources .

The estimation of the functions between two parameters can be easier than that of other parameters, thus a mixed approach can be applied to overcome limitations such as limited samples of observations and inaccurate estimations of a parameter. Therefore, in each activity some functions can have a low level of approximation, while other can have a high level of it; some functions can be deterministic while other can be a stochastic distribution. The methods, tools, and the analyst will properly manage each function of the activities to keep consistent the analyses of the whole system.

The choice between deterministic or stochastic approach is also driven by the further methods and tools integrated with MEIO. For example, in case of dynamic system simulation models where equations models the behavior of the process, the deterministic approach can increase the integration between MEIO and the specific digital model of the process.

2.2.1 MEIO in process and product activities

The main difference between product and process activities is in the used and produced resources; in fact, product activities involve discrete, countable, distinguishable resources, while process activities involve measurable ones [174]. The manufacturing system of a plant is assumed belonging to product or process industry based on its main processes in terms of volume/mix. Hence, according to the APICS dictionary, if the main value is created through mixing, separating, forming, and performing chemical reactions the plant belongs to process industry, else belongs to product industry [29]. MEIO method is not affected by this classification, which is mainly based only on the finished products of the system, because it focuses on the contribution of all the resources involved in the activity. Therefore, the method can concurrently involves activities belonging to both the type of industries, and the same activities can have some resources treated as single product and others as a flow. When resources are discrete the RP MEIO table reports parts, in the other case it reports flows i.e., quantity per unit of time.

The key resource of the activity, i.e., the one assumed as the independent variable to which all the others are compared, determines whether the maximum capacity of the process activity (number of units or amount of product that can be produced, transported or stored, reported in the PP MEIO table) is expressed in terms of process time or produced quantity per unit of time. Process time of the activity is the time (deterministic or stochastic) to produce one unit of product; while the produced quantity per unit of time is the maximum flow (quantity per unit of time) that the process can produce/absorb of the key resource.

2.2.2 Limitations of this approach

The main limitation is the one-variable approach, in fact all the resources, both input and output, are linked with the main one of the specific activity, and this latter one is dependent from the intensity of the use of the process, e.g., the turning speed rate of a lathe, the concentration level of a server, the speed of an assembly machine. However, many activities may be simultaneously dependent from more than one parameter, i.e., the interactions of two factors can affect a third one, e.g., the produced scrap of a lathe may be dependent from the turning speed rate, and also from the quantity of used machinery oil. The management of such a case, within MEIO formalization method, needs further research and it would make the method more articulated and less intuitive for pen and paper approaches. However, the required effort to extend the MEIO approach to the individual activity level may result inappropriate in some cases. In fact, MEIO method aims to be a formalization tool to collect and organize the information of all the activities of a system in terms of economic, environmental, technical, and value creation performance. It aims to be a standardize layer between the individual activities and the data exploitation approaches at system level rather than process level. Therefore, MEIO tool can be a support for as many as possible multi-scale approaches rather than one of the other multi-scale approaches.

MEIO and the multi-scale approach

Multi-scale simulation models concurrently focus on several level of a system to reproduce the behavior of a process and using the derived information at upper level to reproduce the behavior of a system of processes. Therefore, the simulation model of the entire system embeds the simulation models specific for the processes [234]. There is no widespread and common approach, whether the same type and different type of simulation models can be concurrently applied in the various levels, e.g., a system of finite equations (dynamic system model) can be used to model the phenomenon of a process and it can be embedded in a discrete event simulation model.

Differently from EIO models where processes are intertwined through their output, and thus it cannot be provided a multiple definition for the same activity, MEIO approach can model an activity through multiple columns in RP and PP MEIO tables. Therefore, several behaviors of the same process can be defined to describe the various alternatives, e.g., Combined Heat and Power process can run with biogas or methane. However, this increase the articulation of the method, thus should be limited to the fundamental activities. Further details about processes should be avoided for the reasons aforementioned in limitations; moreover, MEIO is more suitable to be a common architecture between multi-scale simulation models than a new multi-scale approach.

MEIO method exploits the Resource-Function (RF) MEIO table to store and make available the functions linking the consumption/production of the resource of an activity with the production or consumption of the resource chosen to normalize the others. The RF MEIO table is not used in this thesis since all the data case study assume a linear relationships between resources; furthermore, they neglect the warm-up period by focusing on the average performance of the activities.

2.3 Application of MEIO formalization for value creation analysis

The MEIO tables allow a structured formalization of process data and resource flows, but they do not give any information on system performance because it is the role of the analysis tool. Process data availability, analysis scope, and considered time horizon are among the main drivers to choose an analysis tool rather than another. The MEIO-SM exploits the VSM concept by focusing on productivity to identify the percentage of waste resources, it can considers also both added and non-added value activities by recording the average time they require. Furthermore, MEIO formalization can be used with other tools both more and less sophisticated. For example, it provides all the necessary data for a mathematical representation of the system, useful for analyzing or optimizing its performance. The first application, proposed by this thesis, of MEIO formalization combines it with a MFCA approach to asses the value creation process of three SCs stemming from the use of byproducts of wine and rice production chains.

2.3.1 InnovaEcoFood regional project

Pomace and rice husk are by-products of wine and rice production chains. They are usually exploited by the market of farm animals to be used as food or barn material. However, lab analysis performed within the scope of the regional project InnovaEcoFood, funded by region of Piedmont, has revealed the presence of several molecules relevant for both pharmaceutical and food industry. In fact, the chemical characterization of pomace shows a moderate presence of anthocyanins, polyphenols and trans-resveratrol while rice hush contains gamma oryzanol, which has crucial anti-oxidant and anti-inflammatory effects, and it positively affects lipid metabolism and cholesterol level regulation. Pharmaceutical and food industry could be both interested in the exploitation of these molecules; however, the economic sustainability of the entire value creation process must be assessed. Hence, the combination of three SCs stemming from wine and rice production chains is evaluated.

Molecules contained in pomace seem sensible to heat treatments to extract them; hence, pomace flour was the best way to exploit them, by drying the fresh and not fermented pomace resulted from some specific grape pressing. Gamma oryzanol contained in rice husk can be extracted to obtain products with a larger concentration of it, e.g., rice husk butter. However, also rice husk flour is a valid alternative. Finally, pomace and rice husk flours and rice husk butter can be used as ingredients for new highly healthy baked products.

Different skills and processes are required, from the initial treatment of pomace and rice husk to the production of the baked products. Figure 2.3 shows the three companies, from three different SCs, selected for the cost-benefit evaluation of the by-products in food and beverage market (FOOD): (i) Agrindustria (in yellow in figure) deals with flours production; (ii) Exenia (green in figure) is focused on treatments to extract the precious molecules from the rice husk; (iii) finally, La

Mandorla (in orange) is a bakery interested in the exploitation of these ingredients to produce baked products, by assessing quality and sale price of new products.

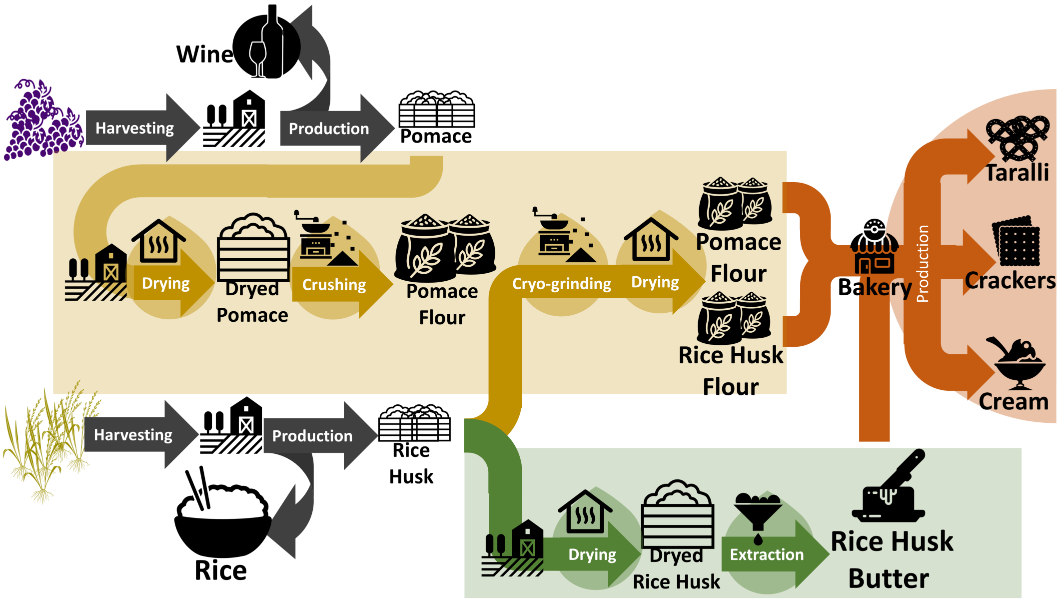


Figure 2.3: Three new production chains stemming from the agricultural by-products of rice and wine production chains: (i) in yellow the flour production chain; (ii) in green the chemical industry for the extraction of precious nutrients; (iii) in orange the production of new highly healthy baked goods.

Agrindustria produces pomace flours through four processes:

1. **Drying.** It receives in input 100 kg of pomace and it obtains 47 kg of dry pomace by using 5 kWh of power and 100 kWh of heat.
2. **Crushing.** It has 0,5% of scrap and it requires 1 kWh of power per 100 kg of dry pomace.
3. **Cryo-grinding.** It has 1% of scrap to obtain cryogrinded flour with an average diameter of 0.5 mm. It requires 10 kWh of power per 100 kg of crushed pomace of input.
4. **Bacterial load reduction and final drying.** It requires 7 l of water, 10 kWh of power and 100 kWh of heat per 100 kg.

Cryo-grinding and bacterial load reduction with final drying are applied also to rice husk, with the same process parameters to obtain rice husk flour.

Exenia obtains rice husk butter, which is a product with a large concentration of gamma oryzanol, through two processes:

1. **Drying.** 1 kg of rice husk provide 0.987 g of dry rice husk, by using 30 kWh of power, and it has an operation cost of 9 €/kg.
2. **Supercritical CO_2 extraction**. 2 g of rice husk butter are obtained from 1 kg of rice husk by using 6.5 kWh of power, 1.84 kWh of heat and producing 5 kg of CO_2.

La Mandorla bakery produces three products by using pomace and rice husk flours and rice husk butter:

1. **Crakers.** 3 kg of water, 0.277 kg of pomace flours, 0.277 kg of rice husk flour, 10 g of rice husk butter and 0.12 kWh are required to obtain 1 kg of crackers.
2. **Taralli.** Taralli are salty biscuits typical of Apulia region; 2 kg of water, 0.277 kg of pomace flours, 0.277 kg of rice husk flour, 10 g of rice husk butter and 0.9 kWh are used to obtain 1 kg of taralli.
3. **Cream.** The spreadable almond cream substitutes butter with rice husk butter to improve healthy characteristics. 3 kg of water, 300 g of almonds, 0.277 kg of pomace flours, 0.277 kg of rice husk flour, 100 g of rice husk butter and 0.27 kWh are required to obtain 1 kg of cream.

2.3.2 Value creation analysis

InnovaEcoFood focused on the investigation of particular molecules in byproducts, which are currently little valued in the farm animal sector. These molecules are crucial for pharmaceutical industry but also for food and beverage industry, which is more relevant in Piedmont. In fact, the opportunities for exploiting these healthy molecules in healthy food products can increase the value of rice and wine production chains, which are crucial for Piedmont; the quality of rice and wine produced in Piedmont makes it famous in the world, indeed. The investigation of the presence of these molecules was accompanied by an initial cost-benefit analysis to assess the economic sustainability of the value creation process. Further analyses are necessary for production chain design, in fact, trends and seasonality deeply affect these by-products as well as operation management and investments for production, stocking and transport infrastructures. In fact, rice husk is recovered after rice harvesting (from October to June), while pomace is produced from the end of August to the end of September, therefore the production chain must be carefully designed to ensure its sustainability during the whole year; however, it is out of the scope of this analysis.

InnovaEcoFood formalization

The whole process chain is formalized through the RP MEIO tables. Table 2.4 represents the processes involved in pomace flour production while table 2.5 those involved in rice husk flour production. Table 2.6 shows the processes of Exenia to produce rice husk butter, and 2.7 summarizes ingredients and energy required for the three finished products, i.e., crackers, taralli, and cream.

	Drying	**Crushing**	**Cryo-grinding**	**Bacterial load reduction and drying**
Fresh pomace (kg)	1/0	0/0	0/0	0/0
Dry pomace (kg)	0/0.47	1/0	0/0	0/0
Pomace flour 10 mm (kg)	0/0	0/0.995	1/0	0/0
Pomace flour 0.5 mm (kg)	0/0	0/0	0/0.99	1/0
Pomace flour FOOD (kg)	0/0	0/0	0/0	0/1
Power (kWh)	0.05/0	0.01/0	0.1/0	0.1/0
Heat (kWh)	1/0	0/0	0/0	0/0
Fresh Water (kg)	0/0	0/0	0/0	0.07/
Waste flour 10 mm (kg)	0/0	0/0.005	0/0	0/0
Waste flour 0.5 mm (kg)	0/0	0/0	0/0.01	0/0
Waste Water (kg)	0/0.53	0/0	0/0	0/0.7

Table 2.4: RP MEIO table for pomace flour production.

	Cryo-grinding	**Bacterial load reduction and drying**
Dry rice husk (kg)	1/0	0/0
Rice husk flour 0.5 mm (kg)	0/0.99	1/0
Rice husk flour FOOD (kg)	0/0	0/1
Power (kWh)	0.1/0	0.1/0
Heat (kWh)	0/0	0/0
Fresh Water (kg)	0/0	0.07/0
Waste flour 0.5 mm (kg)	0/0.01	0/0
Waste Water (kg)	0/0	0/0.7

Table 2.5: RP MEIO table for rice husk flour production.

	Drying	**Supercritical CO_2 extraction**
Rice husk (kg)	1/0	0/0
Dry rice husk (kg)	0/0.987	1/0
Waste Rice husk extracted (kg)	0/0	0/0.98
Rice husk butter (kg)	0/0	0/0.02
Power (kWh)	30/0	6.5/0
Heat (kWh)	0/0	1.84/0
CO_2 **(kg)**	0/0	0/5
Waste Water (kg)	0/0.013	0/0

Table 2.6: RP MEIO table for rice husk butter production.

	Taralli	**Craker**	**Cream**
Taralli (kg)	0/1	0/0	0/0
Cracker (kg)	0/0	0/1	0/0
Cream (kg)	0/0	0/0	0/1
Water (kg)	3/0	2/0	3/0
Power (kWh)	0.12/0	0.9/0	0.27/0
Pomace flour 0.5 mm (kg)	0.277/0	0.277/0	0.277/0
Rice husk flour 0.5 mm (kg)	0.277/0	0.277/0	0.277/0
Rice husk butter (kg)	0.01/0	0.01/0	0.1/0
Almonds (kg)	0/0	0/0	0.3/0
Waste humid mixture (kg)	0/2.555	0/2.555	0/2.555

Table 2.7: RP MEIO table for baked products production: crackers, taralli, cream.

All the RP MEIO tables have been completed by adding the rows of wastes. Wastes were not measured in the production chain, but they have been evaluated by following the MFA principles of material balance. Hence, kgs in input must be the same of kgs in output; hence, when the material balance is not respected, the remaining quantities are assumed to be a mixture of water and traces of waste resources. Furthermore, also energy balance should be assessed by gathering data of dissipated heat in the atmosphere; however, these data are not available nor can they be estimated, therefore, processes are considered energy efficient. Table 2.8 reports prices of resources and finished products for the year 2018.

Resources	Price
Taralli €/kg	10.00
Cracker €/Kg	14.50
Cream €/kg	48.00
Power €/kWh	0.05
Water €/kg	0.01
Almond €/Kg	12.00
Pomace €/kg	0.01

Resources	Price
Heat €/kWh	0.01
Pomace flour 10.00 mm €/kg	0.10
Pomace flour 0.50 mm €/kg	0.15
Pomace flour 0.50 mm FOOD €/kg	2.00
Rice husk flour 0.50 mm €/kg	1.30
Rice husk flour 0.50 mm FOOD €/kg	1.70
Rice husk butter €/kg	250.00

Table 2.8: Tables for the prices of finished products and resources.

Material Flow Cost Accounting approach

The value creation analysis aims to provide an overview of economic and environmental sustainability of the current opportunity to exploit crucial molecules contained in by-products. The whole production chain has been analyzed to gather performance and resource efficiency; however, financial and labor costs are not considered because they are closely linked to the design of the production chain for market competition, which goes beyond the technical exploration set by this project. Value creation analysis has been performed through the application of MFCA to provide a cost also for the entire produced waste. Waste costs are intended as missed revenues because, in this case, disposal costs, environmental costs, and treatment costs are not given. Hence, they are not directly considered in the assessment of value creation, but they are provided as an indication of potential benefits of resource efficiency improvement, by assuming, in this case, that further investments in infrastructures are not necessary to exploit them. Table 2.9 and 2.10 analyze all the processes of Agrindustria to measure the value created with 1 kg of pomace and 4 kgs of rice husk. Table 2.9 and 2.10 show the costs of energy and materials (input) and both the revenues of the finished products and missed revenues of wastes (output) by multiplying resources required in RP MEIO tables and their prices in PP MEIO tables.

	Drying		**Crushing**		**Cryo-grinding**		**Bacterial load reduction and drying**	
	Amount	Revenues and costs	Amount	Revenues and costs	Amount	Revenues and costs	Amount	Revenues and costs
Fresh pomace (kg)	1	-0.01	-		-	-	-	-
Dry pomace (kg)	0.47	+0.0329	0.47	-	-	-	-	-
Pomace flour 10 mm (kg)	-	-	0.46765	+0.046765	0.46765	-	-	-
Pomace flour 0.5 mm (kg)	-	-	-	-	0.462974	+0.06945	0.462974	-
Pomace flour FOOD (kg)	-	-	-	-	-	-	0.462974	+0.925947
Power (kWh)	0.05	-0.0025	0.0047	0.000235	0.046765	-0.002338	0.046297	-0.002315
Heat (kWh)	1	-0.01	-	-	-	-	-	-
Fresh Water (kg)	-	-	-	-	-	-	0.032408	-0.000324
Waste flour 10 mm (kg)	-	-	0.00235	(-0.000235)	-	-	-	-
Waste flour 0.5 mm (kg)	-	-	-	-	0.004677	(-0.000702)	-	-
Waste Water (kg)	0.53	(-0.0053)	-	-	-	-	0.032408	(-0.000324)
Total value or costs (€)	-	+0.014	-	+0.04653		+0.067108		+0.923632

Table 2.9: Value creation for 1 kg of pomace, from waste to the pomace flour adapt for food industry.

	Cryo-grinding		**Bacterial load reduction and drying**	
	Amount	Revenues and costs	Amount	Revenues and costs
Dry rice husk (kg)	4	-0.840631	-	-
Rice husk flour 0.5 mm (kg)	3.962974	+5.151865	3.962974	-
Rice husk flour FOOD (kg)	-	-	3.962974	+6.737055
Power (kWh)	0.4	-0.020015	0.396297	-0.019815
Heat (kWh)	-	-	-	-
Fresh Water (kg)	-	-	0.277408	-0.002774
Waste flour 0.5 mm (kg)	0.04	(-0.052039)	-	-
Waste Water (kg)	-	-	0.277408	(-0.002774)
Total value or costs (€)		+4.291220		+6.71724

Table 2.10: Value creation for 4 kg of rice husk, from rice husk used for farm animal industry to the rice husk flour adapt for food industry.

Pomace is currently a by-products so its purchase is assumed at price zero, while rice husk is purchased at farm animal industry market price. Table 2.11 shows the value creation process for rice husk butter production (in Exenia) by purchasing the same rice husk used for farm animal industry. Waste resources are identified and, when a missed revenue exists, it is reported between brackets. There is the example of CO_2, which is multiplied by 0.015 €/kg of CO_2 emission from the average price of Carbon Trading Scheme of 2018.

	Drying		**Supercritical CO_2 extraction**	
	Amount	Revenues and costs	Amount	Revenues and costs
Rice husk flour 0.5 mm (kg)	3.5	-4.55	-	-
Dry rice husk (kg)	3.4545	+10.3635	3.4545	-
Rice husk butter FOOD (kg)	-	-	0.06909	17.2725
Power (kWh)	30	-1.5	22.45425	-1.122713
Heat (kWh)	-	-	6.35628	-0.063563
Fresh Water (kg)	-	-	-	-
Waste flour 0.5 mm (kg)	0.0455	(-0.000455)	-	-
Waste rice husk extraction (kg)	-	-	3.38541	(-N.A.)
Waste Water (kg)	-	-	-	-
Waste CO_2 (kg)	-	-	17.2725	(-0.259088)
Total value or costs (€)		+4.3135		+13.08622

Table 2.11: Value creation for 3.5 kg of rice husk, from rice husk used for farm animal industry to the rice husk butter adapt for food and cosmetic industries.

Finally, Table 2.12 reports the value creation for La Mandorla, where baked products are produced by using the new flours and butter. The amount of produced taralli, crackers and cream has been chosen to completely exploit pomace and rice husk flours and rice husk butter produced by Agrindustria and Exenia.

	Taralli Production		**Crackers Production**		**Cream Production**	
	Amount	Revenues and costs	Amount	Revenues and costs	Amount	Revenues and costs
Taralli (kg)	0.557	+5.57	-	-	-	-
Cracker (kg)	-	-	0.557	+8.08	-	-
Cream (kg)	-	-	-	-	0.557	+26.74
Fresh Water (kg)	1.671384	-0.016714	1.114256	-0.011143	1.671384	-0.016714
Power (kWh)	0.066855	-0.003343	0.501415	-0.025071	0.150425	-0.007521
Pomace flour FOOD (kg)	0.154325	-0.308649	0.154325	-0.308649	0.154325	-0.308649
Rice husk flour FOOD (kg)	0.154325	-0.262352	0.154325	-0.262352	0.154325	-0.262352
Rice husk butter (kg)	0.005571	-1.392820	0.005571	-1.39282	0.055712	-13.928204
Almonds (kg)	-	-	-	-	0.167138	-2.005661
Waste humid mixture (kg)	1.428605	(-N.A.)	0.871477	(-N.A.)	1.645884	(-N.A.)
Total revenues or costs	-	+3.57	-	+6.08	-	+10.24

Table 2.12: Value creation for 7.5 kg of rice husk and 1 kg of pomace, from rice husk used for farm animal industry and pomace waste to the production of taralli, crackers and almond cream.

The initial amount of 1 kg of pomace and 7.5 of rice husk lead to the production of 0.557 kg of taralli, 0.557 kg of crackers and 0.557 kg of almond cream, through the production of pomace and rice husk flours and rice husk butter. Produced butter and flours are rich of highly healthy molecules, crucial for food industry but also for pharmaceutical and cosmetic industries. However, the application of MFCA sheds a light on the waste of new production chain, by suggesting that humidity and waste water could be recovered from some stages to be reused in others. Moreover, some wastes are currently without any possible exploitation, which leads to a landfill disposal.

The combined application of MEIO formalization and MFCA allowed a deeper value analysis mainly focused on the assessment of economic sustainability, while monitoring the resource efficiency of the new production chains. The results show a positive value creation from waste, which leads to the emergence of new businesses, jobs creation and regional competitive advantage. However, also process productivity could be analyzed to evaluate added and non-added value activities, e.g., by including in the MEIO formalization also transports and inventories. Late, the combined application of MFCA and MEIO-SM can assess also the process productivity (since MEIO-SM implement VSM in MEIO formalization).

MEIO formalization has proven to be a flexible approach to formalize a production system and facilitate the application of further analysis tools.

Chapter 3

MEIO formalization and data-driven approach

The hearth of I4.0 is not in the technological aspects, in fact, they can evolve over time and new technologies can emerge [60], while the crucial role of data remains the same. I4.0 is considered a data-driven paradigm where data are the new key resource around which everything revolves [156]. All the current technologies identified as pillars of I4.0 have been separated in 4 groups according to their role in data management [156]:

1. **Group 1: Data Generation and Capture.** It focuses on technologies that generate and save data at any system level: people, products, machines, and processes.
2. **Group 2: Data Transmission.** It involves all the technologies involved in data transmission both to store data and recover it when it needs.
3. **Group 3: Data Conditioning, Storage and Processing.** It collects those technologies and methodologies of data protection and storage, data recovery and data conformation check, but also the data transformation to create knowledge.
4. **Group 4: Data Application.** It collects all the methods, tools and technologies, which use collected data to act on the system by impacting the value creation process.

MEIO formalization would belong to group 3 where data are processed and stored accordingly to the technologies or tools (group 4), which will use them, for example, MEIO-SM or simulation models. Data are constantly collected, and this is an opportunity to update stored data, so all the approaches of group 3 must be compatible with the data-driven paradigm.

3.1 Data update

The updating of data depends on the approach followed to create knowledge. In the literature there are two ways to use data to update systems and they differ between those using a priori system knowledge and those not using it. Usually, manufacturing systems are designed by following technical and performance requirements, which are used to identify KPIs to monitor system evolution over time. Hence, information about processes and KPIs are available, data are collected over time through the use of sensors or properly set events log, and the digital twin of the system is updated with a specific frequency to represent the physical system state [78]. At the same way, business processes and all the processes involved in the provision of a service, such as in health care field, are designed by following technical and performance requirements; however, they are executed with a large performance variability and often with many unexpected events. Moreover, unexpected events can induce the process to evolve in an unexpected way by introducing new processes in the value creation chain. For example, in a hospital, even if it exists a procedure to receive patients, assign them a priority risk according to their diseases and then schedule medical or technical examination, many unexpected processes can frequently happen by causing a performance deterioration, such as queues in ATM due to poor internet connection, unexpected behavior of employees or patients' diseases, unexpected loops between processes or an ineffective workload division among resources. Hence, in all the cases where unexpected events are frequent, the digital twin representation should avoid a priori knowledge and should be based on the happened events to identify a properly representation of all the actual processes present in the system. Process Mining involves a variety of techniques to extract knowledge about system from process data collected in event logs instead of using a priori information to identify processes and then monitoring [271]. For this reason, Process Mining is useful when a well-defined route does not exist such as hospitals [2] or the other cases where a priori information can explain only a part of system variability. Process Mining generally involves four areas [273]: control-flow discovery; performance analysis; conformance checking and updating; resource organizational structure. Several algorithms and heuristic approaches have been developed for the control-flow discovery phase, where processes are identified [274]. The conclusion of process discovery phase allows a performance analysis, which is mainly oriented to the reduction of non-added value activities, by combining it with VSM [157], and the simulation model formalization through the use of Petri nets and Business Process Networks [274]. Conformance checks can update the model by adding or removing processes or redefining their performances. Multi-dimensional process mining can represent several variants of events and process models by exploiting process cubes approach [272] to allow the organization of resources in more than a way.

I4.0 has disrupted the data usage, in fact, in addition to being a data-driven approach, it is also a paradigm, which leads to extensive data manipulation to modify, reorganize, and improve value chain. The huge amount of data is leading to the identification of balance between data collection and data usefulness, i.e., data productivity [187], and it is exasperating the crucial needs of formalization and loop closures between data collection and decision process [113]. However, these necessities are not directly connected with the amount of new data, thus with its sources. The issue is not a deeper process control thanks to a higher frequency sampling, but the emergence of “plug and produce” resources, which can be allocated in a flexible way, to different processes with different tasks, according to the contingent needs. “Plug and produce” approach is fostered and enhanced by I4.0 [64], which considers the cooperation machine-machine and human-machine crucial for system flexibility [235], thus “plug and produce” is also the reason of the increasing flexibility of systems [64]). However, technologies and tools of group 3 identified by [156], i.e., “Data conditioning, storage an processing”, must be able to update the digital twin of the system by taking into consideration that the resources are flexible. Furthermore, formalization tools and methods must consider, during the update of the digital twin of the system that a priori information could not consider relevant dynamics that affects the real system. Hence, the system representations based on a priori information, i.e., the models, could not be able to exactly replicate the physical system performance since the manufacturing system is always more similar to a system without well-defined routes such as hospitals.

3.2 Data-driven MEIO formalization of a Waste-To-Energy Supply Chain

MEIO formalization is compatible with both the approaches which use a priori information and the other, which do not use it. However, the identification of resource and energy consumption together with process performance assessment requires the development of new Process Mining techniques. Later, the combination between these Process Mining techniques and MEIO formalization can be developed. However, combining Process Mining and MEIO formalization leads to the risk of neglecting resource flows for which do not exist a sensor or an event. Hence, a combination of approaches, which use and do not use a priori information, would be preferable. Conversely, a priori approaches provide a more complete information for MEIO application because they follow the design and analysis phases where all material and energy flows are identified and re-arranged according to MFA principles (see subsection 2.1). In fact, processes are initially identified according to both data availability and investigation aims. Late, during the operational phase, RP and PP MEIO tables are updated by following the updating policies and tools such as frequency of update, sample path lengths, and process monitoring via control charts.

Data-driven MEIO formalization has been used to formalize both process performance and the resource utilization of an Italian company part of a Waste-To-Energy (WTE) SC. According to the goals of I4.0 group 3 (i.e., Data Conditioning, Storage and Processing), this formalization aims to collect and manipulate data to create system knowledge. System knowledge can be exploited by further methods and tools (belonging to group 4) to improve value chain at strategic, tactical and operational level.

3.2.1 Acea Pinerolese and the EngiCOIN project

Data-driven MEIO formalization has been used to formalize the production system of Acea Pinerolese, a company part of a WTE-SC located in Piedmont, Italy. The whole WTE-SC is represented in Figure 3.1 where the red dashed box indicates the part of the system under analysis. In Figure 3.1 from left to right, there are three sources of waste, which produce biogas: wastewater treatment (WWT), landfill (LF) and the Organic Fraction of Municipal Solid Waste (OF-MSW). Biogas produced from WWT, LF and, OF-MSW is exploited through a Combined Heat and Power (CHP) process to produce power and heat for both self-consumption and sale. When power and heat production cannot satisfy market demands and factory needs, extra power is purchased whilst fossil methane is bought to increase heat production via boilers. The current production system produces several wastes disposed in the environment: (i) biogas, (ii) carbon dioxide (CO_2), (iii) heat. The emissions of (i) and (ii) represent an environmental cost for the company due to their climate altering characteristics, while (iii) is an unexploited resource. In fact, power can be sold to the market any time, whilst heat larger than demand must be dissipated. Operational reasons related to biogas production variability and its methane content limit the complete exploitation of produced biogas. Biogas in excess is burnt without resource recovery or emitted in controlled way in the atmosphere.

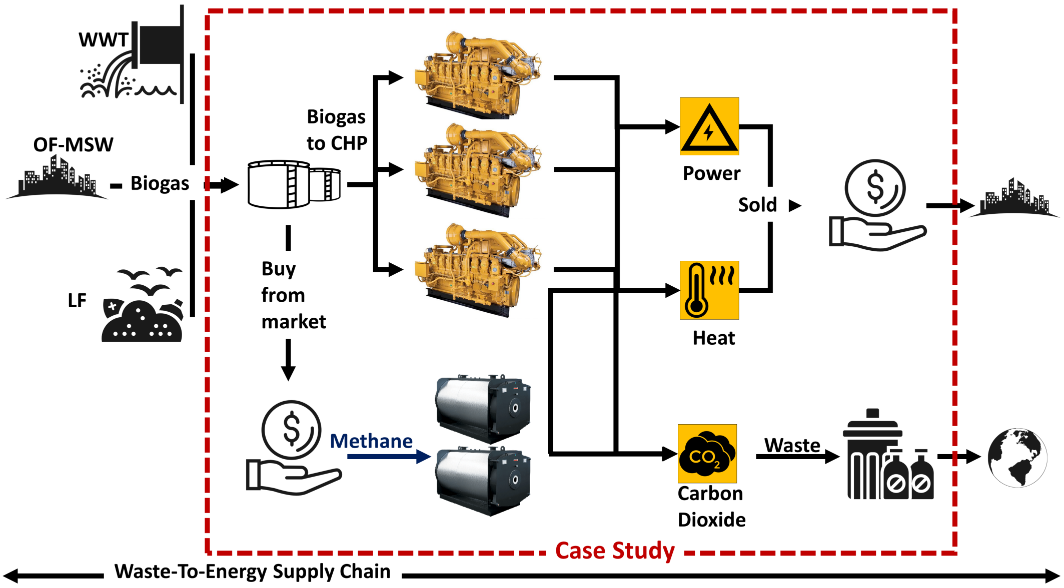


Figure 3.1: Waste-To-Energy Supply Chain and Acea Pinerolese, Piedmont, Italy.

Acea Pinerolese has been identified, within the ENGICOIN European project (ENGICOIN, 2018), as the industrial site where testing the prototypes of new technologies to convert CO_2 in high added-value products. ENGICOIN project is focused on technology improvement, whilst this thesis deepens the economic and environmental effects these technologies would have in the current system, i.e., the impacts on resource efficiency, the opportunities to develop IS, and the combined effects with other system improvements.

The introduction of new technologies to exploit waste is assessed in combination with the adoption of solutions to improve the production system. There are two options of system improvement, and four new technologies to exploit waste. To overcome the operational problems that limit the exploitation of biogas, the Bio Methane Purification (BMP) process is proposed. Instead of direct biogas exploitation, it is converted in biomethane through BMP; biomethane can be used both in the CHP and the boilers. BMP allows to sell new finished products, i.e., biomethane and biofuel, through the introduction of biofuel production (BFP) process. However, BMP divides biogas in biomethane and CO_2 that is a cost when not exploited. Three Microbial Factories (MFs) exploit different bacteria to produce three value-added chemicals: (i) lactic acid, (ii) PHB, and (iii) acetone, produced from MF1, MF2, and MF3, respectively. Furthermore, a polymeric exchange membrane electrolyzer (pem-E) is introduced, too. Pem-E transforms the excess of power in hydrogen and oxygen, used to feed MFs. The introduction of MFs and pem-E allows the production of five new finished products: lactic acid, PHB, acetone, hydrogen, and oxygen.

3.2.2 Data gathering and identification of processes

Figure 3.2 shows the physical infrastructure of the Supervisory Control And Data Acquisition (SCADA) system of the production system under investigation. SCADA is a type of distributed IT system for physical system monitoring and supervision, which includes computers, sensors and actuators, micro-controllers and the infrastructure for data communication and storage [4]. Operational and confidentiality reasons do not allow the actual representation of all the control points (CPs) and the entire system, then the representation is given through the equivalent CPs (ECPs), i.e., fictitious CPs virtually positioned in relevant points of the system and showing the aggregated information of several actual CPs.

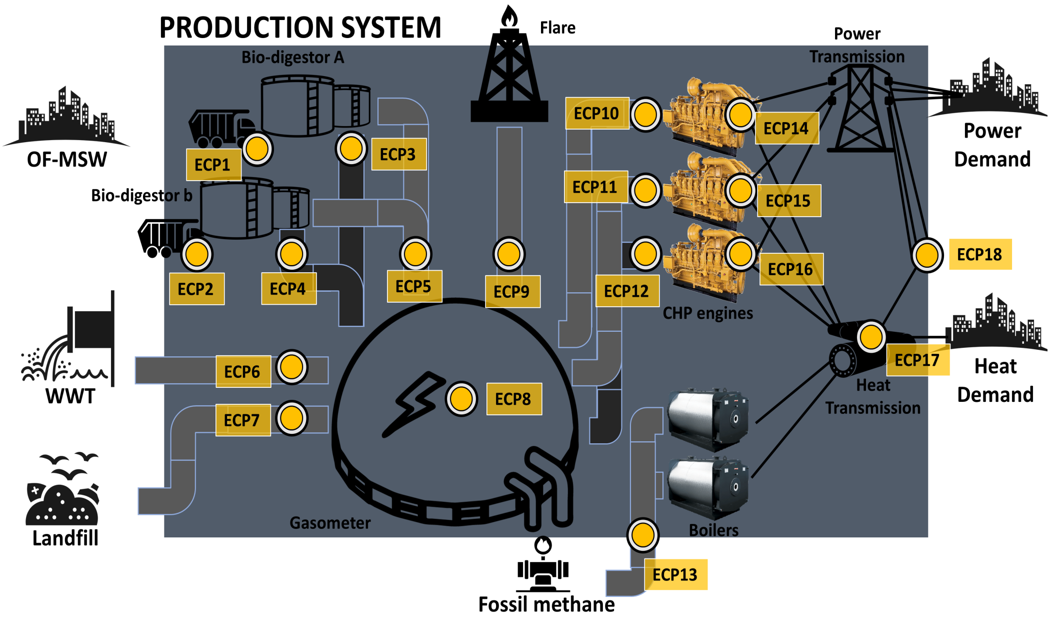


Figure 3.2: Representation of SCADA system of production system (blue area) with 18 ECPs (yellow and white circles).

ECP ID	Description	Observed Quantities	ECP ID	Description	Observed Quantities
ECP1	OF-MSW to BD A	Weight.	**ECP10**	Biogas to CHP1	Flow; CH_4%.
ECP2	OF-MSW to BD B	Weight.	**ECP11**	Biogas to CHP2	Flow; CH_4%.
ECP3	Biogas from BD A	Flow; CH_4%.	**ECP12**	Biogas to CHP3	Flow; CH_4%.
ECP4	Biogas from BD B	Flow; CH_4%.	**ECP13**	Fossil methane to boilers	Flow.
ECP5	Biogas from BDs A+B	Flow; CH_4%.	**ECP14**	CHP1 production	Power; Heat.
ECP6	Biogas from WWT	Flow; CH_4%.	**ECP15**	CHP2 production	Power; Heat.
ECP7	Biogas from LF	Flow; CH_4%.	**ECP16**	CHP3 production	Power; Heat.
ECP8	Biogas inventory	Volume; Pressure; CH_4%.	**ECP17**	Aggregated Heat production	Heat.
ECP9	Biogas to Flare	Flow; CH_4%.	**ECP18**	Aggregated plant self-consumption	Power; Heat.

Table 3.1: Production system ECPs, 10 seconds sampling interval.

The combination of at least two ECPs allow the definition of a process via RP MEIO table. In fact, the downstream ECP of a process leads the data gathering useful for process performance assessment, i.e., throughput, waste and byproducts, but only through the comparison with the upstream ECP it is possible to evaluate the resource efficiency. Then, data manipulation routines can be set to update MEIO tables over time. However, the presence of various subsequent interventions to extend pipelines and the large variability of anaerobic digestion process for OF-MSW, together with incomplete data, have complicated the automatic process, by requiring further assumptions. Assumptions and processes identified in biogas production are reported in subsection 3.2.3.

3.2.3 Biogas production processes

Biogas comes from three different sources: biodigestors (BD) A and B, WWT, and LF. They are independent from each other and their production cannot be increased or decreased in a controlled way in the short-run. Hence, to study process parameters, BDs, WWT and LF can be considered separately.

Anaerobic digestion in bio reactors. A subsequent pipeline extension has doubled the connections between BDs and gasometer. Initial pipeline has two ECPs, to monitor biogas supply from BD A and BD B to gasometer, respectively, via ECP3 and ECP4. However, the new pipeline, which is used when the pressure on the first one increases, is monitored only via ECP5, which does not indicate whether the biogas supplied is produced by BD A or BD B. Biogas production into the BDs is the output of anaerobic digestion process, which involves OF-MSW. OF-MSW are provided once a day, and they affect biogas production for the next 2 weeks; however, ECP1 and ECP2 are able to provide only the weight of OF-MSW, and the composition of each load is largely variable, by affecting chemical reactions in ways that cannot be controlled without further analyses. Hence, biogas production via anaerobic digestion into BDs has been modeled through a normal distribution, by considering the production data of last 36 months.

Biogas production via landfill management and wastewater treatment. Biogas produced via WWT and LF are supplied to the gasometer, and they are monitored through ECP6 and ECP7, respectively. The data collected in the last 36 months have been used to define the stochastic distributions of both production process.

3.2.4 Biogas use

Biogas is exploited in a CHP process that consists of three gas engines to produce heat and power. Gas engine can be fed both with biogas and (fossil or bio) methane, but in any case there is a maintenance intervention every 900 hours of work to change the oil, with a price of 3,3 €/dm^3 and an yearly average consumption of 8250 dm^3. Furthermore, every 300 hours of work, it is necessary to replace the catalyst, and this intervention takes two hours and costs 2500 €/engine. Each activity uses about 8400 hours/year and the gas flow is between 400 and 600 Nm^3/hour. Biogas and methane do not change the flow to the engines, but they have a different output from the point of view of CO_2, power and heat produced through the initial gas volume; for this reason, CHP process is doubled in RP and PP MEIO tables. Data collection is based on a couple of ECPs for each engine (ECP10 and ECP14 for CAT1; ECP11 and ECP15 for CAT2; ECP12 and ECP16 for CAT3).

ECP9 monitors the flow of biogas to the flare. When the biogas production is larger than consumption and biogas volume of gasometer is close to the maximum capacity, part of the biogas is burnt in a controlled way in flare. However, another safety measure implies minimum biogas emissions directly from the gasometer and, which are not measured by any ECP. Hence, safety actions are modeled with other mechanisms introduced together with the mathematical programming model in 5, rather than trough process modeling via data analysis.

3.2.5 Finished products sale and self-consumption

Current production system. Two boilers are used in combination with the three gas engines to produce heat. In fact, when the heat produced via CHP process is not sufficient for both external demand and self-consumption fossil methane it is bought to feed boilers. Fossil methane supplies are monitored by ECP13 without specifying which boiler is exploiting it. The total amount of produced heat is monitored through ECP17. Hence, boilers resource efficiency is monitored by comparing produced heat and consumed methane, whilst MEIO approach, through the application of MFA principles (i.e., material and energy balance), leads to the definition of produced CO_2. Power production is monitored through ECP14, ECP15, and ECP16. Produced power and heat are firstly used for self-consumption, which is not available for single process (excepted in the cases when it is explicitly specified) but in aggregated form and monitored through ECP18.

EngiCOIN extension. The European project is testing four new technologies, which are currently prototypes tested in lab, hence data used comes from lab experiments, while final prototypes will be available since 2021 to begin the tests on field. Process time and throughput of MFs and pem-E are set in deterministic way as suggested by technology development teams. BMP and Biofuel Production Process exploit technologies available on the market and only nominal production data are available.

3.2.6 Resource-Process MEIO tables

Table 3.2 shows the RP MEIO for the current production system. Biogas production is represented through three processes of which only the output, i.e., the biogas, is known. There are two versions of CHP processes: the first one for biogas (CHP-B) and second one for methane (CHP-M). Heat and power produced by both CHP versions of the process are the same; however, the amount of input gas (larger for biogas) and the produced CO_2 change. Heat production via boiler is the last column where missing data about CO_2 are introduced by using chemical reaction to estimate the produced amount. Data are normalized by dividing them for the amount of some input or output resource to reduce the orders of magnitude that can cause several issues for the successive software applications. In PP MEIO table, the maximum production, inventory and load capacity are indicated for the unit of measurement used to normalize. Therefore, the total amount of input required and output produced by each process are obtained by multiplying its input and output values, which are indicated in RP MEIO table, for the process maximum capacity reported in PP MEIO table.

Resource	**P1 (LF)**	**P2 (OF-MSW)**	**P3 (WWT)**	**P4.1 (CHP-B)**	**P4.2 (CHP-M)**	**P5 (Boiler)**
CO2 (g)	-/-	-/-	-/-	-/1025.56	-/623.848	-/1956.67
Biogas (Nm3)	-/1	-/1	-/1	0.534699/-	-/-	-/-
Biomethane (Nm3)	-/-	-/-	-/-	-/-	0.29372/-	1/-
Oxygen (Nm3)	-/-	-/-	-/-	-/-	-/-	-/-
Hydrogen (Nm3)	-/-	-/-	-/-	-/-	-/-	-/-
Chem1 (g)	-/-	-/-	-/-	-/-	-/-	-/-
Chem2 (g)	-/-	-/-	-/-	-/-	-/-	-/-
Chem3 (g)	-/-	-/-	-/-	-/-	-/-	-/-
Electricity (kWh)	-/-	-/-	-/-	-/1	-/1	-/-
Heat (kWh thermal)	-/-	-/-	-/-	-/1.387931	-/1.387931	-/8.805
Biofuel (kWh)	-/-	-/-	-/-	-/-	-/-	-/-

Table 3.2: RP MEIO table for current processes of the production system.

Table 3.3 presents the RP MEIO table for the new processes under investigation. They are based on the nominal process performance provided by suppliers (BMP and Biofuel production process) and the lab performances provided by the researchers involved in the technology development (pem-E and the three MFs). Electrolyzer requires power to produce hydrogen, oxygen and heat. The produced heat is not the same as the one produced by CHP or the boilers due to the different temperature. However, here, they are considered the same through the conversion in thermal kWh, to obtain a comprehensive view of used and dissipated energy. Produced biofuel is measured in kWh because, to use an unified unit of measurement for the output of methane and biogas.

Resource	P6 (Electrolysis)	P7 (BMP)	P8 (Biofuel Production)	P9 (MF1)	P10 (MF2)	P11 (MF3)
CO2 (g)	-/-	-/751.29	-/-	486.72/-	133.33/-	140476/-
Biogas (Nm3)	-/-	1/-	-/-	-/-	-/-	-/-
Biomethane (Nm3)	-/-	-/0.62	1/-	-/-	-/-	-/-
Oxygen (Nm3)	-/0.0833	-/-	-/-	1.9803/-	0.1215/-	-/-
Hydrogen (Nm3)	-/0.1682	-/-	-/-	-/-	0.4858/-	254.45/-
Chem1 (g)	-/-	-/-	-/-	-/1	-/-	-/-
Chem2 (g)	-/-	-/-	-/-	-/-	-/1	-/-
Chem3 (g)	-/-	-/-	-/-	-/-	-/-	-/2.521
Electricity (kWh)	1/-	0.27/-	0.1/-	-/-	-/-	1.1545/-
Heat (kWh thermal)	-/0.1864	0.3/-	1.2/-	-/-	-/-	1/-
Biofuel (kWh)	-/-	-/-	-/4.84	-/-	-/-	-/-

Table 3.3: RP MEIO table for the additional processes and the EngiCOIN technologies.

3.2.7 Process Parameters MEIO tables

Table 3.4 reports the process parameters for all the 12 processes. Max capacity is the maximum amount of input (output) used (produced) if the machine is used at 100% load for the entire time period. The time period chosen for the following analysis is the month. The three biogas production processes have not been constrained by a maximum capacity because their production follows a normal stochastic distribution (see subsection 3.2.3) with average and standard deviation specified for each time period. CHP production cost has been evaluated by combining the cost of catalysts and oil, whilst preemptive stops have been considered in the maximum capacity definition. Investment costs have been identified through an average on similar machines, whilst those for new technologies are initial estimations made by research teams.

Processes	**Max Capacity**	**Investment Cost (€/machine)**	**Production Cost (€/unit)**
P1 (LF)	1E+14 (Nm^3)	0	0
P2 (OF)	1E+14 (Nm^3)	0	0
P3 (WWT)	1E+14 (Nm^3)	0	0
P4.1 (CHP-B)	753721.6 (kWh)	180000	0.025
P4.2 (CHP-M)	752307.7 (kWh)	180000	0.025
P5 (Boiler)	295741.1 (Nm^3)	20000	0
P6 (Electrolysis)	49104 (kWh)	500000	0.05
P7 (BMP)	1056818 (Nm^3)	150000	0
P8 (Biofuel Production)	96.735 (Nm^3)	70000	0
P9 (MF1)	18600 (g)	300000	0
P10 (MF2)	31471 (g)	300000	0
P11 (MF3)	644.45 (kWh)	300000	0

Table 3.4: Process Parameters MEIO table for current production system and processes involved in the EngiCOIN project.

Processes considered part of production line can involve also customer arrivals, demanded quantities of finished products and supply arrivals. They can be represented through stochastic distributions or deterministic parameters and then added to the production system model. In this case, biogas production and heat demand are considered as stochastic processes, and, then average and standard deviation are provided for each considered time period. Month has been chosen as time period and distribution parameters change from a month to the other according to climate conditions and customer preferences for heat demand. Table 3.5 indicates all the distribution parameters for the biogas production processes, i.e. LF, WWT, and OF, and heat demand.

Time period	P1 (Landfill)	P2 (OF)	P3 (WWT)	Heat Demand
Month 1	203694.89 - 42084.24	367674.58 - 6542.03	1279.92 - 969.67	1099726.60 - 7697.98
Month 2	205294.60 - 44123.57	332246.57 - 7069.30	6515.74 - 2197.32	1000069.01 - 11029.42
Month 3	252831.04 - 43784.02	368219.67 - 7120.84	10954.70 - 3546.99	781689.76 - 9329.06
Month 4	254654.16 - 32535.66	355986.63 - 7202.56	22746.64 - 6502.08	368999.37 - 7793.09
Month 5	240968.49 - 25581.47	367253.43 - 8108.96	46548.07 - 10696.31	178511.50 - 9659.90
Month 6	226833.98 - 23957.16	355733.55 - 7249.95	64001.67 - 15422.31	148915.49 - 9040.15
Month 7	231157.49 - 10775.77	366951.53 - 8113.32	93735.69 - 21686.53	94036.64 - 8286.35
Month 8	236522.91 - 16780.11	366807.74 - 6811.99	83865.68 - 20040.95	168645.00 - 10714.57
Month 9	206012.18 - 16873.53	355373.67 - 7954.17	93555.42 - 23845.15	175743.13 - 10284.31
Month 10	228133.64 - 28344.32	367541.86 - 8175.04	91205.96 - 23823.96	270959.33 - 8866.72
Month 11	222442.79 - 23758.99	357529.14 - 7278.20	57217.33 - 18652.21	988198.85 - 10044.92
Month 12	193448.40 - 0.01	367942.91 - 7648.29	73671.0 - 20312.41	1218602.94 - 6322.94

Table 3.5: Process Parameters MEIO table for stochastic distribution, in the form "average - standard deviation", of biogas production processes and heat demand.

3.2.8 Warehouses

All the activities involved in the production system can be represented through MEIO formalization, even transport and storage activities. For this reason, MEIO is flexible enough to be combined with Process Mining techniques, which do not exploit a priori knowledge. Furthermore, the "input/output" format of RP MEIO table allows to model the perishability of resources and both energy and time required to stock or transport an unit of resource. The combined use of MEIO approach and technologies from I4.0 paradigm is applicable also for warehouses and transports formalization, by implementing data-driven approach to update "input/output" format of MEIO, e.g., via RFID technologies or event logs. There are many potential applications useful for warehouse management, and potentially also for transport activities, to assess their environmental impacts, align inventory system and actual stocked quantities, comparing performance by stocking or moving different resources in the same kind of warehouse.

Table 3.6 represents the RP MEIO table for gasometer, which is currently used in the production system under investigation, and some new warehouses, that are under evaluation to support the production of new resources such as biomethane, hydrogen, oxygen and the added value chemical products. Warehouse W6 can be used to storage concurrently all the three type of chemical products. The "input/output" format of W6 indicates the same amount of input for all the three chemicals, and this means that one unit of each of them occupies the same volume of storage. In this case, no energy, of any kind, is required to stock resources, but, if a multi-resource warehouse requires different energy costs to store different resources, then it can be represented through different sub-processes like the case of CHP-B and CHP-M (see subsection 3.2.6 and Table 3.2).

Resources	W1	W2	W3	W4	W5	W6
CO2 (g)	1/1	-	-	-	-	-
Biogas (Nm3)	-	1/1	-	-	-	-
Biomethane (Nm3)	-	-	1/1	-	-	-
Oxygen (Nm3)	-	-	-	1/1	-	-
Hydrogen (Nm3)	-	-	-	-	1/1	-
Chem1 (g)	-	-	-	-	-	1/1
Chem2 (g)	-	-	-	-	-	1/1
Chem3 (g)	-	-	-	-	-	1/1
Electricity (kWh)	-	-	-	-	-	-
Heat (kWh termici)	-	-	-	-	-	-
Biofuel (kWh)	-	-	-	-	-	-

Table 3.6: Resource-Process MEIO table of warehouses show eventual loses of resources during holding activities, eventual energy cost for storage, and proportion of volume occupied in case of multi-resource warehouse.

Table 3.7 shows the maximum capacity for the various warehouses. The same warehouse could be used to stock more than a resource; for this reason, in PP MEIO table, both maximum capacity and operational costs for each resource are indicated. In the case under investigation, warehouse W6 is used for all the produced chemical products, however, they have the same operational/inventory cost, which is reported in row 3. Different resources of the same multi-resource warehouse can occupy different volume of available capacity and this information is reported in RP MEIO table. On the contrary, in this PP MEIO table, it is reported only the maximum capacity for each resource set due to reasons different from required volume, such as operational decisions and safety reasons.

	W1	**W2**	**W3**	**W4**	**W5**	**W6**
Investment Cost (€)	50000	70000	75000	60000	60000	50000
Inventory Cost (€/(tp*unit))	0.01	0.005	0.0065	0.0065	0.0065	0.01
CO2 (g)	10000	-	-	-	-	-
Biogas (Nm3)	-	30000	-	-	-	-
Biomethane (Nm3)	-	-	30000	-	-	-
Oxygen (Nm3)	-	-	-	10000	-	-
Hydrogen (Nm3)	-	-	-	-	10000	-
Chem1 (g)	-	-	-	-	-	100000
Chem2 (g)	-	-	-	-	-	100000
Chem3 (g)	-	-	-	-	-	100000
Electricity (kWh)	-	-	-	-	-	-
Heat (kWh termici)	-	-	-	-	-	-
Biofuel (kWh)	-	-	-	-	-	-

Table 3.7: Process Parameters MEIO table for warehouses.

3.2.9 Discussion

The Multi-layer Enterprise Input-Output approach is based on the Multi-Layer Stream Mapping and the combination of Enterprise Input-Output and Material Flow Analysis. It aims to reconcile the value creation analysis based on the system performance evaluation and resource efficiency analysis devoted to the identification of sources and sinks of materials within the system. However, all the new tools and methods oriented to manufacturing systems must take into consideration the new industrial revolution of Industry 4.0 and digitization, since they are disrupting the production paradigms by introducing new technologies. The most diffused approaches based on Lean principles are struggling to identify their clear roles in the new industrial revolution, by showing the lack of formalization methods. MEIO is a formalization approach to represent production, inventory and transport activities, i.e., both value-added and not-value added activities, of a system. It is based on two tables: (i) Resource-Process and (ii) Process Parameters. Both tables can be based on data collected during an analysis and further continuously updated through data gathering systems. MEIO formalization is a flexible approach to be used in combination with Value Stream Mapping (MEIO-SM) to assess value creation and with even more complex approaches to define the digital twin of the system and to lead to changes to improve value creation via simulation and mathematical programming approaches.

Several IT approaches collect data and match them thanks to collaboration platforms to support IS identification and emergence [144]. However, technical, logistic and regulatory issues can make an IS unsustainable [81]; hence, economic and environmental sustainability must be measured by considering the specific conditions of each IS. MEIO formalization allows the representation of activity performances along both economic and environmental sustainability, then it can be crucial for leading accurate analyses and development of more complex tools and methods, but based on a more effective and lean formalization.

Chapter 4

Summary

Part I of this thesis sheds a light on the emerging necessities of tools able to lead system performance analysis concurrently on all the three dimensions of SD, i.e., economy, environment, and society. New manufacturing processes are more sustainable and performant; however, neither the adoption of new technologies nor the circular business models can make sustainable a stand-alone company if it would not cooperate with others. Some waste resources can be avoided, while others must be exchanged because other stakeholders can give them a larger value, by reducing, in this way, both environmental resource consumption and efforts in disposal activities. The availability of new technologies and the endemic characteristics of a region, such as the local economic activities, produced waste and required products, make the definition of the optimal network structure a complex task. Furthermore, the network structure definition should be a bottom-up approach, which complicates the context due to the difficulty of stakeholders' coordination. In the bottom-up approach, individual companies try to foresee their best role to reduce their environmental damage and achieve competitive advantage. In the literature, also top-down approaches to design EIP exist, where resource efficiency is maximized by design. However, SD is a matter of culture, in fact, technologies, product demands, and produced wastes change over time, by jeopardizing the sustainability of top-down designed EIPs. Individual companies are the only ones able to effectively pursuit eco-innovation over time since they have the most updated information about their business models.

The Eco-innovation requires a continuous system improvement for reducing waste production and improve performances. This thesis suggests to consider IS concurrently with system improvement options, also by adopting new technologies. In the field of sustainable production processes, several tools and methods are proposed to measure the creation of value, the economic sustainability, and the resource efficiency. The most of the tools are too complex and require more resources and knowledge than the amount available in SMEs, while only the most recent approaches, which are based on both Lean principles and flow analyses, are able to concurrently consider productivity and aggregated resource efficiency. For example, the Multi-Layer Stream Mapping (MSM) approach considers value creation in terms of time, but also the used resources and energy. This approach is used in combination with other tools to perform deeper analyses based on environmental and economic performance. Subsequently, according to the KPI approach, widely spread in Lean field due to the immediacy and ease of communication of information, all the data from the various tools are synthesized through MSM to allow aggregated analyses. However, Lean based approaches and flow analyses do not provide a well-defined process formalization, and they are not suitable for complex systems such as the networks of joint EIPs and SCs, and the new manufacturing systems. The networks of joint EIPs and SCs are necessary to achieve environmental goals and competitive advantage, and the others, the new manufacturing systems, are influenced by the I4.0, which makes them reconfigurable and interconnected.

The integration of MSM with the combination of Enterprise Input-Output (EIO) and Material Flow Analysis (MFA) approaches has been proposed to provide a flexible and, at the same time, well-defined formalization tool. MEIO formalization approach is based on two tables: (i) Resource-Process (RP) MEIO table; and (ii) Process Parameters (PP) MEIO table. The RP MEIO tables connect value and non-value-added activities with both the input resources (i.e., raw materials, energy sources, consumables) and output resources (i.e., products, by-products, waste). According to MFA principle of assuring the material and energy balances, input and output must coincide either when data are gathered through sensors and when they are estimated through chemical and physical reactions. From one side, the principle of material and energy balances supports companies to conduct deep investigations about waste and by-products of processes. On the other side, they lead to a more accurate analysis of substances and materials involved in the whole value creation process.

The PP MEIO table contains all the parameters about the single activities according to the further analysis. Basic information includes investment cost to purchase another machine for a specific activity, such as, production machines, trucks, or warehouses; operational costs per unit; maximum capacity in terms of throughput, transport, or inventory capacity. PP MEIO tables can be extended by including also distances between activities, all the resources that can be stocked (transported) through a multi-resource warehouse (truck or others). Furthermore, MEIO formalization can be adapted to deal with simulation approaches, by modifying PP MEIO table. In fact, preemptive and non-preemptive failures, maintenance interventions, demand, and customer inter-arrival distributions, and all the other events that can affect a system, can be represented through PP MEIO table.

EIO approach suggests to follow the resource flows among the involved activities, by connecting them one to the other. It provides insights about the allocation of produced and consumed resources among activities. Furthermore, it is compatible with the additional description of transport and stocking infrastructure proposed by MEIO approach. In fact, transport and stocking activities representation benefits from the application of MEIO approach since it can model: (i) perishability of stocked or transported resources, (ii) inventory losses, (iii) energy and resources required to transport or stock a specific material. Different versions of activities can be provided by allowing the representation of more than one behavior. It results particularly interesting especially in the field of I4.0 where machines and manufacturing resources follow a "plug and produce" approach. Hence, they can be allocated to different processes and/or tasks, by changing their environmental and economic performance. MEIO formalization approach is compatible with Lean principles by design (it is based also on MSM), in fact, the described data can be visualized through KPIs to perform a value analysis based on Stream Mapping approach (i.e., MEIO-SM). However, the MEIO formalization allows the use of different tools and methods to perform the subsequent analyses, by avoiding the changes at the initial study and formalization of the system.

In Chapter 2, MEIO formalization has been applied to a new SC arising from the circular use of the by-products and waste of both wine and rice production chains. The study, which has been performed within the regional project InnovaEcoFood, aims to provide preliminary results on the economic and environmental sustainability of using pomace and rice husk to produce flours and rice husk butter for highly healthy baked products for human food. Only value-added activities have been considered, in fact, the production processes have been represented through MEIO formalization, while transport and inventory activities have been neglected because they were out of the scope of the project. Hence, the value analysis considers the created value without reducing it for the costs and times of all the non-added value activities. Thanks to MEIO formalization, the amount of wasted resources and the opportunities for using part of them as input of other production processes are immediately available. By assigning a cost to all the wasted resources, according to Material Flow Cost Accounting (MFCA), the environmental issue of poor resource efficiency is immediately reported in economic terms. Moreover, the application of MEIO formalization invited stakeholders to reflect on the waste produced by the processes they have chosen.

MEIO formalization is halfway between the data gathering and the technologies able to exploit the acquired system knowledge, which are based on heuristics and/or algorithms. I4.0 is a data-driven paradigm, data are collected and then exploited, by modifying the system, to react or anticipate changes and continue to follow economic and environmental sustainability. Currently, the digital twins, which are the digital representation of physical systems, are often based on a priori knowledge of processes and events that affect it. However, manufacturing systems and SCs are becoming flexible and reconfigurable. In fact, manufacturing systems exploit “plug and produce” production resources, which can change their role over time according to contingent needs. Also, the SCs are becoming resilient through dynamic reallocation of the resources and the changes of the involved stakeholders. Hence, the design of the new systems is becoming complex due to the unforeseeable behavior of resources over time under different situations. Moreover, also the design of both the data gathering infrastructures and the models for system representation and optimization can hardly be reliable when it is based on a priori knowledge.

Process Mining techniques exploit the event logs to identify the processes of the manufacturing systems. They do not use a priori knowledge to also identify the processes that have been neglected in design phase. For example, the business processes and the processes involved in the provision of services are largely affected by process variability because of the unexpected events and the behavior of the manufacturing resources. Whether the data are collected exploiting or not a priori knowledge, the tools and the methods that connect data gathering infrastructures with technologies for data exploitation must be compatible with the continuous update of the process information. The continuous update of process information is a complex task because processes can follow trends, seasonality, or they can be correlated with other processes or auto correlated, depending on the situation. The MEIO formalization can report the stochastic distributions of processes rather than only the deterministic information. Furthermore, the trends and seasonality can be reported on the PP MEIO tables to allow a better process representation.

In chapter 3, the MEIO formalization has been applied to the case study of Acea Pinerolese, an Italian company part of a Waste-To-Energy Supply Chain (WTE-SC), where both stochastic and deterministic processes are involved. Six activities have been investigated: (i) three biogas production processes have been analyzed to identify their monthly stochastic distribution; (ii) a deterministic stocking biogas activity; (iii) a deterministic CHP process to produce power and heat constituted by three parallel machines; (iv) deterministic heat production process via fossil methane combustion in boilers; (v) the stochastic process of heat demand observed by the company; (vi) a stochastic self-consumption demand of power and heat. The case study investigates the adoption of new technologies, which are currently under development in the framework of EngiCOIN European project, to improve resource efficiency through value creation from waste CO_2 while reducing the environmental damage. The technologies under development are three Microbial Factories (MFs), which are able to produce highly added-value chemical products from CO_2 and hydrogen and oxygen. Hydrogen, oxygen and heat are produced through a polymeric exchange membrane electrolyzer (pem-E) exploiting the produced power through CHP process. Furthermore, two system improvement alternatives have been considered together with all the other technologies: (i) biomethane purification (BMP) and biofuel production processes (BP). All these additional processes, i.e., MFs, pem-E, BMP and BP, are deterministic because data have been collected through lab experiments and nominal performance.

Part II

Novel Eco-Innovation methodology based on Industrial Symbiosis and system improvement

Chapter 5

Eco-innovation: an operational way to pursue the Sustainable Development

Eco-innovation can influence the performance of the companies at various levels (see subsection about Eco-innovation in the Introduction), and its dimensions are generally identified as: product Eco-innovation, process Eco-innovation, organizational Eco-innovation, and marketing Eco-innovation. Eco-innovation is often addressed through actions focused on one of its dimensions, even though the holistic approaches are widely indicated as more effective in terms of achieved results [55]. The holistic approaches are complex because they involve deep changes in terms of what a company offers to its customers, how it produces the products, and the entire network of relationships that determine both economic and environmental performance. Many factors may result crucial for the development of a holistic approach, and these factors can be far from be determinant in the same way in different context.

5.1 Leading Eco-Innovation at company level

The identification of drivers and barriers is crucial for the allocation of resources, efforts, policies, regulation. In fact, for a company, the risk of investing in low performance activities is real, especially if the regulation context and the local economy are neglected. At the beginning, Eco-innovation drivers were identified mainly outside the companies: demand side, supply side, institutional and political influence [143]. The indicator approach has helped to measure performances, especially in process Eco-innovation, and the indicators are commonly related to the material flows, the use of resources and worker's health and safety [181]. Garcia et al. [103] collected 30 KPIs for the three dimensions of Eco-innovation, which are reported in Table 5.1

Product KPIs	**Process KPIs**	**Organizational KPIs**	**Marketing KPIs**
Use new cleaner material or new input with lower environmental impact	Reduce chemical waste	Green human resources	Returnable and reusable packaging
Use of recycled materials	Reduce the use of water	Pollution prevention plans	Green design packaging
Reduce/optimize the use of raw materials	Reduce the use of energy	Environmental objectives	Quality certification
Reduce number of products components	Keep waste to a minimum	Environmental audits	
Eliminate dirty components	Resue of components	Environmental advisory	
Product with a longer life cycle	Recycle waste, water or materials	Invest in research	
Product ability to be recycled	Environmental-friendly technologies	Cooperation with stakeholders	
	Renewable energy	New markets	
	R&D	New systems (remanufacturing and transport systems)	
	Acquisition of machinery and software		
	Acquisition of patents and licenses		

Table 5.1: The 30 KPIs identified for the three types of Eco-innovation plus the marketing Eco-innovation.

From the proposed KPIs, it emerges the crucial role that technology detains in spreading Eco-innovation through the improvement of the economic and environmental benefits that it brings [161]. Technology is classified in three groups [148]:

1. **reactive and preventive technologies**, to repair or prevent environmental impacts;
2. **end-of-pipe technologies**, used to reduce the downstream pollutant load of production processes or product consumption;
3. **clean or integrated technologies**, which limit the causes of environmental damage at process or product level.

However, technology is only one among the various determinants that should be addressed, and new technology adoption does not directly implicate a successful and sustainable application of Eco-innovation. Technological infrastructure also represents a hard barrier to CE due to the distance between the performances of the prototypes and processes for industrial competition [71], especially when there is not a market pull for Eco-innovation. In this case, customers want to pay the lowest prices without considering product quality and environmental effects, then it is only technology push, and the technology adoption is limited to the cases of large cost savings [124]. Eco-innovation definitively leads to better financial performance only when pursued by large companies, while SMEs have several difficulties [217]. Arranz et al., [13] highlights that companies are mainly worried by three issues: the large uncertainty that affects the results of Eco-innovation, the complexity they have to manage without structured tools and methods, and the uncertain approval of the market.

5.2 Multi-stakeholder interaction and technology based approach

The Introduction showed the benefits of the IS adoption for resource efficiency improvement from a systemic point of view. In fact, the individual companies cannot achieve the zero-waste production condition through an economic sustainable way. Furthermore, investments devoted to improving environmental performance must be sustainable over the time, also when they are oriented to a network approach together with other companies. On the other side, from a systemic point of view, the improvement of environmental performance must aim to minimize negative impacts and concurrently maximize economic results and return of regenerative substances to the environment. Hence, these investments cannot be limited only to offset the environmental returns, i.e., tax and environmental cost reduction together with cost savings. This thesis proposes to exploit IS network also for producing new products, by concurrently designing EIP and the SCs necessary for the new products. The role of SCs is the delivery of new products to the customers by both exploiting the waste produced by other companies and integrating the produced waste with virgin raw materials when it is necessary. The larger created value allows to raise the bar of initial investments allowing a better waste exploitation.

The disrupting force of the Eco-innovation can be channeled to push the individual companies towards the network creation to achieve better economic and environmental sustainability. According to the technological advancement and the changes in the local economy, companies pursuing the permanent Eco-innovation process will change, in whole or in part, both their membership and role in the networks. Hence, the goal is the pursue of Eco-innovation as a practical way to achieve the benefits brought by the concurrent exploitation of the principles of the CE paradigm and IE [18]. The networks of companies, i.e., the joined network of SC and EIP, can become the starting point for the development of Innovation Pole or Regional Innovation Systems thanks to their capabilities to exploit local knowledge and resources, and they can be supported also by local and regional authorities [256]. In fact, the networks of companies can adopt new technologies easier than the individual companies to gain larger flexibility, by sharing the large investments and burdens, whilst increasing the opportunities of value creation and supporting Eco-innovation [130]. Furthermore, companies, and especially SMEs, need to cooperate among themselves, and with other institutional and not institutional intermediaries to lead Eco-innovation [25]; in fact, both the institutional and the non-institutional intermediaries can help the individual companies through the suggestion of structured approaches and the partnership development role to facilitate the interactions with other stakeholders [151].

This thesis investigates methods and methodologies to support the paradigm shift achievable through Eco-innovation. Carrillo et al. identified three different and incremental results achieved through the pursue of Eco-innovation [44]: the incremental improvements of current value creation systems to reduce negative impacts (add-on and/or end of pipe solutions); the increasing of resource efficiency (sub-system changes); finally, the paradigmatic shift, where the patterns of production and consumption change entirely due to radically new technological/organizational approaches (Eco-effectiveness or systemic changes). The new manufacturing paradigm, i.e., I4.0, can support the methodologies oriented to the Eco-innovation to achieve the production and consumption paradigm shift by facilitating the CE business models and the IS development [266]. In fact, thanks to the improved coordination and complexity management capabilities, it is possible the involvement of various stakeholders in a holistic techno-economic approach to the EI [147]. The sustainable SCs and, more in general, the collaboration networks have a key role in spreading the Eco-innovation based on the new technology adoption, and it has both direct and indirect effects on improving the general environmental performances [67]. Companies would aim to new business opportunities through process Eco-innovation; however, the gap of how to properly lead it remains [136]. From the network point of view, the representation of IS as a form of Sustainable Supply Chain to reduce the environmental damages has been proposed in [129]. However, most of the tools are focused on the level of the design and management of the network rather than focusing on fostering the networking process at company level [213], and only one approach focused on helping companies to identify their potential partners has been found [192]. From the Eco-innovation point of view, many models have been proposed in the literature; however, it has been identified both a lack of structured approaches to pursue Eco-innovation and also tools to allow implementation, control and monitoring of its advancement [283]. The research has widely focused on the identification of drivers and barriers and several indicators to monitor Eco-innovation process have been proposed in the literature [103]. However, the necessity in how to practically support drivers and remove barriers to pursue EI is rapidly increasing [33]. There is a gap in the development of the awareness about the strategic relevance of Eco-innovation, the need of methods to support product and process Eco-innovation, the cooperation and partnership within supply networks and the organizational structure required [148].

Furthermore, the relevance of multi-stakeholder approach is highlighting the necessity of methods able to favorite the long-term commitment of individual companies [33]. Command and control approaches, sometimes followed for IS development (see subsection Industrial Symbiosis in Introduction), are not suitable also for a wide support to the Eco-innovation process [39].

The proposed methodology, which is introduced in the next section, is based on both the new technology adoption and the multi-stakeholder approach, by focusing on the individual companies. It aims to help the individual companies in the development of awareness about the benefits of Eco-innovation process in a quantitative and structured way. However, since the SD has a twofold nature, i.e., it must be developed internally within companies but then, it must gradually involve other stakeholders to remain effective; thus, the relational dimension is addressed together with the awareness development about SD. The network referred to in the methodology is the joined network of EIP and SC, which has been introduced before. The methodology leads Eco-innovation concurrently along all the three dimensions: product, process, and organization. The adoption of new technologies helps to both reduce the waste production through the system improvement, and the exploitation of remaining waste, which cannot be reduced, via IS network. Hence, the methodology does not focus on the implementation or the management of IS, but it focuses on the identification of the characteristics that potential IS relationships should have to completely exploit the wastes of the system. The IS is addressed as a part of the comprehensive strategy to improve resource efficiency rather than a stand-alone action.

5.2.1 Methodology

The methodology involves the potential factors hindering the development of IS in the Introduction, and then put them together with the information coming from the production system. Basing on these factors, the methodology has been developed to support companies during the identification of relevant sources of data, data collection and aggregation, and data exploitation through an optimization model, which is introduced at the end of this chapter. Finally, the proposed methodology has been applied to a case study, in the next chapter, to derive, in a deductive manner, insights about the interactions between both the actions of waste reduction and IS development.

The proposed methodology exploits the mathematical programming approach to addresses most of the barriers identified. Furthermore, since it aims to support companies in their decision-making process, it addresses the production uncertainty due to its potential impact on the effectiveness of the actions aimed at waste reduction or waste exploitation through IS. Production uncertainty is addressed by the methodology through the optimization of the Mixed Integer Linear Programming model combined with scenario analysis, while most of the approaches previously introduced provide a static representation of resources. Furthermore, the “preliminary assessment” phase of IS, addressed in this paper, could neglect the first three barriers identified in literature, i.e., "lack of commitment to sustainable development", "lack of information sharing and cooperation and trust", while the remaining four should be carefully considered. These four barriers (from 4 to 7) involve information that can be sufficiently available in this phase and are determinant for the decision-making process of opting for IS or other actions to avoid waste. Hence, economic feasibility, energy and environmental laws, technical feasibility and local community context are the dimensions considered to develop the methodology aimed at supporting the individual companies to reduce waste and/or reuse them within IS.

Acea Pinerolese has been chosen as case study because it is a Waste-To-Energy company producing heat and power from biogas obtained by landfill, wastewater treatment and the organic fraction of municipal solid waste. The energy and environmental laws deeply influence the production system of Acea. For example, the maximum power production capacity was limited to 1 MW to obtain incentives in the power sales, and the CO_2 equivalent kgs of emissions brought environmental costs. Furthermore, Acea participates in the EngiCOIN European project 2018, which has the main goal of developing new technologies to use CO_2 to produce high added value chemicals. These technologies will be in any case introduced in Acea, as prototypes and not fully developed processes, thus allowing the comparison between the results of the case study of this thesis and the real adoption. Finally, also the adoption of other technologies to simultaneously reduce waste emissions and develop new products are considered at this moment by Acea. Therefore, the concurrent evaluation of technologies for IS and those for waste reduction is performed and the results of the case study, which holistically involves product, process, and organizational dimensions, are provided.

5.3 Eco-innovation methodology based on IS and system improvement

The proposed methodology supports companies starting from data collection and grouping them in (i) geographical and (ii) design factors. Geographical factors are considered as given and not under the control of the company. Conversely, the company can control the design factors, for example, through the introduction of new processes. All the collected factors, i.e., all kinds of involved resources and processes dealing with them, are used to identify alternatives of system improvement and opportunities for IS. All the alternatives of system improvement and IS are modeled together through the proposed mathematical model. Figure 1 summarizes the iterative nature of the methodology, which is based on three pillars: (i) factor assessment, (ii) identification of system improvement and IS opportunities, and (iii) alternative evaluation.

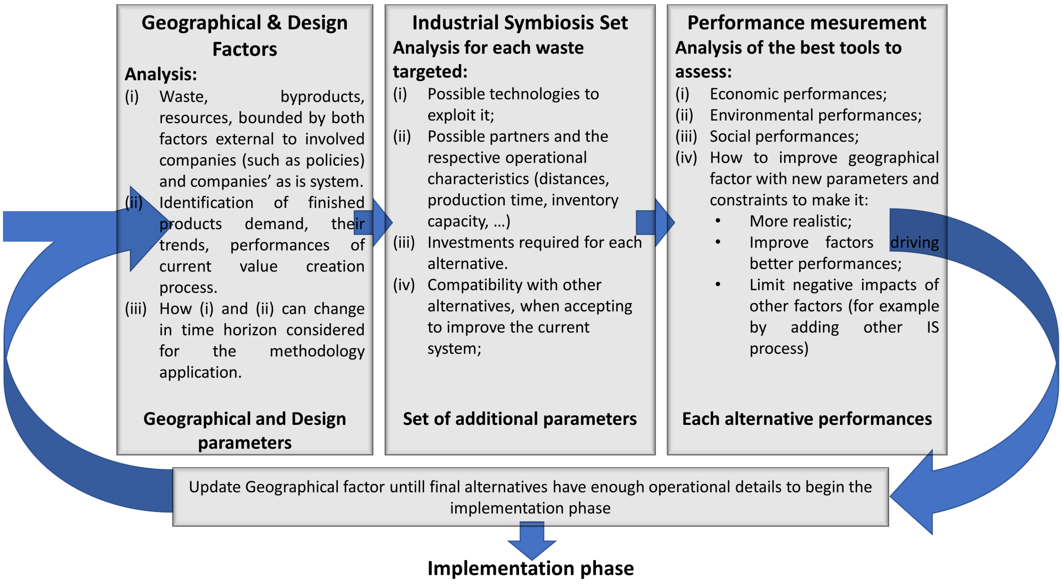


Figure 5.1: Methodology to pursuit eco-innovation.

Pillar 1. Factor Assessment. This phase aims to retrieve the entire information about factors that can hinder IS, and the current production system. The methodology is not bounded to a specific method or tool to collect data, rather it aims to cover all the crucial areas beyond the current production system: energy and environmental policies, the strengths and weaknesses of the local community where the company is settled, and the factors affecting technical and economic sustainability of potential IS. There are three sources of information where collecting data to assess factors: (i) waste and by-products production in a certain area and/or by a specific firm that are currently exploited or that can be exploited; (ii) demand of products and services in the local area or in another targeted area; and (iii) evolution of these parameters along the time according to the current laws and policies. At the end of data collection, the individual company should define the boundaries of its improvement process by defining which factors are controllable (design factors) and uncontrollable (geographical factors). The current production system is analyzed to retrieve data about production performance of processes, waste and by-product production and raw material absorption.

Pillar 2. Alternative identification. It is focused on (i) all the possible implementable IS scenarios to reduce unused waste in resource flows as well as (ii) technological adoption to improve system productivity, by increasing resource efficiency and economic and environmental parameters. Their identification starts from sources of waste emerging in Pillar 1, and it aims to improve performance by modifying design factors. Finally, the current system and the identified IS must be put together to assess the economic and environmental performances. In this phase, the ICT tools and platforms identified in the literature review are useful to identify opportunities for IS and technologies able to support them.

Pillar 3. Concurrent evaluation. It exploits the proposed mathematical model to address different issues, such as to evaluate the benefits of different alternatives under several energy and environmental policies, to draw a Pareto efficient frontier for TBL of different alternatives, and to identify resources able to be shared in WTE-SC.

The outcome of the first iteration of the methodology (end of Pillar 3) hardly is a solution ready for the implementation phase. Rather, it is a set of insights to better understand the roles of the resource flows involved into the analysis. These resource roles will show different performances in different scenarios, and they lead to the need of new constraints to better define the geographical factors. This triggers a new iteration of the methodology, and the process continues till the solutions found have enough organizational details for the implementation phase, i.e., when the decision-maker has identified the best combination of technologies for waste reduction and the kinds of companies to engage for negotiating an IS.

5.4 Problem formulation

A Mixed Integer Linear Programming (MILP) model is used to identify the best size of processes and the number of parallel machines required to properly exploit the involved resource flows. Profit maximization leads the optimization because of its link with the identification of the most profitable system improvements and IS opportunities. The climate altering gas emission (CO_2, bio-methane, and biogas) limitation is ensured by constraints. The solution of the mathematical optimization model represents the best production plan, affected by geographical factors, over the next 15 years. The time horizon has been set equal to 15 years to be in line with the duration of the environmental license required to perform these kinds of activities in Italy. Years are assumed to be equal in terms of geographical parameters, i.e., the monthly stochastic distributions of geographical parameters such as self- power and heat-consumption, external heat demand and biogas production are assumed not to vary year by year. However, monthly stochastic distributions vary month by month to represent seasonality. All the used sets, parameters, and variables are listed in Table 5.2, 5.3, and 5.4, respectively.

Set	**Description**
$j = 1, \ldots, J$	Resources
$t = 1, \ldots, T$	Time buckets
$k = 1, \ldots, K$	Transport modes
$w = 1, \ldots, W$	Warehouses
$z = 1, \ldots, Z$	Machines
$z = 1, \ldots, Z(j)$	Machines having j as output resource
$b = 1, \ldots, B_j$	Incentive levels for resource j

Table 5.2: Set used in the mathematical model.

Parameters	Type	Description
P_j^{MRKT}, P_{jb}^{MRKT}	Experimental	Market prices and incentivized price for consumption rate (CR) of resource j in machine z.
D_m	Experimental	Distance between stakeholder i and the customer.
C_{jk}	Experimental	Unit transportation cost for resource j and mode k.
H_{jw}	Experimental	Unit stocking cost for resource j in warehouse w.
EC_j	Experimental	Unit environmental cost for resource j.
PC_z	Experimental	Unit production cost for machine z.
FW_w, FP_z	Experimental	Unit investment cost for Warehouses (FW) and Processes (FP) infrastructures.
PR_{jz}, CR_{jz}	Experimental	Unit production rate (PR) and consumption rate (CR) of resource j in machine z.
MW_{jw}, MP_z, MQ_j	Experimental	Maximum stocking capacity for warehouse (MW), production capacity for processes (MP), and purchasable quantity (MQ).
σ_z^0, αw^0, $inventory_{jw0}^0$	Experimental	Initial number of machines z, warehouses w, and initial inventories for resource j in w.
L_{jb}	Experimental	Thresholds for incentive level b for installed production capacity for resource j.
M	Experimental	Large number for big M constraints.
ϕ_{jt}, $SELF_{jt}$	Geographical	Demand of product j in t, self-consumption of resource j in t.
ϕ_{zt}	Geographical	Utilization for machine z in time t.

Table 5.3: Geographical and experimental parameters.

Variables	**Types**	**Description**
dq_{ijkt}	Real from 0 to ∞	Quantity sold in t, of j through k to the market.
qm_{jt}	Real from 0 to ∞	Quantity bought in t, of j, from the market.
$inventory_{jt}$	Real from 0 to ∞	Inventory of j in t.
$waste_{jt}$	Real from 0 to ∞	Waste of j in t.
u_{zt}	Real from 0 to ∞	Utilization in t, of machine z.
$incS_{jkbt}$	Real from 0 to ∞	Quantity of resource j sold through k to the market in t with incentivized tariff b.
$incentivizedQ_{jbt}$	Real from $-\infty$ to ∞	Quantity of resource j which can be sold with incentivized tariff b in time t.
aux_{jt}	Real from $-\infty$ to ∞	Auxiliary variable used for balancing $incentivizedQ_{jbt}$ when it is negative.
δ_{jb}	Boolean	Boolean variables to verify if installed production capacity for resource j is included in incentive range b.
ψ_{jb}	Boolean	Boolean variables to select incentivizing policy b for resource j.
ρ_{jt}, τ_{jt}	Boolean	Boolean variables to prevent the contemporary positivity of aux_{jt} and $incentivizedQ_{jbt}$.
$biofuelIncentivable_{ft}$	Real from 0 to ∞	Quantity of resources f allocated to produce biofuel in t.
$bigMBFI_{jft}$, $bigMSS_{jft}$	Boolean	Variables to set at 0 the amount of resource f allocated for biofuel production in t.
δ_z	Integer from 0 to ∞	Number of machines z.
α_w	Integer from 0 to ∞	Number of warehouses w.

Table 5.4: Decision variables.

$$\begin{aligned}&max \sum_{t\in T}(\sum_{j\in J}\sum_{k\in K} dq_{jkt}(P_j^{MRKT} - D_m C_{jk}) - mq_{jkt}P_j^{MRKT}+\\&+\sum_{b\in B}(incS_{jkbt}(P_{jb}^{MRKT} - D_m C_{jk}))) - \sum_{w\in W}\sum_{j\in J}(inventory_{jt}H_{jw})-\\&-\sum_{j\in J}(waste_{jt}EC_j) - \sum_{z\in Z}(u_{zt}PC_z))-\\&-(\sum_{j\in J}\sum_{w\in W}(FW_w(\alpha_w - \alpha_w^0)) + \sum_{z\in Z}(FP_z(\sigma_z - \sigma_z^0)))\end{aligned} \tag{5.1}$$

subjected to

$$\sigma_z \geq \sigma_z^0 \qquad \forall z \tag{5.2}$$

$$\alpha_w \geq \alpha_w^0 \qquad \forall w \tag{5.3}$$

$$inventory_{j0} \geq inventory_{j0}^0 \qquad \forall j \tag{5.4}$$

$$\sum_{k\in K}(dq_{jkt} + \sum_{b\in B} incS_{jkbt}) = \phi_{jt} \qquad \forall j \in \phi, \forall t \tag{5.5}$$

$$qm_{jt} = 0 \qquad \forall j \in \phi, \forall t \tag{5.6}$$

$$qm_{jt} \leq MQ_j \qquad \forall j \notin \phi, \forall t \tag{5.7}$$

$$u_{zt} = \phi_{zt} \qquad \forall z \in \phi, \forall t \tag{5.8}$$

$$inventory_{jt} = \sum_{w\in W} MW_{jw}\alpha_w \qquad \forall j, \forall t \tag{5.9}$$

$$u_{zt} = MZ_z\sigma_z \qquad \forall z, \forall t \tag{5.10}$$

$$\begin{aligned}&\sum_{z\in Z} CR_{jz}u_{zt} = \sum_{z\in Z} PR_{jz}u_{zt} + qm_{jt}+\\&+inventory_{jt} - SELFC_{jt} \qquad \forall j, \forall t\end{aligned} \tag{5.11}$$

$$\begin{aligned}&inventory_{jt} = inventory_{jt-1} + \sum_{z\in Z}(PR_{jz}-\\&-CR_{jz})u_{zt-1} + qm_{jt-1} - \sum_{k\in K}(dq_{jkt-1}+\\&+\sum_{b\in B} incS_{jkbt-1}) - SELFC_{jt-1} - waste_{jt-1} \qquad \forall j, \forall t\end{aligned} \tag{5.12}$$

$$\begin{aligned}&waste_{jt} \geq \sum_{z\in Z}(PR_{jz} - CR_{jz})u_{zt} + qm_{jt}+\\&+inventory_{jt} - \sum_{k\in K}(dq_{jkt} + \sum_{b\in B} incS_{jkbt})-\\&-SELFC_{jt} - \sum_{w\in W} MW_{jw}\alpha_w \qquad \forall j, \forall t\end{aligned} \tag{5.13}$$

$$\begin{aligned}&qm_{jt} \geq \sum_{z\in Z} CR_{jz}u_{zt} + SELFC_{jt}+\\&+\sum_{k\in K}(dq_{jkt} + \sum_{b\in B} incS_{jkbt}) - \sum_{z\in Z} PR_{jz}u_{zt} - \qquad \forall j, \forall t\\&inventory_{jt}\end{aligned} \tag{5.14}$$

$$\sum_{z\in Z}(\sigma_z - \sigma_z^0)MP_zPRjz \geq \delta_{jb}Ljb \qquad \forall j, \forall b \tag{5.15}$$

$$\sum_{z\in Z}(\sigma_z - \sigma_z^0)MP_zPRjz - L_{jb+1} \leq \delta_{jb}M \qquad \forall j, \forall b \tag{5.16}$$

$$\delta_{jb-1} - \delta_{jb} \leq \psi_{jb-1} \qquad \forall j, \forall b \tag{5.17}$$

$$\delta_{jB_j} \leq \psi_{jB_j} \qquad \forall j \tag{5.18}$$

$$\sum_{b\in B_j} \psi_{jb} = 1 \qquad \forall j \tag{5.19}$$

$$\textstyle\sum_{k\in K} incS_{jkbt} \le \psi_{b+1}M \qquad \forall j, \forall b, \forall t \tag{5.20}$$

$$\begin{aligned} &incentivizedQ_{jbt} \le \textstyle\sum_{z\in Z}(PR_{jz} - CR_{jz})u_{zt} - \\ &- \textstyle\sum_{z\in Z} \sigma_z^0 MP_z PRjz - SELFC_{jt} \qquad \forall j, \forall t \end{aligned} \tag{5.21}$$

$$aux_{jt} \le incentivizedQ_{jbt} \qquad \forall j, \forall t \tag{5.22}$$

$$aux_{jt} \ge -incentivizedQ_{jbt} \qquad \forall j, \forall t \tag{5.23}$$

$$aux_{jt} \le \rho_{jt}M \qquad \forall j, \forall t \tag{5.24}$$

$$incentivizedQ_{jbt} \le \tau_{jt}M \qquad \forall j, \forall t \tag{5.25}$$

$$\rho_{jt} + \tau_{jt} \le 1 \qquad \forall j, \forall t \tag{5.26}$$

$$\textstyle\sum_{k\in K} incS_{jkbt} \le incentivizedQ_{jbt} + aux_{jt} \qquad \forall j, \forall t \tag{5.27}$$

$$\begin{aligned} &inventory_{ft} + qm_{ft} - \\ &- \textstyle\sum_{z\in Z(j)} CR_{fz}u_{zt} \le bigMSS_{jft}M \qquad \forall f, \forall t, j = \\ &\qquad\qquad = "biofuel" \end{aligned} \tag{5.28}$$

$$\begin{aligned} &biofuelIncentivable_{ft} \le bigMBFI_{jft}M \qquad \forall f, \forall t, j = \\ &\qquad\qquad = "biofuel" \end{aligned} \tag{5.29}$$

$$\begin{aligned} &bigMSS_{jft} + bigMBFI_{jft} \le 1 \qquad \forall f, \forall t, j = \\ &\qquad\qquad = "biofuel" \end{aligned} \tag{5.30}$$

$$\begin{aligned} &\textstyle\sum_{z\in Z(j)} CR_{fz}u_{zt} \le biofuelIncentivable_{ft} \qquad \forall f, \forall t, j = \\ &\qquad\qquad = "biofuel" \end{aligned} \tag{5.31}$$

$$\begin{aligned} &\textstyle\sum_j waste_{jt} \le 0 \qquad \forall t, \forall j = CO_2, \\ &\qquad\qquad methane, biogas \end{aligned} \tag{5.32}$$

Equation (5.1) is the objective function, which maximizes the total profit. The total revenues depend on (i) the total quantity sold to the market and (ii) the total quantity sold through incentivizing tariff b for the amount exceeding that purchased from the market. Three operational costs are also introduced: (i) inventory costs, (ii) environmental costs, and (iii) production costs. Revenues are decreased by the initial investment made for the extra production capacity σ_z (for process z) and stocking α_w (for warehouse w).

Constraints (5.2)-(5.4) set the inventories and the production and stocking infrastructures to initial levels. Constraints (5.5)-(5.8) model geographical factors. To include the stochastic fluctuations of geographical resources and processes, while keeping the analysis simple, many instances of the problem must be solved. The parameters used to set constraints (5.5) to (5.8) are randomly generated from their stochastic distributions. Constraints (5.5) force the system to completely satisfy the market demand of resource j. Constraints (5.6) and (5.7) define which resource j can be purchased from the market and its maximum amount. Constraints (5.8) model geographical processes belonging to ϕ by properly setting the utilization u_{zt}.

Constraints (5.9)-(5.10) limit the maximum amount of resource j stocked in warehouse w or the utilization of process z at MW_{jw} (which is 0 when resource j is not compatible with warehouse w) and MP_z, respectively.

Constraints (5.11)-(5.14) model the system dynamics. Specifically, constraints 5.11 limit the consumption of resource j, giving higher priority to the internal consumption ($SELFC_{jt}$). Constraints (5.12) represent the dynamics related to the inventory levels. Constraints (5.13) ensure the disposal of what is produced but cannot be sold, stocked, or used to produce other resources. Constraints (5.14) set the minimum quantity of resource j bought.

Constraints (5.15)-(5.27) allow the choice of incentive tariff for resource j. Incentives increase the sale price if additional production capacity is installed. The larger the additional capacity installed, the lower the incentivized sale price (which, however, has to remain larger than non-incentivized sale price) due to the environmental and energy policies of Italian government to favor small plants. Hence, constraints (5.15)-(5.16) set boolean variables δ_{jb} to 1 when additional production capacity is within the incentive range b. Constraints (5.17)-(5.18) link boolean variables to achieve a correct behavior of the possible actions. Constraints (5.19) allow to choose only one incentivized policy for each resource j. Constraints (5.20) forbid the sales at incentivized price of tariff b if tariff b is not selected. Constraints (5.21) explicitly identify the amount of resource j that can be sold at the incentivized price (i.e., the quantity produced exclusively through the installed additional capacity and only with the residual quantities after the satisfaction of internal consumption). Constraints (5.22) to (5.26) properly set the auxiliary variables needed in constraints (5.27) that bound what is actually sold (non-negative amount) by the auxiliary variable reporting what results sellable from constraints (that can be negative).

Constraints (5.28)-(5.31) limit the amount of resource f spendable for producing $biofuel$, since if this is sold at the incentivized price, it is not possible to purchase resource f from the market to resell it as incentivized product (for example, to forbid the purchasing of fossil methane and resell it as incentivized biofuel).

Constraints (5.32) bound the emissions of CO_2, $biogas$, and $bio-methane$ in the environment, so that they are reused within the system.

Chapter 6

The methodology applied to the case study of Acea Pinerolese

IS development is a topic largely discussed in the literature due to its importance also for CE transition [93]. The local economic sector composition strongly influences emergence, characteristics, and evolution path of IS ([57]; [172]; [203]; [88]). IS emergence could be the result of different processes [57], e.g., companies can join the network autonomously or they can be put together by a centralized tenant [95]. IS structure deeply influences economic and managerial conditions able to foster its emergence and development ([192]; [288]), and stakeholders' interactions ([128]; [261]).

Network stability and resilience are fundamental, especially in the case of concurrent design of supply chain and eco-industrial park [46]. Social Network Analysis and Food Web Analysis are used to assess the relevance of nodes and producer-consumer relationships ([248]; [108]). Commitment keeping mechanisms are used to enforce stability [48] and fairness [292]. When IS emergence is the result of companies' autonomous aggregation, Multi-Agent-Based Modelling is able to capture the willingness of stakeholders according to some boundary conditions [6] and to the easiness to get involved [100], or the intensity of the cooperation for the sake of the value chain and environmental performances [291].

When process data are largely available, cost-benefit analysis, also in relation to Credit Emissions Reduction, is used ([280], [239], [207]). Life Cycle Analysis (LCA) is fundamental thanks to its flexibility to benchmark new processes ([58]; [142]; [154]), since it supports the measurement of resource efficiency [153] also in relation to IS development ([204]; [183]). It can also be used in multi-objective optimization together with economic functions [38].

In the literature, some methodologies to improve Eco-innovation and Sustainable Development have been applied at a meso level (inter-company or inter-systems), recognizing IS' contribution to eco-innovation [198]. Levidow et al., [168] proposed an LCA-based methodology, recognizing the difficulty of a generalization of the meso-level. Zheng & Jia [295] dealt with the diffusion of an IS approach for driving eco-innovation from a systemic point of view, Romero & Ruiz, [225] focused on the evolutions in a network of IS relationships, Yazan et al., [290] proposed a game theoretic approach integrated with Agent-Based Simulation. [52] proposed a methodology to build blueprints to enhance IS opportunities avoiding massive exchange of sensitive data, because the focus is on already established networks, i.e., inter-company scope. At the intra-company level, methodologies are mainly based on lean techniques due to their moderate to strong effects on process innovation [189]. Lean techniques are widely used to identify wastes in production systems and improve productivity for sustainability ([131]; [249]), together with Multi-Criteria Decision-Making approaches (e.g., [17]) and simulation and optimization techniques [211].

The proposed Eco-innovation methodology simultaneously addresses the three dimensions of Eco-innovation, i.e., product, process and organizational, via a structured and quantitative approach based on the assessment of environmental and economic benefits brought by the adoption of new technologies. The individual company has a crucial role in the methodology, in fact the whole methodology revolves around it and the local and economic context where it is settled. Firstly, the methodology supports the company to collect all the data required to represent the system through the modeling of its processes, both controllable and uncontrollable process. Secondly, once identified the sources of waste, the identification of the technologies able to reduce waste production or exploit them as raw material begins. The identified alternatives that change partially or entirely the production system are modeled together with the processes currently belonging to the production system to exploit simulation and optimization techniques to identify the best configuration in terms of economic and environmental results. The application of the methodology is enabled by the adoption of the MEIO approach (see Chapter 2) that allows the structured formalization of all the involved activities (production, transport and storage) through the representation of their economic, environmental and efficiency parameters. The MEIO approach brings all of its benefits to the Eco-innovation methodology, such as the opportunity of data-driven approach with automatic data update, and concurrently addressed stochastic and deterministic activities.

6.1 Apply the Eco-innovation methodology

The pillar 1 of the methodology deals with the analysis of the as-is system and the global context where it operates. It starts from resource flows due to their relevance for leading system innovation towards sustainable development [134].

Geographical factors. Wastewater Treatment (WWT), Landfill (LF), and Organic Fraction of Municipal Solid Waste (OF-MSW) belong to the geographical factors because their biogas production is strictly linked to the local communities around the company as well as the heat demand through district heating. Biogas production from waste and heat demand varies according to seasonality, trends, and characteristics not controllable by the company. Biogas and heat, as they belong to the geographical factors, limit the operations management of the company: when too much biogas is produced or its quality is low, it must be burnt or emitted in environment. Similarly, heat demand peaks must be satisfied by purchasing fossil methane to feed the boilers. Conversely, when produced heat is larger than demand, it is wasted due to the impossibility of storage.

Design factors. Combined Heat and Power (CHP) and the boilers are considered as design factors; they are chosen by Acea and properly sized according to its operational efficiency to convert biogas in two other resources: heat and power. Differently from heat, power surplus can be sold to the power market in any moment and there is no constraint on demand, so it can be considered under the control of the company. In the case of scarcity, company can purchase it from the grid. Other design processes are those sized to stock and convey resources such as gasometers, warehouses, and pipelines.

To overcome the operational problems that limit the exploitation of biogas, the Bio Methane Purification (BMP) process is proposed. Biogas is converted in biomethane, rather than directly used in production processes, through BMP and biomethane can be used both in the CHP and the boilers. BMP allows to sell new finished products, i.e., biomethane and biofuel. However, BMP divides biogas in biomethane and CO_2 that is a cost when not exploited.

Three Microbial Factories (MFs) exploit different bacteria to produce three value-added chemicals from CO_2: (i) lactic acid, (ii) PHB, and (iii) acetone, produced by MF1, MF2, and MF3, respectively. Furthermore, a polymeric exchange membrane electrolyzer (pem-E) is introduced, and it transforms the excess of power in hydrogen and oxygen used to feed MFs. The introduction of MFs and pem-E allows the production of five new finished products: lactic acid, PHB, acetone, hydrogen, and oxygen.

System improvements would be directly introduced into the system, while new technologies can be more likely adopted by IS partners thanks to the benefits associated to the above-mentioned new products. Furthermore, through the proposed method, it is tested the hypothesis that BMP introduction reduces the purchase of fossil methane to satisfy heat peak demand and overcome operational problems leading to biogas emissions in the environment. The combined utilization of MFs and pem-E is investigated to exploit CO_2 and the excess of the produced low-temperature heat of the CHP process. The combined effects of system improvement and IS opportunities are grouped in five different alternatives, shown in Figure 6.1 through their system representation. Grey boxes belong to the geographical factors while white boxes belong to the design factors. Each alternative is identified by arrows of the same color, representing all the resource flows involved and the processes. The five alternatives are identified as follow: (i) as-is system (AS_IS, grey arrows), (ii) concurrent evaluation of all the improvements (AA, blue arrows), (iii) system improvements with microbial factory 1 (MF1, light green arrows), (iv) system improvements with microbial factory 2 (MF2, green arrows), and (v) system improvements with microbial factory 3 (MF3, dark green arrows).

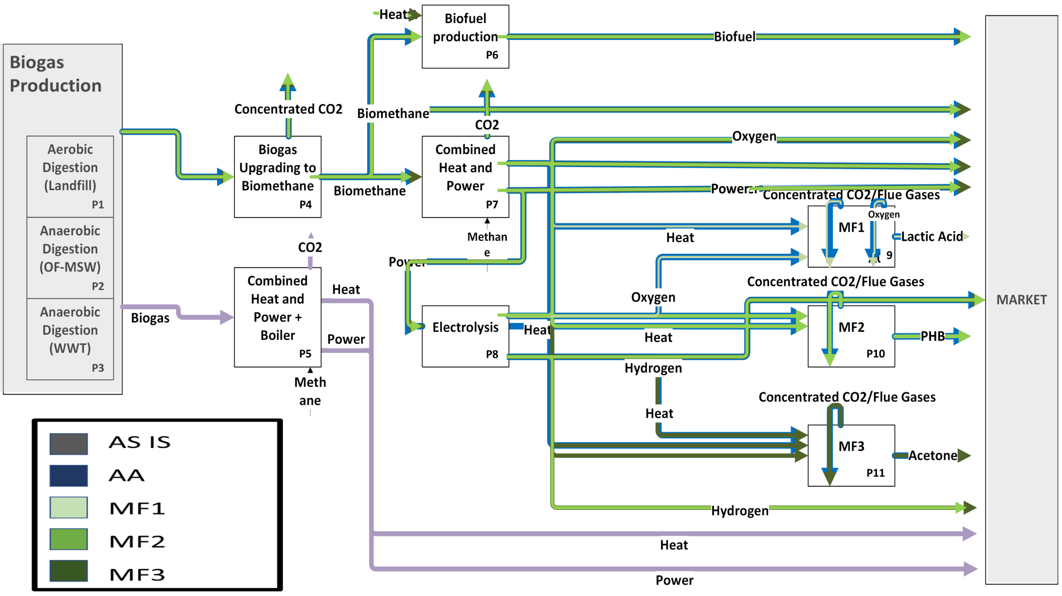
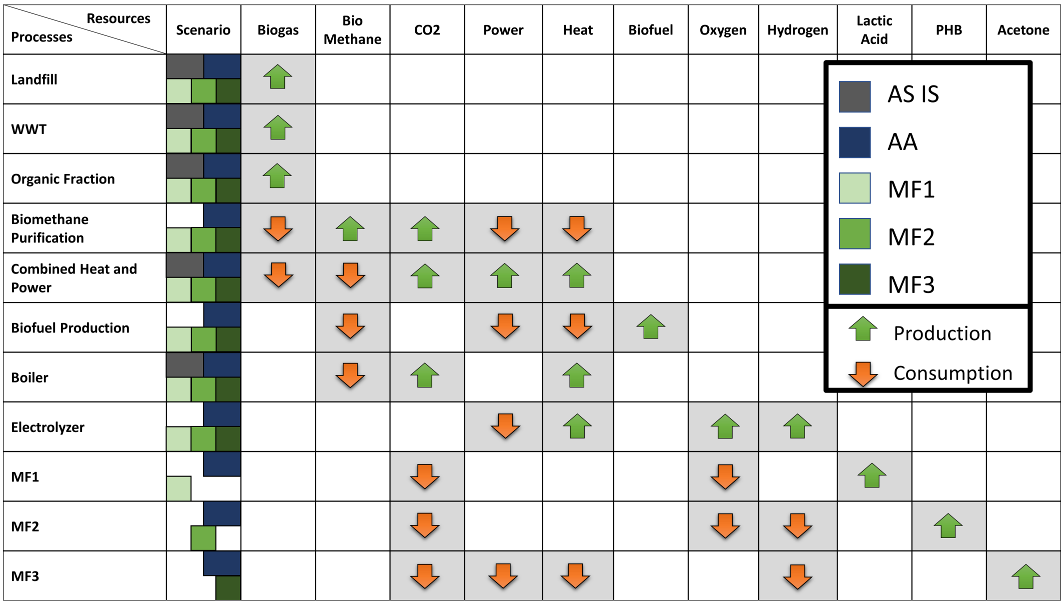


Figure 6.1: Production system under analysis in Acea Pinerolese.

Figure 6.2 briefly summarizes the resources produced and absorbed by the different processes. Colored tags have been assigned to processes to indicate the alternatives to which they belong, i.e., AS_IS, AA, MF1, MF2 and MF3.



Resources Processes	Scenario	Biogas	Bio Methane	CO2	Power	Heat	Biofuel	Oxygen	Hydrogen	Lactic Acid	PHB	Acetone
Landfill	AS IS AA MF1 MF2 MF3	↑										
WWT	AS IS AA MF1 MF2 MF3	↑										
Organic Fraction	AS IS AA MF1 MF2 MF3	↑										
Biomethane Purification	AA MF1 MF2 MF3	↓	↑	↑	↓	↓						
Combined Heat and Power	AS IS AA MF1 MF2 MF3	↓	↓	↑	↑	↑						
Biofuel Production	AA MF1 MF2 MF3		↓		↓	↓	↑					
Boiler	AS IS AA MF1 MF2 MF3		↓	↑		↑						
Electrolyzer	AA MF1 MF2 MF3				↓	↑		↑	↑			
MF1	AA MF1			↓				↓		↑		
MF2	AA MF2			↓				↓	↓		↑	
MF3	AA MF3			↓	↓	↓			↓			↑

Figure 6.2: Resource-process matrix (colored tags indicate in which of five improvement alternatives each process is present).

6.2 Results

The five alternatives, summarized in Figure 6.2, are modeled through the optimization problem presented in chapter 5 and solved through a commercial optimization software, ILOG CPLEX version 12.9.0, whose API have been exploited in an ad-hoc Decision Support System coded in Java with the IDE Eclipse Jee 2019-03 (see Chapter 8). As geographical processes are stochastic, each scenario has 95 replications, and the provided results are the average over all the replications. The experiment has been run on an Intel i7 processor with 1.8 GHz and 12 GB of RAM, in a computer running under Windows 10. All the prices and the incentives for power, heat, and methane refer to the Italian environmental and energy law in force until 2018, while pollutant emission costs refer to the European Trading Scheme for carbon certificates.

The solutions of the mathematical model represent the optimal production plans for the alternative (set of technologies and system improvements) under analysis. Optimal production plan may require investments in production or inventory capacity. Therefore, a solution provides information about both investment profitability and environmental impacts in terms of GHG emissions and wasted resources.

The AS-IS alternative is the base case, and the other alternatives, i.e., AA, MF1, MF2, MF3 are represented by introducing new kinds of processes, warehouses, and resources, to the base case. Hence, the increasing complexity is reflected in the computation time required by CPLEX. Moreover, also the introduction of the set of constraints (Equation 5.32) that model the loop closing of climate altering gas emission (CO_2, biomethane and biogas) increases the model complexity. Figure 6.3a reports the computation time through box and whisker plot, while Figure 6.3b refers to the number of found solutions.

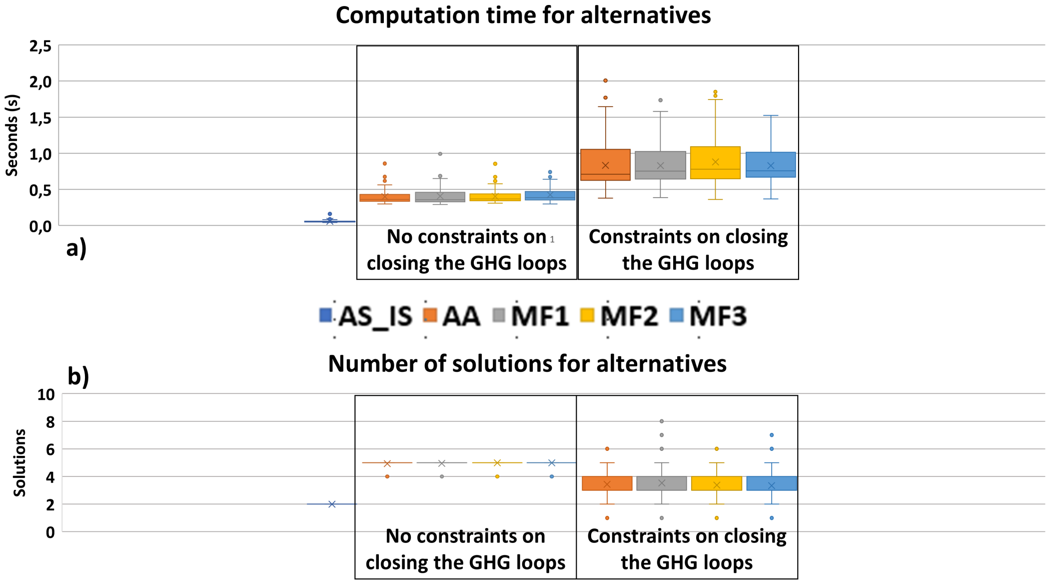


Figure 6.3: Box and whisker plot for (5a) computation time and (5b) number of solutions found for each alternative.

Table 6.1 highlights the differences about average computation time through bilateral hypothesis test for normally distributed samples with $\alpha = 0.001$. The null hypothesis of equal averages is rejected (marked with asterisk in Table 6.1), having Z lower than $Z_{min} = -3.27$ or higher than $Z_{max} = 3.27$.

Z	*AS_IS*	**AA**	**MF1**	**MF2**	**MF3**	**AA LC**	**MF1 LC**	**MF2 LC**	**MF3 LC**
AS_IS	0	-32,44*	-27,94*	-32,20*	-32,73*	-23,86*	-26,48*	-24,75*	-27,84*
AA	-	0	-0,59	-0,48	-1,83	-12,78*	-14,01*	-13,90*	-14,65*
MF1	-	-	0	0,15	-1,09	-12,25*	-13,38*	-13,37*	-13,96*
MF2	-	-	-	0	-1,34	-12,54*	-13,73*	-13,66*	-14,36*
MF3	-	-	-	-	0	-11,88*	-13,00*	-13,02*	-13,59*
AA LC	-	-	-	-	-	0	0,05	-1,05	0,05
MF1 LC	-	-	-	-	-	-	0	-1,16	0,00
MF2 LC	-	-	-	-	-	-	-	0	1,18
MF3 LC	-	-	-	-	-	-	-	-	0

Table 6.1: Z values of hypothesis test for average of computation time (AS-IS versus alternatives without Loop Closure Constraints, and alternatives with Loop Closure Constraints (LC))

The benefits of the adoption of a certain technology depend on the (a) required investments and (b) profit, which are directly correlated with the operational costs. Figure 6.4 reports the investment plan for inventory and production infrastructures in each alternative that requires different number of machines and warehouses in order to reach the optimal production plan.

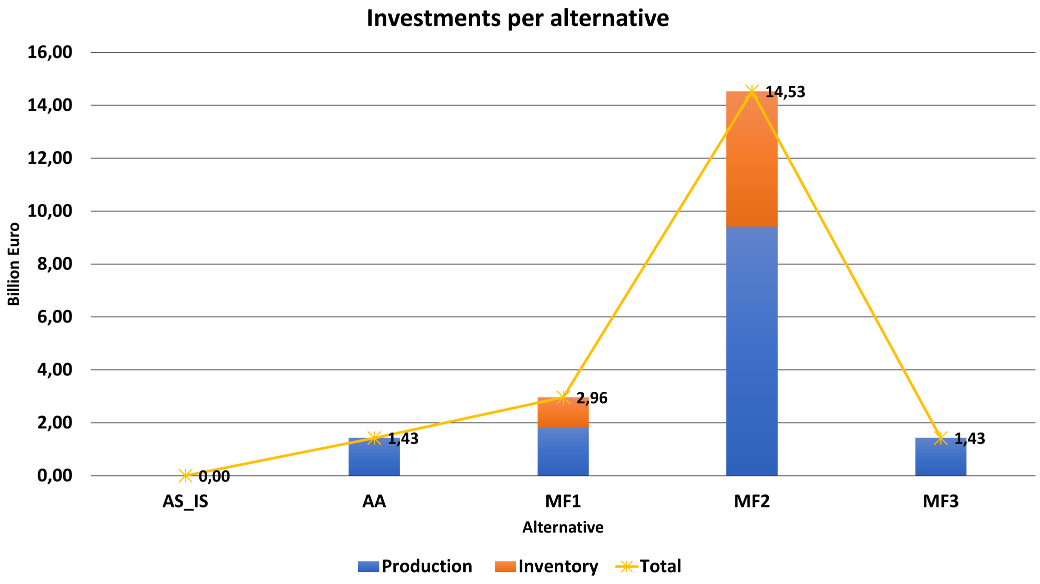


Figure 6.4: Infrastructure investment per alternative, splitting production and inventory infrastructures.

The alternatives focused on MF1 and MF2 technologies require higher investments (Figure 6.4) than those focused on MF3 technology (i.e., AA and MF3). Table 6.2 and Table 6.3 shed a light on the efforts for process synchronization reporting the different required number of parallel machines and warehouses in each alternative. For each process (resource), the average number of parallel machines (warehouses) and its standard deviation are reported to satisfy the constraints of complete CO_2 absorption. Average (left of middle dash) and standard deviation (right of middle dash) are measured over the 95 optimization instances run per each alternative.

Processes/Alternatives	*AS_IS*	**AA**	**MF1**	**MF2**	**MF3**
	1	1	1	1	1
P1: Landfill	-	-	-	-	-
	0	0	0	0	0
	1	1	1	1	1
P2: OF	-	-	-	-	-
	0	0	0	0	0
	1	1	1	1	1
P3: WWT	-	-	-	-	-
	0	0	0	0	0
	3	3	3	3	3
P4: CHP-M	-	-	-	-	-
	0	0	0	0	0
	0	2846.96	2846.25	2832.31	2846.96
P5: Electrolysis	-	-	-	-	-
	0	0.2	0.48	1.41	0.2
	0	1	2.87	9.52	1
P6: BMP	-	-	-	-	-
	0	0	12.89	26.53	0
	0	8.8	8.83	7.93	8.78
P7: Biofuel Production	-	-	-	-	-
	0	0.4	1.15	2.3	0.42
	0	1	1342.31	0	0
P8: MF1	-	-	-	-	-
	0	0	8197.31	0	0
	0	1	0	26535.45	0
P9: MF2	-	-	-	-	-
	0	0	0	81486.94	0
	0	15.41	0	0	15.38
P10: MF3	-	-	-	-	-
	0	0.49	0	0	0.49
	2	2	373.63	1921.19	2
P11: Boiler	-	-	-	-	-
	0	0	2547.63	5964.11	0

Table 6.2: Number of parallel machines (for P1-11) per alternative: average - standard deviation.

Processes/Alternatives	AS_IS	**AA**	**MF1**	**MF2**	**MF3**
W1: CO_2	0	0.17	20.47	171.44	0.39
	-	-	-	-	-
	0	0.9	140.93	536.36	1.6
W2: Biogas	1	2.78	86.06	364.81	2.81
	-	-	-	-	-
	0	1.22	546.28	1117.25	1.45
W3: Biomethane	0	1	4360.64	20042.01	1
	-	-	-	-	-
	0	0	29885.29	62279.49	0
W4: Oxygen	0	0	4392.39	19765.82	0
	-	-	-	-	-
	0	0	30111	61424.37	0
W5: Hydrogen	0	0	8869.55	39913.03	0
	-	-	-	-	-
	0	0	60803.11	124033.95	0

Table 6.3: Number of warehouses (for W1-5) per alternative: average - standard deviation.

Figure 6.5 displays the profit achieved by each alternative. Profit analysis evaluates the potential benefits brought by technology adoption in two ways: (i) by showing the most profitable resources for system improvement and (ii) by providing insights into the most suitable resources to be exchanged within symbiotic relationships.

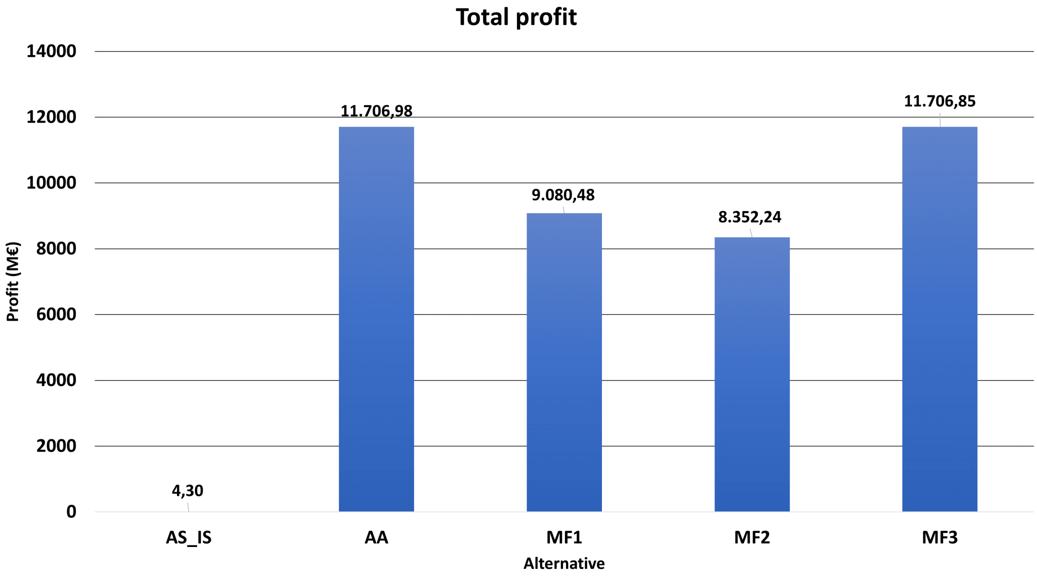


Figure 6.5: Total profit per alternative.

The contribution of each resource to the profit is highlighted in Figure 6.6a except for hydrogen and oxygen, which are reported in Figure 6.6b due to scale reasons. Both MF1 and MF2 alternatives require a larger part of hydrogen and oxygen than MF3 (and AA, which has a similar configuration of MF3) for producing finished products such as lactic acid and PHB, which bring less profit.

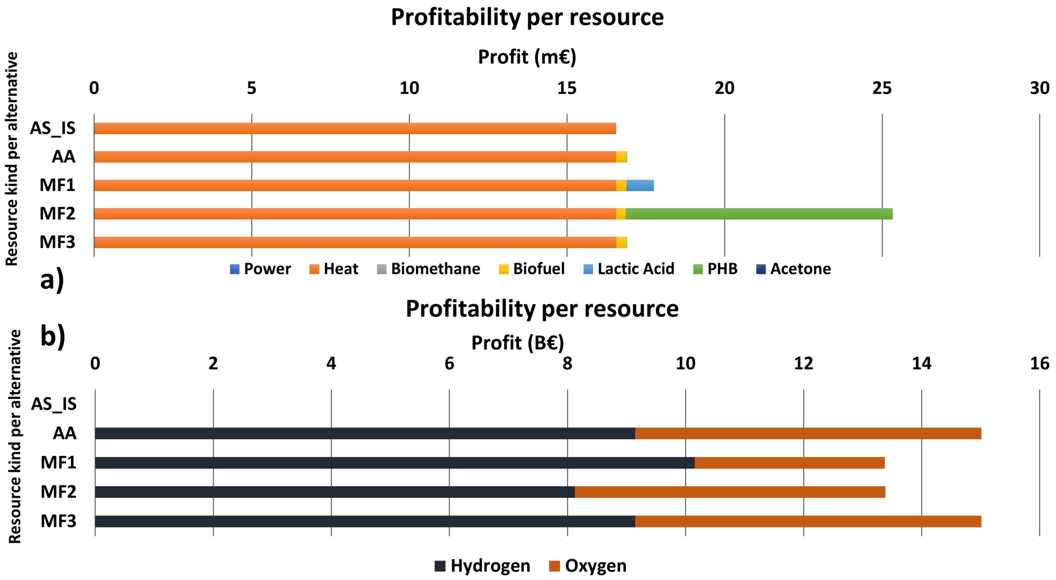
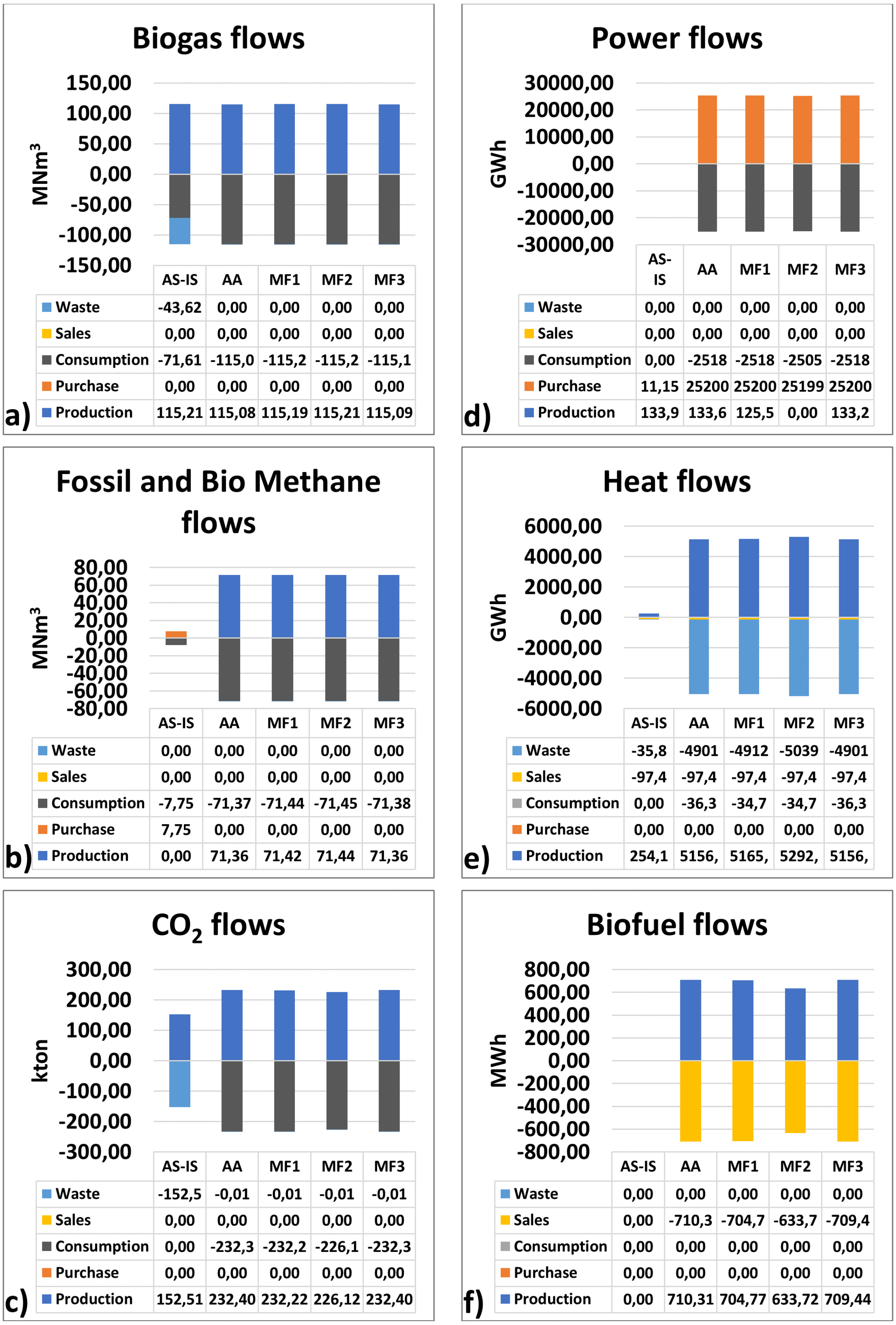


Figure 6.6: Contribution to the profit of each resource in the five alternatives. Power, heat, bio-methane, biofuel, lactic acid, PHB, acetone in 6.6a; hydrogen and oxygen in 6.6b.

The environmental performances are evaluated according to three dimensions: (i) pollutant emission reduction, (ii) closure of loops of resources, and (iii) reduction of fossil resource use. In Figure 6.7, the wasted resources, i.e., biogas (Figure 6.7a), CO_2 (Figure 6.7c) and heat (Figure 6.7e) are showed in light blue. All the other alternatives completely exploit CO_2 and biogas; on the contrary, the amount of unexploited heat in AS-IS increases in all the other alternatives. The stochastic distribution of heat demand belongs to the geographical factor, i.e., it is not under company control. Hence, while the increase in pem-Electrolyzer machines causes a larger amount of low temperature heat production (Figure 6.7e), the total amount produced cannot be exploited due to the fixed demand. The produced CO_2 increases (Figure 6.7c) but it is completely absorbed by microbial factories. However, also purchased resources are relevant. In fact, the CO_2 increasing production is not caused by an increase in the purchase of fossil methane (Figure 6.7b). Figure 6.7b shows how the alternatives for improvement break down the purchase of fossil methane for heat production in favor of better exploitation of produced biogas. The hydrogen (Figure 6.8a) and oxygen (Figure 6.8b) production requirements are satisfied through the increased purchase of power (Figure 6.7d) and, in the alternative MF2, the power production is abandoned (data table in Figure 6.7d). Figure 6.8 puts in relation the production of lactic acid (Figure 6.8d), PHB (Figure 6.8e), and acetone (Figure 6.8c) with the consumption of hydrogen (Figure 6.8a) and oxygen (Figure 6.8b), whose amount is subtracted to the sales. Figure 6.8a and

6.8b show the same production of hydrogen and oxygen in all the alternatives, thus highlighting that the reduction in profit in Figure 6.6b is caused by the amount of their production used to produce chemicals.



a) Biogas flows

	AS-IS	AA	MF1	MF2	MF3
Waste	-43,62	0,00	0,00	0,00	0,00
Sales	0,00	0,00	0,00	0,00	0,00
Consumption	-71,61	-115,0	-115,2	-115,2	-115,1
Purchase	0,00	0,00	0,00	0,00	0,00
Production	115,21	115,08	115,19	115,21	115,09

d) Power flows

	AS-IS	AA	MF1	MF2	MF3
Waste	0,00	0,00	0,00	0,00	0,00
Sales	0,00	0,00	0,00	0,00	0,00
Consumption	0,00	-2518	-2518	-2505	-2518
Purchase	11,15	25200	25200	25199	25200
Production	133,9	133,6	125,5	0,00	133,2

b) Fossil and Bio Methane flows

	AS-IS	AA	MF1	MF2	MF3
Waste	0,00	0,00	0,00	0,00	0,00
Sales	0,00	0,00	0,00	0,00	0,00
Consumption	-7,75	-71,37	-71,44	-71,45	-71,38
Purchase	7,75	0,00	0,00	0,00	0,00
Production	0,00	71,36	71,42	71,44	71,36

e) Heat flows

	AS-IS	AA	MF1	MF2	MF3
Waste	-35,8	-4901	-4912	-5039	-4901
Sales	-97,4	-97,4	-97,4	-97,4	-97,4
Consumption	0,00	-36,3	-34,7	-34,7	-36,3
Purchase	0,00	0,00	0,00	0,00	0,00
Production	254,1	5156,	5165,	5292,	5156,

c) CO_2 flows

	AS-IS	AA	MF1	MF2	MF3
Waste	-152,5	-0,01	-0,01	-0,01	-0,01
Sales	0,00	0,00	0,00	0,00	0,00
Consumption	0,00	-232,3	-232,2	-226,1	-232,3
Purchase	0,00	0,00	0,00	0,00	0,00
Production	152,51	232,40	232,22	226,12	232,40

f) Biofuel flows

	AS-IS	AA	MF1	MF2	MF3
Waste	0,00	0,00	0,00	0,00	0,00
Sales	0,00	-710,3	-704,7	-633,7	-709,4
Consumption	0,00	0,00	0,00	0,00	0,00
Purchase	0,00	0,00	0,00	0,00	0,00
Production	0,00	710,31	704,77	633,72	709,44

Figure 6.7: Incoming (purchase and production) and outcoming (waste, consumption and sales) flows for biogas, bio-methane, CO_2, power, heat and biofuel.

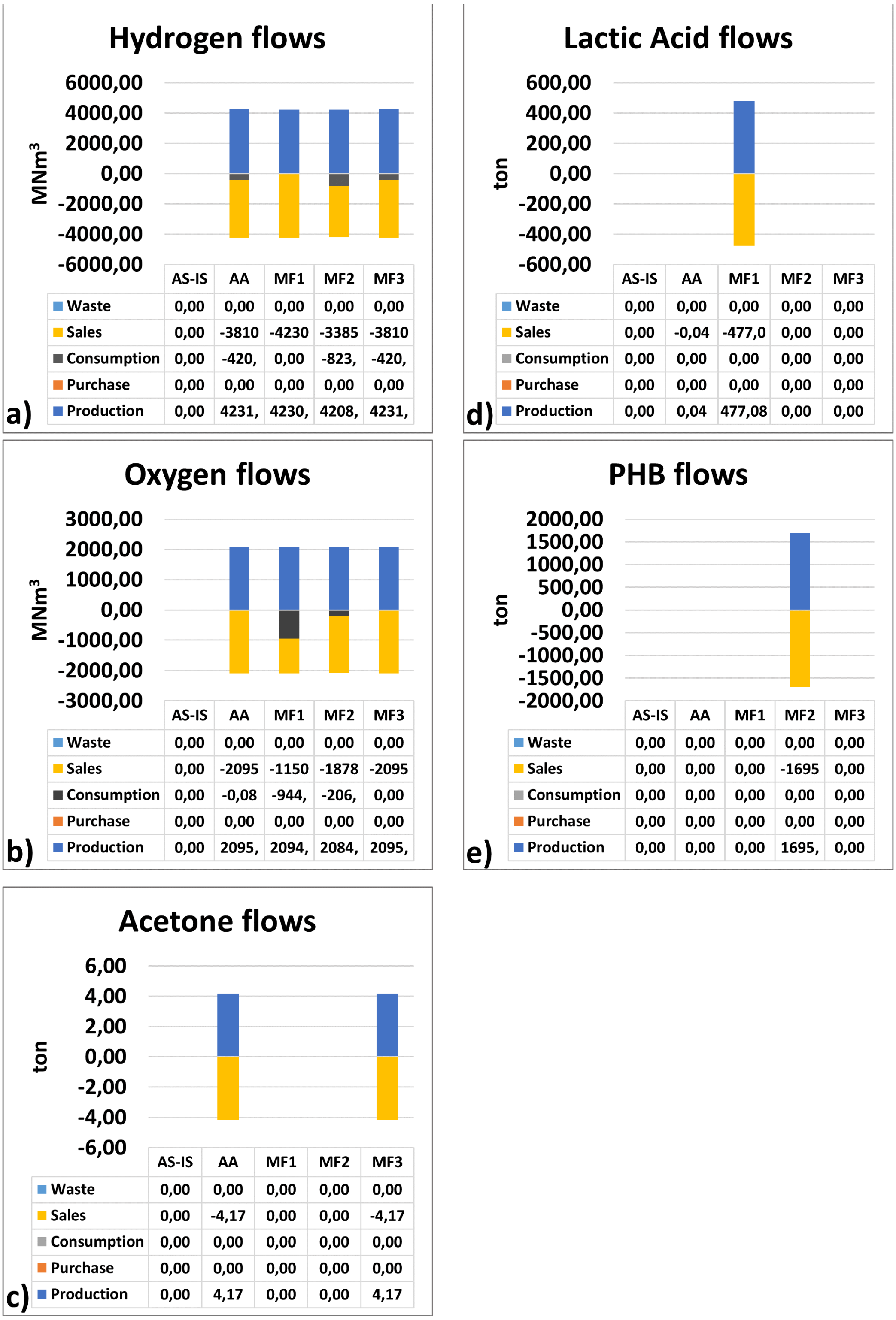


Figure 6.8: Incoming (purchase and production) and outcoming (waste, consumption and sales) flows for hydrogen, oxygen, acetone, lactic acid and PHB.

6.3 Robustness in the Eco-innovation process

The role of environmental and energy policies together with the laws, which set incentives in accordance with the installed production capacity, the quality and the kinds of raw material used for the products, can encourage or discourage the emergence and the development of IS [164]. Also, they can affect also the effectiveness of the Eco-innovation process and the economic and environmental performance of current production systems ([33]; [137]).

The normative aspects has been identified as one of the core factors for the Eco-innovation as well as the uncertainty in the environmental legislation is one of the 7 barriers for the emergence and the development of IS [112]. Companies are worried about the return of the investment they have done [206]. Therefore, the current methodology has been extended by adding also the dimension of time to the geographical and design factors, to model their dynamics and report their parameters under different policies.

The scenario analysis is based on two kinds of scenario: the production scenarios (PS) and the consumption scenarios (CS). The latter represent the different policies under investigation, usually they affect prices, costs, and process parameters such as the maximum installed capacity to receive incentivized price for the sale of a specific product (such as power, produced under certain condition). The former, i.e., the PSs, are used to group the different technologies, whose adoption is under investigation, to avoid to assess them altogether, as in the previous application to the case of Acea Pinerolese. In fact, when all the technologies are concurrently evaluated, the mathematical optimization is drawn towards those leading to the best values of the objective function. However, there are other aspects under investigation beyond the objective function (i.e., the maximization of profits) such as the environmental performances and to understand whether a technology could be useful to establish new IS with other stakeholders or if it is better using it into the current production system to reduce the waste production. Therefore, the Eco-innovation methodology exploits the proposed model through the scenario analysis.

The thesis shows the results of the evaluation of the case of Acea Pinerolese under four different CSs. This application shows that the considered future policies of Carbon Taxes are not able to incentivize the current production system to absorb all the produced climate altering gas. Therefore, further 4 CSs have been added at the end, where the exploitation of the produced climate altering gas is addressed through a constraint into the optimization model.

6.3.1 Production scenarios

In this analysis, the technologies initially identified as system improvements and those identified as suitable for IS establishment have been considered separately, since the different policies could have different strategical impacts on the decision maker by showing that under certain conditions one could exclude the other and vice versa.

Four different PSs have been identified: the current production system, PS0 (gray arrows) to understand its performances over time. PS1 (blue arrows) is the current production system with the technologies for the system improvement, i.e., BMP and Biofuel Production. PS2 and PS3 introduce the technologies initially identified for the IS establishment, i.e., pem-E and MF1, MF2, and Mf3, to PS0 and PS1, respectively, thus PS2 is PS0 + new technologies and PS3 is PS1 + new technologies.

The four production scenarios are graphically represented through an IDEF0 diagram in Figure 6.9 and schematically reported in Figure 6.10. The processes belonging to the geographical factors, i.e., those not controllable by the company, are represented through grey boxes, while white boxes represent processes controllable by the company in terms of size (number of parallel machines) and production. The incoming (outgoing) arrows represent the requested (produced) resources, which connect boxes (processes) with each other. In the figure, four colors have been used to distinguish the four PSs.

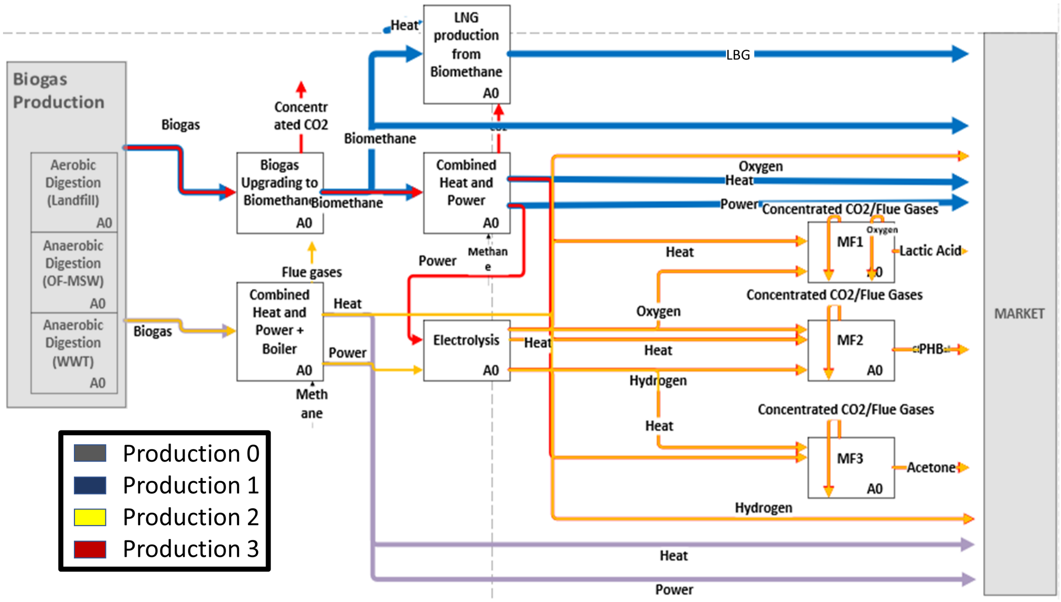
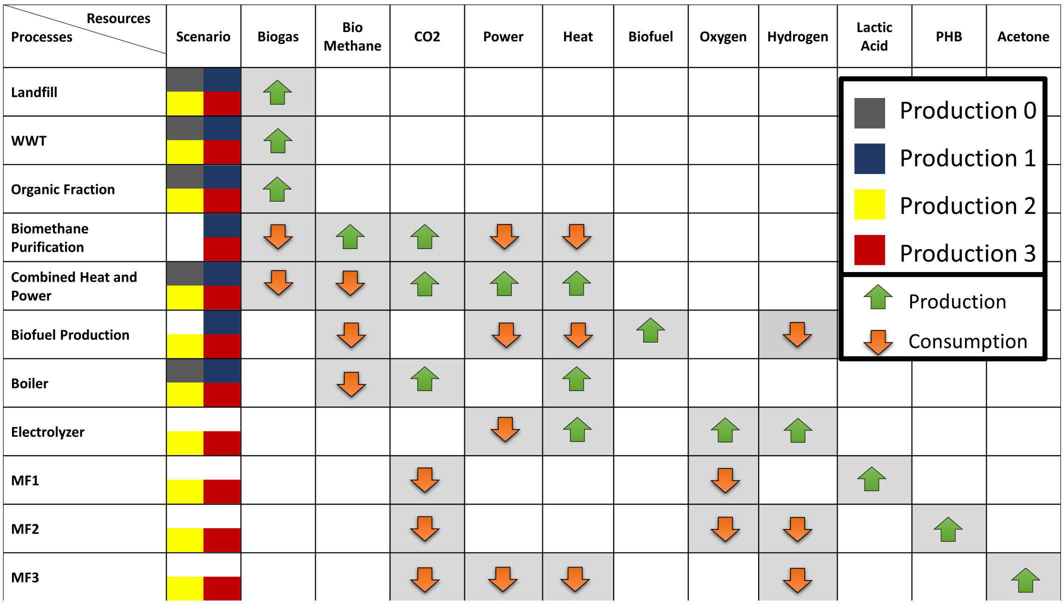


Figure 6.9: IDEF0 of the four different production scenarios. Gray boxes are the geographical processes.

In Figure 6.10, all the involved processes in the four PSs are connected with the resources, which are required as input (downward orange arrow) and/or output (upward green arrow). It is made clear from Figure 6.10 that the introduction of different processes lead to the production of new intermediate and finished products (such as hydrogen and oxygen, biofuel, lactic acid, PHB and acetone).



Resources / Processes	Scenario	Biogas	Bio Methane	CO2	Power	Heat	Biofuel	Oxygen	Hydrogen	Lactic Acid	PHB	Acetone
Landfill	⬛🟦🟨🟥	↑										
WWT	⬛🟦🟨🟥	↑										
Organic Fraction	⬛🟦🟨🟥	↑										
Biomethane Purification	🟦🟥	↓	↑	↑	↓	↓						
Combined Heat and Power	⬛🟦🟨🟥	↓	↓	↑	↑	↑						
Biofuel Production	🟦🟨🟥		↓		↓	↓	↑		↓			
Boiler	⬛🟦🟨🟥		↓	↑		↑						
Electrolyzer	🟨🟥				↓	↑		↑	↑			
MF1	🟨🟥			↓				↓		↑		
MF2	🟨🟥			↓				↓	↓		↑	
MF3	🟨🟥			↓	↓	↓			↓			↑

⬛ Production 0
🟦 Production 1
🟨 Production 2
🟥 Production 3
↑ Production
↓ Consumption

Figure 6.10: Resource-process matrix (colored tags indicate in which of the four PSs each process is present).

6.3.2 Consumption scenarios

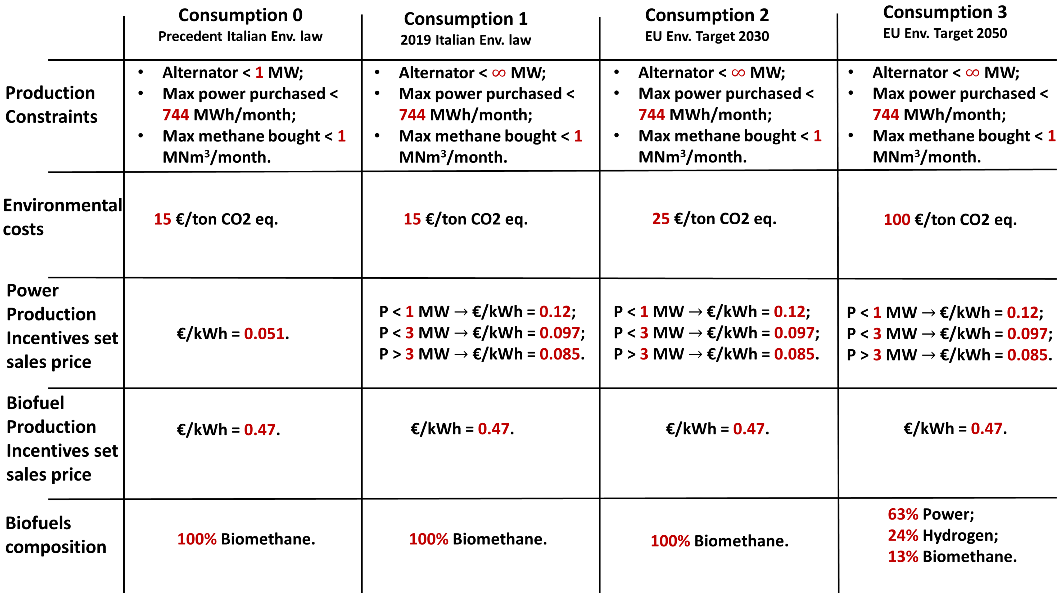
In the case study, 4 CSs are treated: (i) the one proposed in section 6.1 (ii) the current environmental and energy incentives and taxes under the Italian environmental and energy laws in force since 2018 and updated in August 2019; (iii) the scenario related to the low carbon emissions that most of the EU-27 countries are trying to reach before of 2030; (iv) the zero emission target EU Commission set for 2050, for reaching which several agencies identified the key role of hydrogen.

Table 6.4 shows purchase cost and selling price for the resources in CS0. Different selling prices and purchasing costs for industrial symbiotic exchanges are introduced as more companies can be simultaneously considered. However, as the main goal is the identification of the key resource flows, only market prices have been used in the case study.

Resource	Base Scenario (€)				
	Purchase cost	Market selling price	EIP purchase cost	EIP selling price	Environmental cost
CO2 (kg)	-	-	-	-	0.015
Biogas (Nm3)	-	-	-	-	0.186270
Biomethane (Nm3)	0.123	0.123	0.123	0.123	0.17410
Oxygen (Nm3)	-	2.4	2.4	2.4	-
Hydrogen (Nm3)	-	2.8	2.8	2.8	-
Lactic Acid (g)	-	0.002	0.002	0.002	-
PHB (g)	-	0.005	0.005	0.005	-
Acetone (g)	-	0.001	0.001	0.001	-
Electricity (kWh)	0.052	0.051	0.051	0.051	-
Heat (kWh thermic)	-	0.170	0.170	0.170	-
Biofuel (kWh)	-	0.47	0.47	0.47	-

Table 6.4: Table for economic parameters of the CS0.

Figure 6.11 shows the changes among the CS, i.e., the resources and the production aspects affected by the various followed policies in each CS. Specifically, they are: (i) production constraints, (ii) environmental costs, (iii) power production incentives, (iv) biofuel production incentives and (v) biofuel composition.



	Consumption 0 Precedent Italian Env. law	**Consumption 1** 2019 Italian Env. law	**Consumption 2** EU Env. Target 2030	**Consumption 3** EU Env. Target 2050
Production Constraints	• Alternator < 1 MW; • Max power purchased < 744 MWh/month; • Max methane bought < 1 MNm³/month.	• Alternator < ∞ MW; • Max power purchased < 744 MWh/month; • Max methane bought < 1 MNm³/month.	• Alternator < ∞ MW; • Max power purchased < 744 MWh/month; • Max methane bought < 1 MNm³/month.	• Alternator < ∞ MW; • Max power purchased < 744 MWh/month; • Max methane bought < 1 MNm³/month.
Environmental costs	15 €/ton CO2 eq.	15 €/ton CO2 eq.	25 €/ton CO2 eq.	100 €/ton CO2 eq.
Power Production Incentives set sales price	€/kWh = 0.051.	P < 1 MW → €/kWh = 0.12; P < 3 MW → €/kWh = 0.097; P > 3 MW → €/kWh = 0.085.	P < 1 MW → €/kWh = 0.12; P < 3 MW → €/kWh = 0.097; P > 3 MW → €/kWh = 0.085.	P < 1 MW → €/kWh = 0.12; P < 3 MW → €/kWh = 0.097; P > 3 MW → €/kWh = 0.085.
Biofuel Production Incentives set sales price	€/kWh = 0.47.	€/kWh = 0.47.	€/kWh = 0.47.	€/kWh = 0.47.
Biofuels composition	100% Biomethane.	100% Biomethane.	100% Biomethane.	63% Power; 24% Hydrogen; 13% Biomethane.

Figure 6.11: Changes from one consumption scenario to another.

(i) Production constraints. Production constraints have, in CS0, a limit of 1 MW for the maximum power, because the previous Italian environmental law incentivized small-scale plants exploiting biogas and then most of the plants of this type have actually (2019) this characteristic, including the one exploited as case study. Conversely, the current Italian environmental law, i.e., in CS1, the environmental and energy laws affect only the selling price of power; in CS2 and CS3 is kept the same configuration of CS1 due to the lack of information about future policies. There is a limit for the purchase of power and biomethane from the market in each month (time period). In fact, limited purchases are necessary to satisfy geographical factor peaks of demand (heat and power), which cannot be satisfied by the produced resources. However, especially when pem-E is included, sales of hydrogen and oxygen can lead to an excessive purchasing of power and/or methane, by affecting the mission of the company. Therefore, these constraints are set higher than the necessary to understand how hydrogen and oxygen sales can impact on profits and costs.

(ii) Environmental costs. They are derived from the cost of per ton of CO_2 equivalent climate altering gas (according to the European Trading Scheme of CO_2), by following the Global Warming Potential [201]. CS0 and CS1 are fixed at 15 €/ton, while CS2 at 25 €/ton ([70]; [212]; [233]). In CS3, the environmental costs are set four times higher (100 €/ton) than the previous scenario to observe if they would have been enough to foster investment in the new technologies (MFs) by avoiding the pollutant emissions. These prices are used to assess the environmental costs of CO_2, biogas, and biomethane indicated in Table 6.4.

(iii) Power production. The market price of power is put in relation with plant scale by the Italian law. CS0 and CS1 directly report current and previous laws. In CS2 and CS3, the same policy is kept to make comparable the different CS. In each analysis of production and consumption scenario, the power capacity (process size) is chosen, and the market price is set accordingly.

(iv) Biofuel production. It is supported since the first Italian Environmental law (CS0). However, in the current one (CS1), only the produced biomethane via biogas of the Municipal Solid Waste can be used for the incentives. The considered WTE-SC refers exactly to this case; hence, the tariff is kept the same in all the consumption scenarios.

(v) Biofuel composition. It is not critical for the first three CSs, because the main biofuel is the biomethane. However, in the last CS, i.e., CS3, several changes in mobility market must be considered. Power and hydrogen must be considered as new "biofuels" (properly, energy vectors). Hydrogen will play a key role in the next future according to the current experiments (such as the case of SNAM [246]) and the analyses (NAVIGANT report on energy market in 2050 for EU region, developed with and for the main European gas grid companies following EU guidelines for 2050, [262]). Hence, the biofuel composition suitable for incentives has been revised to take into consideration the new kinds of mobility.

6.3.3 Results

All the 16 combinations of PS and CS have been evaluated as in the previous case study of Acea Pinerolese, i.e., 15 years of time horizon and one month as time bucket. Figure 6.12 shows the profits for all the 16 scenarios. The current production system PS0 shows decreasing economic profit with future policies due to the increasing of the environmental taxes. Also the system improvements (PS1), i.e., BMP and biofuel production, which in the previous case study lead to the reduction of the biogas emissions, are not sufficient to mitigate the impacts of environmental taxes, especially in CS4. The adoption of the new technologies, i.e., the MFs and the pem-E, seems crucial for tackling the next energy and environmental policies by leading to larger profits. Nonetheless, the PS3, where the technologies for improving the system are used together with those for the IS, is the best combination for achieving competitive advantage.

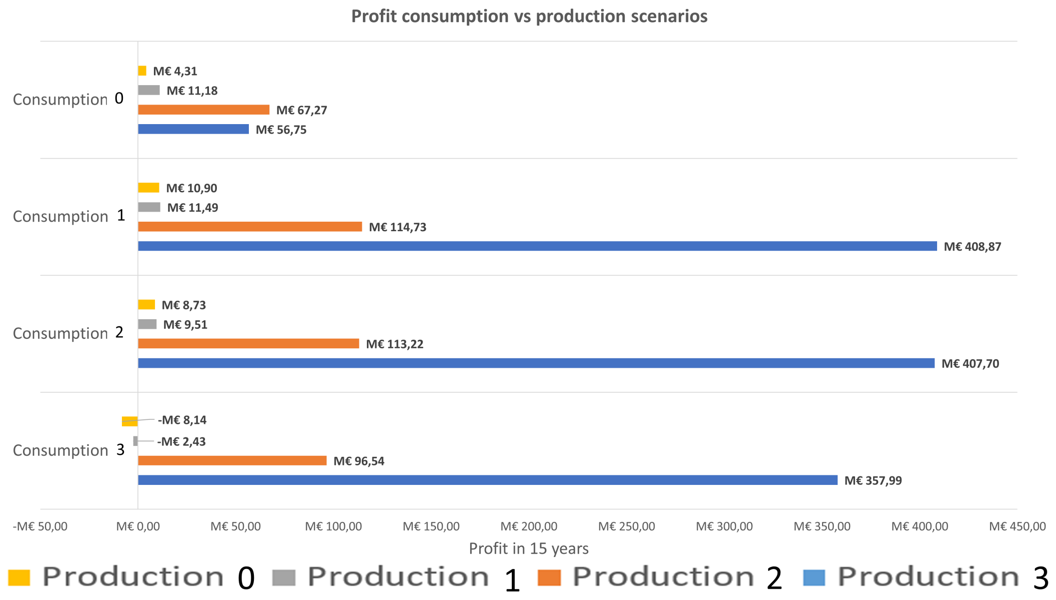


Figure 6.12: For each production and consumption scenario PS and CS the total profit is reported.

The positive and negative effects on the profit of the crucial resources, in terms of finished products, pollutant emissions and supplies, are investigated through the different scenarios by exploiting a combination of waterfall charts and pie diagrams. The waterfall diagram has both profit and losses on the y-axes, and it starts from 0; the initial investment in production and stocking infrastructures are subtracted, and the pie diagram under the label "investments" highlights the percentage of the investment devoted to the production infrastructures and the others for the warehouses. From the level reached by subtracting the initial investments, it is summed or subtracted the amount of profit or cost brought by each resource. The sum of all the profit and costs, at the end, shows the level of the final profit or costs reached for that combination of PS and CS. The pie diagrams under the resources show the proportion of cash flow earn or spent for the supplies, the operational costs and the environmental taxes. In Figure 6.13, PS0 and PS1 are compared under CS0. The adoption of BMP and Biofuel Production do not impact relevantly on the investments; in fact, according to the results of the previous work, the environmental costs of biogas are avoided by adopting BMP, but the environmental costs referred to the emissions of CO_2 increase. The fossil methane supplies is substituted by the production and sale of biomethane, while the amount of power bought from the market increases due to the minor power produced via CHP. The heat demand is managed by a larger use of boilers via the biomethane. The profit from heat is more or less the same due to the stochastic demand of heat that must be met.

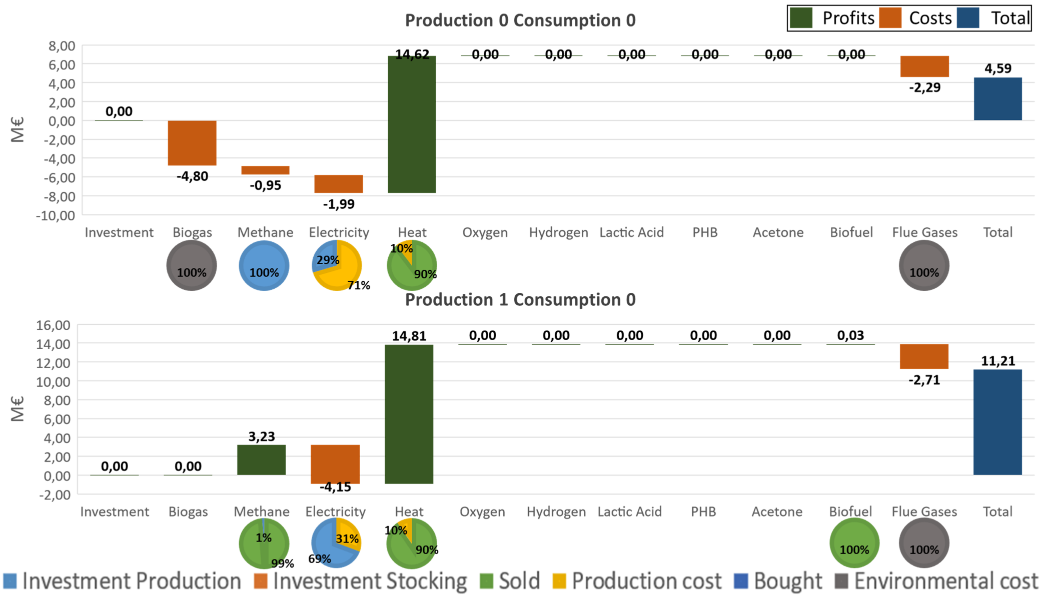


Figure 6.13: Comparison between PS0 and PS1 under CS0 of waterfall diagram and pie diagrams.

In Figure 6.14, the new energy and environmental laws remove the constraint of 1 MW for the installed power production capacity to sell the power at larger market price. This reduces the biogas emissions, thus also in PS0 biogas is fully exploited to produce power and heat, in fact power shows a positive effect on the profit. However, PS1, and the introduction of BP and BP lead to better profit.

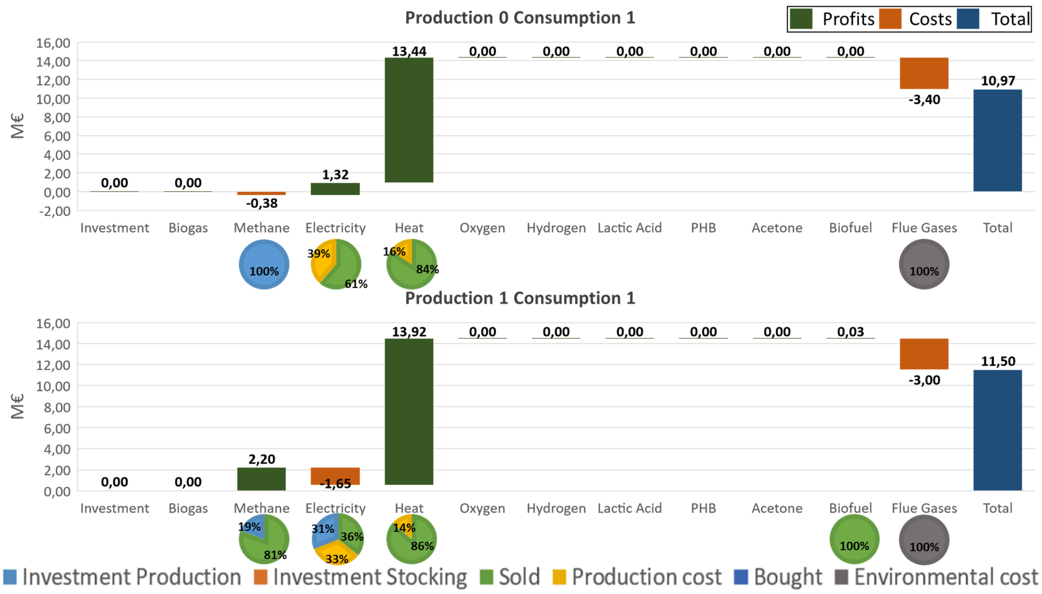


Figure 6.14: Comparison between PS0 and PS1 under CS1 of waterfall diagram and pie diagrams.

Figure from 6.15 to 6.17 compare PS2 and PS3 in CS1, CS2 and CS3, respectively, to show the effect of the environmental costs. The production of hydrogen and oxygen, according to the previous case study, compensates the increase of the environmental costs. However, it is more convenient from an economic point of view the sale of hydrogen and oxygen rather than their use to feed MFs that absorb CO_2. Moreover, the sale of hydrogen and oxygen, in PS2, leads to the increasing supplies of power (increasing to 76% in PS2 and CS1, CS2 and CS3). PS2 and PS3 reach larger profit by purchasing the maximum amount of power allowed by the constraints, from the market. Furthermore, in PS2 and PS3, also fossil methane is purchased to produce extra power through the CHP process. The heat is produced through the CHP, and its profit drop to 4.22 M€from the 13.44 M€of the previous scenarios, due to the operational costs of CHP. As a consequence of the large use of CHP process also the environmental costs increase.

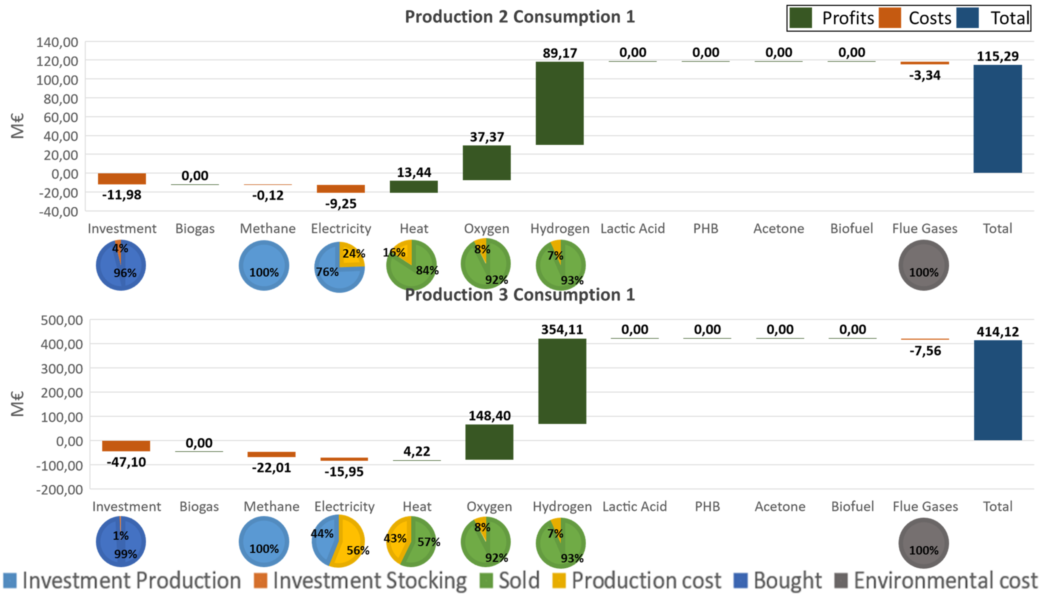


Figure 6.15: Comparison between PS2 and PS3 under CS1 of waterfall diagram and pie diagrams.

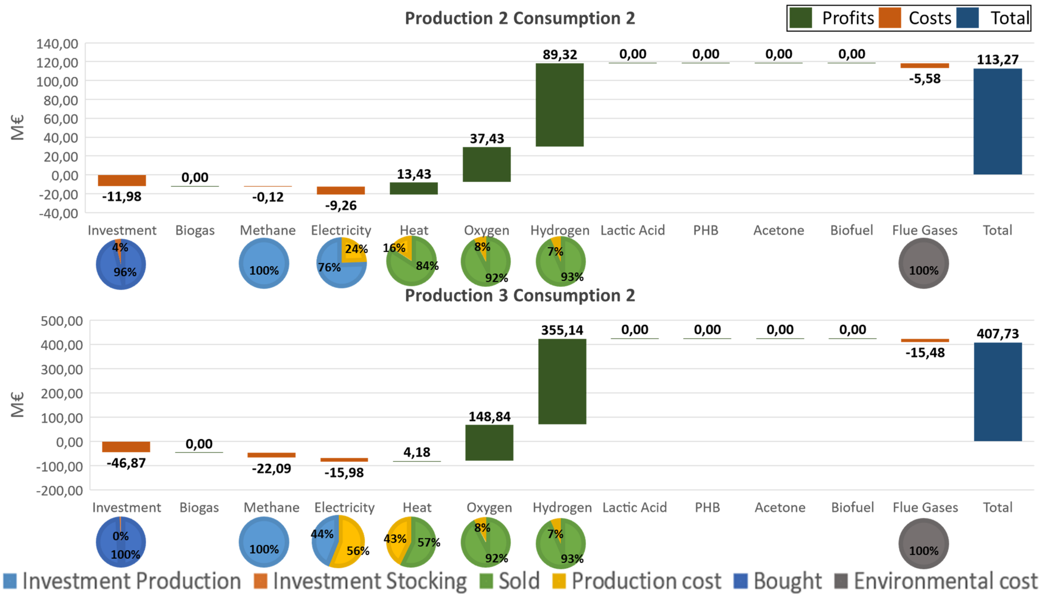


Figure 6.16: Comparison between PS2 and PS3 under CS2 of waterfall diagram and pie diagrams.

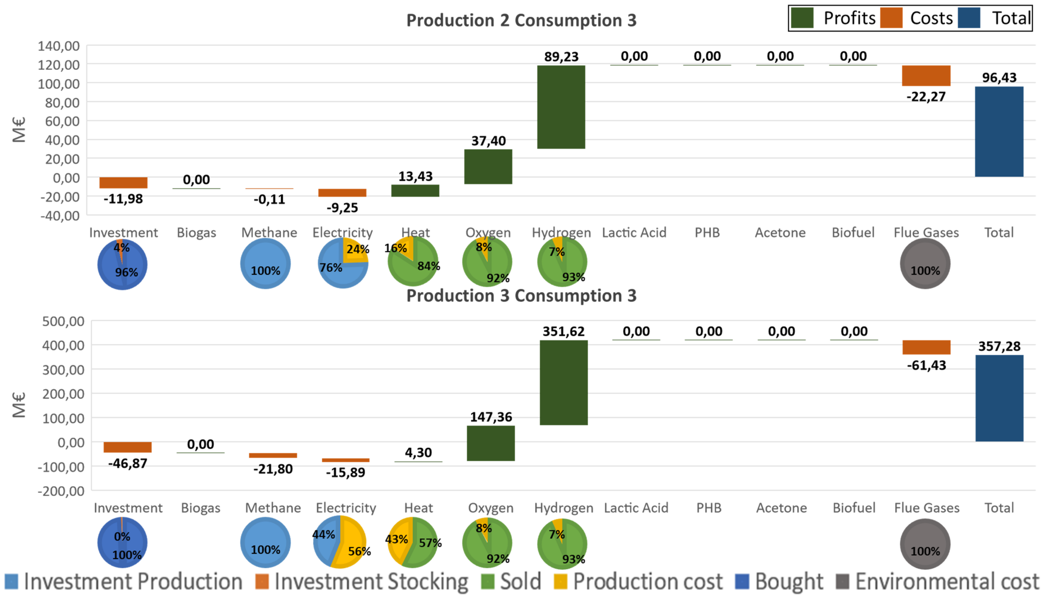


Figure 6.17: Comparison between PS2 and PS3 under CS3 of waterfall diagram and pie diagrams.

Waste production and CO_2 exploitation

The emergent profit brought by the sale of hydrogen and oxygen reduce the effectiveness of the increasing of carbon tax for the reduction of climate altering emissions. The future environmental laws likely will reduce the amount of pollutant, by setting thresholds beyond the increasing of environmental costs. Therefore, four additional CSs, where the climate altering emissions have been fully reduced, have been proposed.

Figure 6.18 and 6.19 show the amount of produced and unexploited biogas and CO_2. Biogas is completely exploited through the adoption of BMP and the new environmental laws (from CS1 to CS3), while the production of CO_2 increases due to the amount of power production to support the sale of hydrogen and oxygen. Furthermore, all the investments are allocated in pem-E and the MFs have been neglected, thus reducing the capacity of absorbing the CO_2. The last four CSs, namely CSN0, CSN1, CSN2, CSN3, have the same parameters as CS3, but CSN0 is dedicated to all the new technologies, while CSN1 is dedicated to MF1, CSN2, to MF2, and CSN3 to MF3.

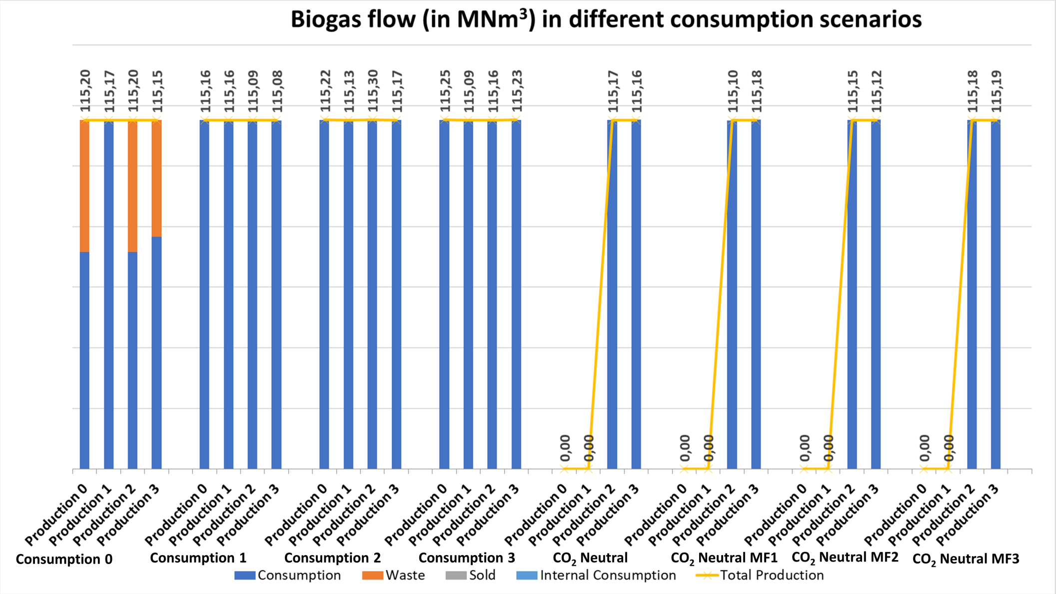


Figure 6.18: Bar charts for the production of biogas, and the amount consumed (blue) vs the amount wasted (orange).

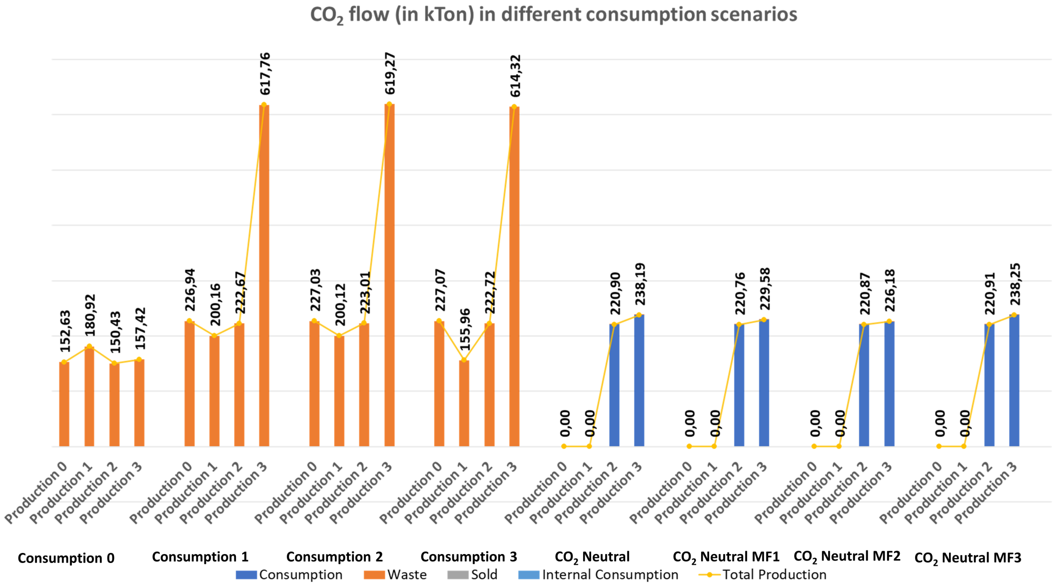


Figure 6.19: Bar charts for the production of CO_2, and the amount consumed (blue) vs the amount wasted (orange).

In Figure 6.20, as in the previous case study, it is showed that the heat production increases and it is partially wasted.

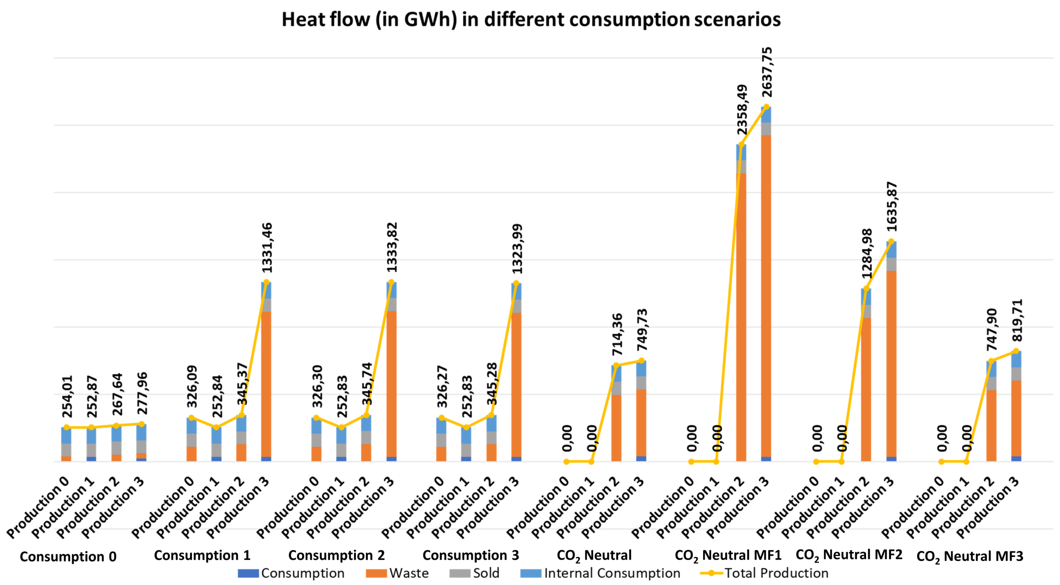


Figure 6.20: Bar charts for the production of CO_2, and the amount consumed (blue), sold (gray), used for self-consumption (light blue).

Figures from 6.21 to 6.24 show the contributions of each resource to the economic and environmental performances. All the evaluated scenarios can completely absorb CO_2, but they do it by exploiting different technologies. Figure 6.21 compares PS2 and PS3, both free to choose the best economic combination of processes and infrastructures, to avoid climate altering emissions. Figure 6.22 forces production systems to use MF1 to produce lactic acid from CO_2; while, in Figure 6.23, it is forced the production of PHB, and Figure 6.24 shows the production of acetone. The carbon neutral scenarios show total profit that cannot be compared among themselves due to the different amount of power and methane purchasable from the market. In fact, MFs require a large amount of oxygen and hydrogen to absorb CO_2. However, they need them in different quantities, thus each scenario can increase the purchasable amount from the market until a solution can be found by the optimization software. CSN uses a combination of MF3 and MF1, because MF3 is able to incorporate a large amount of CO_2, compared with the others. Thanks to this characteristic, there is no relevant difference if biomethane is used instead of biogas, so WTE-SC can make this decision without considering MF3, and this is highlighted also in carbon neutral scenario with only MF3. Conversely, MF1 and MF2 absorb less CO_2, thus they are more affected by the variability in CO_2 production (fluctuations related to heat and power peak demands). Furthermore, a larger number of machines means large investments, and sensibility to CO_2 fluctuations means large investments in stocking infrastructures. MF2 absorbs few CO_2 per machine, so a large number of machines is required, but this leads to a better way to synchronize the process with the production system, thus it does not require large investments in warehouses for hydrogen and oxygen. Moreover, MF2 can produce a lot of finished product (PHB) with the same amount of carbon dioxide, making it relevant from a trade point of view. The other MFs, even though they absorb more CO_2, they are not able to produce relevant volumes of finished products for a plant, so in accordance with the previous case study, they could be used as carbon capture technology, and the produced finished products can be used for the self-consumption.

The last point is the required amount of hydrogen and oxygen, which is evident from Figures 6.22 and 6.23. MF1 and MF2 require a large amount of both, so it is necessary a large number of pem-E, showing the necessity of involving a relevant partner in this industrial field for the IS network.

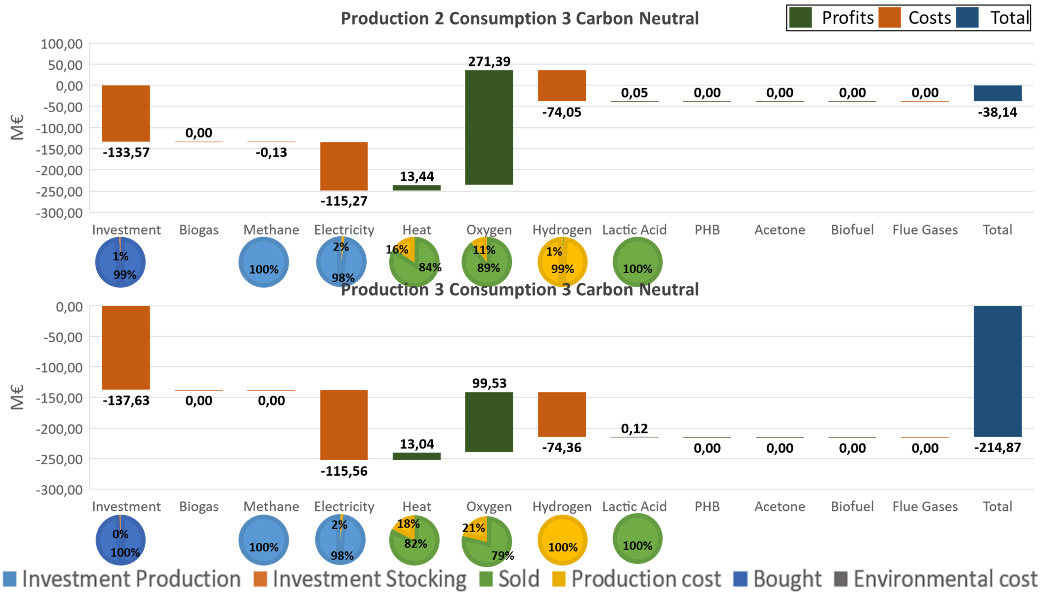


Figure 6.21: Comparison between PS2 and PS3 under CSN of waterfall diagram and pie diagrams.

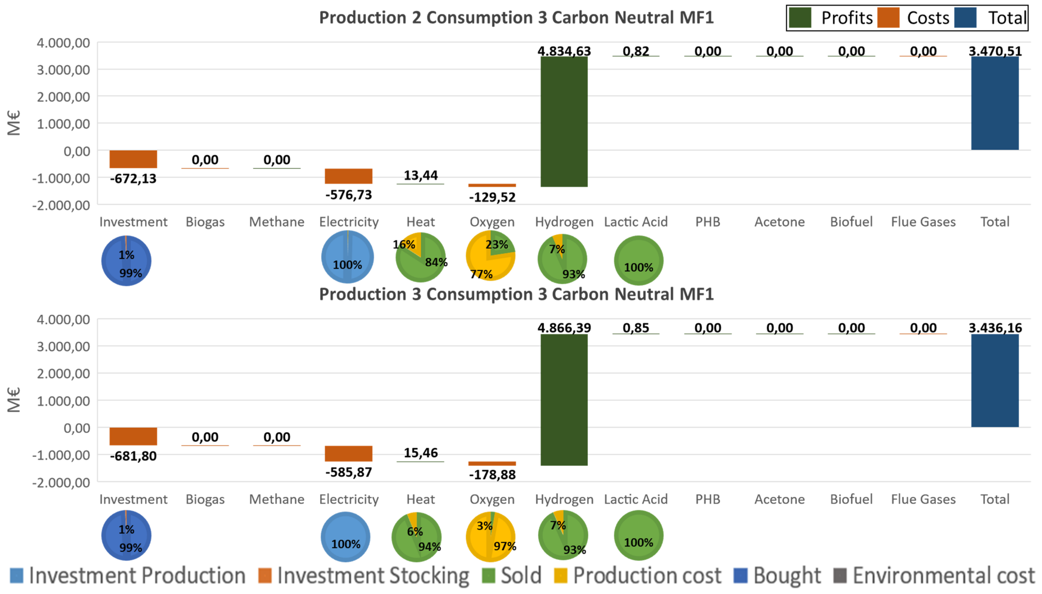


Figure 6.22: Comparison between PS2 and PS3 under CSN1 of waterfall diagram and pie diagrams.

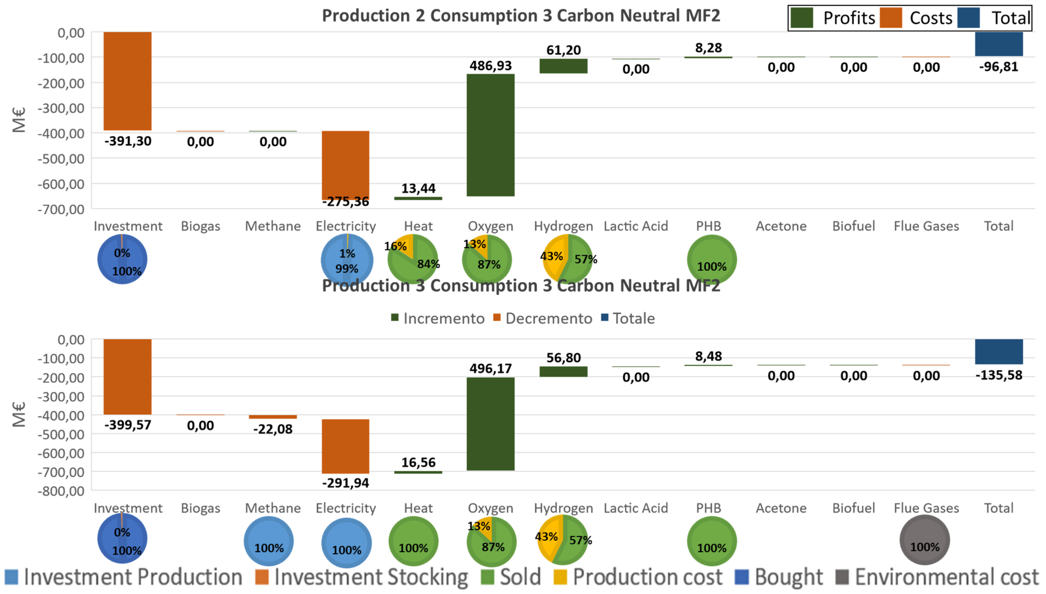


Figure 6.23: Comparison between PS2 and PS3 under CSN2 of waterfall diagram and pie diagrams.

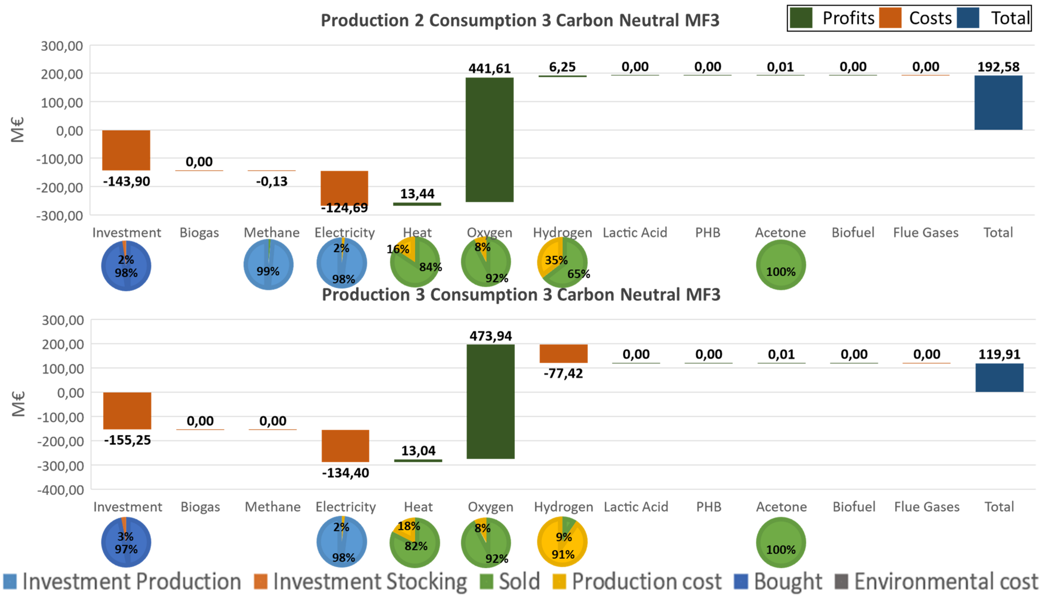


Figure 6.24: Comparison between PS2 and PS3 under CSN3 of waterfall diagram and pie diagrams.

The presented Eco-innovation methodology allows the individual companies to undertaking the continuous improvement process of improving resource efficiency. The methodology may support the identification of alternatives to improve the creation of value at strategical, tactical and operational level, by considering concurrently IS opportunities and the adoption of new technologies. It may help the companies for their strategical planning, by assessing the economic and environmental performance of the production systems under different energy and environmental laws.

Chapter 7

Summary

Part II focuses on the strategies that companies can adopt to improve the resource efficiency along their production processes. They can aim to several objectives through the resource efficiency improvement such as to reduce environmental impacts and gain competitive advantage by reducing purchasing costs and wastes, developing green products, creating value from their wastes and by-products, foreseeing new businesses. This process of continuous improvement of resource efficiency can be identified as the pursue of Eco-innovation. Four kinds of Eco-innovations are identified in the literature: product, process, organizational and marketing Eco-innovation. Generally, they are individually addressed, whilst holistic approaches are supposed to be crucial to significantly improve the business as usual, and effectively improve economic and environmental performances.

The state-of-the-art proposes drivers and barriers for Eco-innovation, and the application of several tools to support a specific type of it. The establishment of an IS can be part of a process of Eco-innovation. In the IE literature, IS is generally considered as a stand-alone action to exploit waste and by-products. Conversely, in this thesis, IS is considered as part of a more comprehensive strategy of the companies to reduce their direct and indirect environmental impacts and concurrently create value from their waste. There is a lack of practical and quantitative methodologies able to lead the individual firms through the first phase of the IS development, i.e., the "preliminary assessment" phase (see the Introduction, the phases of the IS development), especially, methodologies do not consider concurrently IS opportunities and other actions to reduce waste and/or increase the usage of raw materials. Also, the research of quantitative approaches that allow the companies to address the Eco-innovation process concurrently under its three main forms (process, product, organizational) is considered crucial.

Part II proposes an Eco-innovation methodology, based on three pillars, to drive the companies along a continuous improvement process. Far from the presumption of thoroughly contributing to all the three dimensions of Eco-innovation, the methodology aims to stimulate the individual companies to begin a path of continuous Eco-innovation towards the sustainable development, by considering concurrently both the opportunity of establishing new IS and innovating their own production system. The literature review about the IS has been used to identify the issues that methodology should address in the "preliminary assesment" phase of IS life cycle. Specifically, the last four of the seven barriers of IS emergence and development presented in the Introduction have been followed to identify information that methodology should collect to include IS in the evaluation of the comprehensive strategy to improve resource efficiency, by improving both economic and environmental performance. The methodology starts from the identification of all the factors that affect the production system, by grouping them in two classes: factors controllable by the company (design factors), and those not controllable (geographical factors) both internal and external. Internal geographical factors can be set by the companies to delimit the scope of the analysis or avoiding radical changes from the mission of the company. Conversely, the external geographical factors are out of the control of the company, e.g., the demand of finished products, the sources of some raw materials or waste such as the biogas produced by a landfill, the organic fraction of Municipal Solid Waste, the energy and environmental policies that set some constraints at production or operational level. The second pillar suggests to identify new technologies, processes and operational changes able to exploit the sources of waste found in Pillar 1 as results of geographical and design factors. In this phase, the methodology suggests to consider also those technologies that produce products far from the core business of the firms; in fact, the "preliminary assessment" phase of IS development cannot be evaluated independently from the other technical alternatives. Several IT tools and organizational approaches have been introduced, in the literature of IS, in the Introduction, that can be adopted to identify IS opportunities starting from a wasted resource, such as best practices and IS digital platforms. Hence, all the identified technologies answer to the need of understanding which are the wastes that is better to avoid and those that can be exploited through the exchanges in IS, in economic and environmental terms. The last pillar suggests the concurrent evaluation of all the identified technologies by using an optimization model. The results are used to improve the knowledge, and as a consequence, the representation of geographical factors and its implications on the performance of the system. The design factors are improved in each iteration until the representation of the geographical factor is satisfying and the reached level of detail allows to implement the solutions and to identify other firms with specific characteristics to propose them to join in a IS relationship.

The optimization model provides the aggregate production plan for the time horizon target, by sizing the controllable process and introducing those technologies that improve the economic performance. However, the optimization model provides information about also the environmental performances, the amount of produced waste, the purchase of non-renewable resources and the emission of pollutants. Hence, through the scenario analysis, it is possible the comparison of the combination of technologies to improve the economic and environmental performance, by investigating how they affect the resource flows, the production, the exploitation or reduction of wastes.

The methodology has been applied to the case of Acea Pinerolese, an Italian company part of a Waste-To-Energy Supply Chain. It exploits the biogas produced by landfill, wastewater treatment and OF-MSW to produce heat and power. The addition of biomethane purification to use biomethane rather than the biogas, and the biofuel production process are assessed in combination with the introduction of new technologies currently under development within the European project EngiCOIN. They are a polymeric exchange membrane electrolyzer (pem-E) and three microbial factories (MFs) able to exploit the produced CO_2, and a mixture of hydrogen and oxygen, both produced by the pem-E, to produce high value added chemicals such as lactic acid, PHB, and acetone.

The results show that the BMP and Biofuel Production are crucial for the reduction of biogas emissions and to improve the economic performance, while there are two different solutions for the exploitation of CO_2. MF1 and MF2 produce a large quantity of finished products (lactic acid and PHB) while MF3 produces a modest quantity of acetone; however, MF3 results effective in the absorption of CO_2. Hence, if the identification of external partners interested in IS to receive the CO_2 provides positive results, MF1 and MF2 could be adopted within the IS. In the other case, MF3 can be adopted by Acea Pinerolese as a carbon capture and usage technology to reduce the climate altering emissions. Hydrogen and oxygen shows high returns in economic terms, however, the power exploited and the amount of hydrogen and oxygen used to feed MFs suggest further studies.

The proposed Eco-innovation methodology can be used in combination with scenario analysis also to evaluate both the current system and the adoption of new technologies in the current system under different energy and environmental policies. In fact, laws and policies can deeply affect IS and the returns of the investments in Eco-innovation. The case study of Acea Pinerolse has been investigated under four consumption scenarios: the energy and environmental laws in force when it was established (2000s), the current energy and environmental laws (2019), the EU environmental target at 2030, and the EU environmental target at 2050. The

outcomes of the case study show the effectiveness of the methodology also for the strategical planning to improve the economic and environmental performances.

Part III

Firm's perspective: from the tools to support the analyses to the resilience of the network and the link network-operational level.

Chapter 8

A Decision Support System oriented towards resource efficiency

The adoption of the strategies to improve economic and environmental performance has to take into consideration the implementation costs in terms of knowledge, resources, and time. In fact, complex approaches to analyze and represent the production system and the monitoring of its environmental and technical performance over time can jeopardize its economic convenience. Especially for the SMEs, the large implementation costs can be a barrier to their adoption, by discouraging companies to improve their environmental performances.

The methodology, which has been introduced in chapter 5, exploits a MILP optimization model to devise the optimal production plan for the given time horizon. The optimization model allows the choice of the most promising technologies, by both selecting the number of parallel machines, for each process, and sizing the most suitable warehouse to reduce inventory and investment costs. The adoption of a technology and the sizing of the process are complex choices because they change both the produced and required amount of resources. Therefore, the choices regarding the production process cannot ignore also to consider the most convenient resources to be stored in terms of volume, inventory costs, investments for the warehouses, and the system synchronization from the supplies to meet the final customer's demand.

The effectiveness of the methodology in leading the Eco-innovation process thus depends also on the ease of use. The methodology requires the iterative application of the three steps, i.e., (i) the identification of geographical and design factors; (ii) the identification and the introduction of new technologies to reduce waste by increasing value creation both within the production system and through the development of IS relationships; and (iii) the performance assessment of the new technologies within the system and the improvement of knowledge of the geographical factor and the respective changes in the design factor for the next iteration.

The amount of required effort, in both economic and temporal terms, should progressively reduce as it passes from one iteration to another. Furthermore, the methodology should be able to exploit the amount of data provided by the IT systems of the company, such as SCADA and ERP systems, by reducing the intensive introduction of data manually collected, which are largely time, and sometimes also knowledge, demanding. The direct exploitation of data from IT systems improves the accuracy of the measurements, increases the amount of available data and reduces the lag between the data gathering and the output of the methodology.

8.1 A tool to support the operations management

In the literature, several approaches are proposed to provide users (such as decision makers of private and public companies, practitioners, scholars, policy makers) with tools, which standardize the procedures to perform analyses, by increasing their repeatability and overcoming the limited knowledge about the problem. The most widespread and also the oldest ones are the Decision Support Tools (DST) and the Decision Support Systems (DSS); since 1970s they rapidly spread in many sectors [243]. DST has been used in many sectors such has manufacturing [276], healthcare [171], environmental policy investigation [10], supply chain [260]. Furthermore, in any sector, DST are adopted in a wide range of levels, e.g., in manufacturing, they have been used at the operational level such as scheduling [106] and the setting of the parameters of the machines [218], at the tactical level for maintenance [83] and capacity planning ([79]; [47]), and for strategical decisions such as location-allocation problems [242], supplier selection [82], new product development [287]. The main difference between DST and DSS is the integration of additional functions, i.e., DSS integrates DST with modules for data management and storage (e.g., database [86]), and additional tools to update current data (such as forecasting methods [132]) and choose different approaches according to the current state of the system (such as simulation-optimization approaches [259]).

In the last two decades, the technological innovation allowed the diffusion of economic and reliable sensors, actuators, and infrastructure for data transport. Then, the connections between the physical systems and the DSSs for monitoring and controlling the system performance have become increasingly intertwined. DSS has become part of the production systems rather than an external tool limited to the support of the decision maker; thus, the production systems have included both physical and cyber infrastructures, processes, and activities. Cyber-Physical Systems (CPS) are defined as [220]:

> "Physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core."

The Cyber-Physical Production Systems (CPPS) have three main characteristics [190]:

1. **Intelligence.** The elements of the system are able to collect and transmit information while receiving instructions, both from cyber elements and human decision makers, about how to perform current or new tasks;
2. **Connectedness.** The elements can interact with each other, with humans, and with digital elements;
3. **Responsiveness.** The elements of the physical system are able to modify their behavior and their state according to the current necessities.

The cyber part of CPPS can be improved until the inclusion of a complete virtual representation of the physical system, the Digital Twin. A CPPS includes a Digital Twin to enhance the control over specific production resources, by showing their current state, providing information about their performance, and simulate their behavior under specific condition. Hence, differently from a virtual prototype of a system or a product, the Digital Twin (DT) is a virtual instance of the well-defined physical counterpart. The continuous data collection allows the real-time monitoring of the state of the system along all the phases of its life cycle [78], and it can be effectively used in combination with simulation tools [177] to predict the future state of the system [257], how it reacts to specific changes [196], to identify policies for improving efficiency while reducing waste and limiting the consumption of resources [165].

The necessity of a tool to support the implementation of the proposed Eco-innovation methodology has to take into account the digitization level of the company where it should be introduced. The wide range of applicability of the tool defines one of its characteristics: the flexibility. Hence, the tool should be able to be used as a stand-alone support to the decision makers, but also as a part of a wider digital system intertwined with the physical one.

From the flexibility of the tool another of its characteristics is derived: the scalability. In fact, the minimum requirements to support the application of the proposed methodology are enhanced when the tool is introduced in CPPS, since the amount of available data increases, by extending the range of application and improving the accuracy of the results provided.

The proposed tool needs of several supporting modules to ensure scalability and flexibility beyond the base functions for which it has been designed, i.e., supporting the decision maker in the definition of a strategy to improve resource efficiency. Thus, the tool itself becomes a system of intertwined modules collaborating with both the physical part and the cyber one, when it is present, of the production system. The proposed tool is a DSS.

The next section presents the DSS, its characteristics and operating modules; they are designed to fully exploit the benefits brought by the MEIO method (see chapter 2) and the Eco-innovation methodology (see chapter 6). Then, the subsequent section shows the application to the Acea Pinerolese case study; it includes also the result subsection where the achieved performances and characteristics are presented. The last section discusses the adoption of the DSS, while limitations, academic relevance and future research are mainly presented in the Part IV of this dissertation in order to be introduced by considering the big picture outlined by this document.

8.2 The Decision Support System resource efficiency oriented

The proposed methodology involves all of the three main aspects of resource efficiency and Eco-innovation by concurrently addressing the production of new products (or changes in the used raw materials), the introduction of new processes, and the definition of a network of companies able to exploit the produced waste as raw materials for new products. Usually, DSSs are applied to a single dimension of Eco-Innovation, e.g., by supporting the development of new products with limited environmental impacts or optimizing system performance to increase the efficiency via waste reduction. This thesis pursues a comprehensive approach to resource efficiency improvement through the adoption of new technologies to concurrently reduce the amount of produced wastes while exploiting their remaining part through IS. Such a comprehensive approach may have large implementation costs for data gathering, storage, improving the accuracy of them, and update them over time. Furthermore, since the approach is iterative, each iteration should minimize the required time and effort required to perform it. Therefore, a DSS, coded in Java, has been developed to support the application of the Eco-innovation methodology. The previously introduced state-of-the-art has showed different degrees of digitization of the production systems, and the level of monitoring of system performance proportionally increases with the degree of digitization. The DSS has been developed to be adopted from companies with many different degrees of digitization (flexibility), from the data entirely manually provided to those entirely provided by the IT systems, also involving hybrid contexts such as that one of Acea Pinerolese.

8.2.1 Aims and modules

The DSS aims to recover and exploit the data from the current production system to reproduce its operational and environmental performances. The representation of the current system allows the assessment of the introduction of new processes and the adoption of operational changes in terms of improved performances. The DSS is able to concurrently consider both the improvements of the current production system and also IS opportunities to find the optimal strategies to create value from waste, while improving the resource efficiency. Hence, the DSS provides insights about the adoption of new technologies by shedding a light on how they change the resource flows through not only the production system but the whole production network. In the case of emergent technologies, the application of the DSS can show unforeseen opportunities to exploit those technologies. For example, it could emerge that a technology is more useful as a way to reduce the emissions of a waste (e.g., carbon capture and storage technologies) within the system instead of as a new core process for the exploitation of that waste as raw material, e.g., in a symbiotic partnership. Furthermore, the developed DSS can model also environmental and energy policies, by integrating the incentives provided on the basis of installed production capacity, the source of raw materials use for the finished products and the environmental taxes for the pollutant emissions and the landfill disposal. Energy and environmental policies play a pivotal role in Eco-innovation because they support or discourage the diffusion of technologies, the emergence of cooperative networks, and they can actively influence the customers' preferences and the development of new technologies. Therefore, the proposed DSS can perform also scenario analysis to assess the robustness of decisions also under future policies, e.g., higher economic cost of climate altering emissions.

The behavior and the state of the current CPPS is not modified by the methodology and, subsequently, by the DSS; however, the methodology deeply exploits the data collected by the current system, and data remain pivotal. Furthermore, the granularity of data used is a priori not known because it depends on the level of investigation. In fact, the introduction of new processes or the changes in process parameters and operations management (such as new policies for the use of gas engines, the reduction of failures, the increasing in methane content of biogas) can show their impacts along horizons of different length. Data are pivotal for the DSS, which is fed with both the data provided by the SCADA system, manually introduced in the DSS database, and those manually collected and provided by the operators. The DSS has a module devoted to the data elaboration to update the modeling of the system processes to have a virtual representation of the system. The virtual representation aims to represent the production processes and their current performances; however, it has not all the required features to be a DT because it does not allow to know the state of the system and it does not cover all the elements of the physical system (such as pipelines) nor all the control parameters (such as those required for maintenance or chemical and biological safety). Further implementations are allowed by the DSS structure both to be coupled with a DT independent of the DSS and to implement a DT within the DSS itself. Further information about new technologies, processes and operation changes are provided in this phase by the users to be integrated together with the current system modeling.

Another module allows the introduction of prices and costs parameters, and it also allows the representation of energy and environmental policies. Economic, environmental, and operational parameters are intertwined with the related processes thanks to the exploitation of Multi-Layer Enterprise Input-Output (MEIO) formalization tool (see 2) and the MEIO tables. MEIO formalization is used to instantiate a MILP model solved by exploiting the libraries of the optimization commercial software CPLEX. However, the introduction of new modules would allow the exploitation of MEIO tables also to provide KPIs about economic and environmental performance of the system. In fact, MEIO approach, which is integrated in the module of process formalization of the DSS, allows an easy integration with further approaches such as Stream Mapping ones and the Material Flow Cost Accounting to measure how the production of waste economically affects the operations. The potential introduction of advanced approaches for a better control over the system while keeping the focus also on the performance of IS are introduced in the next chapter. Figure 8.1 shows on the left side the physical system, which provides data (highlighted in the central part of the figure), coming from both IT systems and manual collection, to the "Data exploitation and formalization process" module. It successively adds the data from both the "Definition of scope and initial state" and the "Policy and technology assessment" modules, and elaborates the MEIO tables for the "Model instantiation and optimization" module. Finally, it provides three kinds of report to the user.

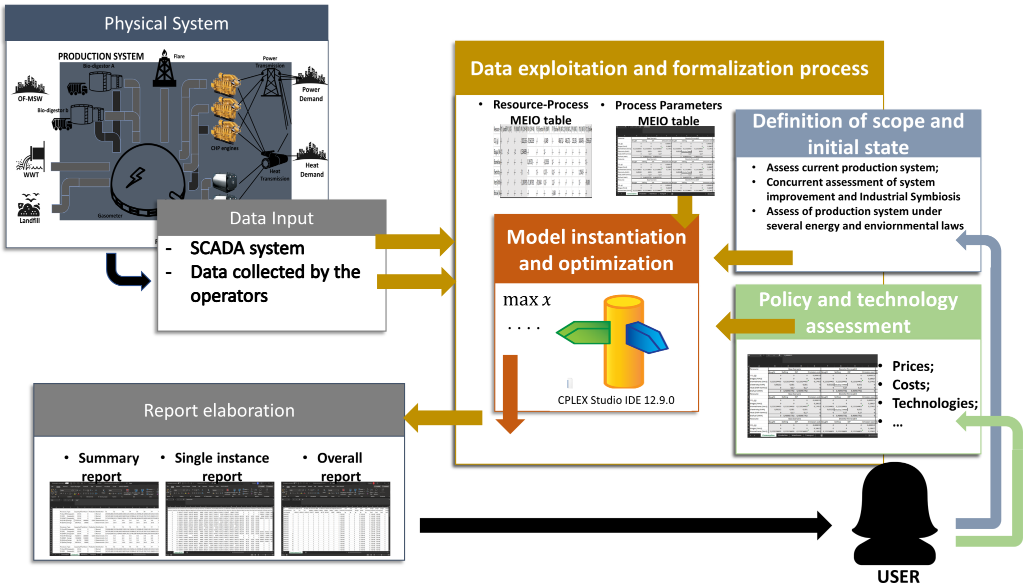


Figure 8.1: The interactions among the user, the physical systems and the four modules of the DSS: "Data exploitation and formalization process"; "Definition of scope and initial state"; "Policy and technology assessment"; and "Model instantiation and optimization".

8.2.2 The functions of the DSS

The DSS performs the following four functions:

1. **Data acquisition.** This function allows the collection of data from the CPPS. It does not allow the direct introduction of data from IT systems, since it depends on the commercial solutions adopted by the single companies. However, commercial IT systems can provide reports, in a standardized way, with a given frequency, that can be elaborated by the data acquisition function. Other data can be provided by the users in order to integrate the data of IT systems with information manually collected.

2. **Scope definition.** This function allows the users to identify the scope of the analysis. In fact, the users can decide to evaluate the system robustness under different policies, to choose the best technologies to reduce system waste and inefficiencies, identify wastes crucial for potential IS.

3. **Formalization.** Data may come from several sources, and they should be integrated to be available and ready to use for both the DSS itself and for additional tools that can be coupled with the DSS to provide further features.

4. **Assessment of economic and environmental performances.** The last function is devoted to the assessment of the performance by exploiting the

data introduced in the DSS and the scope defined by the user. It is part of this function also the production of reports to make clear the results of the analyses.

Four intertwined modules allow the introduced functions: data exploitation and formalization process; scope and initial state definition; policy and technology assessment; model instantiation and optimization.

Data exploitation and formalization process

Data collected are used to represent production, stocking and transport activities, through the application of MEIO formalization tool, to be ready to instantiate the MILP model or to be exploited via other approaches such as Stream Mapping and flow approaches like Material Flow Cost Accounting. Stochastic processes are modeled by providing average, standard deviation, and the information about the stochastic distribution, while deterministic processes are modeled with their nominal parameters or their average performance. At least 100 replications are performed for each scenario, by sampling the parameters from their stochastic distributions in each replication.

This module has to provide also the reports of the performed analyses. It generally provides three kinds of report for each analysis: (i) the summary of all the choices made to instantiate the analysis; (ii) one report for each performed replication of the scenario under analysis; (iii) an overall evaluation of all the replications where the average data for each information are evaluated through all the replications and provided. Reports (ii) are useful to investigate, through comparative approaches or more sophisticated ones such as machine learning techniques, interactions among activities and exploitation of resource flows at the changing of the stochastic parameters. Reports (iii) provide the average information such as the average size of the activities (e.g., number of machines per process, inventory capacity, size of the truck fleet) and the average production, consumption, and disposal of the material flows. Instead of average quantities, the reports (iii) may provide information (iii) according to a predetermined stochastic issues with a given probability of success (e.g., the minimum number of machines in a process that ensures the complete exploitation of produced CO_2 in the 99.9% of the replications).

Definition of scope and initial state

Three kinds of analyses can be performed with the DSS: (i) the assessment of the economic and environmental performances of the current system; (ii) the assessment of the introduction of new technologies by considering concurrently IS opportunities and waste reduction; (iii) the assessment of the robustness of both the current production system and the entire production network (Eco-Industrial Park and Supply Chain) with different environmental and energy policies. In all of the three kinds of analysis, the initial state of the system must be provided, i.e., the initial processes, their number of resources for each activity (e.g., machines, warehouses, trucks), the initial level of inventories and the RP and PP MEIO tables.

The definition of scope affects the scenario generation; indeed, in the case of (i) only one scenario is exploited for the analysis, while in the case of (ii) and (iii) multiple scenarios are required to understand how the involved changes affect the resource flows and the produced waste (see chapter 6). Figure 8.2 summarizes the rules for the choice of the proper number of required scenarios.

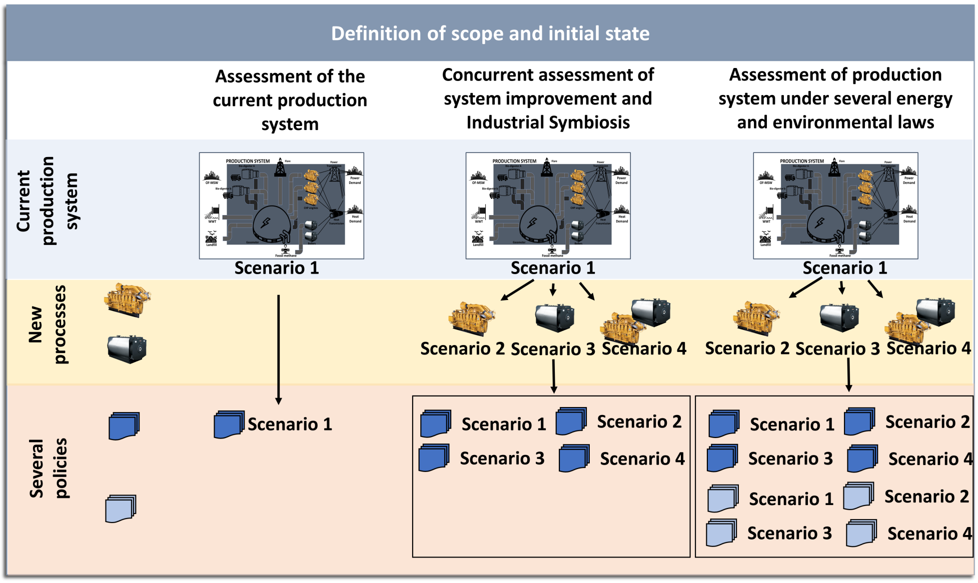


Figure 8.2: The rule for scenario generation under the three different scopes of application of the DSS

In the case of (ii), there are: (a) one scenario to represent the current situation; (b) another one where all the involved technologies and changes are concurrently evaluated; and, (from c.1 to c.n with n the number of involved technologies) one scenario for each new introduced technology combined with the adopted operational changes. The dedicated scenario of each single new technology sheds a light on the arising interactions between the material flows, which are fundamental to understand whether a technology is better as a device to reduce waste production or a process able to involve other partners to produce finished products by exploiting the wastes of the current system. Finally, in the case of (iii), the required scenarios (one or more according to the goal of the analysis) are evaluated under all the different policies required.

Policy and technology assessment

This module collects all the information about the involved policies and the new processes whose adoption has to be assessed. For all the resources (products, raw materials, waste and by-products), market prices, incentivized prices, purchasing costs and environmental costs are provided. The information about the new technologies are integrated in the MEIO tables, while those about policies are directly exploited by the "Model instantiation and optimization" module as parameters of the model.

Model instantiation and optimization

This is the module devoted to the recovery of MEIO tables to instantiate the MILP model of the aggregate production planning with the selection and sizing of processes, warehouses and transport activities. The data about the scenarios and the initial state of the system are used as model parameters. The optimization routine, which can be a commercial solution or developed ad hoc, finds the optimal or near-optimal value of the variables.

8.3 Case study results

8.3.1 The empirical context

The DSS has been developed and tested in the Acea Pinerolese case study mainly to identify the optimal strategy to improve resource efficiency, i.e., identify which combination of technologies would have led to a reduction of waste and inefficiencies while exploiting the remaining part as raw material for new products. Furthermore, the DSS has been tested also to assess the robustness of the identified solution when facing environmental and energy laws subjected to change. This section describes the adaptation of the modules of the DSS to the production system of Acea Pinerolese, and the effects brought by these adaptations on the performance of the DSS itself.

The four functions performed by the DSS and introduced in the previous section are kept since they represent the core features of the approach. They have been adapted to the production systems as follow:

1. **Data acquisition.** Data about biogas production, the inventory level within the gasometer, biogas and biomethane consumption and production of heat and power are recovered from SCADA system and provided to the DSS. In this

phase, data about heat and power demand are provided by the users together with the information about new processes and/or operation changes.

2. **Scope definition.** In this phase, the information about the aims of the analysis are provided together with energy and environmental laws and all the other information required for scenario analysis, such as prices and costs of raw materials, products and waste, the investment required for new activities. This function allows to focus the analysis on the technologies or on the effects of policies on the development of IS opportunities and the system improvement.
3. **Formalization.** All the data are ordered in MEIO tables and used to instantiate the MILP model.
4. **Assessment of economic and environmental performances.** The optimal solutions found are used to provide the final reports.

At the operational level, the customization of the functions on the production system requires a specific configuration of the various modules of the DSS.

Data exploitation and formalization process

This module is devoted to the loading of the data into the DSS, the formalization of value-added and non-value-added activities, and the production of reports after the analyses. This module is designed to exploit the a priori knowledge of the system; hence, it expects the data provided by all the Equivalent Control Points (ECPs) used to monitor the performances of the processes, inventories and transport activities. Part of the data are collected by the SCADA system, while the other part is manually collected and/or put together and provided to the DSS via this module. Table 3.1 shows the data provided by the SCADA system, while the information about the new technologies from EngiCOIN project, i.e., MF1, MF2, MF3, pem-E, BFP, BMP, are provided through Resource-Process MEIO table. All the information about the maximum capacity of the activities (production, stocking and transport), the operational costs and outages (such as failures and maintenance), their acquisition prices, and the finished product demand to complete Process Parameters MEIO table are manually collected and provided by the users of the DSS.

The reports produced are not affected by the adaptation to the case study. The log report summarizes all the parameters used to perform the analysis; the overall report put in relation the source of the resources of the system and their uses, with the technical choices made and the economic-environmental performance; the single reports provide the details of each replication performed to allow the study of the effects of variability on the technical choices.

Definition of scope and initial state

The second module allow to set the initial state of the system and the kind of analysis performed. The DSS can be adopted within CPPS where the digital systems is updated in real-time, thus it is possible the use of the real current state of the physical system as initial state in the optimization model. However, since the scope was the definition of a strategical plan for improving resource efficiency and a tighter interconnection with the IT systems of the company was not possible, the initial state was set as the average state of the physical systems (in terms of inventories, WIPs, utilization of the processes). Therefore, the DSS was mainly devoted to the identification of technologies for reducing waste and inefficiencies, and also for developing new IS. Furthermore, the solutions found have been assessed in terms of robustness under different environmental and energy laws. The introduction in the current production system of Acea Pinerolese of the technologies coming from the EngiCOIN project and those identified by the Acea Pinerolese have been evaluated for the definition of the strategy to improve resource efficiency.

Policy and technology assessment

This module is deputy to the collection of information about the several scenarios where different policies are applied. Furthermore, it collects the information about all the new processes and technologies aforementioned. See chapter 6 for the specific information about both the consumption scenarios and the technologies used.

Model instantiation and optimization

The last module here exploits the library of the commercial optimization solver CPLEX, which has been used to find an optimal solution, which is sent to the "Data exploitation and formalization process" module to create the reports file. Therefore, in this case the DSS does not have an ad hoc solver since the dimension of the model is acceptable to obtain solutions with a limited computation time.

8.3.2 Results

The case study has been developed to test all the four functions of the DSS and their effectiveness. The main goals of the DSS have been satisfied; in fact, it is useful to collect data, formalize them and store to make them available for the use of the DSS or of other software applications. The DSS simplify the application of the Eco-innovation methodology proposed in chapter 6 by reducing the time and resources required, and it results fundamental for the optimization model embedded in it. The effectiveness and the flexibility of the tool have been widely tested by the case study; however, it is not the same for the scalability.

The DSS has been designed aiming to the scalability of its features according with the digitization level of the system where it is introduced. However, its application in a single system does not allow to assess this characteristics. Some features remain poorly tested such as the opportunity to store information about the system and use the real-time update enabled by MEIO rather than upload all the data into the DSS database every time it is used. Furthermore, MEIO allows the formalization of a priori knowledge and the knowledge extracted through data-driven techniques, but the lack of direct connection between the DSS and the IT systems of the company did not allow the opportunity to assess if further modules were been necessary to make homogeneous the information.

The case study is oriented to the support of the decision makers in strategical planning for resource efficiency of a company. However, the reports produced provide information also about the effects of the policies decided by the policy maker on the company itself. Therefore, the company can foreseen potential policies by anticipating them and adapting its processes; this may be source of competitive advantage respect of the competitors.

8.4 Discussion

The main advantage of this tool is the ability to easily adapt to the systems of the companies where it is adopted, by requiring limited knowledge for the use, and showing opportunities of application increasing with the digitization level of the companies themselves. It can be used as a stand-alone tool to identify opportunities to create value from waste reduction and IS development, but it can also be linked with IT systems to provide more detailed analyses by easily changing the identified time horizon. In presence of already established CPPS, the tool can be used also to assess the adoption of new technologies, concurrently with the introduction of new products and the development of IS.

The embedded MEIO tool allows the introduction of further powerful and easily to develop tools to provide KPIs in real time about system performance. For example, the Stream Mapping can assess the instantaneous value creation by identifying the added and non-added value activities, while Material Flow Cost Accounting can provide insights about the wastes that are causing the operational and/or environmental costs. Moreover, MEIO tool can be exploited also by other tools of the CPS to derive benchmark parameters, thresholds, and update process parameters, e.g., in simulation tools, which are largely widespread in CPPS.

The reports produced by the DSS provides managerial and technical insights about the average benefits provided by the introduced technologies or the operational changes; however, they allow also the identification of patterns and hidden interactions in the multi-product production system. The identification of these interactions is crucial, especially for those companies not provided with advanced CPS and monitoring technologies, to understand both the consumption of resources and the possible causes of inefficiency. Furthermore, the scenario analysis where multiple energy and environmental policies are compared allows the evaluation of the emerging weaknesses or strengths of the current system, by shedding a light on the crucial points of the production system.

8.4.1 Limitations

The proposed DSS has been developed to support the individual companies in the pursuit of Eco-innovation through the introduced methodology. The methodology mainly impacts on the strategical and tactical level. The DSS can be adopted both by companies strongly oriented to CPPS and by smaller companies with limited resources, knowledge and lower level of digitization such as some SMEs. However, the impacts of the methodology adoption in the short run, i.e., operational level, have not been explored and they are not clear.

The adoption of new technologies can have disruptive effects on the operational level [284]; it can cause congestion in the production lines, the arising of hidden costs and also an hidden decrease of resource efficiency. Furthermore, the establishing of a new network where IS and raw material supplies are intertwined can influence the material planning; furthermore, the agreements among the several stakeholders could manifest their effects also on production constraints. On the other side, the individual companies could be subjected to the disruptive events that have repercussions on the entire network highlighting the crucial role of the network robustness.

The proposed methodology and the DSS do not consider the operational level where the production system is intertwined with the processes linked to the several IS. The uncertainties of the production such as product demands, quality of the produced waste, exact match of demand and supply of waste over time, can jeopardize the economic benefits of the overall strategy of the companies to improve their resource efficiency. These issues are crucial [99] and the next chapter investigates them to allow to this thesis to offer a well rounded, even though it does not respond to all the numerous questions of the topic, approach to the resource efficiency improvement within the companies.

Chapter 9

Belonging to the ISN: from long to short run

The operational issues of IS are becoming clearer in the recent literature. The waste exploitation as raw material in a network of companies presents several open questions such as the effects on material planning, how the operations of a company can affect those of the others, and the link between network level and operational level [129]. The mismatching between the amount of produced waste and the demand of waste itself can jeopardize the established networks because it implies a shift of operational costs from a stakeholder to another, by changing the win-win condition over which IS is based on [289]. This last part of the thesis goes deep into the introduced win-win condition to propose a mechanism to maintain the stakeholders' commitment over time by reducing the risk of disruptions. Furthermore, the application of this mechanism helps to make explicit the link between the performances at network level and those at the operational level of the individual firms.

9.1 Resilience in Industrial Symbiosis Network

In the Introduction of this thesis, the 7 main barriers to the emergence and the development of the Industrial Symbiosis Network (ISN) has been reported [112]. Each ISN, established or potential, can be hindered from one or more of the 7 barriers, and understanding which they are is fundamental for the analysis of the resilience.

Resilience is generally intended in systems engineering as the capacity of a system of maintaining its structure and functions after a disruptive event [62]. In ISNs, functions and structure can be intended in several ways leading to different approaches to the resilience. The network analysis approach is mainly focused on the connections (exchanged quantities) between the nodes (stakeholders) and the consequences of the disruptive events, i.e., the events leading to the removal of an edge (partial disruptive event) or a node (complete disruptive events) ([62]; [169]). According to this kind of analysis, the functions and the structure of ISNs are preserved when the network is highly connected, thus ISNs are more resilient when there are many companies exchanging the same resource (redundancy) and the benefits of the companies increase with the number of exchanged resources (the number of edges) [62]. However, in some cases, the role of the anchor tenants, one or more stakeholders in dominant position, is crucial for the development of an ISN [279]; in these cases, the anchor tenants keep all the others in the same network, thus they become the vulnerable nodes of the ISNs that must be protected and monitored [170] to avoid disruptive events that would have domino effects on the whole ISN [169]. The same insights have been found for the resilience of infrastructures used ([163];[23]), even though damages at infrastructures have a more temporary connotations than the disruptive events previously introduced.

Functions and structure of ISNs can be investigated also from an ecosystem point of view, where the goal is the largest absorption of produced waste, i.e., closing the loop of resource usage rather than dispose them. Two approaches have been largely adopted to investigate the resilience according to the closure of the loops of the resources: the Food Web Analysis and the Agent-Base Simulation. Food Web Analysis analyzes the ISN by focusing on the amount of stakeholders producing a waste and the amount of those requiring it. The overall resilience of an ISN is largely affected by cyclicity and connectance because they ensure to maintain its functions after a disruption that excludes one or more stakeholders. An ISN with a large value of connectance, i.e., stakeholders largely connected among themselves, involves a high level of ciclicity for the wastes, i.e., many companies are able to exploit a certain waste, thus the probability that a waste keeps to be absorbed by the EIP although a company leaves is larger [109]. Through the application of Agent-Based approach, redundancy, i.e., the presence of stakeholders producing or absorbing the same waste, emerged as a factor capable to increase the long term economic and environmental performance of the individual companies although it increases the transaction costs [100]. Furthermore, nodes capable to produce and consume many different kinds of waste (i.e., large diversity) are important due to their role in increasing the connectance, and subsequently the stability, of the ISN [97].

A different approach to the resilience is its improvement during design phase, by taking into consideration potential uncertainty during the operational activities such as the occurrence of disruptive events, and the eventual opportunistic behavior of the stakeholders. A two-stage optimization has been proposed where the first round defines the network and second considers the uncertainty at operational level to derive constraints to reiterate the optimization until all the uncertainty scenarios have been evaluated [162]. When uncertainty information to identify scenarios is not available, the robust network configurations are found by considering stakeholders as a black box [15] or trying to foreseen opportunistic behaviors through game theory approaches [59].

Network analysis and Food Weeb Analysis are mainly oriented to the investigation of drivers and barriers of the resilience. Optimization-based and Agent-based approaches consider also the nature of the interactions between stakeholders e.g., through sharing of benefits and costs brought by ISN [12], or contracts to make decision about who pay operational costs [6]. The roles of technology and the initial investments are marginal in the state-of-the-art of resilience in ISN. In fact, optimization based-approaches tries to balance the initial investment and the future benefits, also considering opportunistic behaviors and uncertainty, as previously introduced, like the proposed methodology of chapter 6. On the other side, the interactions among stakeholders are mainly focused on the cases where the technologies to exploit waste of other companies are widely available.

9.2 A study about technology implications on resilience

The "technical feasibility" is one of the 7 barrier to the diffusion of IS (see Introduction) and it makes worse the effect of other barriers such as "the economic infeasibility", "the lack of commitment to sustainable development" and "the lack of cooperation and trust". The adoption of new technologies leads to a lock-in effect towards the ISN; the lock-in effects can have positive effect in terms of commitment over time [129], but its effect have not been comprehensively addressed including those potentially negative [158]. Hence, the stakeholders' commitment to the ISN assumes a crucial role because not only the operational costs are involved but also the recovery of the initial investments.

This thesis supports the recurrent goal in developing new IS to find partners able to create value from the waste, in accordance with the definition of waste as a product that the customer lacks [56]. The proposed Eco-innovation methodology fosters the continuous improvement of the production system to increase the resource efficiency also by involving new partners, i.e., trying to be the principal initiator of new ISN emerged from the following dynamics: (i) self-organization, (ii) organizational boundary change, and (iii) Eco-cluster development [31]. A further approach is the tentative to develop new products by considering the use of abundant waste and resources of the current region. This thesis does not want to focus on the new product design, but on the preliminary considerations that should be made during the assessment of the potential partnerships. Both the suggested approaches, i.e., the Eco-innovation methodology and the consideration to exploit the local waste during the new product development, go in the direction of integrating SCs and EIPs in a joint network. The joint network can help to overcome the obstacle of the environmental investments limited to meet their returns [269]. In fact, the use of waste also to create new products allows a deeper and more extensive exploitation of the wastes, which can lead to a minor environmental impacts.

9.2.1 A model to investigate the economic sustainability under benefits sharing approach

The integration of SCs and EIPs when technological investments cannot be neglected poses three issues: (i) taking into consideration a fair allocation of the costs among the all the involved stakeholders; (ii) ensuring the economic viability; (iii) considering the whole system as an interaction of stakeholders, which can reduce their involvement over the time, rather than a monolithic entity. The following Mixed Integer Non-Linear model is supposed to be used by the principal investigators of the ISN such as anchor tenants, governmental and private third parties involved in the development of industrial areas, brokers of EIP, to evaluate several alternatives through the selection of production, stocking and transport infrastructures.

The fair allocation of the investments is modeled through the equalization of the Payback Periods (PbPs) of the companies by taking into consideration only the investments, the cost and the revenues referred to the ISN [46]. Therefore, at least for the years of the PbP, all the stakeholders may be equally motivated to avoid opportunistic behavior. In the design phase, it is introduced the mechanism to improve the robustness of the network.

The variables and parameters used in the model are summarized in tables 9.1 and 9.2, respectively, where i refers to stakeholders ($i = 1, ..., N$), z to production processes ($z = 1, ..., Z$), w to stocking technologies ($w = 1, ..., W$), k to transportation modes ($k = 1, ..., K$), j to treated materials ($j = 1, ..., J$), and t to time periods ($t = 1, ..., T$).

v_t	value created by EIP in period t
cf_i	average net cash flow for stakeholder i
oc_{it}	operative costs of i in t
ct_{it}	total cost of transportation for i in t
cs_{it}	total cost of stocks for i in t
ep_{it}	total cost of production for i in t
pb_i	payback period of i
pc_{it}	positive contribution received by i from EIP in t
nc_{it}	negative contribution payed by i to EIP in t
s_{it}	cost avoided thanks to EIP by i in t
ti_i	total investment of i
$tq_{ii'jkt}$	quantity of j moved from i to i' using mode k
$tq_{i'ijwkt}$	quantity of j moved from i to i' using mode k and stocked using w
pq_{ijzt}	quantity of j produced by i through z in t
pq_{ijwzt}	quantity of j produced by i through z in t and stocked using w
sq_{ijwt}	quantity of j stocked by i using technology w in t
$qu_{ij'jwzt}$	quantity of j from w and used in process z by i in t
q_{ijwt}	demand of j satisfied from inventory w by i in t
$\alpha_{ii'k}$	binary variable (1 if transportation mode k is chosen from i to i'; 0 otherwise)
β_{ijw}	binary variable (1 if stocking technology w is chosen in i ; 0 otherwise)
σ_{iz}	binary variable (1 if transformation process z is chosen in i ; 0 otherwise)

Table 9.1: Variables

D_{ijt}	demand of j for i in t
MP_{jt}	market price for j in t
NP_{jt}	EIP price for j in t
AC_{ijt}	cost of j avoided by i in t
$FT_{ii'k}$	fixed transportation cost from i to i' for infrastructure k
FW_{ijw}	fixed stocking cost for technology w and product j in firm i
FP_{iz}	fixed cost transformation for process z in firm i
$L_{ii'}$	distance between i and i'
$UT_{ii'jk}$	unit transportation cost from i toi' for j by mode k
US_{ijwt}	unit stoking cost for j in inventory type w in firm i in t
UP_{ijzt}	unit cost production of j for i using z in t
$C_{izjj'}$	quantity of j' in one unit of j by z for i
XW_{ijw}	max capacity of stoking type w for j in i
XP_{ijz}	max capacity of production process z for j in i
$XT_{ii'jk}$	max capacity of delivery mode k for j from i to i'

Table 9.2: Parameters

$$\max \textstyle\sum_{t\in T} (v_t - \sum_{i\in N} oc_{it}) \tag{9.1}$$

s.t.

$$oc_{it} = ct_{it} + cs_{it} + ep_{it} \qquad \forall i \in N \tag{9.2}$$

$$cf_i = \frac{\sum_{t\in T}(s_{it}+pc_{it}-nc_{it}-oc_{it})}{T} \qquad \forall i \in N \tag{9.3}$$

$$\begin{aligned} ti_i = &\textstyle\sum_{k\in K} \sum_{i'\in N\setminus i} FT_{ii'k}\alpha_{ii'k} + \\ &+ \textstyle\sum_{w\in W} \sum_{j\in J} FW_{jiw}\beta_{ijw} + \sum_{z\in Z} FP_{iz}\sigma_{iz} \qquad \forall i \in N \end{aligned} \tag{9.4}$$

$$pb_i = \frac{ti_i}{cf_i} \qquad \forall i \in N \tag{9.5}$$

$$pb_i \leq pb_{i'}(1+\delta) \qquad \forall i, i' \in N \wedge i \neq i' \tag{9.6}$$

$$pb_i \geq pb_{i'}(1-\delta) \qquad \forall i, i' \in N \wedge i \neq i' \tag{9.7}$$

$$\begin{aligned} v_t = &\textstyle\sum_{i\in N} \sum_{j\in J} \sum_{i'\in\{N\setminus i\}} \sum_{k\in K} NP_{jt}tq_{ii'jkt} + \\ &+ \textstyle\sum_{i\in N} nc_{it} + \sum_{i\in N} \sum_{j\in J} MP_{jt}D_{ijt} \qquad \forall t \in T \end{aligned} \tag{9.8}$$

$$\textstyle\sum_{t\in T}(v_t - \sum_{i\in N} oc_{it}) = \sum_{t\in T} \sum_{i\in N} pc_{it} \tag{9.9}$$

$$\textstyle\sum_{t\in T}\sum_{i\in N} nc_{it} = \sum_{t\in T}\sum_{i\in N} pc_{it} \tag{9.10}$$

$$\textstyle s_{it} = \sum_{j\in J}\sum_{z\in Z} AC_{ijt}pq_{ijzt} \qquad \forall i \in N, \forall t \in T \tag{9.11}$$

$$\textstyle ct_{it} = \sum_{i'\in N\setminus i}\sum_{k\in K}\sum_{j\in J} UT_{ii'jk}L_{ii'}tq_{ii'jkt} \qquad \forall t \in T, \forall i \in N \tag{9.12}$$

$$\textstyle cs_{it} = \sum_{w\in W}\sum_{j\in J} US_{ijwt}sq_{ijwt} \qquad \forall t \in T, \forall i \in N \tag{9.13}$$

$$\textstyle ep_{it} = \sum_{z\in Z}\sum_{j\in J} UP_{ijzt}pq_{ijzt} \qquad \forall t \in T, \forall i \in N \tag{9.14}$$

$$\textstyle \begin{aligned} sq_{ijwt} &= \sum_{i\in N\setminus i}\sum_{k\in K}(tq_{i'ijwkt} - tq_{ii'jwkt}) + \\ &+ sq_{ijwt-1} + \sum_{z\in Z}(pq_{ijwzt} - \sum_{j'\in J} qu_{ij'jwzt}) - q_{ijwt} \end{aligned} \qquad \forall w \in W, \forall i \in N, \forall j \in J, \forall t \in T \land t \neq 1 \tag{9.15}$$

$$\textstyle D_{ijt} = \sum_{w\in W} q_{ijwt} \qquad \forall i \in N, \forall j \in J, \forall t \in T \tag{9.16}$$

$$\textstyle tq_{ii'jkt} = \sum_{w\in W} tq_{ii'jwkt} \qquad \forall i, i' \in N, \forall t \in T, \forall j \in J, \forall k \in K \tag{9.17}$$

$$\textstyle pq_{ijzt} = \sum_{w\in W} pq_{ijwzt} \qquad \forall i \in N, \forall t \in T, \forall z \in Z, \forall j \in J \tag{9.18}$$

$$\textstyle pq_{ijwzt} = \sum_{j'\in J}\sum_{w\in W} C_{izjj'}qu_{ij'jwzt} \qquad \forall i \in N, \forall t \in T, \forall w \in W, \forall z \in Z, \forall j, j' \in J \tag{9.19}$$

$$sq_{ijwt} \leq XW_{ijw}\beta_{iw} \qquad \forall i \in N, \forall t \in T, \forall w \in W, \forall j \in J \tag{9.20}$$

$$pq_{ijzt} \leq XP_{ijz}\sigma_{iz} \qquad \forall i \in N, \forall t \in T, \forall z \in Z, \forall j \in J \tag{9.21}$$

$$tq_{ii'jkt} \leq XT_{ii'jk}\alpha_{ii'k} \qquad \forall i, i' \in N, \forall t \in T, \forall k \in K, \forall j \in J \tag{9.22}$$

The objective function (9.1) is the maximization of the total net income of the ISN, over the entire time horizon. It is defined as the difference between the value created by the ISN and the operational costs, which are the sum of transportation costs ct_{it}, stocking costs cs_{it}, and production cost for the treated materials ep_{it}, as defined in (9.2). The minimization of the operational costs reflect the complexity of the ISN design. For example, products can be transformed before or after the transports in order to reduce stocking and transportation costs. The operational costs sustained by each firms are identified in (9.12) for transports, in (9.13) inventories, and in (9.14) for production. Revenues are defined in equations (9.8), Equation (9.9) identify the total created value as available for sharing through positive contributions, and equation (9.10) ensures the equality of positive and negative contributions over the entire time horizon.

Equations (9.6) and (9.7) assure that all the stakeholders are equally engaged in the network by equalizing their PbP, which is defined in (9.5), through the parameter δ, i.e., the maximum allowed percentage of difference in PbP between two different stakeholders. The PbP for stakeholder i is defined as the total investment ti_i (equation (9.4)) over the average expected net cash flow cf_i, in Equations (9.3). Specifically, the net cash flow of firm i is defined as the time average of the incoming cash flow minus the outgoing cash flow while the total investment is the sum of all the fixed cost a firm has to enter the ISN.

Equations (9.11) model the cost savings brought by the belonging to the ISN. Constraints (9.15) ensures the flow balance between two time periods for each product where for each inventory w the initial inventory sq_{ijwt-1} is reduced by the quantity sold out of the ISN q_{ijwt} to satisfy the external demand (Equations (9.16)), the quantity used in production process z, i.e., $qu_{ij'jwzt}$ to produce other products (equations 9.19) and quantity $tq_{ii'jwkt}$ sold at other stakeholders of the network by using transport k (Equations (9.17)). The inventory w is increased by the produced quantity of j (Constraints 9.18) and purchased within the ISN.

Finally, constraints (9.20), (9.21) and (9.22) are used to limit the maximum inventory, the maximum production and the maximum transportation amount for each treated material, using each process, stocking technology or transportation mode, in each firm and in each period.

The proposed model combines in a joint network SCs and EIPs, where the targeted wastes are exploited through the introduction of new technologies to produce both new products for the external market and raw materials for the other stakeholders. It mainly aims to: (i) propose a fair allocation of the costs among the all the involved stakeholders; (ii) assess the economic viability; (iii) consider the whole system as an interaction of stakeholders. However, the equalization of PbP can be an extreme measure; in fact, if all the firms have the same short PbP, it means that a larger contribution is provided by the stakeholders well-performing to the others. Furthermore, no assumptions have been made about how the the most performing companies have to share among themselves the cost of providing contribution to the others.

9.2.2 Commitment Keeping Mechanism for the negotiation phase

Since all the ISNs are different one from the other due to the involved companies, their profitability, the sold final products, and the available infrastructures, also the redistribution of the benefits, within the ISN, can be performed in different manners. For this reason, the role of the company, which shares the same wastes and/or the same infrastructures for waste exploitation i.e., ceteris paribus, changes in accordance to the ISN where it is. Moreover, in presence of investments and redistribution of benefits as CKM, also the Return On Investment (ROI) of the companies is affected by the selection of the others stakeholders for the ISN. The mechanism of sharing benefits of the ISN has some positive effects, e.g., large firms benefit from the technological innovation brought by SMEs and an alliance with these latter can help them in overcoming the financial barriers to effective economic and environmental performances [54]. The use of the equalization of the PbP as a Commitment Keeping Mechanism (CKM) reduces the risk that companies neglect the ISN for the sake of their own businesses; however, the intertwining of the ROI of a company with the performances of the others can lead to opportunistic behaviors. To avoid these behaviors, it is necessary, during the initial negotiation phase, a mechanism that leads to the agreement of all the stakeholders to the set of the positive and negative contributions that modify the PbP of each one of them. Furthermore, through this mechanism each stakeholder would also have the opportunity to compare similar networks to exploit its waste by assessing the involved stakeholders and the economic performances that the company would achieve from its belonging to one of them.

This part of the thesis aims to investigate the implications of the used CKM (i.e., the rule to equalize PbP) for four possible archetypes of stakeholder. Since a clear characterization of tenant and anchor tenant is not provided in the literature, four archetypes have been hypothesized to represent the dynamics of the anchor tenant and the tenants on the basis of the state-of-the-art ([263]; [254]; [31]):

- Low initial investment I_i, high cash flow CF_i. She is the anchor tenant who proposes the partnerships to the others. The anchor tenant has a low initial investment but large profit from the sales to the market. The anchor tenant invites the other tenants to join in the ISN, e.g., to accomplish the launch of new green products. After the initial excitement, the anchor tenant could decide to reduce the involvement in the ISN, also due to the the low lock-in effect, by jeopardizing the ROI of the other stakeholders;

- Low initial investment I_i, low cash flow CF_i. Stakeholders with a low lock-in effect due to the lower technology investment. They can put low effort in ISN due to the limited revenues;
- High initial investment I_i, high cash flow CF_i. This stakeholder is subjected to a great lock-in effect but the large returns limit this effect over time;
- High initial investment I_i, low cash flow CF_i. This stakeholder is subjected to a large lock-in effect, and the low returns highlight a marginal centrality of its role. She may have tried to finance the adoption of new processes through several partnerships, and ISN could be one of them.

During the negotiation phase the quantities and the technologies involved are already been defined, thus they are considered given, also for the numerical example at the end of subsection 9.2.2. For each one of the N companies, which are involved in the ISN, a set of parameters is provided to describe the emergent costs and revenues referred to the belonging to the ISN itself. The first set of parameters represents the initial investment made by the stakeholder i: IS_i initial investment for stocking infrastructures, IT_i initial investment for transportation infrastructures (e.g., pipelines, new roads, or warehouse docks), and IP_i initial investment for productive capacity. The aggregated initial investment I_i required to every stakeholder i is defined in (9.23).

$$I_i = IS_i + IT_i + IP_i \tag{9.23}$$

The stakeholder i is subjected to operational costs during the operational phase of the network. For the negotiation phase only the operational costs linked to the activities of ISN are considered. The operational cost OC_i for company i depends on the foreseen transportation costs tc_i, production costs pc_i and stocking costs ic_i:

$$OC_i = tc_i + ic_i + pc_i \tag{9.24}$$

There are three main revenues brought by the belonging to the ISN: (i) the avoided costs ac_i, such as environmental taxes or raw materials purchased at a price inferior than market price; (ii) the revenues from the sales np_i internal at the ISN, i.e., the sales of by-products, waste, and products (only those sold at special prices for some selected companies within the ISN); (iii) the finished products sold into the market (the considered finished products are those for which the investments are being made in the ISN). The revenue P_i of company i is defined in (9.25):

$$P_i = ac_i + np_i + mp_i \tag{9.25}$$

The PbP is the number of periods required to company i to recover the investment I_i required by the ISN, given its expected cash flow. The expected cash flow CF_i is assumed to be the average cash flow during all the T periods following the investment. It is defined as follows:

$$CF_i = \frac{\sum_{t=1}^{T} P_{it} - OC_{it}}{T} \tag{9.26}$$

The CF_i of the company i is modified through the application of the CKM by the addition (subtraction) of a positive (negative) contribution to increase (reduce) it. Both the positive and negative contributions reduce the differences among the stakeholders' PbP through the reduction of the CF_i of those that are better performing for the benefit of the others with less performance due to different type of investment or less profitable role within the ISN. The contribution here is presented as an independent quantity; however, it can be provided, during the operational phase, in different ways, such as, through a reduction of sale prices for selected stakeholders, and/or a different allocation of operational costs.

The model to assess the impacts of different Payback Period

The introduced problem is represented through the solution of the following Mixed Integer Linear Programming (MILP) model. The goal of the optimization model is assessing the stakeholders' ROI and economic performance with different PbPs. The increasing of the PbP leads to a partial redistribution of the entire value created by the ISN, while the equalization of them leads to the complete redistribution of value created within the selected years. The sum of all the positive (negative) contributions pc_{ij} (nc_{ij}) received (paid) by company i from (to) company j cannot exceed the amount necessary to each stakeholder to recover her investment and it cannot compromise the net benefits of belonging to the network of each one of them. The optimization model does not find any feasible solution when the number of periods (fixed in the experiment) for the complete investment recovery is too short to be reached although the redistribution mechanism. The main stakeholder appointed for providing contributions to the others is the one with the highest ROI (the anchor tenant). However, when the other stakeholders exceed the main contributor's ROI, they will contribute in turn. Considering the ROI weighted by the invested amount I_i it is important to measure the profitability reachable by the stakeholders. Hence, in (9.27), y represents the maximum ROI. It is bounded from below by constraints (9.28), where the cash flow CF_i introduced in (9.26) is modified by the addition (subtraction) of all the positive (negative) contributions pc_{ij} (nc_{ij}) received (paid) by company i from (to) company j, and it is weighted by the investment made I_i. PbP of each stakeholder, which takes into consideration the positive pc_{ij} and negative nc_{ij} contributions, can be reduced to the target payback period only when constraints (9.29) holds. The average cash flow CF_i, multiplied by the given target PbP, $\widehat{T}$, minus the investment made I_i and the ISN contributions, has to be greater than 0 (it is equal to 0 if the $\widehat{T}$ is exactly the PbP of the investment). Constraints (9.30) and (9.31) ensure that to every positive contribution pc_{ij} provided to i by j corresponds a negative contribution nc_{ij} paid by j for i. When a stakeholder i receives positive contributions the boolean variable $x_{0,i}$ is equal to 1 thanks to the big M constraint (9.32), while $x_{1,i}$ is equal 1 when stakeholder i provides negative contribution towards other stakeholders (constraints (9.33)). Constraints (9.34) forbids stakeholder i to provide and receive contributions within the same time horizon ($\widehat{T}$). Positive pc_{ij} and negative nc_{ij} contributions are continuous variables greater than or equal to 0 (constraints (9.35)).

$$\min y \tag{9.27}$$

$$y \geq \frac{CF_i * \widehat{T}}{I_i} + \frac{\sum_{j\in N} pc_{ij}}{I_i} - \frac{\sum_{j\in N} nc_{ij}}{I_i} - 1 \qquad \forall i \in N \tag{9.28}$$

$$CF_i * \widehat{T} - I_i + \sum_{j\in N} pc_{ij} - \sum_{j\in N} nc_{ij} \geq 0 \qquad \forall i \in N \tag{9.29}$$

$$nc_{ij} \geq pc_{ji} \qquad \forall i,j \in N \tag{9.30}$$

$$nc_{ij} \leq pc_{ji} \qquad \forall i,j \in N \tag{9.31}$$

$$\sum_{j\in N} pc_{ij} \leq Mx_{0,i} \qquad \forall i \in N \tag{9.32}$$

$$\sum_{j\in N} nc_{ij} \leq Mx_{1,i} \qquad \forall i \in N \tag{9.33}$$

$$x_{0,i} + x_{1,i} \leq 1 \qquad \forall i \in N \tag{9.34}$$

$$nc_{ij}, pc_{ij} \in \Re^+ \qquad \forall i,j \in N \tag{9.35}$$

$$x_{0,i}, x_{1,i} \in K = \{0,1\} \qquad \forall i \in N \tag{9.36}$$

The numerical experiment

A numeric experiment has been proposed to investigate the effect of the CKM rule that modifies the stakeholders' PbPs. The initial investment is assigned in a random manner with the assumption that the "low initial investment" varies from three to ten time less than the "high initial investment". Companies from different industrial fields may have different ROI and PbP according to the nature of the business. Therefore, four scenarios are proposed to represent different requirements of PbP of the four archetypes of the stakeholders. The cash flow CF_i of each stakeholder i varies in order to obtain 4 different scenarios of initial PbP:

1. each stakeholder has a short payback period (from 3 to 7 years);
2. each stakeholder has a long payback period (from 12 to 16 years);
3. three stakeholders out of four have a short payback period (from 3 to 7 years) while one has a longer one (from 12 to 16 years);
4. three stakeholders out of four have a long payback period (from 12 to 16 years) while one has a shorter one (from 3 to 7 years).

Every scenario is evaluated several times, each time increasing the time period $\widehat{T}$, from the lowest one (i.e., the aggregated minimum payback period $\widehat{T}^*$ obtained dividing the total initial investment by the sum of all the stakeholders' cash flows) to the longest PbP of the stakeholders. In each evaluation, the positive and negative contributions of all the stakeholders and how their Return On Investment (ROI) changes are observed and compared to the ROI they would get if the commitment keeping mechanism were not applied. Table 9.3 shows the complete set of analyzed scenarios.

Stakeholder type	I_i (M€)	Scenarios (4 different scenarios)		
		1. All short PbP		
		Single PbP	CF_i	T_{min}-T_{max} ($\widehat{T}^*$)
I.low-CF.high	30	3.00	10.00	6-7 (5.6334*)
I.low-CF.low	10	5.00	2.00	
I.high-CF.low	110	7.00	15.71	
I.high-CF.high	100	6.00	16.67	
		2. All high PbP		
I.low-CF.high	30	12.00	2.50	15-16 (14.963*)
I.low-CF.low	10	15.00	0.67	
I.high-CF.low	110	16.00	6.87	
I.high-CF.high	100	15.00	6.67	
		3. 3 out of 4 short PbP		
I.low-CF.high	30	3.00	10.00	6-15 (5.8078*)
I.low-CF.low	10	15.00	0.67	
I.high-CF.low	110	7.00	15.71	
I.high-CF.high	100	6.00	16.67	
		4. 3 out of 4 long PbP		
I.low-CF.high	30	4.00	7.50	12-16 (11.526*)
I.low-CF.low	10	15.00	0.67	
I.high-CF.low	110	16.00	6.87	
I.high-CF.high	100	15.00	6.67	

Table 9.3: Experimental plan for 4 stakeholders, four different scenarios, each one repeated for every T between T_{min} and T_{max} plus the aggregated minimum PbP $\widehat{T}^*$.

9.2.3 Results and implication

The model, which is solved using the commercial optimization software ILOG CPLEX version 12.9.0 implemented in a Java applet, gives back the flows of positive and negative contributions among the stakeholders. The proposed CKM minimizes the maximum cashflow to redistribute the contribution, and this has a positive effect when all the stakeholders have short PbP. In fact, Figure 9.1 shows that their contribution to support the one with the longest PbP are proportional to their profit (which are similar, differently from all the other cases). When the firms negotiate to equalize the PbPs to the shortest one, also the second stakeholder (orange) contributes. Conversely, when the negotiated PbP increases, the amount of required contribution to support the others decreases. The orange stakeholder receives flatter cashflow than the anchor tenant; hence, the anchor tenant is the only one who provides the little contribution.

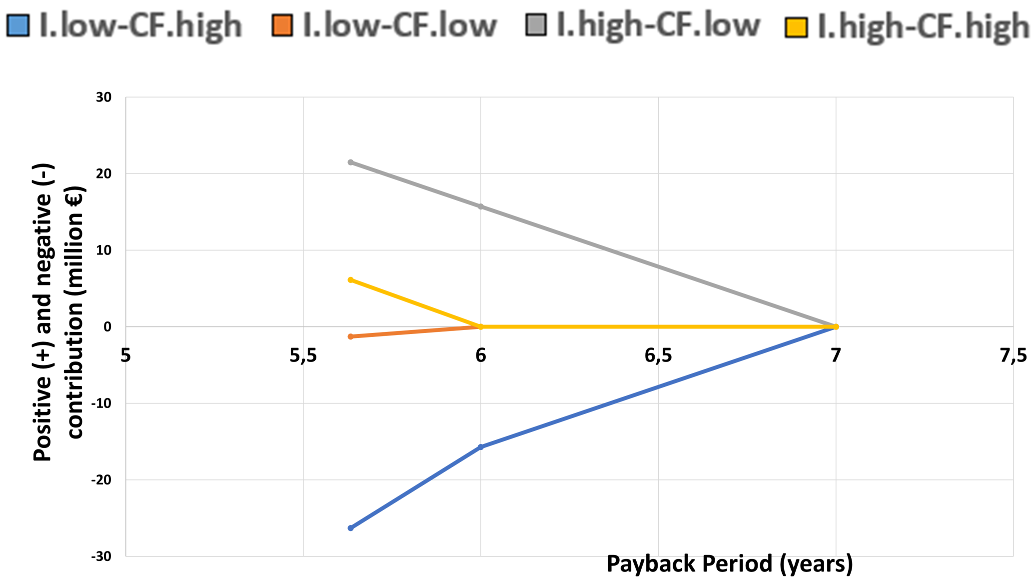


Figure 9.1: Scenario "All short PbP". The contributions provided or received per each stakeholder in each one of the different PbPs from the shortest ($\widehat{T}^{*}$=5.6334) to the longest (7 years).

In the scenario "3 out of 4 long PbP" (in Figure 9.2), all the stakeholders need the anchor tenant's support to reduce the PbP, and increase the willingness in investing into the ISN, because of their limited cashflow. However, also in the case where there is only one stakeholder (in Figure 9.3 the "3 out of 4 short PbP") from a field at lower PbP, if the others do not have a ROI similar to the anchor tenant's one, the costs are almost entirely supported by the anchor tenant.

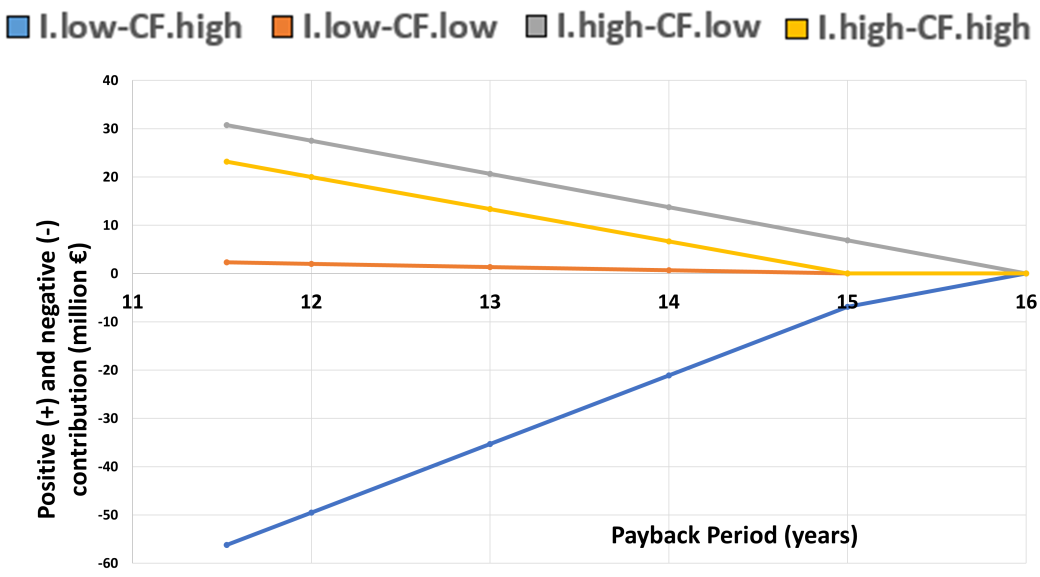


Figure 9.2: Scenario "3 out of 4 long PbP". The contributions provided or received per each stakeholder in each one of the different PbPs from the shortest ($\widehat{T}^{*}$=11.526) to the longest (16 years).

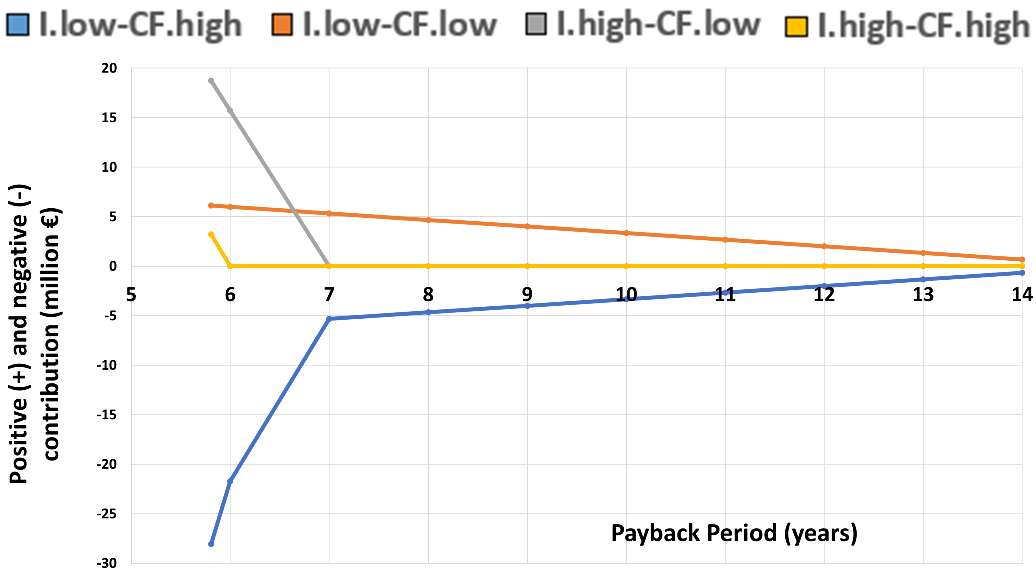


Figure 9.3: Scenario "3 out of 4 short PbP". The contributions provided or received per each stakeholder in each one of the different PbPs from the shortest ($\widehat{T}^{*}$=5.8078) to the longest (15 years).

The scenarios where all the stakeholders have similarly short or long payback periods, i.e., "All short PbP" and "All high PbP", represent the cases where all the companies come from industrial field with similar ROI and cashflows from the ISN. In the first case, i.e., "All short PbP", everyone agrees that joining ISN is profitable, thus the redistribution of benefits exchanged is not so relevant because the profit is fairly distributed. In fact, Figure 9.4 shows the limited difference between the minimum time horizon ($\widehat{T}^*$=5.6334 years) asked to all the stakeholders to recover, in an aggregate manner, the overall investments, and the years required to recover the overall investments in an individual manner (7 years), i.e., without redistribution. In the case the stakeholders negotiate to equalize the PbP of all at $\widehat{T}^*$, the anchor tenant (blue one) that would have achieved a ROI=187,73%, during the first $\widehat{T}^*$ years contributes with part of its benefits (87,73%), together with stakeholder 2 (orange one) for (12.66%), to support stakeholders 3 (gray) and 4 (yellow) to achieve the PbP. If the negotiated PbP is 6 years, only the anchor tenant contributes to support stakeholders 3 (gray), which is the only one requiring a support due to the fact that stakeholder 4 (yellow) can achieve it by herself.

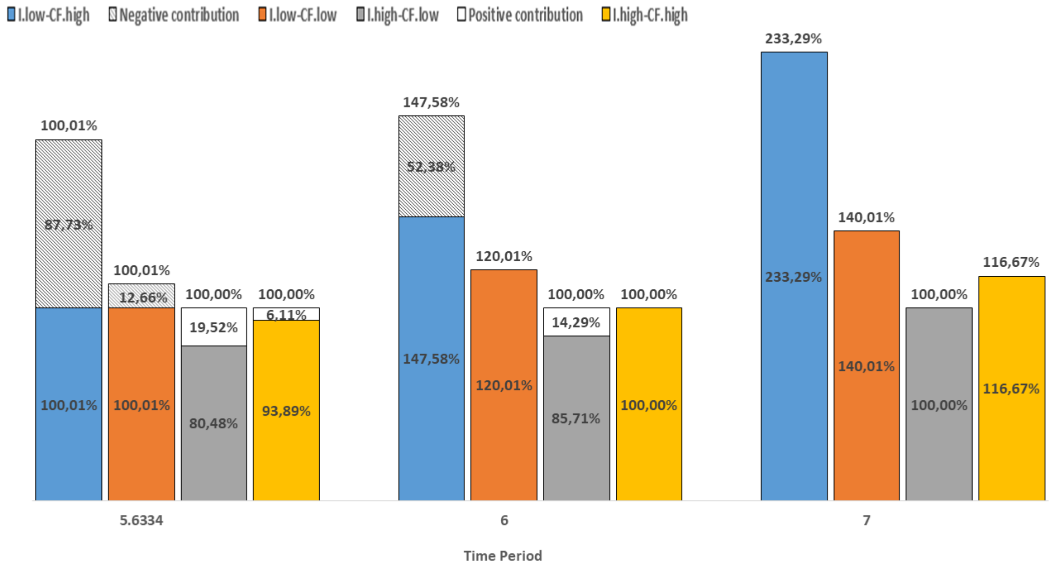


Figure 9.4: Scenario "All short PbP". ROI of the anchor tenant (in blue) and the other stakeholders, for different Payback periods, from the lowest ($\widehat{T}^*$=5.6443) to the largest (T_{max}=7).

In the other case, i.e., "All long PbP", joining the ISN is convenient only if the long PbP is suitable for the industrial field of all the stakeholders; Figure 9.5 shows flatter profit than the previous case (time period is more than twice than Figure 9.4).

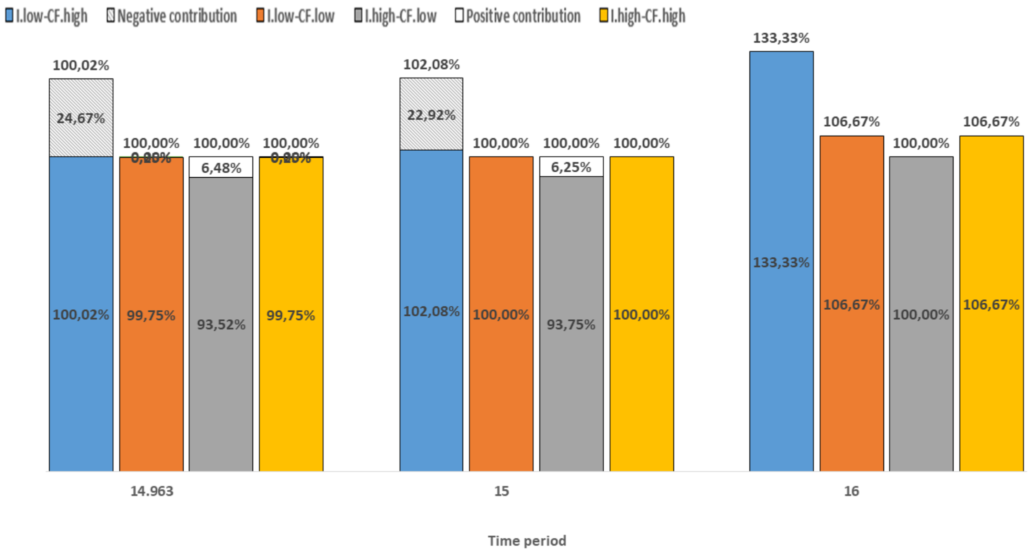


Figure 9.5: Scenario "All long PbP". ROI of the anchor tenant (in blue) and the other three stakeholders, for different Payback periods, from the lowest ($\widehat{T}^{*}$=14.963) to the largest (T_{max}=16).

The cases where there are simultaneously involved both well performing and low performing stakeholders emphasize the role of the redistribution. In the scenario "3 out of 4 long PbP", showed in Figure 9.6, the anchor tenant is a firm from an industrial field with usually short PbP, conversely the others have long PbP. This is the case where the effort of the anchor tenant has a large positive effect on the other stakeholders, effectively supporting them in their Eco-innovation process. The other stakeholders are supported in the adoption of new technologies to create value through the conversion of their waste in new products, thus fostering the development of new markets. Therefore, in this scenario, the stakeholders are subjected to a lock-in effect from the initial investments and they are interested to keep high their commitment towards the ISN and the anchor tenant. On the other hand, the anchor tenant aims to the profitability achieved through the ISN; hence, no one of them is stimulated to reduce the commitment in this scenario.

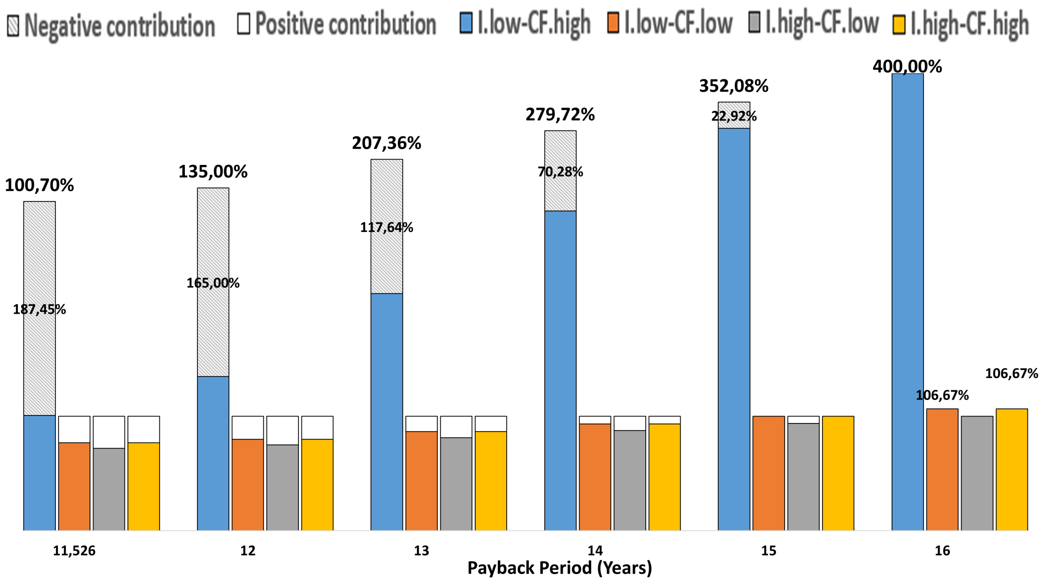


Figure 9.6: Scenario "3 out of 4 long PbP". ROI of the anchor tenant (in blue) and the other three stakeholders, for different Payback periods, from the lowest ($\widehat{T}^*$=11.526) to the largest (T_{max}=16).

In the last scenario, i.e., "3 out of 4 short PbP", both the anchor tenant and other two stakeholders come from an industrial field with short PbPs, whilst the last one comes from a field with long PbP. Figure 9.7 shows the three companies achieving, in a limited number of years, the PbP, while the last one could require up to the double of time, when no contributions are provided. However, the used CKM, i.e., the mechanism of redistribution, is supported only by the anchor tenant. The other two stakeholders can reduce their effort along the years, especially if they found other opportunities to exploit the new technologies. Hence, the lock-in effect of the initial investments for adopting new technologies affect mainly the anchor tenant. In fact, she could depend from the prices that the other two stakeholders will set, and furthermore she has also to support the remaining company (orange one in the figure), through the contributions. In this scenario, shorter PbP, where all the stakeholders have interest in keeping the commitment, is suitable, but more expensive for the anchor tenant.

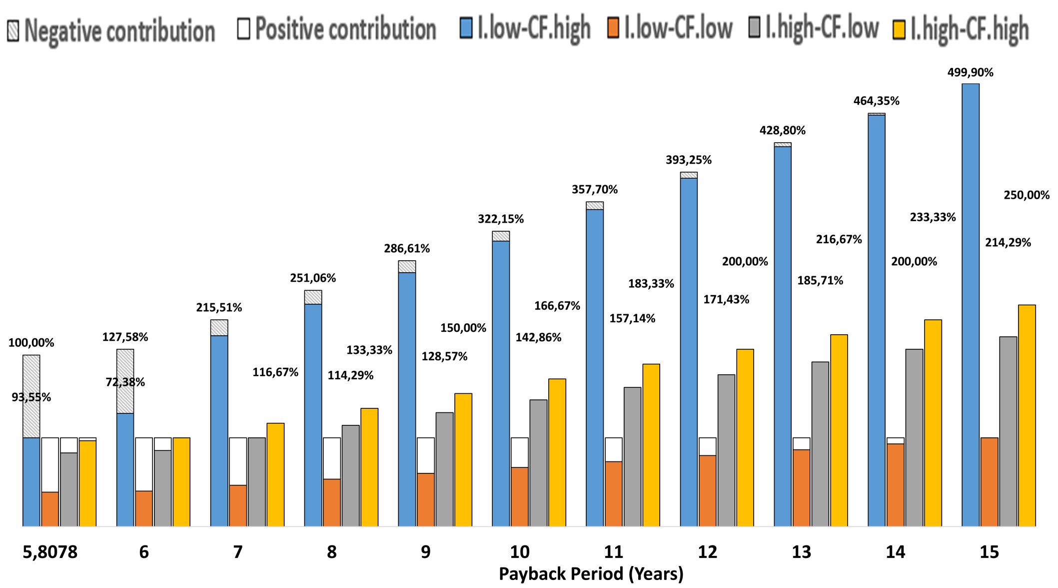


Figure 9.7: Scenario "3 out of 4 short PbP". ROI of the anchor tenant (in blue) and the other three stakeholders, for different Payback periods, from the lowest ($\widehat{T}^{*}$=5.8078) to the largest (T_{max}=15).

Limitations

This part of the thesis aims to investigate a scarcely explored field of ISN in presence of large investments with the risk of lock-in effect. The proposed analysis sheds a light on the effects of the application of Commitment Keeping Mechanism (CKM) based on the negotiation of a common PbP to identify the amount of contribution that should be provided during this initial period. The proposed CKM can be used for the twofold reason of: (i) design the network by allocating the investment and the successive benefits redistribution to ensure robustness to the ISN; (ii) assessing the potential ROI of the ISNs to allow a company to compare different ISNs where it is supposed to play a similar role.

The proposed CKM paves the way to other tools based on it, by investigating further policy of application. In this research, the maximum weighted cashflow of i is minimized. However, in different ISNs where stakeholders have other characteristics, other rules can be applied. Moreover, the analyses could be deepened by considering not only the negotiated PbP, but a fixed horizon of years where shortening the PbP, the others years are still kept in consideration.

An extensive research on the archetypes of the stakeholders is necessary, by considering both financial, productive, and economic factors. Furthermore, a comprehensive investigation on the most frequent scenarios must be followed to contribute to the literature of IS emergence in presence of investments.

Implication for the link network-operational level

This CKM is compatible with the framework described in the first chapter of this thesis, i.e., the necessity of improving Supply Chains to provide them with the tools to make them easily reconfigurable. The CKM, in fact, only involves the economic aspects (revenues, operating costs and capital expenditure) referring to the current ISN being designed, without involving the current production activities and any additional ISNs to which the company already belongs. Furthermore, this approach defines, at least until the recovery of the investments but hopefully even later, the amount of quantities of waste, by-products and finished products (for both ISN and the market) should be produced to achieve the economic performance agreed in the negotiation phase. Differently from the cases where no or limited investments are made, the whole value network is set to achieve these goals, e.g., by improving inventory capacity for "wastes", which are now products for others, to partially decouple their production from that one of finished products for the current business. In fact, each company can be involved in different ISNs to exploit its wastes, and this approach allows to manage them independently one from the others and from the production system of the current business. Fixing a priori the periodical positive (negative) contributions that a firm has to provide to (receive from) another in the various terms, e.g., discounted prices for waste used as raw materials, it is possible mitigate the propagation over the network of production uncertainty by compensating it with an equivalent economic contribution. This is the link that connects the network level with the operational level through the identification of a clear demand for the "waste" of the individual company, and clear operational costs incurred when it does not respect it, in order to properly plan its production.

The relationship between the network level and the operational level is crucial for the improvement of economic and environmental sustainability of the Factories of the Future [50]. This link paves the way to new approaches to fill the gap in literature of indicators and methods to measure, evaluate, monitor and control IS at company level [94]. Companies struggle to assess the economic viability of IS over time [219] and the monitoring results easier through the definition, during negotiation phase, of the contributes of each stakeholder.

IS is particularly encouraged when variable production costs after implementation are low [296]; in fact, changes in operational costs such as in the disposal of waste and the purchasing price of raw materials, largely affect the economic benefit and, consequently, the willingness to cooperate in IS [92]. However, in accordance with the studies based on the Agent-based approaches introduced in the beginning of this chapter, ISNs are also subjected to disruptive events such as the removal of an edge or a node ([62]; [169]). The impacts of these events, in the Supply Chain Management field, have worse effects when large initial investments are considered. Also the ISNs are subjected to the fluctuations of operational level such as those investigated in [97] such as, the fluctuations in the production levels of main products; the adoptions of new production technologies; a different waste quality; reductions in both waste disposal and input purchase costs; increases in the operational costs of IS; changes in benefit-sharing policy negotiated by the company. However, this chapter suggests that when the ISNs require relevant initial investment and the use of CKM to manage both the lock-in effects and to ensure the stakeholders' commitment, some benefits may be observed in their resilience to the operational uncertainty, by paving the way to further researches. Moreover, from the point of view of the individual companies, the mitigation of the propagation of the operational uncertainty over the entire network, by fixing the periodical contributions from/to the several ISNs, allows to treat each of them as a black box. In this way, the sharing of sensible information at operational level among companies is limited although each company is able to monitor technical, economic, and environmental performance of its entire production system, included the several ISNs where it is involved. In this context, the Industry 4.0 framework and the digitization play a crucial role to improve the monitoring capabilities and manage the increasing complexity of the Cyber-Physical Production System.

Chapter 10

Summary

10.1 The single firm and the ISN

This third part of the thesis addresses the perspective of the firms on the entire previous work. From a systemic point of view, the integration of Supply Chain (SC) and Eco-Industrial Park (EIP) allows to overcome the barrier of investments limited to the compensation of environmental costs and taxes, by aiming for the creation of value from each produced waste. However, such a complex system poses several issues from the design and managerial point of view beyond the cultural one. Part II presented a methodology to approach the Eco-innovation as a process of continuous improvement, by identifying sources of waste and potential use after having fixed the controllable and uncontrollable factors. Industrial Symbiosis (IS) has been introduced as a way to include in the analysis also processes and technologies out of the current business, to understand whether a waste can have a value for some others or if the best approach is avoiding it. Apparently, the introduction of IS can seem out of place; however, in accordance with the state-of-the-art, IS is a process that, in some situations, originates within the individual firms, and the first approach of the firms is the evaluation of performances. The proposed methodology (see chapter 6) first defines a process of data collection and factors analysis, then together with the new technologies, processes and operational changes, introduces also the alternative of IS into the set of the alternatives. Finally, it suggests several criteria to understand which technology is suitable for the waste reduction and those suitable for the establishment of IS with other stakeholders.

The proposed approach paves the way to new questions and further difficulties for the firms, especially the SMEs, with limited availability of economic resources and technical knowledge. Thus, Part III addressed two further issues: the development of a Decision Support System (DSS) to support the spreading of the Eco-innovation methodology, and the investigation of the concepts of resilience and robustness in the Industrial Symbiotic Networks (ISNs) in presence of relevant initial investments.

10.1.1 Resource efficiency supported by DSS

The development of the DSS followed two principles: (i) being as flexible and adaptable as possible, (ii) supporting and facilitating the application of the Eco-innovation methodology.

DSS flexibility

The DSS flexibility makes it usable from both the companies with a low and high digitization level, independently from the complexity of the production system. The DSS can exploit the data provided from the IT systems of the companies, and it does not have limits about quantity and frequency of sampling. In this way, it is possible the update of the physical processes modeled in the DSS by exploiting the current performance of the system. Furthermore, it is possible the evaluation of technologies, processes and operational changes whose effects must be investigated in different time horizons.

The developed preliminary version of the DSS, which has been applied to the Acea Pinerolese case, is fed partially with data coming from the SCADA system of the company and partially with data manually collected. SCADA system produces .csv reports that are imported together with the data manually collected within the DSS. The DSS results scalable, because the more detailed the data are, the more accurate the analyses can be. Hence, it is suitable for the use by companies with any level of digitization. Furthermore, a higher level of digitization may increase the features of the DSS itself due to the increased availability of data that allows to perform more analyses.

The use of the DSS is oriented to the evaluation of new technologies, processes and methods, when introduced in the current production system, by assessing both economic and environmental performance. However, it can be applied in a wide range of occasions not only for the adoption of new technologies, but also to perform "what-if" analysis, scenario analysis, testing the performance of the current system under different external factors (such as prices, costs, incentives).

DSS functions and modules

The DSS performs four functions through the use of four intertwined modules, which are: (i) data exploitation and formalization process; (ii) scope and initial state definition; (iii) policy and technology assessment; (iv) model instantiation and optimization.

Data exploitation and formalization process. This module is the interface between the DSS, the users, and the digital interface collecting data from the physical system, when it is integrated within a Cyber-Physical Production System. This module performs the function of **data acquisition** and **formalization**. In fact, it first collects and saves all the data, when they do not need to be updated; then, it exploits the MEIO formalization tool to formalize all the introduced activities both value and non-value added ones. After the optimization, this module produces and provides the final reports to the user. Three kinds of report are produced: (i) a summary report, (ii) a report for each instance to investigate the details of the production planning; (iii) the overall report, where all the instances are taken into consideration to provide average information more robust to uncertainty.

Definition of scope and initial state. This module performs the function **Scope definition**, by putting together the data provided with those coming from IT systems and/or stored within the Data acquisition module. Then, it creates the various scenarios for the analysis, according to the goals of the user: (i) assessment of the economic and environmental performance of the system; (ii) assessment of the introduction of new technologies by concurrently considering IS opportunities and system improvement; (iii) evaluating current or possible production system under different energy and environmental policies.

Policy and technology assessment. This module contributes to the function **Data Acquisition** by collecting all the parameters, which are provided by the user, about future policies and new technologies to provide them to the Data exploitation and formalization process module.

Assessment of economic and environmental performances. This module performs the last function, i.e., **Assessment of economic and environmental performances** by instantiating the model through the exploitation of MEIO tables and scenario parameters, and then by recalling the ILOG CPLEX libraries to provide the optimal solutions. Customized approaches to optimization solution can be implemented to substitute the libraries of the commercial software CPLEX.

10.1.2 From the network to the operational level

The robustness and the resilience of the networks are a crucial topics for the ISNs. Part III introduced the state-of-the-art, which deals with two issues: the capabilities of the network of performing the same function, and keeping the same structure after a disruptive event. The network analysis approach focuses on two kinds of disruptive events: removal of an edge (i.e., the exchange of a waste among two companies) and of a node (i.e., the removal of a company). The role of redundancy and the necessity of highly connected networks emerge as a necessity to improve the resilience. On the other side Food Web Analysis methods observe the capability of a ISN of internally exploiting the own waste, also when a company leaves the network or a mismatch between waste production and consumption happens. Also in this case, the presence of more companies producing and absorbing a specific waste (redundancy) improves the resilience of the network, together with connectance and diversity, i.e., companies that exchange and absorb more than a waste, which allows a larger number of connections among themselves. However, these approaches do not consider the lock-in effects and the recovery of large initial investments.

The individual companies who pursue the Eco-innovation process, at the end of the preliminary phase of evaluation of establishing future IS, wonder how to allocate the larger initial investment, and if they will be subjected to lock-in effects further exploited by the other stakeholder in opportunistic manner. This thesis do not provide an exhaustive answer to these complex questions, but tries to shed a light on the role of mechanisms to fairly allocate investments and how it can prevent also the potential opportunistic behaviors.

First, it has been proposed an optimization model to concurrently design the joint network of SC and EIP by using the equalization of the Payback Period as Commitment Keeping Mechanism. Then, the use of the Payback Period as CKM has been explored to observe whether it could affect the potential opportunistic behavior of companies together with the eventual lock-in effect. Four archetypes of stakeholders have been identified to be used in the scenario analysis. Four different scenarios have been considered by assigning to the four archetypes different Payback Periods to represent companies from different business sectors. The CKM has been modeled through the minimization of the largest cashflow weighted for the initial investments. The analyses have been performed for the whole time horizon, which ranges from the minimum number of years (where all the companies reach the Payback Period) to the maximum number of years (where there is no redistribution and all the stakeholders reach the Payback Period independently from the others).

The proposed rule for the use of Payback Period as CKM shows its effectiveness in the case of stakeholders with similar weighted cashflows, while on the other side, when they have different weighted cashflow and one performs better than the others, she also supports the costs of providing contributions to them. In the case of three companies with a low cash flow and one company (the anchor tenant) with larger cash flow, the rule seems appropriate to stimulate the innovation process of the SMEs avoiding lock-in effects and opportunistic behaviors. On the contrary, when only one company has little cash flows, the rule should be properly modified to support the anchor tenant in providing positive contributions to the less performant company. In fact, with the current rule, the other two well performing companies are free to increase prices for the anchor tenant, which is dependent by them.

Part III paves the way to further research on the effects of investment and the lock-in effect on resilience and robustness of the ISNs. Moreover, the proposed approach clearly divides the network level from the operational level, by introducing the interface of quantities of waste that must be provided and the potential fees when the mismatches happen. However, differently from the case where no investments are considered, here the companies can properly design the aggregated production network to decouple as well as possible their core production from the production of waste for ISNs. In fact, the investments are dedicated to the introduction of processes to prepare the wastes for storage and transport to reduce the fluctuations caused by the core production. This approach leads to relevant benefits because an individual company can belong to several ISNs to exploit different wastes in each of them and manage them in a separate way. Furthermore, the management of each ISN separately from the others, and from the core business, allows a better monitoring, and a better management of the operational level. Further studies are required to investigate new KPIs and methods to monitor ISNs under this perspective as well as the effect on the operations management.

Part IV

Implications, limitations, and future research

Chapter 11

The contribution to the sustainable production

This thesis focuses on the resource efficiency by concurrently considering it under three different sides: the technological aspect, the analysis of the performances, and the paradigm of continuous improvement. The real paradigm shift will happen when the sustainable production will be part of the culture of all the companies. The transition towards the sustainable development should be led, within any company, from the awareness that their waste can be a resource for themselves or for some other stakeholder of the community. Supply Chains are organizations of companies optimized to convey the created value from the producers to the final customers, while Eco-Industrial Parks are usually considered as networks of Industrial Symbioses, i.e., exchanges of waste between companies or processes to use them as raw materials. The integration of Supply Chains with the Eco-Industrial Parks where the companies are involved may improve the overall resource efficiency by reducing the use of virgin resources, reduce the waste production, and reuse of waste to create value.

Companies are struggling to make this step because of the managerial difficulties and the lack of tools and methodologies, which increases the amount of resources required for the initial investment and the knowledge. Furthermore, the pursuit of sustainable development in such a deep way requires accurate analysis to ensure also the economic sustainability and avoid operational issues in the future. In fact, operational issues such as poor production planning, abundance of non-value added activities, mismatch between produced waste and their demand, can increase the operational costs but also can be source of new waste and scarce efficiency in the use of the resources.

The Eco-innovation is considered the practical way that leads the companies in their path towards the Sustainable Development. The state-of-the-art identifies four kinds of Eco-innovation: process Eco-Innovation; product Eco-Innovation; organizational Eco-Innovation; marketing and packaging Eco-Innovation [126]. However, the companies achieve the better results when they adopt an holistic approach to Eco-innovation [55], but the scarcity of practical and quantitative methodologies hinders its pursuit, especially by SMEs due to their limited resources and knowledge.

The Industrial Symbiosis has a key role in the holistic approaches to the Eco-innovation because, especially in presence of investments that radically improve the current production system, it leads the companies to improve their organizational level to cooperate for the development of new products by exploiting the current waste as raw materials through the adoption of new processes. The literature about Industrial Symbiosis is focused on the overcoming of the identified barriers, improving the network design and understanding the dynamics followed by the stakeholders when they join or abandon an ISN. However, every IS emerges from the first of the six phases of IS implementation identified in [293]: the preliminary assessment. The preliminary assessment phase addressed by the companies is a well-rounded process where every potential alternatives to improve the current performances is evaluated, thus it cannot focus from the beginning only on IS. A framework to put together IS and all the other opportunities had to be introduced to support the preliminary assessment phase; it seems poorly involving IS, but the definition of a framework for the preliminary assessment must consider all the aspects of IS, by finding a way to support a company in addressing them. In this thesis, IS is considered as a part of a strategy rather than a stand-alone action.

Any developed methodology and tool must consider several aspects led by these changing times that companies are dealing with. In fact, market rapidly changes and a new industrial revolution, Industry 4.0, together with the massive digitization required to the companies, are continuously pushing companies towards new investment decisions and the adoption of new technologies, manufacturing paradigms and business models. A new methodology for resource efficiency and Eco-innovation as well as new tools for the analysis of the performances of the activities, risk being obsolete even before they are applied. Hence, all of the methodologies, tools and analysis that are addressed in this thesis try to always look at the emerging paradigms to observe if they are fostered or hindered by them. The Eco-innovation methodology required the development of a Decision Support System to be effectively exploitable from both large companies with a larger availability of knowledge and from SMEs. The DSS follows the ratio of a tool adaptable to companies with different level of digitization.

Finally, the competition is moving from the company level towards the network level [68], the Supply Chains are simultaneously becoming more intertwined and more reconfigurable [80] to achieve resilience and robustness. In this context, this thesis tried to address these two latter concepts, i.e., resilience and robustness, for the kind of introduced networks that is the interconnection of SC and EIP. Resilience and robustness in ISN (i.e., network of Industrial Symbioses) are already benefiting from a good interest among scholars due to the importance they have for the firms approaching to the IS. The state-of-the-art is focused on both the analysis of the performance of the overall network and the cases where companies join and leave without affording large investments with lock-in effects. This thesis does not go deep this aspect, while it focus on a scarcely explored field, i.e., the internal point of view of the individual companies towards network designed ad hoc to exploit waste to produce new products, trying to remain each one of them in their own business field. This aspect has been addressed to offer a well-rounded approach to the issues of the pursuit of sustainable production from the perspective of the individual firm.

These explanations were necessary to frame the managerial insights and the scientific contributions of each of the three parts of this thesis in accordance with "*le fil rouge*" that has led the whole research: the resource efficiency in the sustainable production systems. The next three sections provide further insights for each one of the three parts.

11.1 MEIO: the formalization method

The MEIO method proposed is a flexible tool for a wide range of situations. It improves the weaknesses of several tools present in the literature by combining them together to develop a new method. In fact, the combined use of these tools, i.e., Material Flow analysis combined with Enterprise Input-Output and the Multi-Layer Stream Mapping, would result in a longer work with some redundancy, some gaps, scarcely integrated with complex systems characterized by a high level of digitization. Conversely, the MEIO method here proposed exploits the principles of MFA to identify the unit of analysis and all the resources and substances present in a system combined with the Enterprise Input-Output approach that represent the processes connecting them virtually via their input and output. Processes are enriched by the addition of all the "layers" considered in the Multi-layer Stream Mapping, to add the connotation of added or non-added value, required time, and process efficiency, not only in terms of resources but also in terms of time. The result is a tool based on the elaboration of three tables able to formalize production processes, inventory and transport activities.

The scientific contribution to the production research ranges from the definition of a formalization method able to represent many characteristics of the activities in the production chains, to the capacity of this method to be used in combination with a wide range of other tools and approaches. The MEIO tables can model in the same format of the production activities also the inventory and transport ones, even providing for them the opportunities of modeling many of their typical issues. In fact, MEIO tables can represent the perishability of products during transport and storage; the consumption of materials and energy and the production of pollutant (which are waste that can be avoided or exploited) during these activities specified by considering the used resources and the involved materials; the loss of products and materials during inventory and transport activities.

The MEIO formalization method is a tool able to formalize many data received by the IT systems of the company, from both stochastic and deterministic activities. These data can be updated according to the different granularity required by the situations. These characteristics made it a valuable tool to be used in combination with automatic approaches as simulation and optimization models. In fact, the MEIO formalization tool does not provide by default an a priori connection among processes, by leaving the production resources free to organize by themselves to maximize/minimize an objective function. Hence, external factors would drive the interconnections of activities, such as the final products demand or an event list, and in backward manner they connect all the required processes until the supply of raw materials. The case study of Acea Pinerolese shows the data import through reports of the SCADA system and data provided manually, thus the activities formalized via MEIO method reflect the current system performance; however, no a priori production routes have been provided to the optimization model used for the Eco-innovation methodology. The introduction of a priori knowledge into the system can be implemented, as it happens in the first case study proposed (i.e., InnovaEcoFood) to allow the further application of less complex but more specific tools such as Material Flow Cost Accounting.

The industrial contribution of the MEIO formalization tool is mainly due to its wide range of applications. It can be used in simpler contexts, where pen and paper approaches are more suitable, e.g., as an improved version of the Value Stream Mapping, i.e., the MEIO Stream Mapping. Nonetheless, the MEIO method overcomes the major barriers, addressed in section 1.3, that limit the adoption of methods based on Lean principles in the contexts of the new manufacturing paradigm and those of complex production systems.

Finally, the ease of use of the MEIO method makes it suitable also for companies with limited resources and poor access to knowledge, without distinctions of business sectors, from product to process industry, by allowing to further customization of the method.

11.2 The Eco-innovation methodology

The methodology contributes to the literature by positioning itself as a quantitative approach to support and lead, within the companies, the Eco-innovation process based on IS implementation and system innovation. It is the first methodology that evaluates IS opportunities mainly from the perspective of the individual company to outline the initial requirements and identify potential partners' characteristics. Furthermore, the novel MILP optimization model concurrently considers IS opportunities together with system improvements to construct a holistic scenario set-up for the value creation from waste, where IS is considered as a part of the comprehensive strategy to improve resource efficiency.

The methodology underlines the role of each technology into the holistic scenario set-up, by identifying the system rules driving its waste exploitation. It sheds a light on the importance of tackling resource efficiency both by system innovation and IS partnerships. The case study shows that BMP adoption is the best example of system improvement as it solves the two main causes of biogas incomplete exploitation. In fact, the previous Italian Environmental and Energy law (revised in 2018) set the maximum amount of power production capacity at 1 MW to qualify for the incentives. This was the cause of the under sizing of the system leading, together with the low methane content of some flows, to the biogas waste. The application of BMP to purify biogas avoids the direct use of biogas by using bio-methane, which can be used both in boilers and CHP, thus decoupling the production of power and heat. BMP adoption and the increase of biogas and biomethane storage reach a twofold goal: (i) to avoid climate altering emissions of biogas and (ii) to substitute fossil methane purchases in the case of peaks of heat demand.

Unlike in the case of BMP, figuring out whether other technologies are better suited to system improvement or IS relationships is more difficult. Therefore, it is necessary to resort to the rules of the system, which drive waste exploitation identified by the methodology. In particular, four factors emerge, for steering waste exploitation: (a) initial investment, (b) final amount of chemical products and related revenues, (c) economic convenience of using hydrogen and oxygen to absorb CO_2 instead of selling them, and (d) amount of power and methane requested to produce oxygen and hydrogen to feed microbial factories.

MF1 and MF2 present difficulties in process synchronization that lead to high investments (factor (a)) in production and inventory infrastructures to be overcome (Figure 6.4 and tables 6.3 and 6.2). However, lactic acid and PHB sales, out of the Acea Pinerolese system, are very profitable (factor (b)) for a chemical producer due to the relevant amount produced thanks to the available CO_2 (Figure 6.5a). Factors (c) and (d) lead to a decrease in profit due to the purchase and consumption of resources necessary for the absorption of CO_2 to produce chemicals. In fact, MF1 and MF2 use larger quantity of hydrogen and oxygen to produce lactic acid and PHB (Figure 6.5b), which are promising for high revenues considering the avoided environmental taxes stemming from CO_2 emissions. Hence, MF1 and MF2 are definitively more suitable to establish IS with other companies since the generated profit is higher. However, oxygen and hydrogen producers can recover less revenues in this scenario. Conversely, as MF3 technology performs better in terms of operations management (and initial investments), it could be a solution to reduce the CO_2 of the production system directly adopted by Acea Pinerolese. Moreover, MF3 produces low quantity of acetone, which is usable only on-site, increasing the cyclicity.

By leading the Eco-innovation process through the proposed methodology, iteratively applied, a light is shed on waste emissions and use. The increasing amount of unexploited heat (alternatives AA, MF1, MF2, MF3) becomes the starting point for the research of new partners for IS, such as greenhouses capable to exploit low temperature heat dissipated by pem-Electrolyzers. While the increasing demand of hydrogen and power is not necessarily purchased from the market, the company can look for other IS partners who have such resources in excess. This is a significant step towards closing the resource loops.

Hydrogen and oxygen proved to be fundamental to support these system improvements and IS opportunities. Potential partners could take the excesses of (usually underpriced) power and CO_2 to produce the other chemical products. i.e., hydrogen and oxygen. Part of the profit could be used for investments to support system improvement and network operations. Thus, not only resource flows but also monetary flows increase their circularity, which is a critical step to achieve continuity in IS implementations. Furthermore, hydrogen could have a relevant role also as renewable fuel; Acea could consider it within the next steps of Eco-innovation process. However, this large production requires large amount of power (Figure 6.8), suggesting that probably part of the hydrogen could come from other processes that could be considered in the next iterations of the proposed methodology (e.g., hydrogen could be obtained by methane purification). Biofuel (incentivized by current Italian environmental and energy law) is an emerging profit source maintained in all the alternatives; hence, future research could deepen whether biofuel production could be fostered through additional system improvements.

The proposed mathematical model can be solved in few seconds and it provides optimal solutions. It is as general as the whole methodology to improve its adaptability to companies of different sizes, industrial sector and country. However, the time required to find optimal solutions grows rapidly as resources, processes, and the number of cycles that need to be closed increases. Especially the number of cycles that need to be closed, fundamental condition for the value creation process, has a negative effect on model complexity. This limitation is crucial because the methodology should deal with the network of processes, companies, and resources also beyond the boundaries of the case study. Furthermore, the time horizon and the duration of time period (time discretization) in the optimization model can amplify irrelevant interactions between resources or hide important ones. Hence, the alternatives should be assessed with different time periods and time horizon, moving from months to days and even minutes, to understand resource interactions at strategic, tactical, and operational level. However, reducing time interval increases the number of time periods, by increasing the model complexity even more.

The methodology can be applied to any company from any industrial field; however, the insights cannot be generalized. For example, biomethane, hydrogen and oxygen seem crucial for the transition towards sustainable and circular development for Acea. Nonetheless, this result strictly depends on geographical factors. Different policies, technological advancements, resource availability, and the presence of different local companies could overturn these insights. Hence, the need to include this methodology in a wider framework is emerging.

11.2.1 Robustness in the Eco-innovation process

The methodology and the DSS allow the introduction of multiple energy and environmental scenarios to evaluate the current production systems and also the introduction of the new technologies, processes and operational methods.

To extend the methodology and the DSS to the assessment of several energy and environmental laws improves their effectiveness. In fact, policies and governmental roles have a crucial role in Eco-innovation as well as in the development of ISN because they can encourage or discourage their emergence and development [258]. According to the literature, the extension of the methodology to the comparison of multiple policy effectively allows the companies to make strategical decisions in a better way. It allows to perform scenario analysis to the companies that implement it. Furthermore, it paves the way to new studies for the policy makers where they can consider the point of view the firms and simulate their rational reactions to the entry into force of new energy and environmental laws.

From the industrial side, the inclusion of the comparison of scenarios for future policies allows the firms to foreseen their future impacts on their environmental and economic performances, thus improving their strategical plans. Moreover, the comparison of future scenario policies leads to the further application of methods for the analysis of sensitivity to improve the robustness of the decisions about new IS and investments for adopting new processes and technologies.

11.3 Within the firm: investments and tools for Eco-innovation methodology

The diffusion of the concepts supported by this thesis is tightly linked to the ease of implementation and use of the proposed methods and methodologies. The proposed Eco-innovation methodology involves many data and factors and also the adoption of the optimization model. To improve the adoption of the methodology also from users with a limited knowledge and companies with poor resources dedicatable for the Eco-innovation, it has been developed a Decision Support System. The development phase has been focused on the functions rather than the graphical interfaces and their proper design.

The integration in the same DSS of the MEIO formalization tool and the modules to instantiate the optimization model contributes to the scientific literature by proposing the first architecture powered by the MEIO tool. Furthermore, the integration confirms the adaptability of the approach to different sources of information since the MEIO tables are based on data from IT systems and the parameters introduced by the users.

The industrial relevance of the DSS is provided by the three main functions of the tool. In fact, it is versatile and it can be used to evaluate the economic and environmental performances of the current production systems, as well as the introduction of new processes, technologies and operational changes into it, both under the current policies as well as under future or different energy and environmental laws and incentives.

The use of the DSS necessities of a low level of digitization of the current company. Nonetheless, when it is adopted in context with higher level of digitization, which uses technologies of I4.0, it increases its potential applications proportionally with the level of detail of the provided data, by exploiting also data from IT systems.

11.3.1 Investments in the development of a joint network

The last element considered in this thesis to support the companies in the preliminary assessment phase for the development of new IS is the role of the initial investments. The thesis is mainly oriented to the ISNs arising from the initiative of a company during its continuous improvement process towards the sustainable production. Hence, the paradigm of the anchor tenant or the third party who involves all the other stakeholders is the most suitable to describe the context. Furthermore, beyond the proposed Eco-innovation methodology also in other fields the cooperation among companies for achieving sustainable goals is advancing.

Life cycle engineering has an important role in waste identification and value creation thanks to its attention to the product life cycle. Life cycle engineering focuses over each phase of product life, identifying, during its production, the required inputs and the produced outputs, and this makes it a powerful approach for identifying potential sources of value [27]. Furthermore, Life cycle engineering can foreseen the potential applications of the products after their normal use by the consumers. The importance of identifying unexploited outcomes from each life cycle phase is at the basis of costing models as Total Life Cycle Cost Model, which highlights the achievable value creation hidden in waste. However, it is focused on a company level perspective, e.g., one of its practical application is for material selection in CE perspective and it does not actually consider the presence of other stakeholders but it is mainly product characteristic oriented ([35], [36]). Even though life cycle approach supports the idea that reducing waste within a company is fundamental, since producing waste is unavoidable [208], sometimes it is adapted also for inter-company approaches. In fact, Material Flow Cost Analysis [216] and big data approaches [28] can be used to identify and design how to exploit the overall waste along the whole supply chain, both optimizing processes and developing new partnerships with companies that could use the produced waste. However, these collaborations among companies, according to CE and Circular Industrial Ecology Model paradigms, usually base their success on the exploitation of the previous inefficiencies, and completely neglect the careful selection of the network of stakeholders for waste exploitation. Among the most important selection criteria, there should be also both the economic effort and the investment period required to each stakeholder for joining the network. In fact, even if the arising partnerships are promising, most of them depend on the local industrial context (e.g., [265]), and they cannot be exported in different regions with different partners. Partners, and probably also the other sites of the current company (if any), have different cost structures that require different agreements on the basis of the required investments and their returns. Economic indicators are largely used also in Life Cycle Engineering to compare different investment possibilities [210], or flow optimization for multi-product cycle [125] but they have never been used as a mechanism to keep the commitment of the partners, and to assess how much this mechanism costs to the companies.

Design for Industrial Symbiosis proposes to design new products considering both the exploiting waste and by-products of other SCs and providing, at the end of their life cycle, waste and by-products useful to be used as raw materials [179]. However, in the state-of-the-art the role of investments and their lock-in effects have not been sufficiently explored. Hence, the scientific contribution of this thesis, especially chapter 9, is the identification of a mechanism to fairly allocate the investment, and using itself as a Commitment Keeping Mechanism to maintain the effort of the stakeholders. The CKM, which is based on the equalization of the Payback Period to a fixed number of years for all the stakeholders, does not provide an exhaustive investigation on the topic, which remains poorly explored, but sheds a light on the crucial role the investments have. Furthermore, it contributes also to the scientific literature by highlighting its potential application as a link between the network and the operational level, by providing an interface that connects and, at the same time, decouples the operational activities of the current business and the other for the emerging belonging to the ISNs.

The industrial relevance of this analysis, which is interesting also for the scientific literature, is in the opportunities to manage the several ISNs to which the company belong to in a separate way one from the other and from the main core business. Therefore, it paves the way to the definition of new KPIs and methods to monitor the state of each IS and its performances, and the opportunity to improve the well-rounded management of the operational level of the individual companies.

Chapter 12

Conclusion and future research

This thesis addresses the improvement of the resource efficiency in the production systems to reduce their environmental impacts without neglecting the economic aspects, which are crucial for the competitiveness of the companies. The reduction of waste is a crucial topic in the production systems; however, only in the last two decades it is keeping into consideration also the environmental aspects beyond the reduction of the inefficiencies. In fact, the production of undesired waste together with the finished products is mostly unavoidable in many sectors. It can be partially limited, and the remaining wastes can be collected and disposed in a second time; however, it is an economic and also environmental cost. In other cases, the remaining waste can be exploited as raw materials by other companies or other processes via Industrial Symbiosis. The research is investigating further technologies and methods to exploit the generation of current waste, while the best practices to establish specific symbiotic relationships between pre-determined industrial sectors are spreading. However, new wastes will be generated e.g., microbial factories in chapter 6 probably will have biological waste to be disposed, and the market dynamics together with normative efforts will subsequently change the establishment and the development of the networks of companies.

This thesis wants to provide a contribution to the industrial and scientific fields that goes beyond the current contingencies through a well-rounded investigation of the methods, tools and methodologies to support companies in undertaking this Eco-innovation path. A comprehensive approach should involve the monitoring of the economic and environmental performances of the production systems. The monitoring is an activity with no or low added-value for the customers; hence, its cost should be low. However, the production systems are becoming complex and they have been involved in a new manufacturing paradigm that requires new tools and methods to monitor its performance. On the other side, a comprehensive approach should concurrently evaluated the reduction of inefficiencies and the produced waste, and the exploitation of the remaining one via IS. Moreover, it should also be adaptable to the principles of I4.0 to avoid being born old.

Industrial Symbiosis, monitoring activities, and reduction of waste of the systems are always subjected to their ease of use, the implementation costs, and the risk management activities of the companies. Hence, even when they are concurrently addressed, their crucial issues cannot be neglected. Moreover, they could negatively influence each other, e.g., the increasing complexity of both monitoring activities and operations management due to the joining to symbiotic partnerships.

This thesis proposes new insights about the proposed approach, far from the presumption of offering exhaustive answers to all the research questions that are emerging from this approach. The next section highlights the academic relevance of this dissertation; then, the last one conclude this thesis by outlining the future steps, i.e., the future research, emerging from the current limitations, that may help the improvement of resource efficiency for the sustainable production systems.

12.1 Academic relevance

This section summarizes all the scientific advancements respect of the state-of-the-art that are proposed in this dissertation. The entire document contributes to the literature by proposing a holistic approach for supporting the companies in the development of a strategy to improve economic and environmental performances. The approach is holistic since it puts together four different aspects: (i) the definition of new methods able to address the challenges of both monitoring economical-environmental performance and supporting the advent of Industry 4.0 paradigm; (ii) the development of a comprehensive and general methodology for improving resource efficiency, by involving both system improvements and new partnerships to create value from reducing and reusing waste and byproducts; (iii) the development of tools to foster the diffusion of the methods and methodology by lowering the barriers to their adoption; (iv) the performing of analyses devoted to both the identification of valuable partnerships for the improvement of economical-environmental performance and the reduction of the risk of manufacturing systems coupling.

One of the merit of this thesis is the identification of the relationships among the aforementioned four aspects, which are summarized in the approach to the resource efficiency defined in the Introduction, i.e., Technology-Analysis-Improvement. Scientific contributions in each one of the three domains should always take into consideration how they affect the others to be effective and easy to adopt for companies. Therefore, the scientific advancements, devoted to the improvement of resource efficiency, within the single domain or in the border between two or three domains, should be discussed also in terms of how influencing the others. This approach to the assessment of the scientific advancements in the field of resource efficiency is here applied to highlights the several contributions proposed by this thesis.

12.1.1 Monitoring and control of performances for resource efficiency

The Multi-layer Enterprise Input-Output (MEIO) formalization tool has relevance in several academic fields since it supports both the development of new methods to perform analyses and it concentrates the entire information of a system with a structured and standardized formalization. The manufacturing systems, but also logistic systems and systems for providing services, are becoming complex due to the Internet of Things and the proliferation of independent resources (operators, machines, robots) simultaneously involved within the several activities. The introduction of the MEIO method paves the way to the development of new methods concurrently involving several dimensions of system performance: economic, environmental, technical and value creation. Furthermore, it fosters the research in new methods to monitor and control system performance by allowing mixed approaches, i.e., with both stochastic and deterministic activities.

Nonetheless the rigorous structure of the MEIO method, it is flexible to be applied in a such a dynamic field like the Cyber-Physical Production System, where the digital counterpart of a system is becoming crucial. However, this field, supported by the technologies in rapid expansion of I4.0 paradigm, is subjected to a proliferation of methods and practical approaches that often are incompatible the one with the others, hindering their effective spreading in the industrial sector. MEIO method can provide the necessary formalization to collect and organize data of the systems, by increasing the interoperability between different approaches, technologies, methods and tools. The improved interoperability may allow to overcome technical difficulties, by combining solutions that before were incompatible; moreover, it may foster the development of new methods and approaches.

MEIO method supports the concept of a formalization tool able to combine a priori information with the information coming from data-driven techniques such as those belong to the Process Mining. Systems are becoming decentralized, i.e., the single components of a system can modify their role according to the contingent necessity identified by the component itself. Hence, the digital counterpart of a system developed with a priori knowledge may become obsolete during the operations due to the unforeseen modifications brought by the single operators, robots, machines. MEIO method allows the combination of data-driven techniques able to identify variation in the system and techniques of system modeling based on a priori knowledge, paving the way to further research in system modeling.

12.1.2 Industrial Symbiosis as part of the resource efficiency strategy

The Eco-innovation methodology proposed in the Part II of the thesis has its major scientific contribution in the definition of a comprehensive strategy to enhance resource efficiency at company level. It integrates the Industrial Symbiosys in a wider set of solutions to reduce the production of waste and exploiting the remaining part by providing it to other companies able to use it as raw material. Furthermore, the approach is able to meet several factors contingent to the IS, i.e., the technical and economic feasibility, the normative influences, the allocation of investment for new technologies, which can be devoted to reduce the waste production while increasing the technical efficiency within the single company or the transformation of waste in new raw materials for establishing new industrial partnerships.

IS has been considered and studied as a standalone strategy so far, while the proposed methodology paves the way to new approaches integrating IS with other strategies. Moreover, the performed analyses may help to evaluate the trade off between IS and other solutions also in further approaches. In fact, economic, technical, and environmental criteria have been used to evaluate the several solutions, and their combinations, under different environmental and energy laws.

The Eco-innovation methodology may result interesting also for those sectors highly affected by energy and environmental laws. Scholars involved in risk management arising from environmental performance may consider the introduction of IS in their models to mitigate the effects of energy and environmental laws. Furthermore, the integration of IS and further solutions of waste reduction can be adopted to support the policy maker in the evaluation and definition of new policies.

12.1.3 Tools and analyses for a holistic approach to the resource efficiency

The Decision Support System, proposed in Part III, contributes to the scientific literature by integrating the MEIO method to collect, update, and systematize data, and the Eco-innovation methodology, together with scenario analysis modules. It represents a new combined approach to monitor economic-environmental performances and mathematical models for decision making to evaluate the best strategy for enhancing resource efficiency, evaluate how the system is affected by normative changes, and identifying the suitable waste for subsequent IS.

In the field of CPPS, many architectures and approaches are emerging to enhance the physical systems. The proposed DSS, beyond its adaptability with state-of-the-art approaches, represents a new kind of architecture between the physical system and the modules of the digital systems, where all the data are collected, formalized, and keep updated, leading to an improvement of interoperability among different software applications and approaches.

The Industrial Symbiotic Networks represent an opportunity to improve the overall resource efficiency; however, they expose the new network of companies to the propagation of disruptive events due to the production uncertainty and the fluctuating commitment of the stakeholders. The thesis proposes an innovative approach based on the archetypes of stakeholders involved in a ISN. Furthermore, it sheds a light on a poorly explored context in literature where large initial investments are required and they can affect the creation of value of the single companies in the future.

The novel framework highlights the relevance of the choice of the right partnerships to ensure the sustainability of economic and environmental performances over time. Moreover, the concept of the Commitment Keeping Mechanism (CKM) introduces the idea of a dynamic set of rules that can be used during negotiation phase for both reducing risks of fluctuating commitment and set measurable targets of economic and environmental performance that should be reached along the time by each single stakeholder.

The use of the Payback Period as CKM paves the way to new models and new rules to determine effective ISNs. The individual companies can have a more clear picture to allocate investments to reduce/trade their waste, since the preliminary phase of IS emergence when they are defining their comprehensive resource efficiency strategy.

Finally, the use of the CKM allows to decouple both the capex allocation and the operations management that are referred to the current business of the company from those referred to each single ISN the company is part of. In fact, setting measurable targets in terms of both economic-environmental performances and waste-resources that have to be provided, for each time period, allows a better foreseen of emerging costs and opportunities. A better foreseen often leads to define models and strategies to optimize performances by reacting to the disruptive events and mitigating the propagation of their negative effects since they were been identified just in time.

12.2 Future research and conclusion

This research proposes an innovative approach whose the main quality is its adaptability over time. In fact, resource efficiency strategy defined by a company need periodic revisions to identify new opportunities and mitigate the effects of negative events. Therefore, this holistic approach needs of further research to identify potential barriers to its adoption because of specific industrial fields, manufacturing systems, and geographical contexts. Moreover, it paves the way to future improvements to enhance its capability of monitoring economic-environmental-technical performances, involves other stakeholders and to create value with them.

Each individual aspect of the holistic approach can be subjected to further improvements to overcome its current limitations. Some of the opportunities for future research about the individual topic of the approach are here introduced to drawn the big picture where they can play a more pivotal role.

12.2.1 Multi-Layer Enterprise Input-Output approach

The MEIO method proves to be a valuable and effective tool to model the production systems, especially because of its well-rounded approach to the economic and environmental performance. Moreover, its applications in pen and paper approach is quickly improved by the combination with IT systems and automatic way to provide data, by making it a relevant tool also in the context of I4.0.

The main limitations of MEIO method emerge when it is applied to complex contexts where the Cyber-Physical Production Systems are particularly advanced and they exploit multi-scale modeling and approaches such as combining different simulation techniques, and real-time control and updating. These topics are in the current frontier of the production research, and the outcomes of the challenge of spreading I4.0 among the industrial sectors depend also from them. The increasing amount of data becomes useless if it cannot be applied to gain any forms of competitive advantage. Therefore, future research should improves these aspects to provide a modeling of processes according to the level of required detail, in a comprehensive way that allows the adoption of various techniques.

Process mining techniques are proving to be useful to model all those systems where a priori information can be misleading. The MEIO method is compatible with Process mining algorithms to identify processes; however, what is not monitored cannot be controlled, thus further studies are necessary to lead to the definition of the events that should be monitored. The definition of the events can introduce new processes along the time, processes that were not thought during the initial design phase, which modify the use of materials, energy and resource in general. These changes in the use of resources could introduces some mismatches that do not allow the material and energy balance exploited by the MEIO method (one of the principles inherited by Material Flow Analysis). Further research is required to understand the interactions of MEIO method with Process mining techniques in the case of automatize the continuous update of the system.

12.2.2 The Eco-innovation methodology and the Decision Support System

The methodology is effective for guiding the Eco-innovation process within companies, from the collections of geographical and design factors to their use for identifying critical resource flows and, especially, the evaluation of improvement strategies. Furthermore, it highlights the twofold nature of the actions aimed at creating value from waste. It leads to combine the introduction of new technologies within the system and the exploitation of residual waste through these technologies within IS. In fact, some technologies improve operation performance of the system, while others are suitable for IS improvement. Hence, the twofold nature of value creation from waste (i.e., resource efficiency improvement) deeply affects technology assessment. Value creation depends on technological efficiency, but technological efficiency must be also contextualized in the right network of companies, and then assessed. It is not possible to reduce the waste production to zero, but residual waste can be raw material for other companies. IS plays a pivotal role for interaction rules of the mentioned network.

The factors affecting the technological choices for value creation from waste change from company to company. They depend on the industrial field, technological advancement, local network of companies, resource availability, and governmental policies. However, the application of the methodology facilitates the emergence of these factors, at the end of the evaluation phase, highlighting their relations with the technologies under investigation. Once these factors have been identified for the specific production system, it is possible to address the creation of value from waste also by starting from the factors. It is possible the selection of the technologies that favor IS and those that favor the waste reduction through the ranking of their performance according to the several factors. The outcomes of the optimization model show that the model is suitable also for technology forecasting, by providing guidelines for the development of emergent technologies in the field of resource efficiency improvement. Furthermore, the optimization model is able to exploit energy and environmental laws in terms of constraints and incentives, highlighting its potential application to strategical planning of companies, as it emerged through the application to the case study of Acea Pinerolese.

The methodology should deal with larger systems and smaller time discretization. This increasing complexity calls for further research in new approaches to solve the mathematical model. Moreover, there is a need for structuring the result analysis framework to fairly compare all the scenarios from multiple perspectives. The DSS exploits the library of CPLEX to solve the optimization models; however, complex systems with large amount of activities and resources can reach larger sizes than those of the case of Acea Pinerolese. In those cases, the libraries of CPLEX could need much more computation budget to provide the optimal solutions, by making difficult the application of scenario analysis. Hence, the complexity of the mathematical model can be reduced, but also ad hoc approaches to solve the optimization models can be added to the DSS.

Future research may exploit the comprehensive strategy for enhancing resource efficiency by integrating it in models for supporting policy makers. In fact, the methodology allows to analyze the effects of environmental and energy laws on the rational choices of the companies.

The DSS shows an example of architecture where MEIO method is put at the interface between the physical system and the digital system. Further studies are necessary to improve this use of the MEIO method, and to go deep in the analysis of the physical systems where this approach can be replicated.

12.2.3 Further steps on the internal perspective of the firms

This thesis focused on the ISNs originated from the initiative of the individual companies, where large investments are required to design production network. The most of the studies focus on networks without lock-in effects and where the consequences of the operational uncertainty lead to the abandon of the IS. Here, it has been proposed a mechanism to fairly allocate the investment, and then it has been investigated to understand its effect on the negotiation phase. The proposed method has the merit to shed a lights on this field, but it requires further research on the definition of the archetypes of the stakeholders. Furthermore, a larger taxonomy of potential structure of stakeholders should be addressed to investigate their characteristics, understand their barriers and drivers and then improve the CKMs.

The rule applied to the CKM shows good results in some cases, by supporting the anchor tenant in the design and production of green products, and the other tenants, especially SMEs, in their Eco-innovation process. In fact, SMEs can address investments larger than those they could made on their own. Furthermore, these investments open to new markets for exploiting the waste typical of each region, thus fostering the local attitude to the sustainable development. Conversely, in other cases, the rule applied to the CKM results ineffective to hidden the lock-in effects and keep the commitment of all the stakeholders. Therefore, this thesis can be a starting point for further researches on other rules adapt for those situations.

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