The resource efficiency in sustainable production system: Monitoring consumptions, reducing waste, and reusing them as raw materials

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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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# Contents

# Introduction

Sustainable development has become fundamental for stakeholders in many sectors ([94]; [11]), especially to achieve and support competitive advantage ([80]; [60]). Companies not pursuing sustainable development may incur higher costs [41], thus losing competitive advantage [16]. The achieved goals must be measured according to the Triple Bottom Line (TBL), i.e., social, environmental, and economic sustainability [42]. However, achieving positive results on all the three dimensions of TBL requires different approaches in different application fields [6]. Radical changes are required in manufacturing systems [79], business models ([36]; [62]) and top management ([9]; [98]). Sustainable development can disrupt both strategic ([83]; [87]) and operational levels in supply chains [15]. Eco-innovation is leading the transition towards a sustainable development condition fostered by many national and supranational institutions (e.g., [64]; [25]; [26]).

The thesis proposes a comprehensive approach to support the transition towards the sustainable development, by focusing on both 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 Symbiosis and Circular Economy paradigm to propose a methodology able to support both Eco-innovation process and sustainable development capabilities of the 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 PhD thesis develops a theoretical framework based on Industrial Symbiosis and Circular Economy paradigm and it proposes a quantitative methodology able to support both Eco-innovation process and sustainable development capabilities of companies. Furthermore, a Decision Support System has been developed to foster the spread of the methodology, especially among SMEs, and a formalization method to support the concurrent assessment of economic, environmental, technical performances and value creation of production systems with both high and limited levels of digitization.

The Istituto Italiano di Tecnologia funded and supported this research work providing data and information of 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 analyses designed during this PhD.

# Thesis structure

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, here summarized in chapters from 1 to 3, respectively) specifically focuses in a certain topic that remains crucial, and assumed given, for the subsequent ones. The last part (Part IV) concludes the thesis. To facilitate the readability, each one of the parts of the thesis introduces the state of the art referred to the main topic to which it is dedicated the part itself, rather than an extensive chapter on the beginning.

The chapter 1 of this summary introduces the Part I of the thesis, i.e., the pivotal role of the resources into the value creation process. It starts from the state of the art of the tools and the methodologies to measure and formalize the value creation and the resource efficiency of the systems. Lean principles and tools, especially the value stream based approaches, the Enterprise Input-Output models and Material Flow Analysis approaches are investigated. A new formalization tool based on the integration of Multi-Layer Stream Mapping and the combination of Material Flow Analysis with Enterprise Input-Output (MEIO) approach has been proposed to fill the gap in the literature of methods and tools capable of formalizing both efficiency and economic-environmental performance of the systems. MEIO is used in combination with other techniques such as the stream mapping (MEIO-SM), or mathematical programming models and simulation/optimization approaches. The first case study is introduced, i.e., the combined application of Material Flow Cost

Accounting with MEIO formalization in InnovaEcoFood project, to show the effectiveness of the formalization method in value creation analysis. Part I ends with the description of Acea Pinerolese and the EngiCOIN project and the application of data-driven MEIO formalization tool. The method shows the perfect compatibility with Industry 4.0 approach and the effectiveness in formalizing systems with both deterministic and stochastic processes.

Part II focuses on the Eco-innovation process within the single companies and it is summarized in Chapter 2 of this summary, together with the brief literature review about sustainable development and Eco-innovation methodologies. 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 that are useful for improving productivity through waste reduction, and the other technologies to exploit the remaining wastes via IS network. The application of the methodology to the case study of Acea Pinerolese is introduced to support the discussion about the potential benefits of this quantitative methodology to pursue Eco-innovation.

Chapter 3 addresses the contents of the third part of the dissertation, which deal with the barriers faced by the single companies when developing strategies to improve resource efficiency. There are two main topics: (i) the development of digital tools able to support the aforementioned proposed methodology to reduce its implementation costs, (ii) the analysis of the risks when a company join in a IS network (ISN) and how to mitigate them by properly choosing the potential partners while decoupling the production systems to mitigate the propagation of production uncertainty within the ISN.

Finally, Part IV of the dissertation puts together the managerial insights from Part I to Part III, the benefits of Eco-innovation methodology and how it changes when other stakeholders are concurrently considered. Chapter 4 is dedicated to the discussion of the respective Part IV. It summarizes the scientific and industrial contribution of this PhD thesis, highlighting the new research questions for the scientific community, and then it concludes the work.

# 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 deep 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 the barriers and the drivers to guide economic activities in the transition to sustainable development worldwide.

Circular Economy and Industrial Ecology have a crucial role in this field, and they represent the essential bases for approaching the sustainable development.

## The Circular Economy

The Circular Economy (CE) paradigm is mainly intended as a way to lead economic prosperity through recycling, reuse and resource reduction [50]. Even though sustainable development was not among the factors that determined CE conceptualization [50], its intrinsic characteristics have direct and positive effects on it. Nowadays, the relationship between Sustainable Development and CE have been widely recognized and made explicit, especially the characteristics of regenerative system, waste reduction and resource efficiency improvement ([38]; [58]). CE does not focus specifically on network of companies; however, it has a relevant influence in Supply Chain Management, especially for the implementation of 6Rs networks (i.e., Reduction, Reuse, Recycling, Recover, Redesign, Re-manufacture) ([39]; [7]).

## Industrial Symbiosis

IS is the key concept of the Eco-Industrial Park resource efficiency. 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 Circular Economy (CE) ([29]; [76]), due to its focus on the flows of material exchanged between environmental and anthropological ecosystems [40]. IS is in continuous evolution [13], but its contribution for achieving competitive advantage [46] is not questioned. Originally, IS was considered relevant only to increase resource efficiency by using waste as a raw material [37]. Later, IS demonstrated to be effective as a tool for fostering eco-innovation-based company networks [56], and as a way to lead entities to gain a greater collective benefit ([23]; [22]).

## Eco-innovation

Eco-innovation is assuming a crucial role in the achievement of sustainable development 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 [14] and it can lead to cost savings through the improvement of corporate image, production efficiency, organizational capabilities [30]. Eco-innovation may help companies to achieve competitive advantage [28] by leading to larger advantages than non-eco innovation [10]. In fact, a sustainable business model is a key factor for achieving the competitive advantage, and it cannot neglect the sustainable operations [61]. Furthermore, it is determinant for the transition towards CE in many ways and fields ([28]; [29]). For this reason, Eco-innovation has been defined in a deliberately broad way by the Eco-Innovation Observatory of European Union [65]:

> "(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."

From the micro level point of view, the research results fragmented [43] 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 [21].

# Aims and methodology

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.

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.

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 analyzing the arising risks and the potential benefits. 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 developed methodology, by collecting the feedback of the companies and the other stakeholders 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 reasons of the selection of the single case studies, the collection of data, and the specific methodology used.

# Chapter 1

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

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

## 1.1 Tools and methods for system analysis

Value analysis can be normally used to increase product value and/or cut costs [74]. Lean Management aims to reduce waste and non-added value burdens within companies to make them performing and reactive ([66]; [24]). 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 [66]. The most famous tool to identify sources of waste is the Value Stream Mapping (VSM) [3].

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 ([34];[67]) and value creation ([63]), paving the way to new paths for pursuing sustainable development [33]. In some cases, new technologies can improve the effectiveness of some principles of Lean [77]. Tortorella et al. highlight that the adoption of new technologies should be driven by the pursuit of Lean principles [91]; 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 [51] and struggling to achieve better results in sustainable development. 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 [82]. Recently, also value chain model is becoming inappropriate to represent the value creation process in current production systems.

**Input-Output models.** Leontief in 1951 [55] 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. Input-Output tables have been extended to include also waste production and abatement activities [54]. Enterprise Input-Output (EIO) has been introduced to model and analyze the interactions among processes within a company [4]. EIO tables have been used to analyze and represent the exchange of resources within complex systems (e.g., supply chains [5]), and usually applied in combination with other techniques, e.g., agent-based simulation, which exploit its system representation [95].

**Material flow approaches.** Material Flow Analysis (MFA) statically describes the flows of resources (or substances, [45]), which are both used and produced by companies or processes (e.g., [85]). It can deal with parameter uncertainty (e.g., [17]) and the conditions of limited information [81]. MFA tracks resources and energy from their introduction into the system to the sales or disposal point [75]. Material Flow Cost Analysis (MFCA) usually starts from MFA and goes deep into the economic value of resources by separately considering material flows, services, economic indicators and energy consumption ([31]; [49]; [1]). MFCA is focused on resource management [73], by reducing waste and scraps [57] and improving productivity [69]. It underlines the contribution of each specific resource to value creation and when a resource is disposed as a waste, it represents a cost.

**VSM-based: the Multi-Layer Stream Mapping approach.** The Multi-Layer Stream Mapping (MSM) has been proposed with the four-dimensional paradigm of MAESTRI Total Efficient Framework, oriented to Efficiency framework; IoT platform; Management system and IS [8]. MSM is a methodology to evaluate the resource efficiency of production systems, by following the lean principles of waste and value [47]. MSM extends the set of resources considered from the dimension of time, which is the standard resource considered by VSM, to all the raw materials, the consumables and the 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 ([86]; [52]).

## 1.2 Multi-layer Enterprise Input-Output Stream Mapping

System formalization has to be able 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.

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 [70]:

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 activities, 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.

MEIO-SM approach always provides 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-SM.

## 1.3 Application of MEIO formalization for value creation analysis

### 1.3.1 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 has not been assessed yet. Hence, the combination of three SCs stemming from wine and rice production chains is evaluated.

Different skills and processes are required, from the initial treatment of pomace and rice husk to the production of the baked products. Three companies, from three different SCs, selected for the cost-benefit evaluation of the by-products in food and beverage market (FOOD): (i) Agrindustria deals with flours production; (ii) Exenia is focused on treatments to extract the precious molecules from the rice husk; (iii) finally, La Mandorla is a bakery interested in the exploitation of these ingredients to produce baked products, by assessing quality and sale price of new products.

#### Material Flow Cost Accounting approach

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 further 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).

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

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 to improve value chain at strategic, tactical and operational level.

#### 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 1.1 where the red dashed box indicates the part of the system under analysis. In Figure 1.1 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, which are 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.

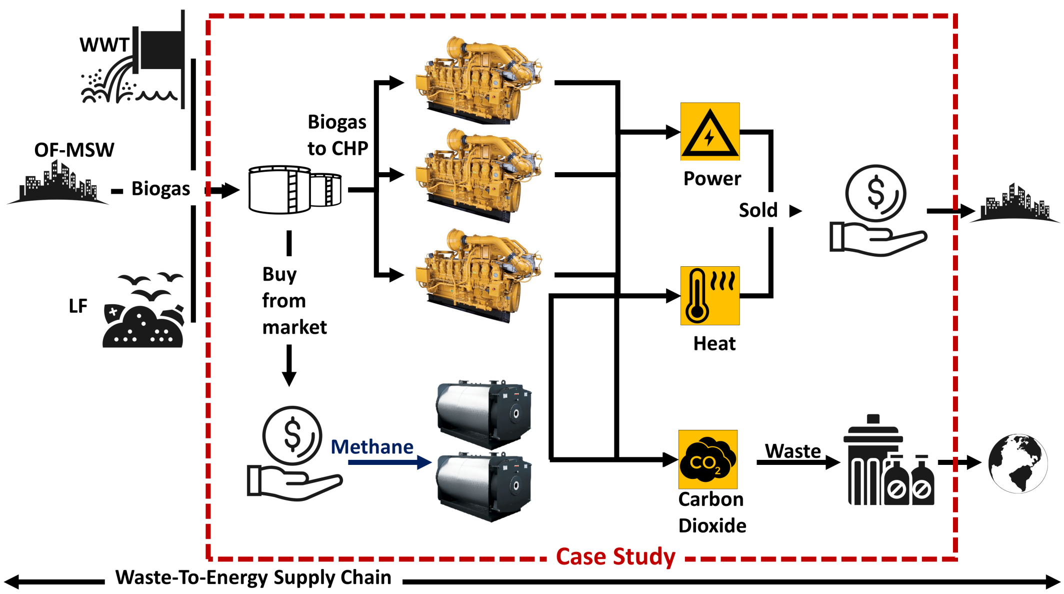


Figure 1.1: Waste-To-Energy Supply Chain and Acea Pinerolese, Piedmont, Italy.

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.

Figure 1.2 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 [2]. 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.

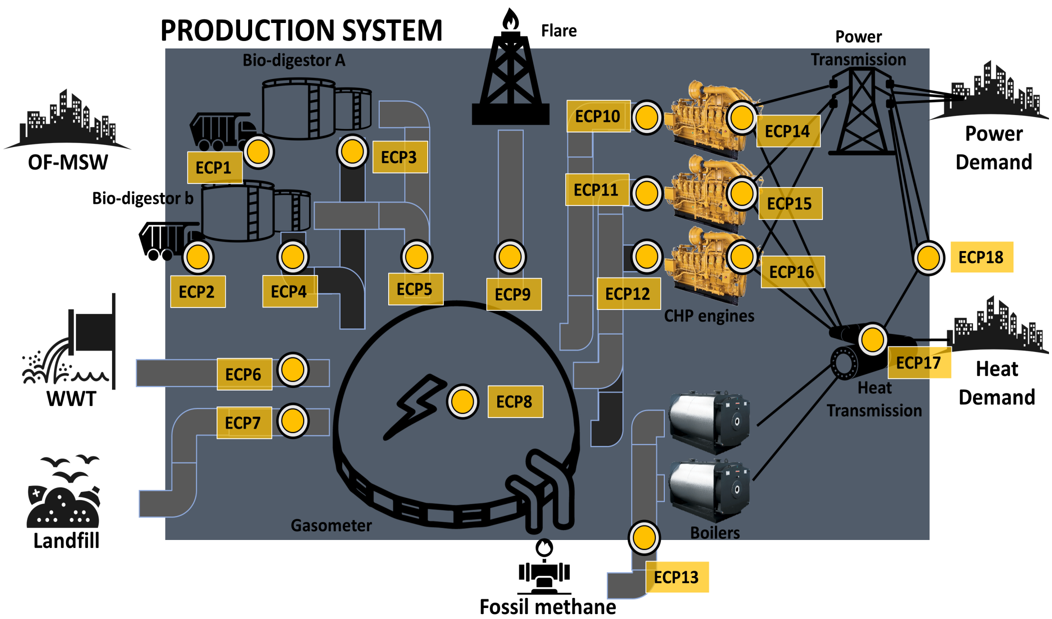


Figure 1.2: Representation of SCADA system of production system (blue area) with 18 ECPs (yellow and white circles).

| 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 1.1: 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.

### 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 [48]. However, technical, logistic and regulatory issues can make an IS unsustainable [32]; 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

# Methodology for eco-innovation based on Industrial Symbiosis and system improvement

The lack of practical and generalizable methodologies to lead single companies to approach IE and achieve Sustainable Supply Chain Management ([53]; [93] is emerging. Eco-innovation is identified as the practical way to achieve the sustainable development for the companies. The thesis proposes a quantitative methodology to lead the Eco-innovation process of an individual company, through the simultaneous consideration of (a) system improvements to achieve better resource exploitation, and (b) IS opportunities to create value from the remaining waste. The methodology takes into consideration current energy and environmental policies to assess the adoption of new technologies devoted both to the improvement of the current system and enabling potential IS relationships. Furthermore, the methodology exploits the scenario analysis to shed a light over future production and consumption scenarios and the projection of impacts of technological improvements on sustainability. The initial system information is formalized through the MEIO approach proposed in Chapter 1 and collected by following the proposed methodology. Later, the solution of the mathematical model, represented through an optimization Mixed Integer Linear Programming model, provides insights about the adoption of the optimal number of machines and warehouses to improve the current system and enabling IS relationships.

## 2.1 Eco-innovation continuous process through the three-step iterative methodology

This 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. The methodology has an iterative nature based on three pillars: (i) factors assessment, (ii) identification of system improvement and IS opportunities, and (iii) alternatives evaluation.

Pillar 1 is the assessment of a set of factors consisting of: (i) waste and by-products production in a certain area and/or by a specific firm; (ii) demand of products and services in the local area or in another targeted area; and (iii) evolution of these parameters along the time.

Pillar 2 is the identification of all the possible and implementable IS scenarios to reduce the waste in the resource flows, and increase both the resource efficiency and the economic and environmental performances. Their identification starts from sources of waste emerging in Pillar 1. Finally, the current system and the identified IS must be put together to assess the economic and environmental performances.

Pillar 3 represents the identification of the most suitable tools to assess alternative implementation. The tools can exploit the proposed mathematical model to address different issues, such as to evaluate 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.

Hardly, the outcome is a solution ready for implementation phase. Rather, it is a set of insights to better understand the roles of the resource flows involved into the analysis. The resource flows will lead to different performances in different scenarios, and they will drive the definition of new constraints to better define the geographical factors. This triggers a new iteration of the methodology, and the process continues till the found solutions have enough organizational details for the implementation phase.

## 2.2 Case study

**Geographical factors.** WWT, LF, and OF-MSW belong to the geographical factor 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 vary according to seasonality, trends and local production of waste not controllable by the company. Biogas and heat, as they belong to the geographical factors, negatively affect the operations management of the company; in fact, 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 the produced heat is larger than the demand, it is wasted due to the impossibility of storage.

**Design factors.** Combined Heat and Power (CHP) process and the boilers are design factors, 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 any time, and there is no constraint on demand, so it is 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.

**Technologies for system improvement.** 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 and biomethane can be used both in the CHP and in 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 exploite for some purpose.

**Technologies for enabling IS.** 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, which 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, it is tested through the proposed method the hypothesis that BMP introduction reduces the purchase of fossil methane to satisfy heat peaks demand and overcomes operational problems leading to biogas emissions in the environment. The combined utilization of MFs and pem-E is investigated to exploit $CO_2$ and low temperature heat produced by CHP process. The combined effects of system improvement and IS opportunities are grouped in five different alternatives, represented in Figure 2.1, which 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.

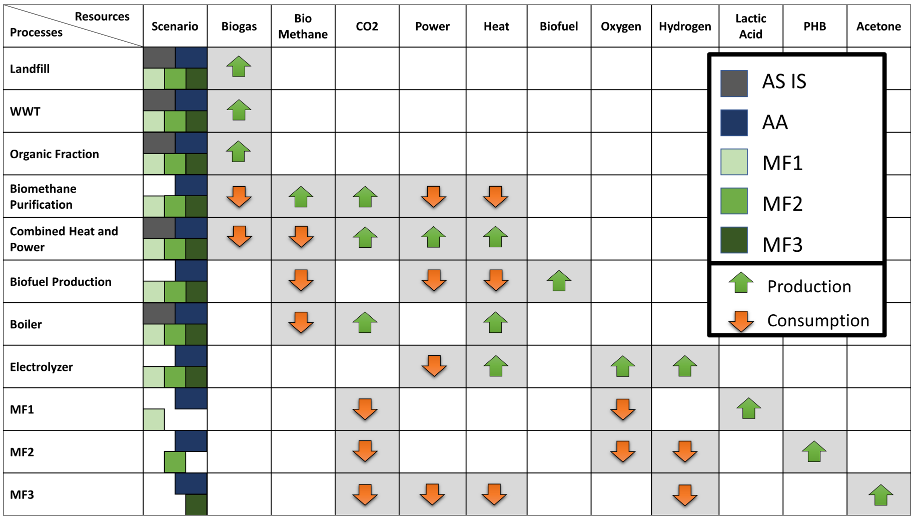


Figure 2.1: Resource-process matrix (colored tags indicate in which of five improvement alternatives each process is present).

### 2.2.1 Robustness over time

The proposed methodology supports companies in their eco-innovation process; however, innovation is a future-oriented process. The proposed approach in the previous section is used in combination with scenario analysis and resource flow approaches to evaluate the robustness of the choices of the technology adoption over the time, when new energy and environmental laws come into effect. The interactions between technologies, the ones preferred for system improvements and the other for the development of IS, can change over time, as resource prices and resource legislation change. Scenario analysis allows to highlight the impacts of both technology groups and their mutual interactions. Scenarios must be designed to consider technology groups one by one and later combined together.

### Consumption Scenarios

Four Consumption Scenarios (CS) have been identified to model the changes of geographical and design factors according to future policies: (i) the proposed CS of the previous case study, (ii) the current environmental and energy incentives and taxes under the Italian environmental and energy laws in force since 2018 and updated at August 2019; (iii) the scenario related to the low carbon emissions, which most of the EU-27 countries are trying to reach before of 2030; (iv) the zero emission target that EU Commission set for 2050, where international agencies have identified hydrogen as key resource. Figure 2.2 shows the changes among CS, i.e., the resources and the production aspects affected by the various policies followed 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<br>Precedent Italian Env. law | Consumption 1<br>2019 Italian Env. law | Consumption 2<br>EU Env. Target 2030 | Consumption 3<br>EU Env. Target 2050 |
|---|---|---|---|---|
| Production Constraints | • Alternator < 1 MW;<br>• Max power purchased < 744 MWh/month;<br>• Max methane bought < 1 MNm$^3$/month. | • Alternator < ∞ MW;<br>• Max power purchased < 744 MWh/month;<br>• Max methane bought < 1 MNm$^3$/month. | • Alternator < ∞ MW;<br>• Max power purchased < 744 MWh/month;<br>• Max methane bought < 1 MNm$^3$/month. | • Alternator < ∞ MW;<br>• Max power purchased < 744 MWh/month;<br>• Max methane bought < 1 MNm$^3$/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;<br>P < 3 MW → €/kWh = 0.097;<br>P > 3 MW → €/kWh = 0.085. | P < 1 MW → €/kWh = 0.12;<br>P < 3 MW → €/kWh = 0.097;<br>P > 3 MW → €/kWh = 0.085. | P < 1 MW → €/kWh = 0.12;<br>P < 3 MW → €/kWh = 0.097;<br>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;<br>24% Hydrogen;<br>13% Biomethane. |

Figure 2.2: Changes from one consumption scenario to another.

**Production constraints** In CS0, the production constraints have a limit of 1 MW for the maximum power, because the previous Italian environmental law incentivized small-scale plants exploiting biogas. In the current Italian environmental law (and it is assumed also for future scenarios) this constraint affects only sale price of power. 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 peaks of demand, when production is not enough. However, especially when pem-E is included, sales of hydrogen and oxygen can lead to an excessive purchasing of power or methane, changing the company mission. Hence, the constraints are more flexible than necessary to understand how hydrogen and oxygen sales can impact on profits and costs.

**Environmental costs.** They are derived from the cost per ton of $CO_2$ equivalent climate altering gas (according to the European Trading Scheme of $CO_2$) following the Global Warming Potential [68]. In CS0 and CS1, they are fixed at 15 €/ton, while CS2 at 25 €/ton ([27]; [71]; [78]). In CS3, the environmental cost is set four times higher than CS2 to account for unpredictable shocks and see if it would have been enough to foster investment in new technologies (MFs) to avoid emissions. These prices are used to assess environmental costs of $CO_2$, biogas and, biomethane.

**Power production.** Power sale price is put in relation with plant scale by Italian law, to determine the incentives associated to each specific plant according to its size. CS0 and CS1 report previous and current laws. In CS2 and CS3, the same policy is kept making comparable the different CS. In each analysis of production and consumption scenario, the power capacity (process size) is chosen into the optimization model, and the market sale price is set accordingly.

**Biofuel production.** It is incentivized since the first Italian Environmental law. However, in the current one (D.M. 2 Marzo 2018), only the biomethane produced through biogas emitted by MSW is incentivized. The considered WTE-SC refers exactly to this case; hence, the tariff is kept the same in all the consumption scenarios.

**Biofuel composition.** It is not critical for the first three CS, because the main incentivized biofuel is biomethane. However, in the last CS, several changes in mobility market must be considered. Electricity and hydrogen must be considered as new "biofuels". Hydrogen will play a key role in the next future according to current experiments (such as the case of SNAM [84]), and analysis (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, [89]). Hence, incentives for sustainable mobility have been revised; one kwh of biofuel is made up of 63% power, 24% hydrogen and the remaining 13% biomethane.

### Production Scenarios

Four production scenarios have been identified. Production scenario (PS) 0 is the *as-is* system. PS1 adopts the system improvement technology of BMP to substitute biogas use with biomethane (only system improvement technologies). PS2 and PS3 introduce the technologies considered as the most suitable for the development of industrial symbiosis (i.e., pem-E, and MFs) respectively to PS0 and PS1. To summarize, PS2 focuses on technologies for IS development, by neglecting those system improvement oriented; while, PS3 investigates the interactions between both the kinds of technology, by including all the available technologies.

# Chapter 3

# The internal point of view of the companies

## 3.1 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 and inefficiencies 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.

### 3.1.1 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 the used data 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 operation 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 Digital Twin (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 chapter 1 of this summary) 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 Analysis 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 3.1 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.

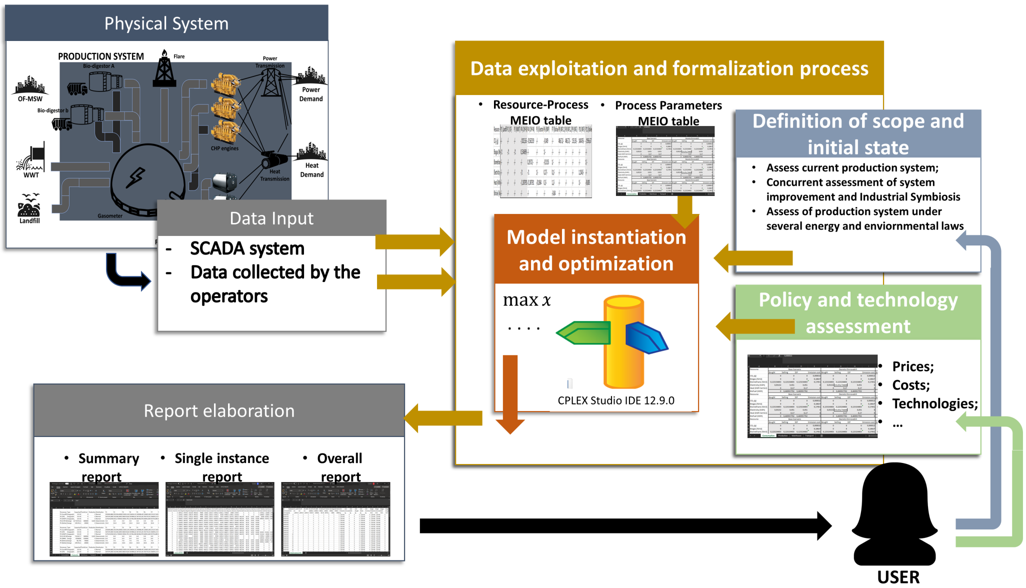


Figure 3.1: The interactions among the user, the physical systems and the four modules of the DSS: "Data exploitation and formalization process"; "Definition of scope and initial state"; "Policy and technology assessment"; and "Model instantiation and optimization".

### 3.1.2 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.

Part II of the thesis highlighted the relevance of the cooperation between companies by showing that even though the intention of pursuing eco-innovation must emerge within the individual companies, sooner or later it will have to consider interactions with other companies to be effective. The integration of SC and EIP aims to stimulate individual companies to invest in eco-innovation more than the required amount ot compensate their environmental costs, due to the emerging revenues coming from new products. Although the constraint on invested amount identified by [92] is overcome, new barriers about the network stability emerge. Literature deals with network stability and resilience through several approaches. Game approaches have been used to find optimal strategies for cooperation [97] also combined with Multi-Agent Simulation [96]. Several optimization model have been proposed (e.g., [59]) also in multi-objective form [12] to properly design the network. The thesis contributes to the literature by proposing an approach useful for individual companies during the selection of partnerships for IS to evaluate the potential performances achievable by the network. It is based on the concept of "Commitment Keeping Mechanisms" (CKM), which acts for the entire duration of the partnership, adapting to the economic and environmental performance of the network. This approach helps individual companies to identify the best cluster of technologies and number of other companies through the comparison of economic and environmental performances under different CKM.

### 3.1.3 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 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.

## 3.2 Commitment Keeping Mechanisms for stability and resilience

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 [44]. 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 [95]. 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.

### 3.2.1 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 Mixed Integer Non-Linear model, proposed in thesis, 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 [18]. 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.

### 3.2.2 Commitment Keeping Mechanism for the negotiation phase

Since all the Industrial Symbiosis networks (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 [20]. 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.

That 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 ([90]; [88]; [13]):

- 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.

**Implication for the link network-operational level**

This CKM is compatible with the framework described in the first chapter of this summary, 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 [19]. 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 [35]. Companies struggle to assess the economic viability of IS over time [72] and the monitoring results easier through the definition, during negotiation phase, of the contributes of each stakeholder.

# Discussion

The contribution of this thesis is the identification of an approach oriented to the sustainable development from both the systemic and the individual company point of view. The integration of the individual companies into a joined network of IS and SCs overcomes most of the barriers of the diffusion of IS. It supports the achievement of economic and environmental performance. The emerging difficulties of managing the large networks, characterized by many incoming and outcoming flows, and coordinating the operations of many companies can be overcame through the adoption of technologies of I4.0 paradigm.

Eco-innovation can be the practical way to pursue sustainable development within companies; however, the most of the studies focus on the identification of barriers and drivers and KPIs. Hence, there is a lack of practical, quantitative and structured methodologies able to lead companies. However, the concurrent pursue of product, process and organizational Eco-innovation is tightly linked to the improvement of current production systems and their interconnection with those of other companies. The tools and the methods used for the value creation analysis and the assessment of efficiency of the production systems are not fully compatible with methods and tools for environmental analysis. Furthermore, both the kind of tools cannot exploit the benefits of new manufacturing paradigm, which is fundamental for the proposed approach of integrating IS and SCs. Hence, a new formalization approach based on Multi-layer Stream Mapping together with a combination of Material Flow Analysis and Enterprise Input-Output approach. It is a formalization method flexible to be exploited via basic tools for value analysis, such as MEIO Stream Mapping, but also exploited via more complex approaches such as Material Flow Cost Analysis, mathematical programming and simulation approaches. It has been applied to the InnovaEcoFood project to assess the value creation process; and in Acea Pinerolese, and the EngiCOIN project, to show the MEIO data-driven version.

This thesis contributes to the literature with a quantitative approach to support and lead the Eco-innovation process within companies. The proposed methodology combines the need for cooperation of companies with system innovation. It is focused on the point of view of the individual companies to identify the characteristics of the potential partners, instead of the interactions of multiple stakeholders. Hence, it is complementary to the various approaches to identify partners for IS and to design and improve symbiotic networks. It sharply fills the gap in the literature of practical methodologies to concurrently evaluate IS opportunities and new technologies for system improvement. The MEIO formalization method provides data for the mathematical programming model where design and geographical factors ares used for assessing the adoption of new technologies.

The methodology shows to be effective for guiding the Eco-innovation process within companies, from the geographical and design factor collection to their use for identifying critical resource flows. 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. Some technologies improve operations performance of the system, while others are suitable for IS improvement. Furthermore, the extension of the mathematical model for addressing the multiple stakeholders interactions allows the investigation of mechanisms to increase the robustness of the joined network. A Commitment Keeping Mechanism based on the Payback Period has been proposed to ensure the network stability, by incentivizing the individual companies to avoid the decreasing of effort.

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