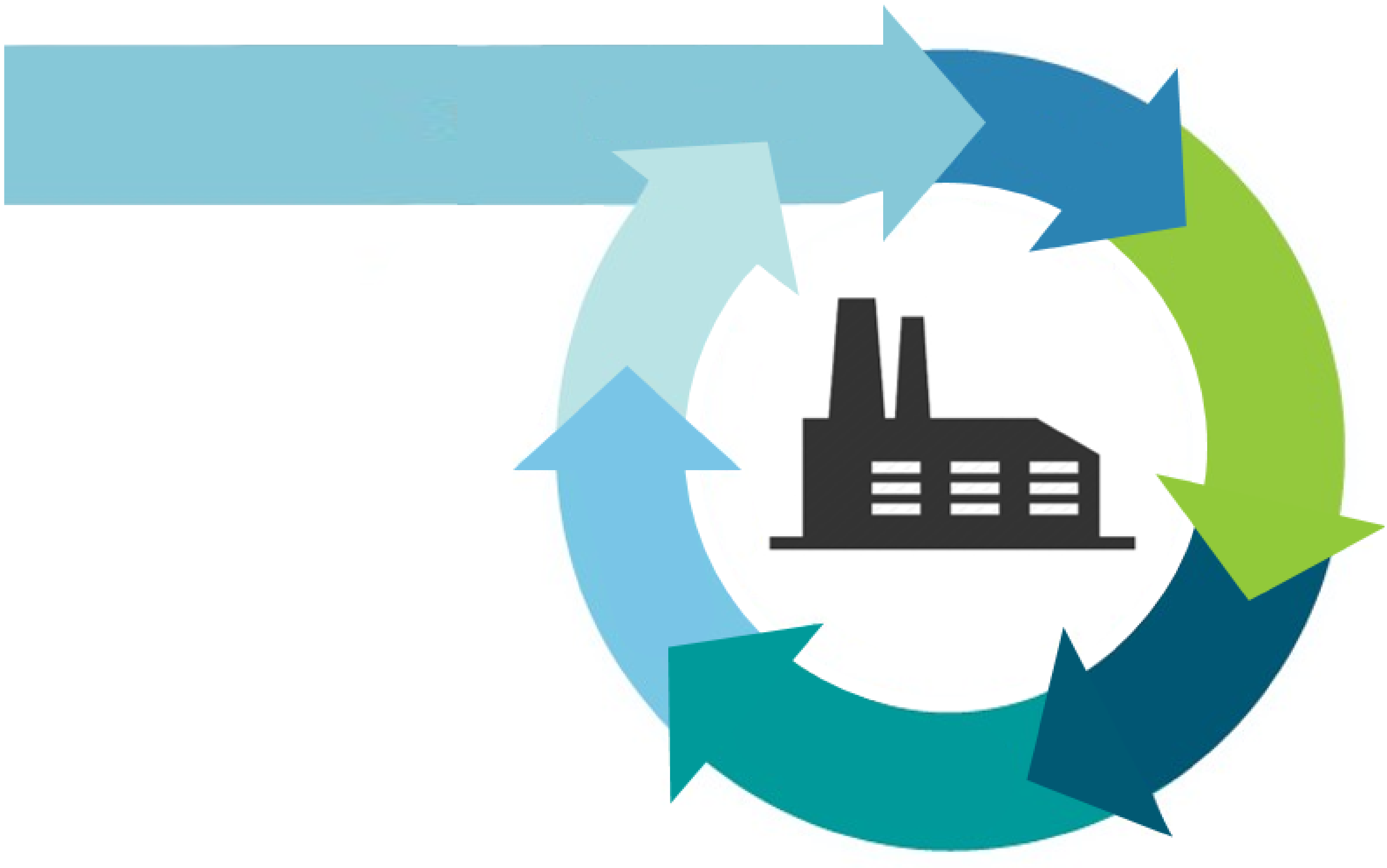
INNOVATION OF THE **PROCESS-EQUIPMENT** SYSTEM IN A CONTEXT OF **SUSTAINABILITY**



Gregorio
Ridaura Aldana

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Innovation of the process-equipment system in a context of sustainability

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Gregorio Ridaura Aldana

UPC
Universitat Politècnica
de Catalunya

Thesis for the Degree
of Doctor in Sustainability

IS.UPC
Institute of Research in
Science and Sustainability
Technologies

CDEI-UPC
Center of Industrial Equipment
Design

Author:
Gregorio Ridaura Aldana

Directors:
Dr. Carles Riba Romeva
Dr. Irene Buj Corral

Corresponding author:

Gregorio Ridaura Aldana

ridaura@cdei.upc.edu

Center of Industrial Equipment Design (CDEI)

Universitat Politècnica de Catalunya (UPC)

Llorens i Artigas 4, plant 0, building U, 08028

Barcelona, Spain

Tel:+ 34 93 401 08 31, Fax: 934 011 989

http://www.cdei.upc.edu

Whenever a piece of equipment or a system is being designed the consequences are also, explicitly or implicitly, being designed.

If the consequences are to be taken seriously, then the time to take account of them is at the design stage.

(Klein, 1994, p.208)

ABSTRACT

In search to contribute to the current fight against climate change, the industrial sector is immersed in a transition to the Circular Economy (CE) to achieve resource efficiency through the redesign of products and production processes. However, the implementation of the CE closed loops is still in an initial phase and focuses mainly on the recycling of products. Early works on CE emphasized the need to implement an emissions reuse closed loops through technology, but this issue has not been addressed by scientific and industrial experts with a successful implementation in the industry.

Equipment can play a critical role in the redesign of production processes through the implementation of emissions reuse closed loops, as it is in the operational phase of the equipment in which most environmental resources are consumed and most emissions are generated in production processes. The implementation of the emissions reuse closed loops through equipment will only be possible if the equipment consumes resources in production processes more efficiently, reduces waste and emissions and reuses them as a new primary material resource.

The presented thesis proposes a conceptual model for the implementation of the CE emissions reuse closed loops in production processes through equipment as a way to accelerate the transition from industry to CE. The conceptual model integrates the concepts of reduction, reuse, recycling and recovery of emissions of the Cleaner Production (CP) and the transverse analysis of the diachronic and synchronous dimensions of the equipment. The implementation of the proposed conceptual model will only be possible through the redesign of production processes. In this sense, the presented thesis also proposes a process redesign methodology for its implementation.

The redesign for emissions reuse (R4ER) methodology has been verified through application in an equipment manufacturing company and a research institute. The results of the presented thesis have demonstrated that the application of the methodology has allowed the reduction of the consumption of resources, the generation of emissions as well as the reduction of operating costs in a sterilization central and a grinding wheel production process.

UNESCO Codes: 3310.01 Industrial equipment; 3310.03 Industrial processes; 5306.02 Technological innovation.

Keywords: Redesign of processes; Circular economy closed loops; Cleaner production; Reuse of emissions in equipment.

RESUMEN

En busca de contribuir a la lucha actual contra el cambio climático, el sector industrial se encuentra inmerso en una transición hacia la Economía Circular (CE) para lograr la eficiencia de los recursos a través del rediseño de productos y procesos de producción. Sin embargo, la implementación de los bucles cerrados de la CE se encuentra aún en una fase inicial y se centra principalmente en el reciclaje de productos. Los primeros trabajos sobre CE enfatizaron la necesidad de implementar bucles cerrados para la reutilización de emisiones a través de la tecnología, pero este tema no ha sido abordado por expertos científicos e industriales con una implementación exitosa en la industria.

Los equipos pueden jugar un papel crítico en el rediseño de los procesos de producción a través de la implementación de bucles cerrados para la reutilización de emisiones, ya que es en la fase operativa de los equipos en donde se consumen la mayor parte de los recursos ambientales y se generan la mayor parte de las emisiones en los procesos de producción. La implantación de los bucles cerrados para la reutilización de emisiones a través de los equipos sólo será posible si los equipos consumen recursos en los procesos de producción de forma más eficiente, reducen los residuos y las emisiones y los reutilizan como nueva materia prima.

La tesis presentada propone un modelo conceptual para la implementación de los bucles cerrados de la CE para la reutilización de emisiones en los procesos de producción a través de los equipos como una forma de acelerar la transición de la industria a la CE. El modelo conceptual integra los conceptos de reducción, reutilización, reciclaje y recuperación de emisiones de la Producción más Limpia (CP) y el análisis transversal de las dimensiones diacrónicas y síncronas de los equipos. La implementación del modelo conceptual propuesto sólo será posible a través del rediseño de los procesos de producción. En este sentido, la tesis propone también una metodología de rediseño de procesos para su implementación.

La metodología de rediseño para la reutilización de emisiones (R4ER) ha sido verificada mediante su aplicación en una empresa de fabricación de equipos y en un instituto de investigación. Los resultados de la tesis han demostrado que la aplicación de la metodología ha permitido la reducción del consumo de recursos, la generación de emisiones así como la reducción de los costes operativos en una central de esterilización y un proceso de producción de muelas abrasivas.

Códigos UNESCO: 3310.01 Equipos industriales; 3310.03 Procesos industriales; 5306.02 Innovación tecnológica.

Palabras clave: Rediseño de procesos; Bucles cerrados de la economía circular; Producción más limpia; Reutilización de emisiones en equipos.

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Barcelona, January of 2020

APPENDED PUBLICATIONS

This thesis includes and is based on the following publications:

I) Ridaura, G., Llorens, S., Carrillo C., Buj-Corral, I., Riba-Romeva, C. (2018), A Conceptual Tool for the Implementation of the Circular Economy Emissions Reuse Closed Loops through Process Equipment. *Sustainability*, Vol. 10(11), 3912, https://doi.org/10.3390/su10113912

Author contributions: Ridaura and Llorens had the initial idea of the manuscript; Ridaura wrote an original draft. Carrillo, Buj and Riba participated in the formal reviews and supervision.

II) Ridaura, G., Llorens, S., Carrillo C., Buj-Corral, I., Riba-Romeva, C. (2018), Equipment suppliers integration to the redesign for emissions reuse in industrial processes. *Journal of Resources, Conservation and Recycling*, Vol. 131, Pages 75-85. https://doi.org/10.1016/j.resconrec.2017.10.030

Author contributions: Ridaura had the initial idea of the manuscript and wrote an original draft. Carrillo provided the resources for the research and Llorens, Buj and Riba participated in the formal reviews and supervision.

Also, this thesis includes parts presented in the following conferences:

Ridaura, G., Llorens, S., Carrillo C., Riba-Romeva, C. (2015), Equipment Supplier Integration in Sustainable Processes and Services Redesign (poster presentation). *Global Cleaner Production and Sustainable Consumption Conference*, 1 November 2015, Sitges, Spain.

Ridaura, G., Riba-Romeva C. (2015), I.E.S. Industrial Equipment Symbiosis, the Future of the Sustainable Industrial Equipment Design (oral presentation). *Global Cleaner Production and Sustainable Consumption Conference*, 3 November 2015, Sitges, Spain.

Additional publications by the author, but not included in the thesis:

Ridaura, G., Rodriguez, N., O´Cleirigh, S. (2013), Vision of the Renewable Energy and Community Participation in Catalonia (poster presentation). *6th UPC International Seminar on Sustainable Technology Development*, 28 June 2013, Vilanova i la Geltrú, Spain.

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INDEX OF ABBREVIATIONS

Abbreviation	Description
€	Euro
4Rs	Reduce, Reuse, Recycle and Recovery
ARC	Analysis of Relations of Coexistence
BAT	Best Available Techniques
BPC	Business Process Change
BPM	Business Process Management
BPR	Business Process Redesign
C	CEQUIP Survey
c	Specific Heat Constant
CDEI-UPC	Center of Industrial Equipment Design, Universitat Politècnica de Catalunya
CE	Circular Economy
CEQUIP	Cluster of Equipment Manufacturing Companies in Catalonia
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
CONACYT	National Council of Science and Technology of Mexico
COP21	Paris Climate Conference
CP	Cleaner Production
CT	Cleaner Technologies
DFMEA	Design Failure Mode and Effects Analysis
EMS	Energy Management System
ER	Equipment Review
EU	European Union
EVT	Environmental Technology Verification
FR	Functional Requirements
GHG	Greenhouse Gases
GmII	Grinding Machine II
GW	Grinding Wheels Case Study
l	Liter
IDE´s	Energy Performance Indicator
IDEF0	Integration Definition for Function Modeling
IE	Industrial Ecology
IFW	Institute of Production Engineering and Machine Tools
IS-UPC	Sustainability Institute, Universitat Politècnica de Catalunya
JIT	Just in Time
kcal	Kilocalories
Kg	Kilogram
kWh	Kilowatt hour
LCA	Life Cycle Analysis
LUH	Leibniz University Hannover
m	Mass
MDGs	Millennium Development Goals
MEIE	Mechanical Engineering and Industrial Equipment
MFCA	Material Flow Cost Accounting

min	Minute
NE	New Equipment Case Study
ºC	Celsius Degrees
OECD	Organisation for Economic Co-operation and Development
OM	Operation Management
Op.	Operation
PD	Design Parameters
PDCA	Plan-Do-Check-Act
PSD	Production System Design Framework
PZH	Hannover Centre for Production Technology
Qi	Total Volume of Input
Qo	Total Measure Volume of Output
R4ER	Redesign for Emissions Reuse
ResCom	Resource Conservative Manufacturing
RQ1	First Research Question
RQ2	Second Research Question
S	Sterilizer
SC	Sterilization Central Case Study
SD	Sustainable Development
SDGs	Sustainable Development Goals
SM	Sterilizer Manufacturing Case Study
Sm	Sintering Machine
SOI	Sustainability-Oriented Innovation
SOp	Sterilizer Operation
SPC	Statistical Process Control
T	Temperature
Tf	Final Temperature Sterilizer
Tfs	Final Temperature Sterilizer
Ti	Initial Temperature
TiWm	Initial Temperature Wasch Machine
TPS	Toyota Production System
TQM	Total Quality Management
TTS	Theory of Technical Systems
VSM	Value Stream Mapping
Wm	Wasch Machine
WmOp	Wasch Machine Operation
ΔQ	Heat Variation
ΔS	Stored Water Volume Change

1. INTRODUCTION

The presented chapter justifies the importance of research in the area of innovation of the process and equipment in a context of sustainability. Based on the current necessary transition towards sustainable production processes in the industry, the research objectives and questions are defined. In addition, the methodology followed for the development of the thesis and the thesis structure are presented.

1.1 BACKGROUND

1.1.1 General framework

It is a fact that humanity is currently facing the great challenge of surviving as a specie on planet earth. This great challenge lies in facing two global problems: Climate change and global poverty, since vulnerability to global warming depends not only on climate but also on the development model (Milanovic, 2016; Roser and Ortiz-Ospina, 2019; Steffen et al., 2015).

The current efforts of world governments have allowed two principal global agreements on climate change and sustainable development that are a universal call for action to end poverty, protect the planet and ensure that all people enjoy peace, harmony and prosperity. In December 2015, 195 countries adopted the fist-ever universal, legally binding global climate deal at the Paris Climate Conference (COP21). The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C (UN, 2015a). Climate change has a strong relationship with sustainable development (Kyte, 2014), For this reason, in the same year, more than 150 heads of state and government adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) to achieve a sustainable world in the period 2016-2030 (UN, 2015b). The SDGs are heirs of the Millennium Development Goals (MDGs) and seek to expand the successes achieved with them, as well as achieve those goals that were not achieved (UN, 2018). The SDGs present the uniqueness of urging all countries, whether rich, poor or middle-income, to adopt measures to promote prosperity while protecting the planet. These two agreements provide a set of common standards and achievable targets to reduce carbon emissions, manage the risks of climate change and natural disasters, and to build back better after a crisis.

Climate change also affects public health, food and water security, migration, peace and security (Kyte, 2014). If climate change is not stopped, it will put back what has been achieved with development in recent decades and will make it impossible to continue moving forward. Implementing actions against climate change promotes sustainable development and vice versa. Investments in favor of sustainable development help to address climate change by reducing emissions and increasing climate resilience. If the Paris Agreement and the Agenda for Sustainable Development are not met decisively by governments in their fight against climate change, humanity could cross a point of no return by 2035. The year when the possibilities of limiting global warming to 2°C in 2100 would be reduced (Aengenheyster et al., 2018) threatening our future existence on the planet.

In this scenario, the industrial sector plays a fundamental role in the implementation of these two agreements since this sector is responsible for the generation of the third largest amount (21% in 2010) of global greenhouse gases (GHG)(IPCC, 2015). Figure 1 shows the global GHG emissions by economic sector in 2010.

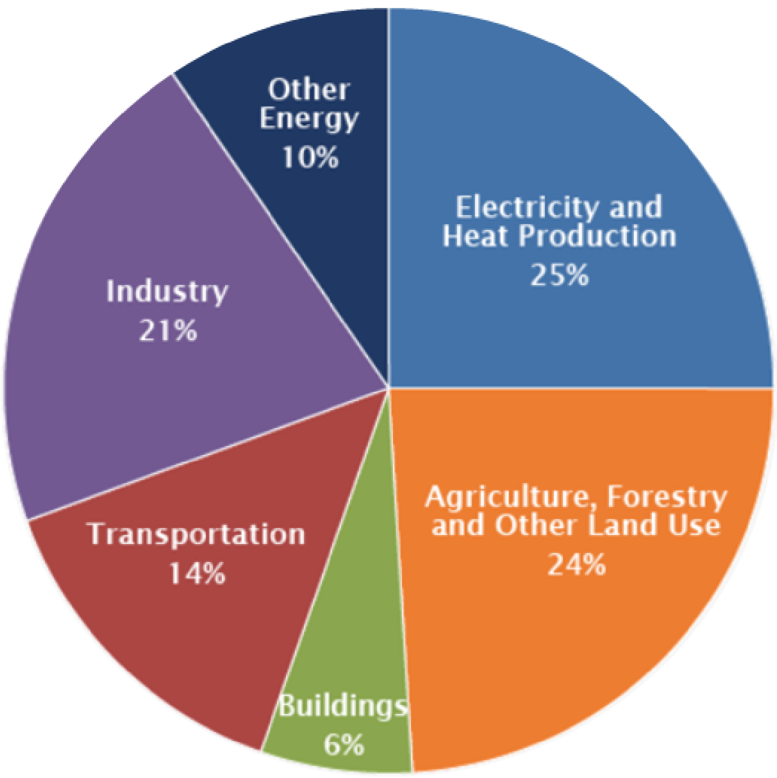

Figure 1. Global GHG emissions by economic sector in 2010 (IPCC, 2015).

The 2030 Agenda for Sustainable Development and its 17 SDGs includes, unlike the Millennium Development Goals (MDGs), new areas such as climate change, economic inequality, innovation, sustainable consumption, peace and justice, among other priorities. The goals are interconnected, meaning success in one affects the success in others. In this sense, the industry has also an essential role in the implementation of measures that allows the fulfillment of different objectives but especially through SDGs 12: Responsible

Consumption and Production (UN, 2019). The goal is to ensure sustainable consumption and production patterns promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs and a better quality of life for all. It involves different stakeholders, including business, consumers, policy makers, researchers, scientists, retailers, media, and development cooperation agencies, among others.

Overall, the SDG 12: Responsible Consumption and Production seeks to reduce the industry ecological footprint, which is the amount of environment required to produce the goods and services necessary to maintain our lifestyle (WWF, 2019), by changing the methods of production and consumption of goods and resources. This objective urges industries, businesses and consumers to recycle and reduce waste, as well as to support developing countries to move towards sustainable patterns of consumption by 2030. Figure 2 shows the global map of ecological footprint of consumption in 2014.

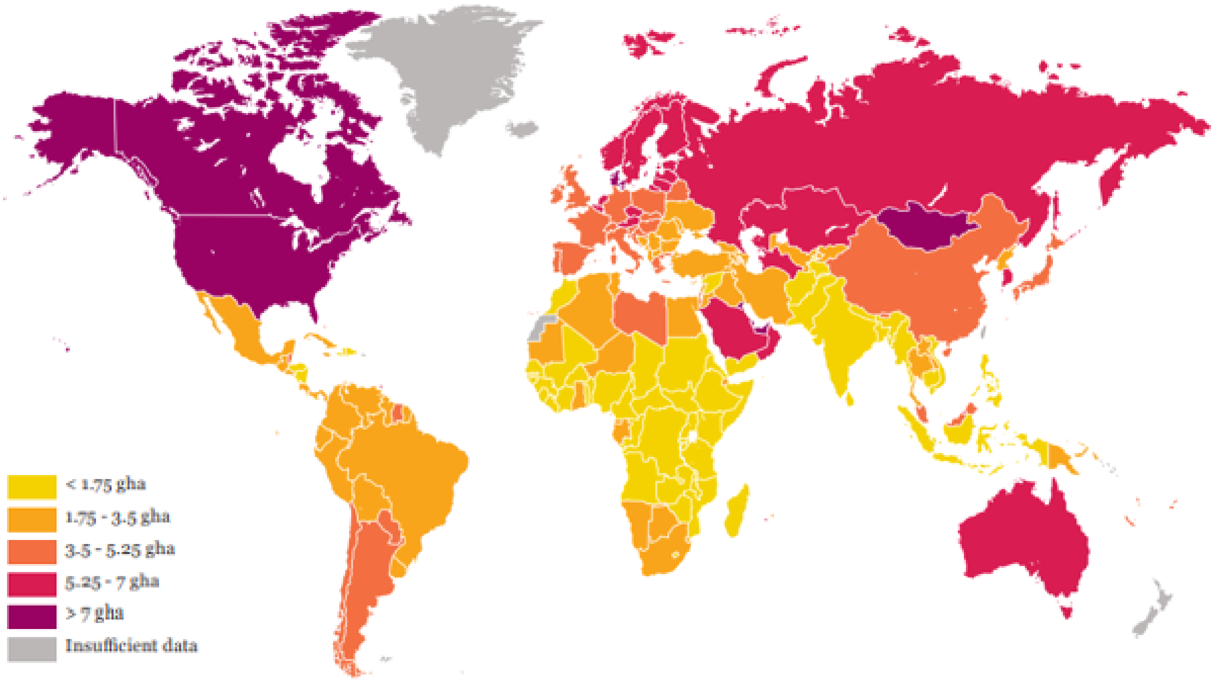

Figure 2. Global map of ecological footprint of consumption in 2014 (WWF, 2018).

At European level, the industrial sector was responsible for the generation of 849 million tons of CO_2 equivalent (CO_2eq) in 2016. Figure 3 shows the GHG emissions by economic sector in the European Union (EU) from 1990 to 2016.

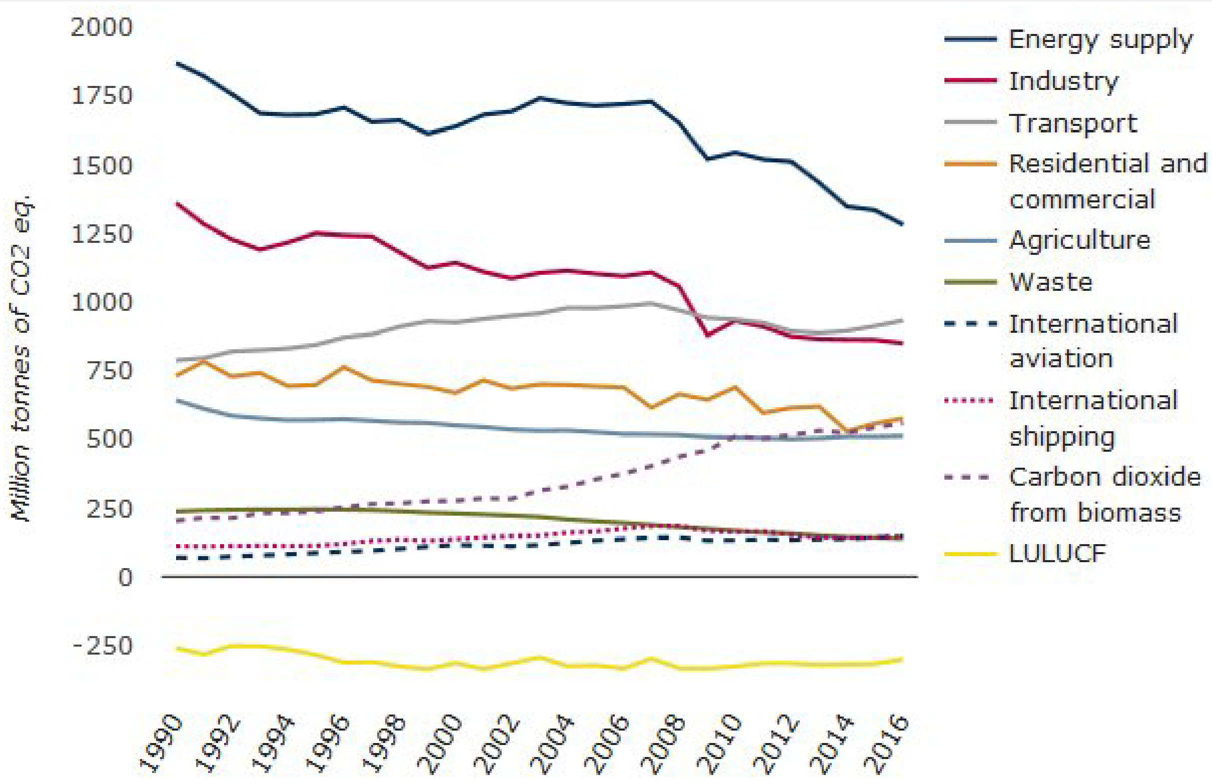

Figure 3. GHG emissions by sector in the EU-28 (EEA, 2018).

The EU contributes to the achievement of the objectives of these two agreements in the fight against climate change through the European Union's climate strategies. The targets seek to reduce progressively the European GHG emissions at least 20% in 2020, 40% in 2040 and up to 80% below in 2050 compared to 1990 values (EC, 2019a) and with the implementation of the 2030 Agenda for Sustainable Development and its 17 SDGs in different ways.

In relation to the industrial sector, the EU has opted for the implementation of the Circular Economy (CE) philosophy to address the SDG 12: Responsible Consumption and Production (EC, 2019b). In contrast whit the linear economy, which assumes that natural resources are abundant, easy to obtain and cheap to dispose (EEA, 2016), CE is “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops” (Geissdoerfer et al., 2017). The CE concept is based on the effective design and implementation of products and production processes to improve resource efficiency with a circular flow (closed loop) of materials involving the recovery, reuse and recycling of wasteful resources (Jawahir and Bradley, 2016; Jiao and Boons, 2014). Figure 4 shows a CE conceptual diagram for the EU.

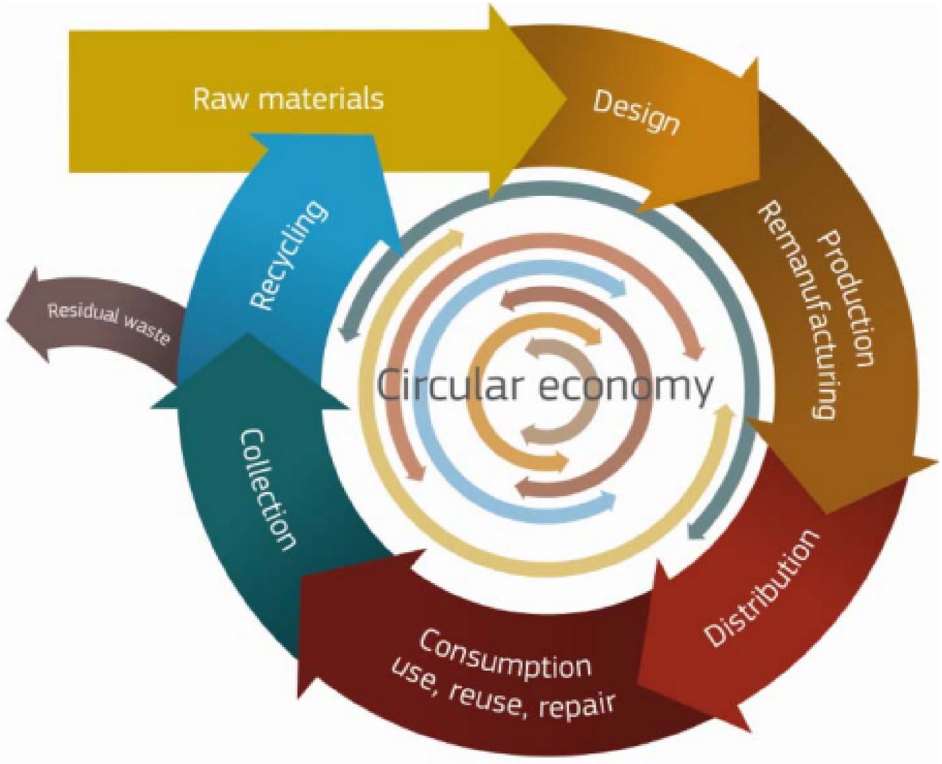

Figure 4. CE conceptual diagram (EC, 2014a).

There are considerable efforts to seize the implementation of the CE in the EU in recent years. In 2011, the vision that by 2050 the EU's economy will grow in a way that respects resource constraints and planetary boundaries, all resources will sustainably managed, from raw materials to energy, water, air, land and soil and the climate change milestones have been reached. The publication by the EC of the *Roadmap to a Resource Efficient Europe* (EC, 2011) set the EU on the path to this transformation. This initiative focused in the coordination of cross-national action plans and policies on the formulation of sustainable growth.

In July 2014 with the Fitness Check of Five Waste Stream Directives (EC, 2014b), the Commission started reviewing the body of EU legislation about waste reviewing the targets in directives as waste, packaging and packaging waste, landfill of waste, end-of-life vehicles, batteries and accumulators and waste batteries and accumulators, waste electrical and electronic equipment. Later, in September of that same year, the Commission launches the program: *Towards a circular economy: A zero waste programme for Europe* (EC, 2014a) with the aim of proposing the CE as a support for sustainable growth, setting up an enabling policy framework, modernizing waste policy by turning waste into a resource and setting a resource efficiency target for the EU. The program emphasized that:

> "An important starting-point is the design of production processes, products and services. Products can be redesigned to be used longer, repaired, upgraded,

> remanufactured or eventually recycled, instead of being thrown away. Production processes can be based more on the reusability of products and raw materials, and the restorative capacity of natural resources, while innovative business models can create a new relationship between companies and consumers" (EC, 2014a).

More recently, in December 2015, the EC adopted an ambitious new CE Package to help European businesses and consumers to make the transition to a stronger and more CE where resources are used in a more sustainable way. The plan comprises actions in the industrial sector covering the complete cycle: from production and consumption to waste management and the market for secondary raw materials and a revised legislative proposal on waste. The proposed actions will contribute to "closing the loop" of product lifecycles through greater recycling and re-use, and bring benefits for both the environment and the economy. The action plan will extract the maximum value and use from all raw materials, products and waste, fostering energy savings and reducing greenhouse gas emissions. The EU action plan for the CE promotes the reparability, upgradability, durability, and recyclability of products by developing product requirements under the Eco-design Directive (2009/125/EC). The objective is to improve the efficiency and environmental performance of energy-related products.

But, even when products or materials are designed in a smart way, an inefficient use of resources in the production processes can cause an important amount of waste and the loss of business opportunities (EC, 2015a). In this context, the EC proposed:

> Production processes must be redesigned to use resources more efficiently, and with this, reduce the generation of waste, create business opportunities, boost the innovation and preserving our environment (EC, 2015b).

To achieve this, the CE action plan includes guidance on best waste management and resource efficiency practices in industrial sectors in Best Available Techniques (BAT) (EC, 2019c) and will issue guidance and promote best practices on mining waste. Also, the EC proposed (in the revised legislative proposals on waste) to clarify rules on by-products to facilitate industrial symbiosis and to help create a level-playing field across the EU.

As can be seen, today more than ever the industrial sector must adapt their production processes the actual context of sustainability through the inclusion of the closed loops in the redesign of products and production processes. However, even with all the actions carried out to date by the EU, the implementation of CE closed loops is still in an initial phase and focuses mainly on the recycling of components of products (Ghisellini et al., 2016; Stahel, 2016). Thus, there is a clear scientific and industrial need to develop solutions to accelerate the transition from industry sector to CE through the implementation of closed loops not only in recycling of products, but also in the reduction, reuse, recycle and recovery of emissions in production processes (Jawahir and Bradley, 2016).

1.1.2 The critical role of the equipment in the implementation of the CE closed loops in production processes

Early works on CE emphasized the need to implement an emissions reuse closed loop through technology, but this issue has not been addressed by scientific and industrial experts with a successful implementation in the industry (Jawahir and Bradley, 2016). In this sense, equipment can play a critical role in the redesign of production processes (Camilleri, 2018) through the implementation of CE emissions reuse closed loop (Jawahir and Bradley, 2016; UNEP, 2017) since is the operation phase of the equipment in which most of the environmental resources in production processes are consumed (Mohammadi et al., 2014) and most of the emissions are generated (Jönbrink et al., 2011).

The implementation of the emissions reuse closed loops through the equipment will be only possible when the equipment consumes resources in production processes in a more efficient way, reducing waste and emissions and reusing them as a new primary material resources (Delft, 2014). This implementation must be supported by appropriate analysis and evaluation tools (Alves et al., 2015) that simultaneously consider all of the equipment involved in a production process as part of whole system, where a reduction in the consumption of resources in the equipment directly results in a reduction in the consumption of resources in the production process since changes in technology allow important changes in the production process (Darses, 2002; Pisano, 1996).

The presented thesis proposes a conceptual model for the implementation of the emissions reuse closed loops through equipment process as a way to accelerate the transition from industry to the CE. The conceptual model combines the concepts of reduction, reuse, recycling and recovery of emissions from the Cleaner Production (CP) (Gomes da Silva and Gouveia, 2020) and the transverse analysis of the diachronic and synchronic dimensions of the equipment (Llorens, 2015), with the objective of establishing a basis for the development of a methodology for the sustainable redesign of production processes.

The redesign for emissions reuse (R4ER) methodology integrates different tools such as the Integration Definition for Function Modeling (IDEF0), the Life Cycle Analysis (LCA), the Material Flow Cost Accounting (MFCA) and the extension of the Analysis of Relations of Coexistence (ARC) of the equipment (Llorens, 2015) to environmental issues (EARC). The main objective of the R4ER methodology is the reduction of resource consumption, emissions generation, as well as operating costs of production processes through the redesign of the process that allows the reuse of emissions between the equipment.

1.2 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

The discussion presented above establishes two conclusions. The first conclusion states that there is a current need for the industry to reduce the emissions of its production processes to the environment in order to contribute decisively to the achievement of the objectives of climate change agreements through the sustainable redesign of production processes. The second conclusion establishes the critical role of the equipment in the sustainable redesign of industrial processes through the implementation of emissions reuse closed loops.

However, although the literature reviewed shows a substantial body of existing knowledge that evidences the existing process-equipment relationship, no previous studies have been found that explore the possibility of innovate this relationship in a context of sustainability. Based on this, the following objective is formulated:

The objective of the presented thesis is to **develop knowledge that contributes to the innovation of the process-equipment system in a context of sustainability.**

In order to achieve the research objective, the following research questions have been formulated:

RQ1: How can the process-equipment system be innovated in a context of sustainability?

RQ2: What characterizes the innovation of the process-equipment system in a context of sustainability?

The first research question will be answered through a proposal on how the process-equipment system can be innovated in a context of sustainability. The second research question will be answered with the characterization of the proposed innovation.

1.3 DEVELOPMENT OF THE THESIS

In order to carry out the presented thesis, it was essential to have the resources and infrastructure of different academic and industrial entities in the cities of Barcelona and Castelldefels in Spain and Hannover in Germany.

- Since 2012, the author participated in different workshops, courses, contests, conferences and seminars of the Institute for Sustainability Science and Technology (IS-UPC) of the Universitat Politècnica de Catalunya as well as the use of resources at UPC libraries. In 2013, the author attended some classes of the master's degree in Sustainability Science and Technology of the institute. The IS-UPC promotes and coordinates the interdisciplinary and transdisciplinary research, the development and innovation in sustainability and environment in the UPC;

- From 2012 to 2016 a full PhD stay was made in the Center for Industrial Equipment Design of the Universitat Politècnica de Catalunya (CDEI-UPC). This stay allowed to establish a first contact with the design of machines and development of industrial equipment and with this motivate the realization of the presented thesis by following the research line of the center. Likewise, the author participated in the internationalization process of the CDEI to Mexico (see appendix C). The CDEI-UPC is an expert center in the development of industrial equipment with a very broad field of activity, from the conception, design, simulation and calculations of equipment and products until handling their prototypes and testing stages. The CDEI-UPC is also part of the Network of Centers for Technological Innovation Support of the Generality of Catalonia (TECNIO brand) and the CIT-UPC Technology Center of the Universitat Politècnica de Catalunya. The CDEI-UPC has become a key player supporting many important equipment manufacturer companies. Derived from this relationship, there has been an opportunity to implement the proposal of the presented thesis in a company;
- From 2013 to 2016, a PhD stay was made in an equipment manufacturing company. During this time an ISO 50001: 2011 energy management system (EMS) was implemented to the manufacturing process of sterilizers (see appendix D). Also, the methodology proposed in the presented thesis was applied in a sterilization central within the portfolio of products of the company. The company is the Europe's sterilization leader and is responsible for the design, manufacture, marketing and technical service for sterilizers, washing machines and surgical units;
- In 2015, the project was presented in an oral and poster session at the Global Cleaner Production and Sustainable Consumption Conference in Sitges, Spain;
- In the period of 2016 to 2018 two manuscripts were wrote and published in indexed journals (see appendix A);
- In 2018 the second retrospective case study was carried out during an international PhD stay of 3 months in a research Institute of Production Engineering and Machine Tools (IFW) of the Leibniz University in Hannover, Germany. The IFW focuses on all aspects of production engineering, from the machining process and the development of machines to production planning and organization. It combines experimental, theoretical and simulation-based methods, covering basic and applied research and offering services and consulting. The institute is an intermediary between research and practice, keeping the close links between university and industry. In addition to R&D, teaching is another focal point of the institute;
- Additionally, from 2013 until today, the author has participated as a docent of the subject Design for Energy Efficiency in industrial Equipment within the Master of Mechanical

Engineering and Industrial Equipment (MEIE) at the School of Professional & Executive Development of the Universitat Politècnica de Catalunya.

1.4 THESIS STRUCTURE

This research thesis is divided into two main parts. Part 1 provides an overview of the research conducted (Figure 5) and part 2 comprises the appendices of thesis including the research publications published during the development of the thesis.

- Part 1 consist of eight chapters (summarized in Figure 5). In the introductory Chapter 1, the general framework motivating this research as well as the objective and research questions are presented. The chapter ends with an explanation of the development and structure of the thesis. In the Chapter 2, the frame of reference of the presented thesis is summarized and an explanation of the literature gap found are presented. Chapter 3 describes the research methodology starting with the choice of the research approach, the research design and the data collection process. Finally, the chapter concludes with a discussion about the reliability and validity and a description of the process for the data analysis. In Chapter 4 the results of the four case studies and the survey are presented. The Chapter 5 answers the first research question by developing a conceptual model for the implementation of the reuse of emissions closed loops through process equipment. In the Chapter 6, the answers for the second research question is synthesized into a methodology for the sustainable redesign of production processes. Chapter 7 describes the general aspects of the cases of implementation presented in the previous chapter in two different entities related to the equipment manufacturing industry. Finally, the Chapter 8 presents the discussions and conclusions of the thesis as well as suggestions for future research.
- Part 2 comprises five appendices. The appendix A presents the research articles published during the development of the presented thesis. Paper I is the main article related to the first research question as it proposed a conceptual model for the implementation of the emissions reuse closed loops through the equipment and the Paper II is related to the second research question by characterizing the previously proposed model in a methodology for the redesign of sustainable production processes. Appendix B shows the improvement proposal sheet used in the Case SM. Appendices C and D show an overview of the process of internationalization of the CDEI-UPC to Mexico and the implementation of an EMS in an equipment manufacturing company, respectively. Appendices E and F present the format used in the application of the Survey C and the curriculum vitae of the researcher.

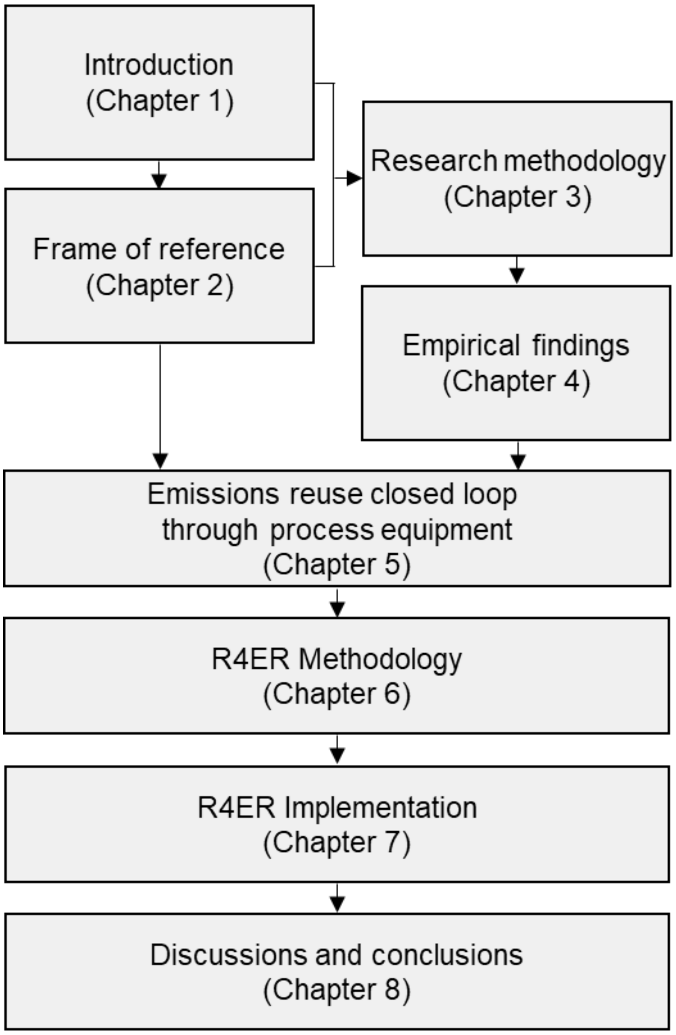

Figure 5. Thesis structure.

2. FRAME OF REFERENCE

In this chapter, the frame of reference of the presented thesis is summarized and divided into two main areas of research: the process-equipment system and the innovation of production processes in a context of sustainability. The chapter ends with an explanation of the research gap found in the reviewed literature.

2.1 PROCESS-EQUIPMENT SYSTEM

Before beginning with the development of this chapter, it is essential to mention the definitions of the principal terms related to this research. The definition of the terms varies between different authors, those adopted in the presented thesis are described below.

- An operative *process* is a "process in which an equipment product or process equipment works as an operator. It is also the set of tasks (or operations) and the relationships involved in a manufacturing process or providing a service" (Riba et al., 2005, p. 5). This definition implies that an operative process involves not only the equipment that operate in it, but also the relationships between the operations and between the equipment.
- The term *equipment* can be defined as the element of machine, tool, accessory, installation or program that participates together with other elements of equipment (equipment set) in an operative process as technical operators (Riba et al., 2005). Processes are structured set of operations in which the operands are subject to a transformation by the operators (humans, technical and environmental) with the concourse of secondary flows that are necessary to the transformation. Equipment as a technical operator producing deliberate effects on an operand in an operative process.
- Finally, a *system* is defined as "a collection of different components, such as for example people and machines, which are interrelated in an organized way and work together towards a purposeful goal" (Bellgran and Säfsten, 2010, p. 38). The definition emphasizes the need to have a holistic view of the components of the system to avoid sub-optimization of the different parts of the system and thus reduce the risk of disturbances.

According to systems theory, a system has a hierarchical and relational structures (Göpfert, 1998). The hierarchical structure decomposes the system into multiple subsystems where the higher system always contains the lower subsystems called elements (Schuh et al., 2004). The relational structure describes the system as a whole that can only be understood through the analysis of the horizontal input/output relationships between the elements at system level (Skyttner, 2005).

A system must adapt to changes in its internal and external environment (Hitomi, 1996). The external environment is everything outside of the boundaries of the system that influences and is influenced by the system (Wu, 1992). In contrast to closed systems, systems that interact with their external environment are open systems (Dekkers, 2015).

The addition of the word *system* to the *process-equipment* concept refers to the technical subsystem defined by Wu (1994) and Groover (2008) as the hardware that is directly linked to the production process including machines, equipment, tools, fixtures and robots. Consequently, in the presented thesis the term *process-equipment system* is defined based on the different concepts presented by Riba et al., (2005) as the system formed by an operative process, the equipment, the operands and secondary flows involved in which the transformation from input into desired outputs takes place. Figure 6 represents the process-equipment system model as a foundation for the presented thesis.

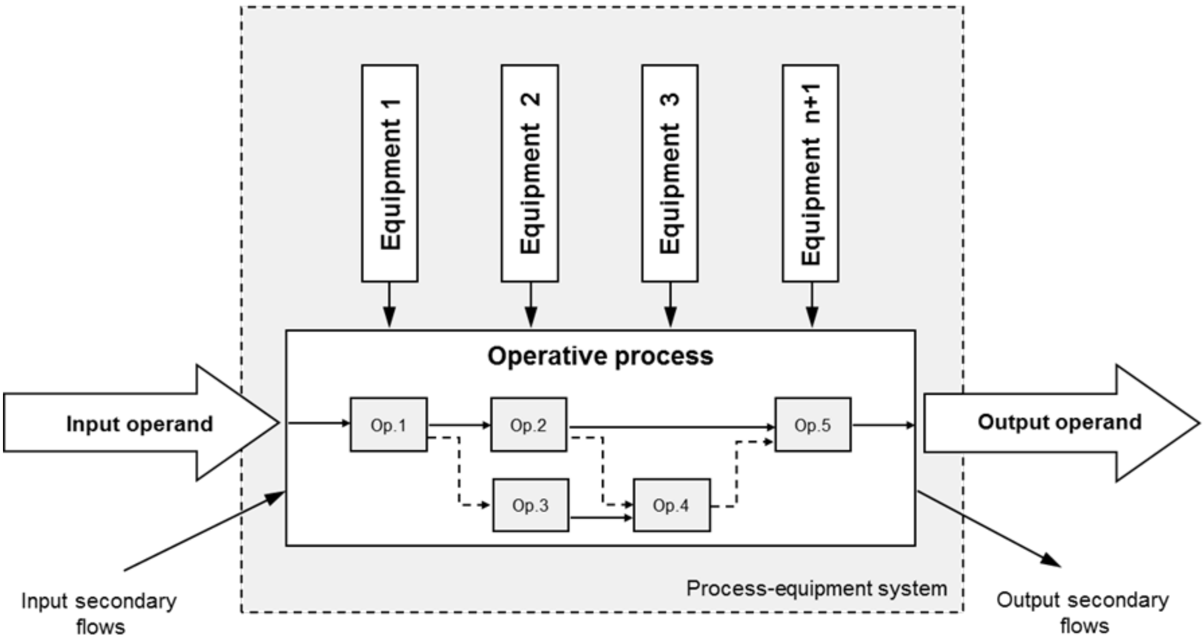

Figure 6. The process-equipment system model. Adapted from (Riba et al., 2005).

The analyzed process-equipment system in the presented thesis is an open system that forms part of a larger production system. Overall, this system is dependent on and is affected by the current context of sustainability, to which it must be adapted.

2.1.1 The holistic perspective in the process-equipment system

The application of the systems perspective to the production systems facilitates the use of the holistic perspective (Bellgran and Säfsten, 2010; Bradford and Childe, 2002; Vaughn, 2002). Contrary to reductionism (Wu, 1992), holism understands that systems have a number of relationships with different complexities, which are not easily understood when analyzing the isolated components of a complete system (Bond and Morrison-Saunders, 2011). Therefore, a holistic perspective considers all subsystems and elements of a system as well as the relationships between them (Rösiö, 2012).

The holistic perspective should be the base for the design of production systems (Bellgran and Bruch, 2015) since this implies the consideration of all of the technical and physical parts, the humans and the way of organization of the work in its design (Bellgran, 1998; Bennett, 1986). The aim is eliminating disturbances and avoiding sub optimization (Bellgran and Säfsten, 2010; Rösiö, 2012). Bruch and Bellgran (2013) found that there is a need for the use of the holistic perspective in the design of production systems to ensure their fit with the internal and external environment. The holistic perspective in the design of production systems focuses first on the system as a black box that interacts with its external environment and then on how the subsystems in the internal environment are combined in the search of the general objectives of the system and finally, on the individual elements within the subsystems (Rösiö, 2012).

The notion that a holistic perspective is needed when designing production systems is widely accepted (Bellgran, 1998). In this sense, different authors have mentioned (Bi et al., 2008; Bonney et al., 2000; Jackson, 2000; Mehrabi et al., 2000; Ueda et al., 2001), exemplified (Bellgran and Säfsten, 2010; Cochran et al., 2001; Duda, 2000; Kulak et al., 2005; Matt, 2008; Park and Choi, 2008; Wu, 2001), and explained in detail (Rösiö, 2012; Vaughn and Shields, 2002) the use of the holistic perspective in the design of production systems.

The use of the holistic perspective should focus on all sub-systems of the production system, including the technical system (Bellgran and Säfsten, 2010). The holistic perspective in the technical system understands the system by analyzing the relations between the equipment (Roser et al., 2004). The importance of the use of the holistic perspective has been mentioned, exemplified or explained in detail in the design (Bellgran and Säfsten, 2010; Bennett and Forrester, 1993; Bi et al., 2008; Chryssolouris, 2006; Cochran et al., 2001; Hubka and Eder, 1988; Nof et al., 1997; Rampersad, 1994; Riba et al., 2005; Rösiö, 2012; Stäbler et al., 2017; Vaughn and Shields, 2002) improvement (Buttles-Valdez et al., 2008; Glawar et al., 2016; Pretorius, 2000; Roser et al., 2004; Schuh et al., 2004; Stålberg and Fundin, 2016) of the technical system. However, few authors have dealt with the redesign (Stålberg and Fundin, 2016) and innovation (Llorens, 2015; Manceau and Morand, 2014) of the process-equipment system. Table 1 shows the different authors that were found in the literature and who have mentioned the use of the holistic perspective in the technical system.

Table 1. The use of the holistic perspective in the technical system found in the literature.

Reference	Design	Improvement	Redesign	Innovation
Hubka and Eder, (1988)	■	□	□	□
Bennett and Forrester, (1993)	■	□	□	□
Rampersad, (1994)	■	□	□	□
Nof et al., (1997)	■	□	□	□
Pretorius, (2000)	□	■	□	□
Vaughn and Shields, (2002)	░	□	□	□
Cochran, (2002)	▨	□	□	□
Roser et al., (2004)	□	■	□	□
Riba et al., (2005)	■	■	□	□
Chryssolouris, (2006)	■	□	□	□
Bi et al. (2008)	▨	□	□	□
Buttles-Valdez et al., (2008)	□	░	□	□
Schuh et al. (2005)	□	░	□	□
Bellgran and Säfsten, (2010)	▨	□	□	□
Rösiö, (2012)	▨	□	□	□
Manceau and Morand, (2014)	□	□	□	░
Llorens, (2015)	□	□	□	■
Stålberg and Fundin, (2016)	□	░	□	□
Glawar et al., (2016)	□	▨	□	□
Ståbler et al., (2017)	▨	□	▨	□

Mentioning ░ Explanatory ▨ Detailed description ■

2.1.2 The process as a frame of reference for equipment design

Beyond the need to use the holistic perspective in the design of technical system presented in the previous point, having a holistic view of the production process when designing equipment is essential (Hubka and Eder, 1988; Mohammadi et al., 2014; Riba et al., 2005). In this sense, there is a framework of previous research activities that have underlined that the concept and design of an equipment should be initiated taking into account the process in which the equipment operates. The main theories, methodologies and projects using this approach are described in detail below.

a) Theory of technical system

The first record to understand the design relationship between existing equipment and the production process in which they interact was introduced by Hubka and Eder (1988) when they presented the Theory of Technical Systems (TTS). With the TTS, the authors provided an integral vision of technical system (equipment) by classification and categorization the knowledge about technical equipment in a nature, structure, origin, development and empirical observations and also by definition of a suitable terminology about technical systems.

Technical systems (together with human beings, the information and management systems, and the active environment) exert onto the operands the effects that are necessary to accomplish the desired transformation. Hubka and Eder (1988) mentioned that a technical system is defined for the purpose of this structure in terms of its functions. A *function* "is a property of the technical system, and describes its ability to full-fill a purpose, namely to convert an input measure into a required output measure under precisely given conditions" (Hubka and Eder, 1988). Consequently, they define the *function structure* of a technical system as "a set of elements (functions) and a set of relationships of these functions to one another" (Hubka and Eder, 1988 p. 75). Later, and with the aim of complementing the previous definitions, Hubka and Eder (1992, 1996) established a nexus between the transformation process (process) and the corresponding technical systems (equipment) when they represent the structures of a technical through an one-to-one correspondence between the elements of structure (organ, constructional, and function) and a technical process structure, where all of the function implements the capacity to perform the corresponding process. Figure 7 shows the one-to-one correspondence between the elements of the function and a process structure of a technical system.

Complementary to the previous viewpoints and in order to show the diversity and complexity of processes involving the equipment products, Hubka and Eder propose a schema of technical system life cycle (Hubka and Eder, 1992, 1996, 1988), which is the first precedent of life cycle of an equipment. They defined the technical system life cycle of a system of processes which consist of planning, originating, distributing, using and disposing the technical system emphasizing that "the task (aim, purpose) of technical systems consists of exerting particular effects on the operands in the technical process" (Hubka and Eder, 1988). The TTS presented by Hubka and Eder (1988) represents the base of the research line of the presented thesis when they statement that the technical systems (equipment) are the principal means by which the transformation is achieved and therefore their analysis should be based on the transformation process that reflects the activity in which they are used.

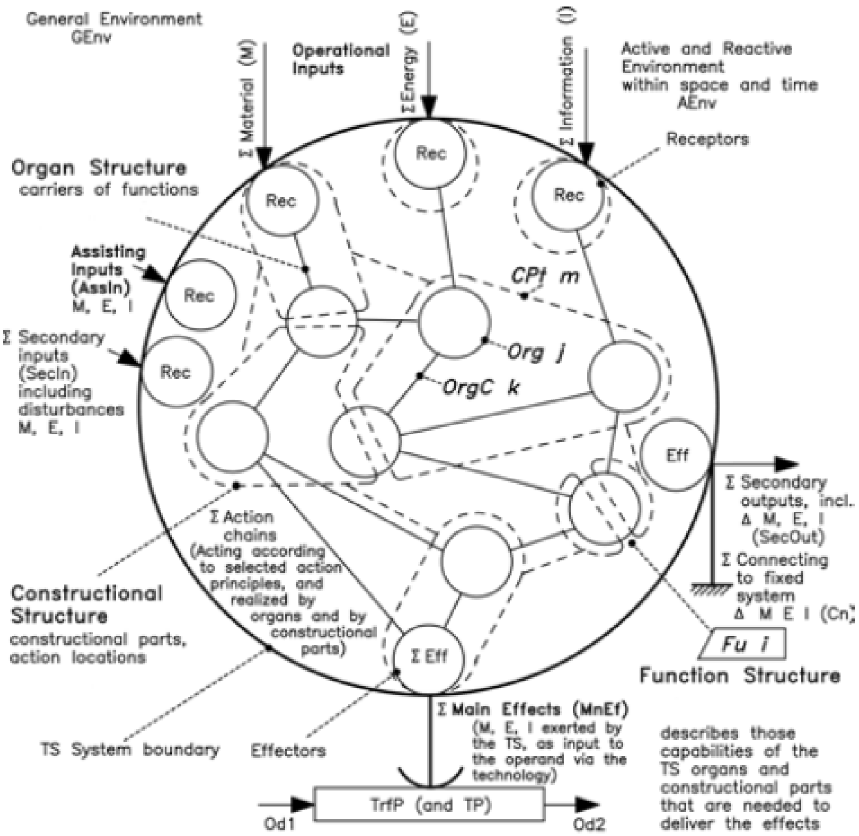

Figure 7. Elements of the structure and a technical process structure in one-to-one correspondence (Hubka and Eder, 1992, 1996).

b) PSD framework

In order to generate guidelines for the design of equipment through the structured decomposition of the functional requirements of a production system, Arinez and Cochran (2000) presented the Production System Design (PSD) Framework. The framework incorporates the production system requirements that affect decisions ranging from investment to the design and operation of the equipment. It consists of the structured decomposition of the Functional Requirements (FR) of the production system that are related to the design parameters (PD) of the equipment through design matrices (Arinez and Cochran, 1999). The PSD framework consists of four main steps: I) identification of requirements, II) creation of views, III) requirements analysis and IV) design decomposition (Cochran et al., 2001). Figure 8 shows the PSD Framework applied to the equipment design.

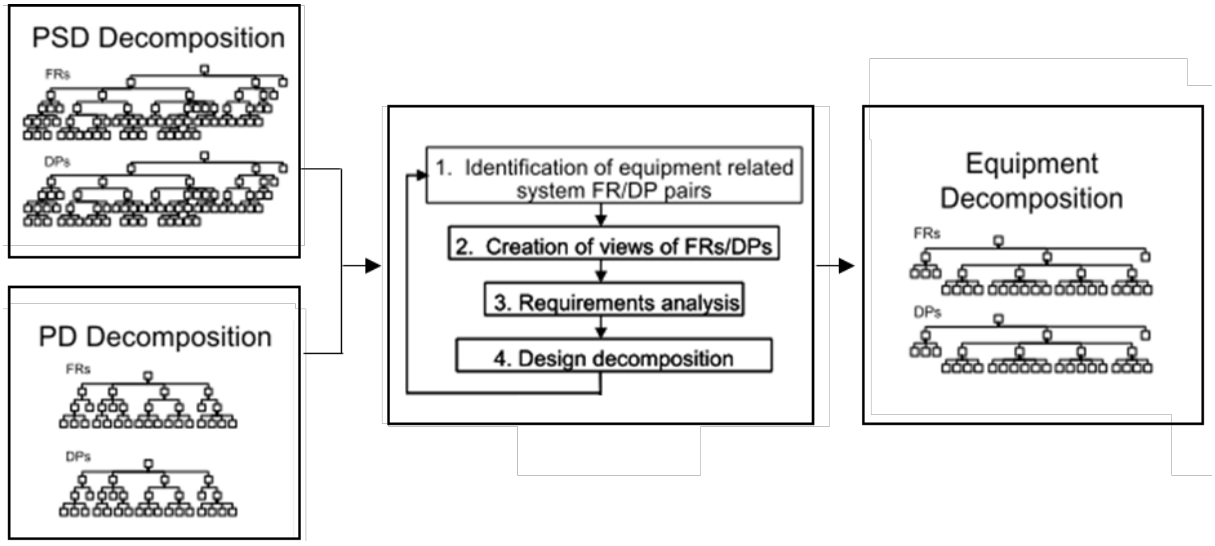

Figure 8. PSD Framework applied to equipment design. Modified from (Arinez and Cochran, 2000)

The first step identifies the FR and DP system requirements that influence the design of the equipment from PSD and PD decomposition. Step two, the identified FR and DP requirements are transformed into "views" for the understanding of the requirements by the designer. A view comprises a subset of PSD PDs with a common design attribute that all PDs related to the equipment in the whole share (Arinez and Cochran, 2000). The next step (3) analyzes the requirements and converts them in objectives and goals that are measurable and verifiable. Finally, the step four is the generation of the equipment design decomposition itself by establishing the FR-DP links between decompositions.

The PSD framework presented by Arinez and Cochran (2000) represents an antecedent of the research line of the presented thesis when proposed an equipment design approach that quantitatively links the production system requirements to the design phase of equipment through the decomposition of the production system. The PSD provides structured design methods that allow equipment designers to understand high-level requirements through their decomposition into equipment design parameters.

c) GAMMA Project

Later in the course of the GAMMA project (Riba et al., 2003), the authors influenced by aspects of Hubka's and Eder's model identified the necessity of a new design perspective that includes the equipment to be designed and the production process to which it contributes.

Contrasting with the end-user products that are used in situations where the relationship between the user and product is direct, the equipment intervenes in more complex production processes (manufacturing of products or services) where the relation between the user and the equipment becomes more indirect (Riba et al., 2003). For the former, conception, design and development product by product, or by families, can provide reasonably satisfactory results but, when this same procedure is applied to the equipment, the great innovation possibilities underlying these complex systems are largely lost (Riba and Molina, 2006). Under this new perspective, Riba et al., (2005) defined a new frame of reference for the design and development of the equipment involved in the production processes under the term *process-equipment.* While the previous design philosophies only accentuate the manufacture and the minimization of cost in the equipment, the *process-equipment* philosophy is pronounced the usability and the effectiveness of the whole system (Riba et al., 2005).

Contrary to the model of Hubka and Eder (1992, 1996) where if only one equipment is considered, the product function and the process tasks are in one-to-one correspondence (see Figure 7), the authors state that if the whole production process is considered, the relationship between process and equipment is much richer and more complex, and the allocation of a task (or part of a task) to different equipment becomes one of the more essential and creative activities during the conception and design stage (Riba et al., 2005). With the purpose of the implementation of this philosophy, the authors articulate new concepts to explore the relationships between the process and the equipment.

Riba et al., (2005) defined the *operative process* as a “process in which an equipment product or process equipment works as an operator. It is also the set of tasks (or operations) and the relationships involved in a manufacturing process or providing a service”. Under this definition, the authors defined the *process architecture* as a “set of constructing rules of the process elements and their relationships” and the *process equipment architecture* as “the result of establishing the constructing rules for the elements and their relationships, and priorities of process equipment”. With these definitions, the authors evidence the existing relationship between the operative process design and the definition of its process equipment architecture. Riba et al., (2005) proposed a schema, adapted for the technical system life cycled presented by Hubka and Eder (1992, 1996, 1988) to emphasize this relationship. Figure 9 shows the design relationships between the operative process and the process equipment architecture.

Riba et al., (2005) mentioned that, when there is a need for a process, the process design and equipment planning represent the first relationship (R1) that allows the definition of the process equipment architecture. In the same way, the design of the equipment and the design of the manufacturing process of the equipment represent the second design relationship (R2) between the process and the equipment. The diagram continues with the manufacture and transfer of the equipment to the user to be part of the subsequent implementation of the process. Subsequently, the equipment together with other operators (human and technical) exert the desired effects on the input operands in the operative process. Finally, the equipment undergoes maintenance and is subsequently removed and disposed of at the end of its life cycle.

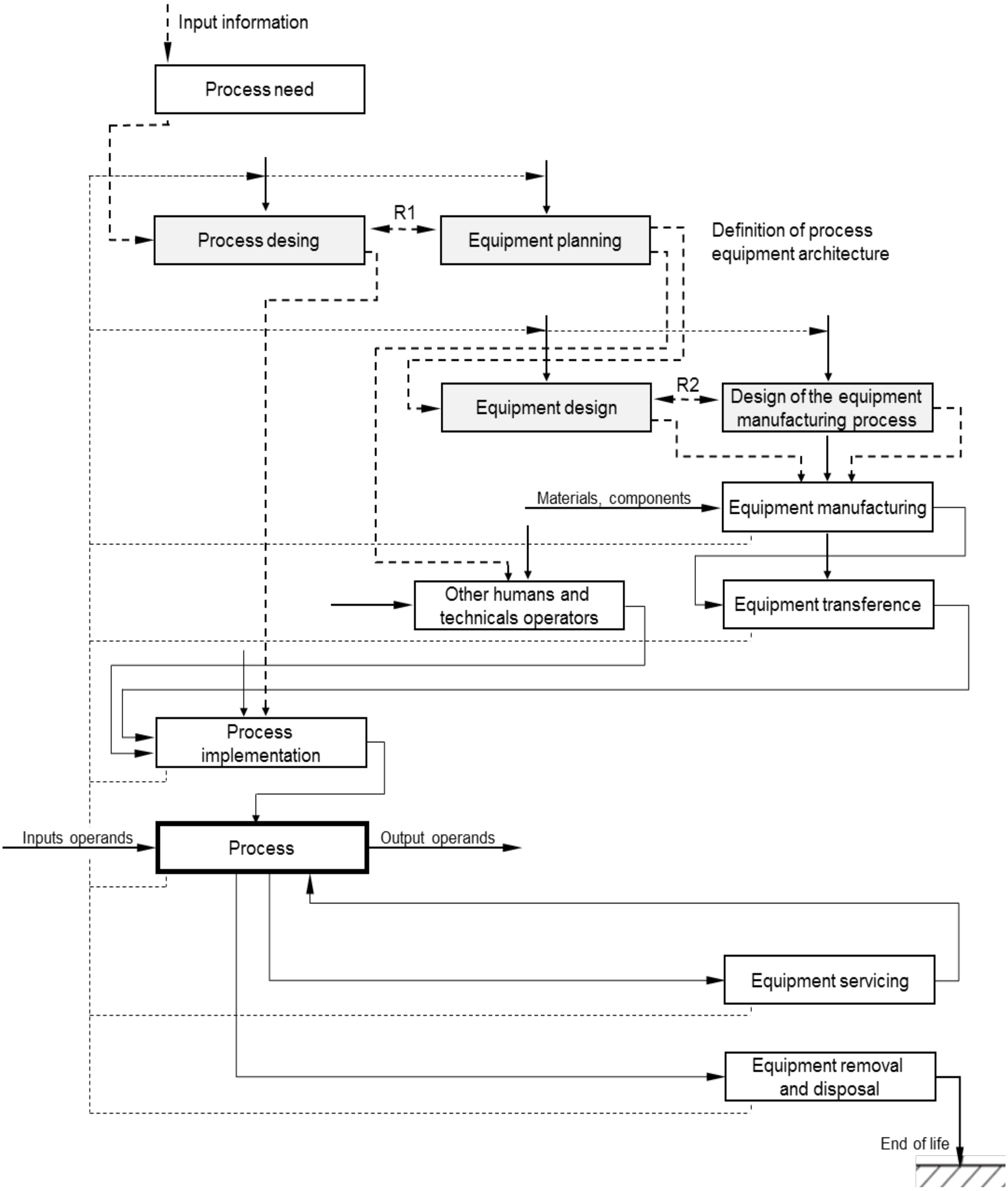

Figure 9. Design relationships between the operative process and the equipment (Riba et al., 2005).

Analogous to the previous concept, the equipment portfolio architecture "articulates the relationship between a process family with the respective equipment portfolio (Riba et al., 2005). A process family is a set of processes that share part of the process (sub process) and the equipment portfolio is the set of different equipment offered by a company (Riba and Molina, 2006). Figure 10 shows the design relationships between the operative process and the process equipment architecture.

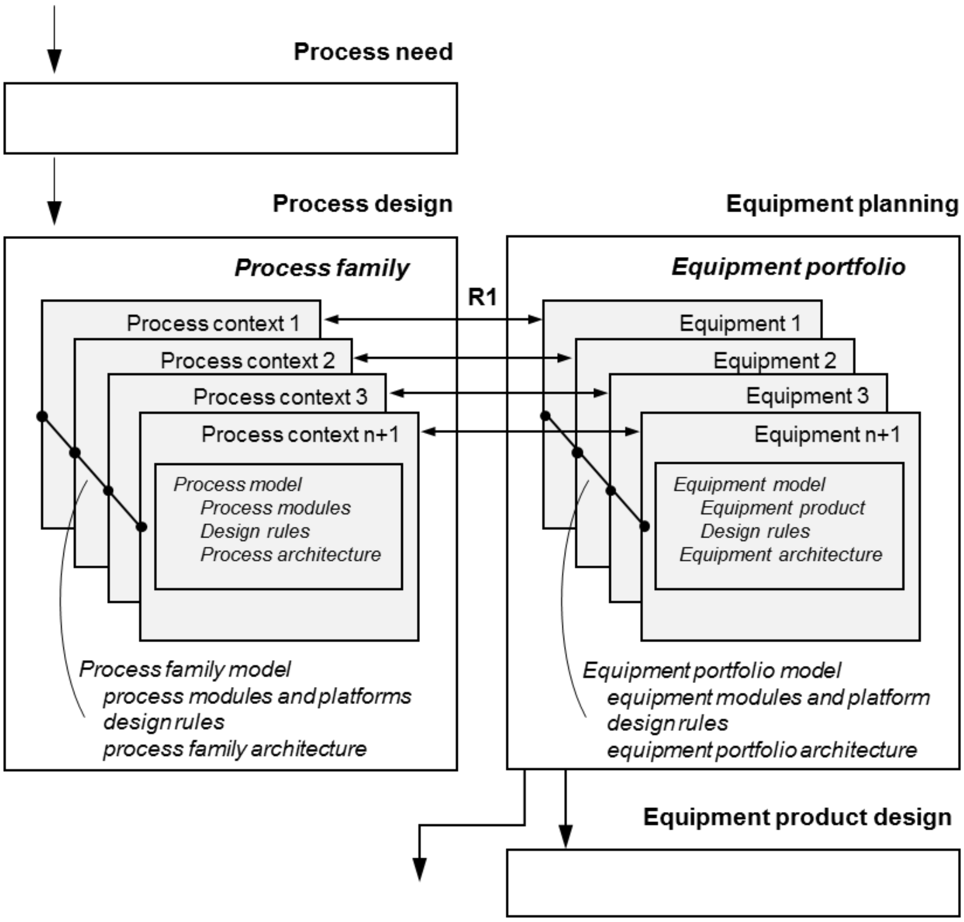

Figure 10. Relationship between a process family and its equipment portfolio (Riba et al., 2005).

The equipment portfolio architecture is the result of establishing the rules of construction of the product equipment types, platforms, scaling, variants and other basic relations and priorities of the equipment portfolio (Riba et al., 2005). In the same way that process equipment architecture looks for the effectiveness and profitability of a whole process, the equipment portfolio architecture allows the equipment costs to be reduced and availability and versatility to be improved. The process-equipment philosophy presented by Riba et al., (2005), is the formal establishment of the research line followed by the presented thesis when the authors statement that the conception and design of an equipment should be initiated by considering the operative process in which it operates.

d) Methodology for the redesign of the equipment range architecture

For the purpose of complementing the concepts proposed during the GAMMA project (Riba et al., 2003), Llorens (2015) structured a design methodology for the redesign of the equipment range architecture of the equipment manufactured by a company. The *equipment range* “is the virtual set of equipment that operates in a family of operative processes of an activity”. Consequently, the *equipment range architecture* is defined as “set of rules for structuring a range of machines (or products) and including, among others, the consideration of the architecture of machines, the architecture of the families of machines and architecture of the members forming the range” (Llorens, 2015) . Unlike other methodologies where the focus of attention is on the product, the methodology for the redesign of the equipment range architecture is based on the analysis of the actual operating process and the different context (domestic, self-service or industrial) in which the equipment operates. The methodology consists of five main steps: I) identify, analyze and represent the operational process; II) identify, analyze and represent the existing contexts, III) get the scheme of the family of operational processes, IV) analyze and represent the architecture of existing product range and V) redefine operational processes and architecture product range. Figure 11 shows the methodology for the redesign of the equipment range architecture.

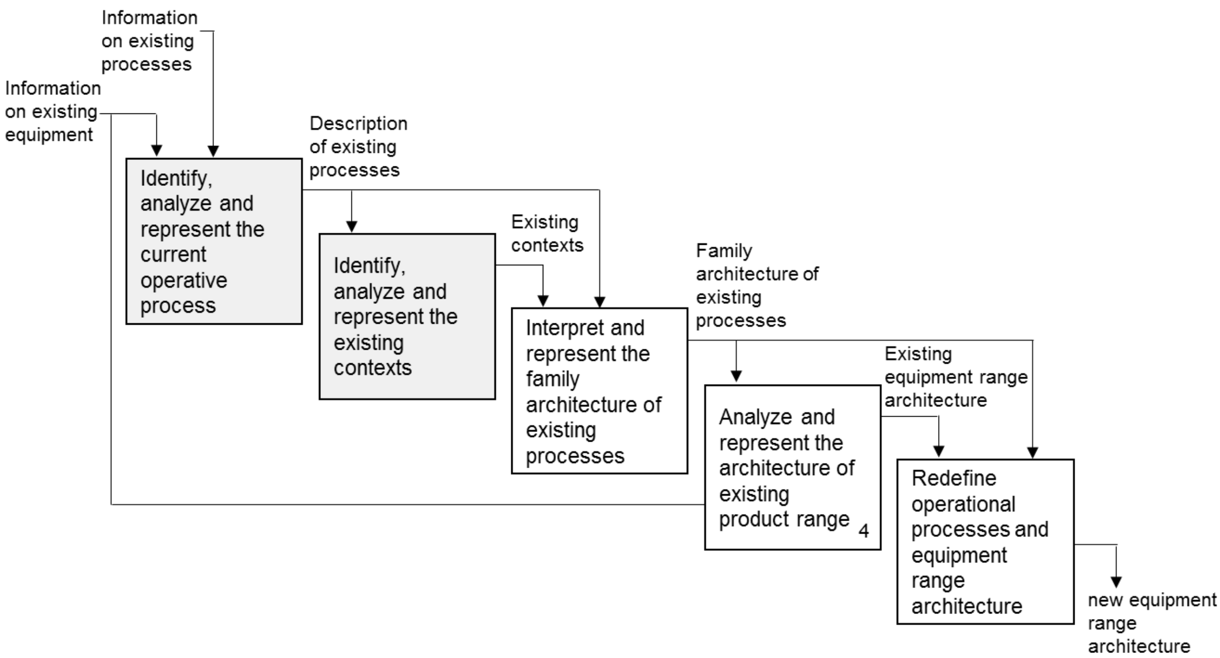

Figure 11. Methodology for redesign the equipment range architecture. Adapted from (Llorens, 2015).

The methodology for the redesign of the equipment range architecture proposed by Llorens (2015) constitutes a great contribution to the research line of the presented thesis by analyzing in a transversal way the operative process where the equipment operates and the complete range of the equipment that coexists and interacts in the same production process.

e) DIA project

The increase of the environmental requirements in the design and development of industrial equipment motivated the implementation of the DIA project (Riba et al., 2009). The project represented a change in the direction of the research line towards sustainability of the presented thesis. The DIA project consisted in the application of the Life Cycle Analysis (LCA) with the objective to identify and quantify the use of materials and energy and the generation of emissions by the equipment, in order to determine their impact with the objective of evaluating and implementing environmental improvement strategies. The LCA was specifically adapted to the equipment products, from their manufacturing to the end of their life cycle, but with emphasis on the use stage. Figure 12 shows the focus area of the DIA project.

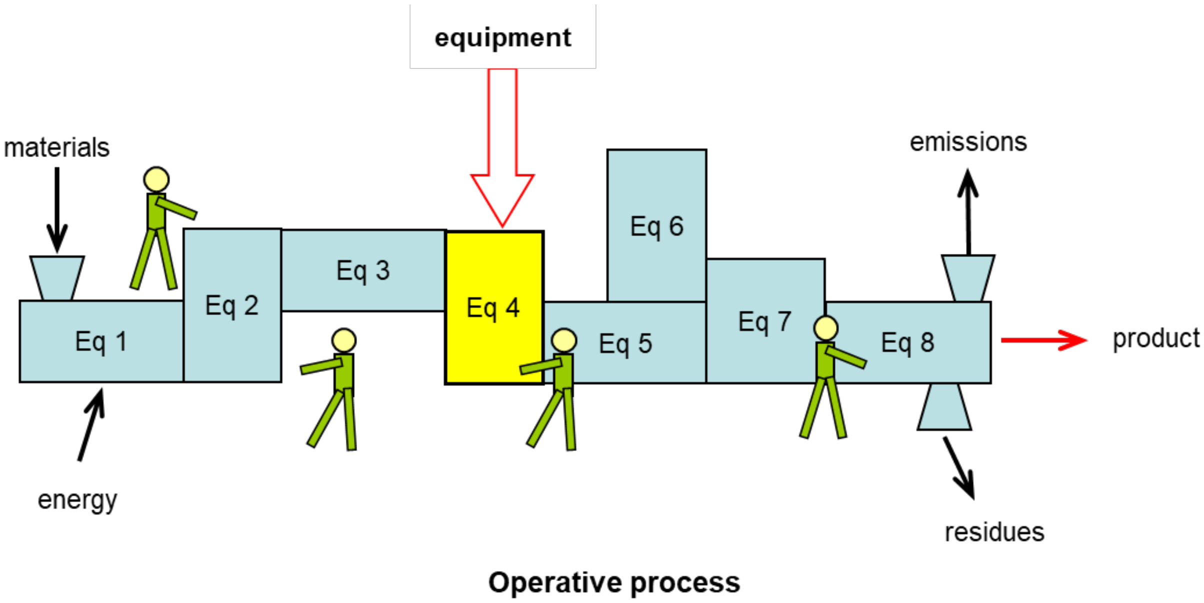

Figure 12. Focus area of the DIA project (CDEI, 2010).

According to Presas and Riba (2010), the results of the DIA project allowed to understand that the energy consumed and the CO_2 emissions generated in the operation phase of the equipment can be between 10 and 50 times larger than in the manufacturing phase of the equipment. Therefore, the main contribution of the DIA project to the presented thesis is that in the search for the reduction of the environmental impact of the industrial equipment the frame of reference of the analysis of the equipment should be extended to the operative process and to the context in which the equipment operates.

f) Design in blue methodology

Influenced by the conclusions of the DIA project, in 2010 the CDEI-UPC promoted a design methodology called Design in blue (CDEI, 2011), which takes its name from the concept of the Blue Economy (Pauli, 2010). In contrast to the green economy, it advocated a simple change of unsustainable technologies for sustainable technologies accepting an increase in costs, the Blue Economy proposes a paradigm shift that eliminates the unsustainable production and consumption so that the good and innovative become competitive. It suggests that business models improve the quality of life of all evolving in harmony with ecosystems, using available resources and ensuring that process residues become resources for another process (Pauli, 2010). Based on this, Riba (2012) identified steps in the Design in blue methodology that set the paradigm shift in the design and development of equipment: I) the consideration of the operational process, II) assessment of the energy consumption and environmental impact and III) the consideration of the social, cultural, natural environment and technological context. Figure 13 shows the Design in blue methodology.

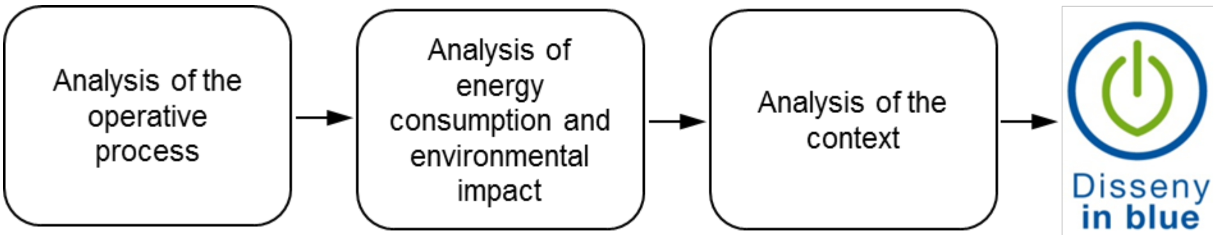

Figure 13. Design in blue methodology. Modified from (CDEI, 2010).

The consideration of the operational process as the basis of the analysis should be extended to the consumption of energy and environmental resources as well as to the context in which the equipment operates. The Design in blue methodology proposed by Riba (2012) represents the formal introduction of the energy and environmental concerns in the design and development of equipment in the research line of the presented thesis.

g) Methodology for the design of appropriate machines

Continuing with the increase of the environmental requirements in the design and development of equipment, Blanco (2018) developed a methodology for the design of appropriate machines for context of rural communities. *Appropriate technologies* are defined as “a strategy that enables men and women to rise out of poverty and increase their economic situation by meeting their basic needs, through developing their own skills and capabilities while making use of their available resources in an environmentally sustainable manner” (Murphy et al., 2009). Blanco emphasized that, although the characteristics of the context are often factors that greatly affect the design of equipment, they are not regularly taken into account in this type of projects (Blanco, 2018). In this sense, the objective of the methodology for the design of appropriate agricultural machines presented by Blanco in (2018) is to include an adequate analysis of the characteristics of the context before starting the conventional mechanical engineering design process. Figure 14 shows the inclusion of the context analysis in the sequence of the methodology stages for the design of appropriate agricultural machines.

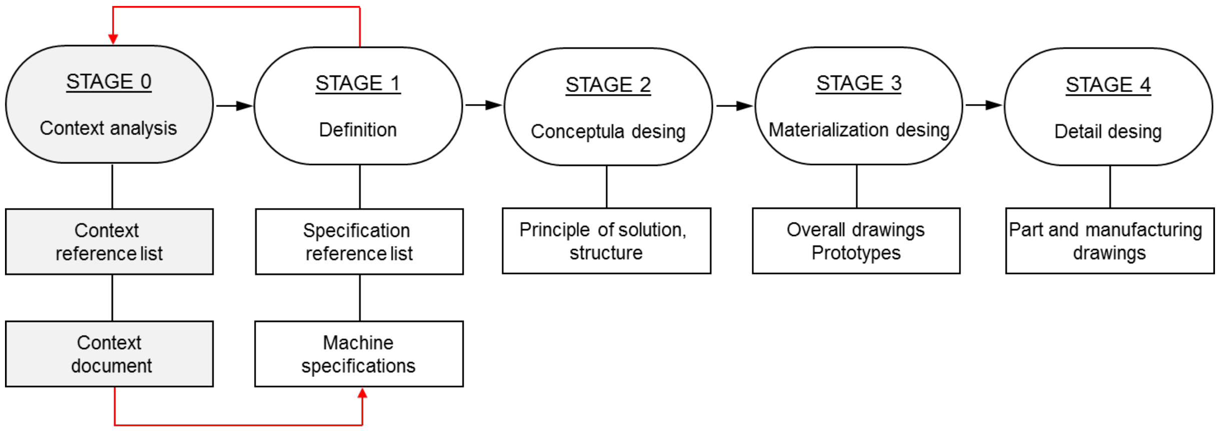

Figure 14. Design methodology for appropriate agricultural machinery (Blanco, 2018).

To carry out the context analysis stage, Blanco (2018) proposed that the project engineers should make a list of context references, with which the design team has to prepare the project context document that will help to write the specifications and define the machine in the next definition stage. In this sense, the methodology represents another essential antecedent of the presented thesis, proposing a context reference list tool that contemplates the aspects that can influence the design of the machine, such as the environment, the users, the infrastructure, the technology, the environment and especially the operative process.

2.1.3 Equipment diachronic dimension

The consideration of the life cycle of the equipment and the consumption of associated resources are one of the fundamental bases of the Concurrent Engineering (Riba and Molina, 2006). One of the main premises of Concurrent Engineering is to emphasize in the diachronic dimension of the products through Life Cycle Design. Its refers that the totality of the elements within the life cycle of an equipment, from functionality, manufacturing, use and maintenance, disposal and recycling must be taken into consideration from the design phase of the equipment (Kusiak, 1993) and not just simply respond to the requirements of its main function during the use function of the equipment for which the equipment was created (Riba, 2002). In this sense, a first approximation of the equipment life cycle was proposed by Hubka and Eder (1996, 1988) when the authors proposed a schema of technical system life cycle in order to show the diversity and complexity of processes in which equipment is involved. Following this line, Riba (2002) defined the *product life cycle* (equipment product) as a "set of stages that an equipment runs since the time that its created until its end of life" (Riba, 2002). Then, Lager and Frishammar (2010) developed an equipment life cycle conceptual model when examining the intensity of the collaborations of the equipment suppliers and the users during the equipment life cycle (Lager and Frishammar, 2010). Table 2 shows an evolution of the stages of the equipment life cycle presented by different authors.

Table 2. Evolution of the stages of the equipment life cycle between different authors.

<table>
<tr><th>Hubka and Eder, 1988, 1996</th><th>Riba, 2002</th><th>Lager and Frishammar, 2010</th></tr>
<tr><td>Product planning</td><td>Decision and definition</td><td>Concept study</td></tr>
<tr><td>Design</td><td rowspan="2">Design and development</td><td rowspan="2">Development</td></tr>
<tr><td>Production planning</td></tr>
<tr><td>Manufacturing and assembly</td><td>Manufacturing</td><td>Manufacturing</td></tr>
<tr><td>Distribution</td><td>Distribution and marketing</td><td>Purchasing</td></tr>
<tr><td rowspan="2">Operation</td><td rowspan="2">Use and maintenance</td><td>Start up</td></tr>
<tr><td>Operation</td></tr>
<tr><td>Liquidation, elimination</td><td>End of life</td><td>Phased out / scrapping</td></tr>
</table>

a) Life cycle analysis (LCA)

The Life Cycle Assessment (LCA) is an essential design tool in the diachronic dimension of the equipment (Zbicinski et al., 2006). The LCA is a systematic method for the environmental analysis for products in general including equipment (Lam and Hills, 2011; Rosen and Kishawy, 2012) in a holistic way (Kauffman and Lee, 2013; Singh et al., 2016). It is a comprehensive tool that give to the equipment designers the opportunity to better understand the environmental impact of the equipment, providing a valuable information regarding opportunities to improve the environmental performance of the equipment (Hendrickson et al., 1998). The LCA approach performs an inventory of energy and material consumed through equipment life cycle, evaluates the potential environmental impacts derived from the identified resource consumption identified and interpreting the results to support equipment designers in the decision making (EPA, 2006). Equipment is used directly and predominantly to handle, store or transport materials and to act upon or effect a change in material to form a product and its subsequent packaging (TAX, 2014). As a result, there is a constant conclusion in the performed LCA to different equipment, the most important stage within the equipment life cycle is the operation phase, since is here where the exercise of the function for which the equipment has been designed takes place (Riba, 2002) and the majority of resources during the equipment life cycle are consumed (Mohammadi et al., 2014).

2.1.4 Equipment synchronic dimension

Besides this first perspective, there is a second perspective in the concept and design of an equipment. The synchronic dimension considers the relationship of an equipment with other equipment or a set of equipment throughout its life cycle. In this sense, different authors have mentioned the importance of considering several equipment products in their design manufacture and use in order to obtain advantages when considering community, compatibility, standardization and modularity (Elgård and Miller, 1998; Meyer and Lehnerd, 1997; Meyer and Utterback, 1992; Robertson et al., 1998). Riba and Molina (2006) mentioned that, when an equipment is analyzed through the diachronic dimension (life cycle), the relationships between equipment in the origination and destination stages are especially relevant. Figure 15 shows the equipment relationships at the origination and destination stages.

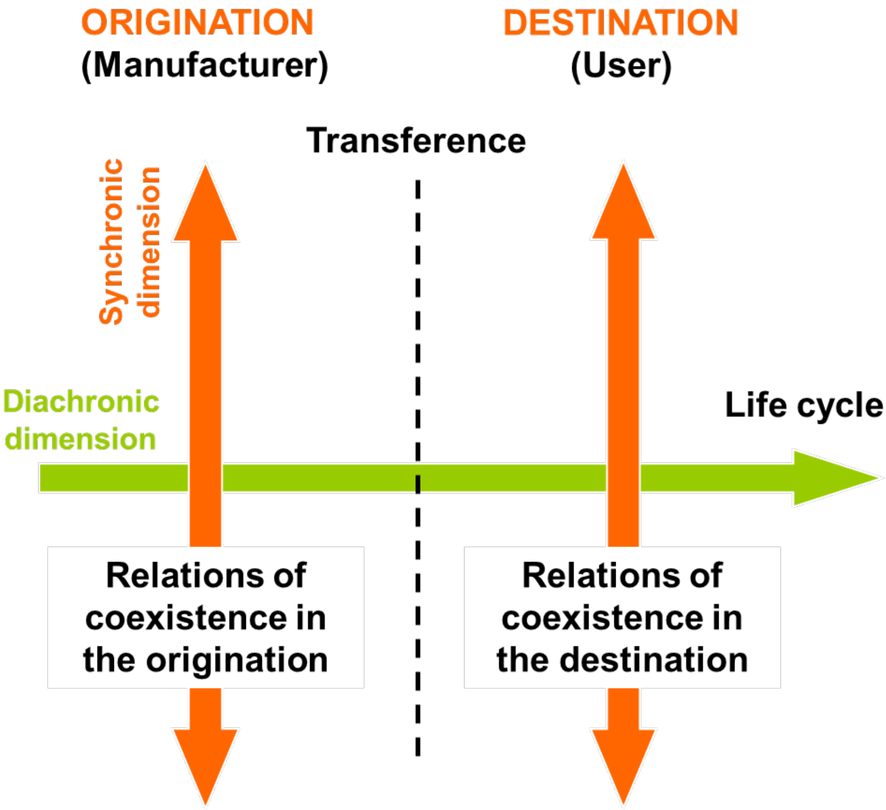

Figure 15. Equipment relationships at the origination and destination (CDEI, 2010).

The origination stages are the phases of the equipment life cycle through it is originated and that includes the concept, design and development and manufacturing stages. The destination are stages of the life cycle to which the equipment is destined and includes the use, maintenance and end of life. Table 3 shows the relationships between equipment through the equipment life cycle.

Table 3. Relationships between equipment through the equipment life cycle. Adapted from (Riba and Molina, 2006).

Stage	Equipment life cycle phase	Relations between equipment
Origination	Concept study	Equipment family
	Design and development	
	Manufacturing	
Destination	Use and maintenance	Equipment portfolio
	End of life	
Origination + Destination	Vision from an activity (beyond a manufacturing company)	Equipment range

There is a relationship between equipment in the origination stage. The *equipment family* is the set of equipment of a company that coexist and interact, share architecture elements (modules and or platforms) in their desing, development and manufacturing (Riba and Molina, 2006). The objective of an equipment family is the use of resources in the origination in the most efficient way possible in order to save costs. There is also an equipment relationship in the destination stage. The *equipment portfolio* are a set of equipment that a company offers to the market wich coexist and interact in the destination stages as a use (production process), maintenance and end of life phases with the objective to optimizing the opportunities to offer a comprehensive solution for the customer needs (Llorens, 2015). The *equipment portfolio* has a maximum interest when the portfolio is extended to all the products offered by the market which interact in an activity (Riba and Molina, 2006). From the point of view of a company that designs, manufactures and sells equipment products, the *equipment range* ist the set of equipment necessary for an activity that can be beyond those that manufactures a company, whose architecture is conceived to optimally solve the origination conditions such as the optimization of the design and manufacturing resources and the destination oportunities and the destination opportunities in the search to offer the maximum satisfaction to the users (Riba and Molina, 2006).

a) Analysis of relations of coexistence (ARC)

Coexistence is the life in the company of another or other individuals, who are related and share things in common (Merriam-Webster, 2019). The Analysis of Relations of Coexistence (ARC) is a tool that allows to understand the relationships between equipment throughout the equipment life cycle. There are different types of relationships between equipment such as information flow, energy flow, value flows, spatial proximity, work processes and disciplinary assignments among others (Daenzer and Huber, 1999). The objective of carrying out the ARC is to seek opportunities to saving costs, facilitating production, managing complexity, optimizing market response capacity and equipment functionalities (Llorens, 2015).

The ARC of the equipment was performed by Llorens (2015) when structured a design methodology for the establishment of the equipment range architecture considering an operational process in which a complete range of equipment coexist and interact (Llorens, 2015). With this, the author established a new framework for analysis and definition of the equipment range architecture through transversal visions of the LCA (diachronic dimension) and the analysis of the ARC (synchronic dimension) of the equipment. The application of the mentioned methodology was based on a real time case study in a Catalan laundry company. The company designs and manufactures products of high complexity of medium volume of production with a certain level of maturity. The case study included the definition of a new range of equipment architecture applied to an industrial laundry process (Llorens, 2015).

The analysis and representation of the existing equipment range architecture allows to understand the relationships of coexistence in the industrial laundry process generating proposals to redefine the operational processes and consequently, the definition of a new equipment range architecture. For example, two different operations can be converted into a combined operation resulting in a new type of equipment. The market study confirmed that some companies of the competition are making new designs in this line and the analysis of technical and the economic viability confirmed the possibility of the company to face a new product project to develop an equipment of single process that executes two operations at the same time.

2.2 INNOVATION IN A SUSTAINABILITY CONTEXT

The most general and accepted definition of Sustainable Development (SD) is derived from the Brundtland Report (1987, p.54). It was defined as the [economic] “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This definition emphasizes the economic dimension of SD more than the social or environmental dimensions (Castro, 2004). Silvestre and Tîrca (2019) defined the innovations that are based in this mainstream understanding definition of SD as *sustainable traditional innovation*. This type of innovations are consistent on reducing negative socio-environmental concerns in ways that maximize profits and financial outcomes (Silvestre and Dyck, 2017).

The current context of sustainability influenced by the scenario of the point of no return for 2035 (Aengenheyster et al., 2018) presented in the introduction of the presented thesis, requires a new way of thinking about sustainable innovations that can address the challenging socio-environmental crises that the humanity is facing (Silvestre and Dyck, 2017). Under this perspective, the typology of innovations for SD presented by Silvestre and Tîrca (2019) redefined the *sustainable innovations* as those that emphasizes the environmental and social dimensions of SD. The final objective of this type of innovations is to improve the overall social and environmental well-being rather than the economic dimension (Silvestre and Dyck, 2017). An example of sustainable innovations that places equal emphasis on the three pillars of sustainability (economic, environmental and social) is the Sustainability-Oriented Innovation (SOI) (Silvestre and Tîrca, 2019).

2.2.1 Sustainability oriented innovations (SOI)

The SOI is one of the main forms that companies currently use to address sustainability (Maletic et al., 2015). *SOI* is defined “as an intentional changes to an organization’s philosophy and values, as well as to its products, processes or practices to serve the specific purpose of creating and realizing social and environmental value in addition to economic returns” (Adams et al., 2016, p.181).

The SOI activities are based on three main contexts of sustainability: I) Operational optimization, II) organizational transformation, and III) systems building (Adams et al.,2016). The *operational optimization* context is the internal oriented perspective for sustainability of the company (doing the same things but better approach). The principal drivers of the innovation activity respond to regulatory requirements and implementation of new practices in the search to gain efficiency. The innovation process focuses on innovations in efficiency to reduce the environmental and social impacts of operations while the company maintains the business as usual. The learning challenge of the company is the identification of possible gaps in unlearning knowledge, competences and expertise in sustainability tools, and external knowledge experts through the exploitation of the internal existing knowledge management. Necessary linkages of this context are those that allow to connect all personnel of the company with the necessary knowledge for the appropriate compliance of the legislations and regulations. This context is possible through the company's innovation capabilities, which serve as a basis to increase the level of sustainability in the company (Adams et al., 2016).

a) The technological dimension of the SOI in production processes

SOI can be classified also according to their I) technological, II) organizational or III) social/institutional dimensions (Jay and Gerard, 2015). Technological innovations play a fundamental role in the global challenge of sustainable development (economic, environmental and social aspects) (Cunha. et al., 2011). The *technological dimension of the SOI* is the development of technological changes for improving sustainability through the creation of new and improved products, processes and infrastructure which improves sustainability (Jay and Gerard, 2015; Parameswaran, 2016).

There are different types of technological innovations such as I) product, II) process, III) organizational and IV) systems. In the case of the technological dimension of SOI are the product and process innovations (Hansen and Grosse-Dunker, 2013; Klewitz, 2017). A *SOI process innovations* are defined as the "redesign operations within the value chain to produce goods and services by using less resources, managing non-product output effectively (waste, hazardous materials, sewage etc.), and increasing the eco-efficiency of production activities" (Klewitz and Hansen, 2014, p.8). Bocken et al., (2014) extended the taxonomy of SOI into eight different archetypes and examples. The first three are oriented towards technological innovations in products and processes. Maximize material productivity and energy efficiency, create value from waste and substitute with renewables and natural processes. Table 4 shows the taxonomy of the SOI technological dimension.

Table 4. SOI technological dimension types and archetypes. Modified from (Patala, 2016).

Dimension	Type	Archetype	Aim	Examples
Technological	Product / Process	Maximize material and energy efficiency	Optimized use of resources; do more with fewer resources'	Low carbon manufacturing; Lean manufacturing; Dematerialization (of products/ packaging); Increased functionality (to reduce total number of products required)
		Create value from waste	Elimination of the concept of waste; reduced waste and virgin material use	End-of-life strategies (reuse, refurbish, remanufacture, recycle); CE Closed loop Cradle-to-cradle; Industrial symbiosis
		Substitute with renewables and natural processes	Reduced use of nonrenewable resources, emissions associated with burning fossil fuels, and synthetic waste to land-fill	Substitute with renewable resources; Move from non-renewable to renewable energy sources; Renewables-based energy innovations; Biomimicry; Green chemistry

Bocken et al., (2014) defined the archetype of *create value from waste* as " the concept of waste is eliminated by turning waste streams into useful and valuable input to other production and making better use of under-utilized capacity" (Bocken et al., 2014). The archetype seeks to reduce waste by creating a new value for those it perceives as waste (Patala, 2016). The creation of value from waste tries to close the loops of materials by using the waste as inputs for other products or production processes with the aim of reducing the demand for raw materials and reducing the generation of emissions (Bocken et al., 2014).

2.2.2 CE Closed loops

The concept of closed loops is based on the analogy established between the efficient flows of materials and energy from biological ecosystems and industrial systems in the Industrial Ecology (IE) (Lifset and Graedel, 2002). The IE studies the flows of materials and energy in industrial systems (Ellen MacArthur Foundation, 2013) through the reuse of resources in a single production process and the industrial symbiosis (Bellstedt, 2015). The objective of closed loops in production processes is the reuse of any kind of waste or by-products, emulating an eco-industrial system (Sarkis, 2001). Unlike industrial symbiosis where two or more companies exchange waste as resources (Murray et al., 2015), closed loops in production processes allow the circulation of resources and emissions between the different actors of the process reducing the consumption of resources and minimizing the amount of relative emissions (Despeisse et al., 2012). Closed loops should be as closed as possible (Repo and Anttonen, 2017). Graedel and Allenby (2002) described two different models of closed loops resources flows in production processes: I) the quasi-cyclic resource flows where there is a certain degree of cycling circulation of resources within the system reducing the need for external resource inputs and the generation of waste and emissions and the II) cyclic resource flows where a complete closed loop circulation of resources within the system requiring only renewable energy for its self-sufficiency.

The definition of closed loops in production processes has been modified derived from the incorporation of concepts that share the closed loop idea such as CE (Geissdoerfer et al., 2017). For example, Kondoh et al. (2005) defined a *closed loop manufacturing system* as “the manufacturing system that reutilizes modules, components and materials of post-use products in their production processes so as to minimize environmental impact of products as well as their manufacturing”. Guide and Wassenhove (2009) added the term supply chain management and defined the *closed loops* as “the design, control and operation of a system to maximize value creation over the entire life-cycle of a product with dynamic recovery of value from different types and volumes of returns over time”. Later, Morana and Seuring (2011) mentioned that *closed loop supply chain management* “deals with all kinds of product return, both from unwanted products as well as from products at the end of their life-cycle”. Finally, Souza (2013) defined the *closed loops* as “supply chains where, in additional to typical forward flows, there are reverse flows of used products (postconsumer use) back to manufacturers”. Figure 16 shows the current concept of closed loops in a production system.

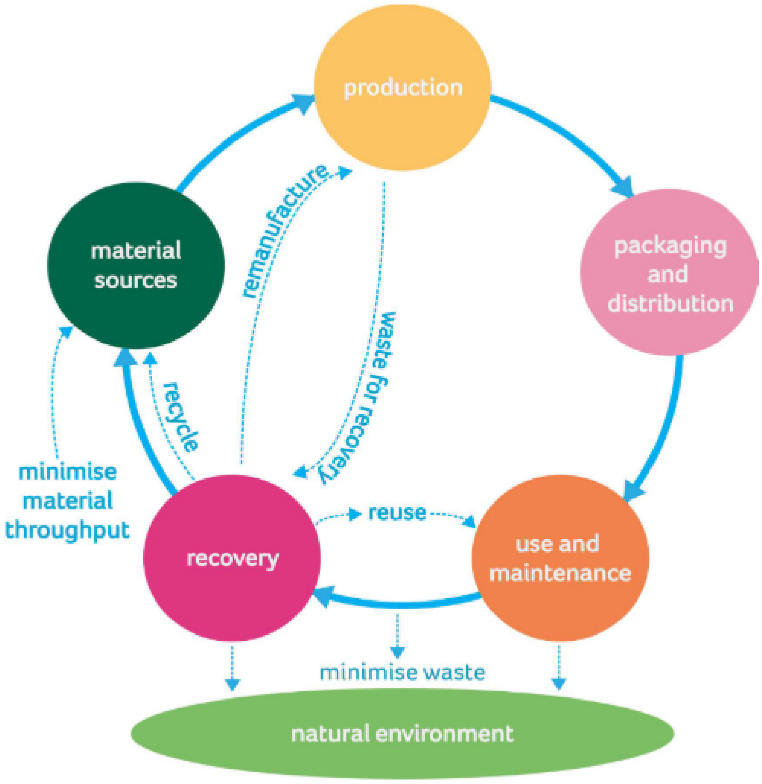

Figure 16. Closed loop production system (Prendeville et al., 2014).

The tendency towards closed loops of products that are designed for multiple life cycles has also been supported by the development of tools for the implementation of closed loops of products in production systems. For example, the EC has developed different tools and instruments to facilitate the transition towards more CE products in Europe (EC, 2019d). Another examples of tools for the implementation of closed loop in the design of products were developed by the project Resource Conservative Manufacturing (ResCoM) (ResCom, 2017).

The definitions and practices identified in the literature as well as the recently developed tools for the implementation of closed loops show that most efforts focused on the reuse of products rather than the reuse of emissions in production processes.

2.2.3 Cleaner production

Cleaner Production (CP) is a key concept for the implementation of CE closed loops at the company level (Ghisellini et al., 2016; Sousa-Zomer et al., 2017) through focusing on the reduction of material inputs and the reduction of emissions in production processes (Shahbazi et al., 2013). CP is “a strategy for addressing the generation of pollution as well as the efficient use of resources at all stages of the production process” (Su et al., 2013). The application of the CP in production processes is based on three main tools (source reduction, recycling and product modification) and their respective subdivisions (Gomes da Silva and Gouveia, 2020). Figure 17 shows the main tools of the CP and their subdivisions.

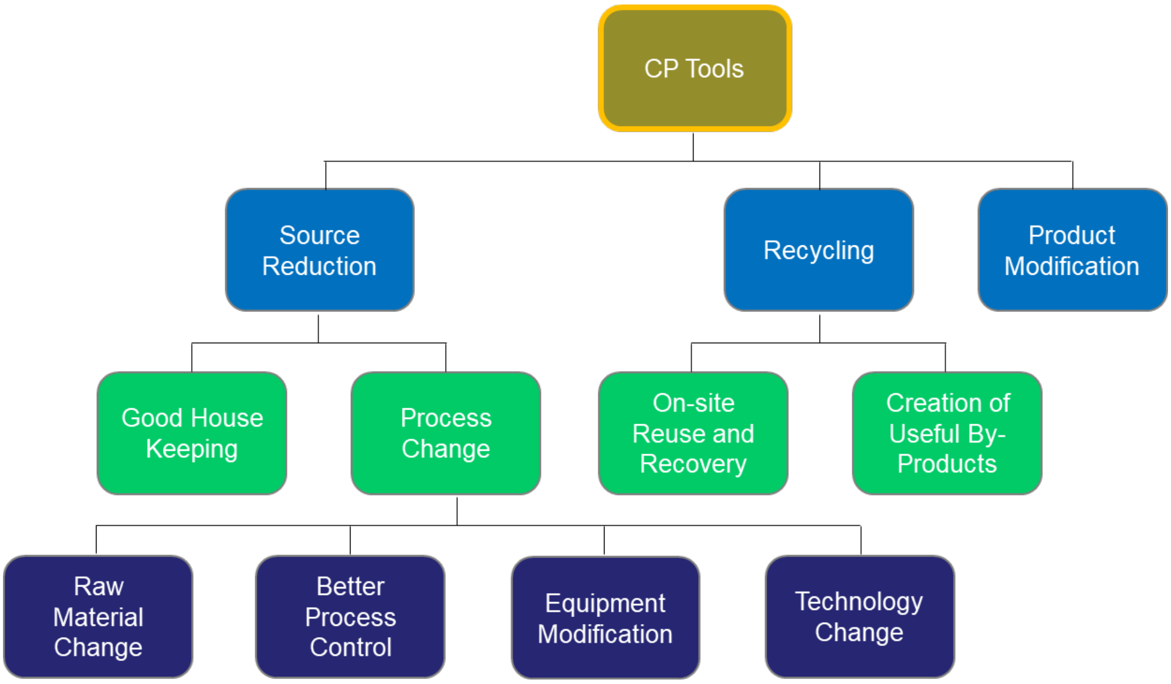

Figure 17. Cleaner production tools (Gomes da Silva and Gouveia, 2020).

The waste and pollution, prevention which are the principals objectives of the CE closed loops in production processes can only be achieved through the incorporation of several CP principles and tools (Ghisellini et al., 2016; Gomes da Silva and Gouveia, 2020; Sousa-Zomer et al., 2017). Figure 18 illustrates how CE incorporate several CP tools.

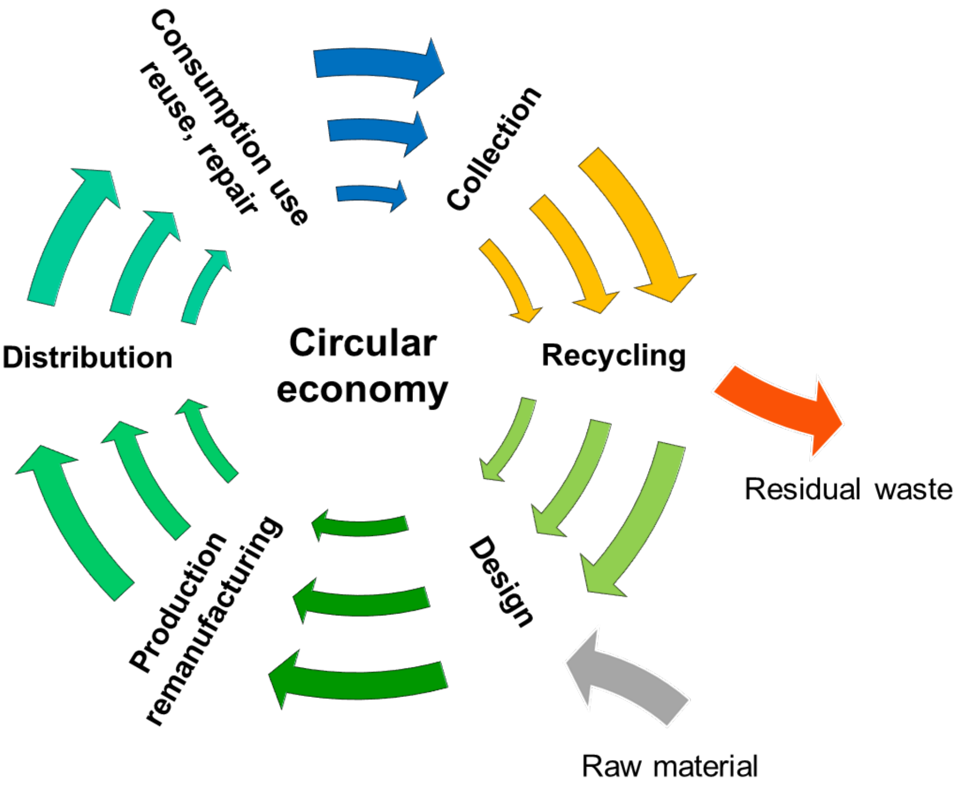

Figure 18. Incorporation of CP tools by the CE (Gomes da Silva and Gouveia, 2020).

Unlike the mainstream definition of closed loop of products (see Figure 16), Gomes da Silva and Gouveia (2020), based on the study carried out by Nilsson et al. (2007) considered that there are CP principles with particular relevance in the implementation of the emissions reuse closed loops in production processes:

- Material replacement: Selection of raw materials that allow a reduction in the consumption of resources in the life cycle of the product including auxiliary or operative materials used in its production.
- International organization: Efficient consumption of material resources and increase energy efficiency in the production process, avoiding all types of waste;
- Internal recycling: Increase efficiency through the implementation of cycles for the reuse of materials, energy, water, solvents in order to take advantage of their recycling and obtain an economic advantage;
- Technological updating: Improvement of production processes through the integration of new technologies that minimizing waste and reducing the generation of emissions.

For the implementation of the mentioned principles in production processes, CP employs Eco-design, Environmental Management Systems, Best Available Technics (BAT), and Cleaner Technologies (Nowosielski, 2007; Zhang et al., 1997).

a) Cleaner technologies in production processes

Cleaner Technologies (CT) is considered as one of the most important methods for the application of the CP principles in production processes with the aim of achieving closed loops (Nowosielski, 2007).

The OECD defined *CT* as the “technologies that extract and use natural resources as efficiently as possible in all stages of their lives; that generate products with reduced or no potentially harmful components; that minimize releases to air, water, and soil during fabrication and use of the product; and that produce durable products which can be recovered or recycled as far as possible; output is achieved with as little energy input as is possible” (EC, 2017).

The objective of CT is to prevent pollution by improving production efficiency through the adoption of innovative technologies that minimize or reduce waste (Adams et al., 2012). Cleaner technologies can be divided into end-of-pipe engineering solutions (hard technologies), and in methods of operation and management, which are capable of ensuring an effective reduction in resource consumption (soft technologies) (EC, 2017). In the equipment manufacturing industry, CT are classified in: energy economizing, environment-friendly equipment, and resource conservation equipment (Shan et al., 2012).

2.2.4 Emissions reuse in industrial equipment

The gradual incorporation of environmental concepts to the design and development of process equipment have allowed for the commercialization of equipment with the capacity to reuse their own emissions. The reuse of emissions in equipment is not new. There are different equipment with the capacity to reuse emissions in the market, for example, the instrument washer disinfector by the company Steelco, an Italian washer disinfectors and sterilizers manufacturer (Steelco, 2019). The equipment features preheating water tanks above the wash chamber. The amount of water necessary for the prewashing flows from the first tank directly to the wash chamber quickly and without any pump activity. The tank preheated water at 65 ºC allowing the reduction of the washing time and the cycle time. The same tank is used to preheat the rinse water while the machine is operating in washing stage. The time saving heating prevents the camera to cool and therefore to lose energy. The preheated rinsing water can be recycled from the previous cycle of thermal disinfection, adding a significant reduction of energy, water and time. The demineralized water of the tank, preheated at 85ºC allows radically to reduce the time of the thermodisinfection phase and consequently, the total cycle time. Preheated demineralized water flows directly into camera in a fast manner without use of the pump minimizing heat loss. It is estimated that this instrument washer equipment can save up to 54,000 liters of water in a year of average use. Figure 19 shows the instrument washer disinfector with its preheating tanks.

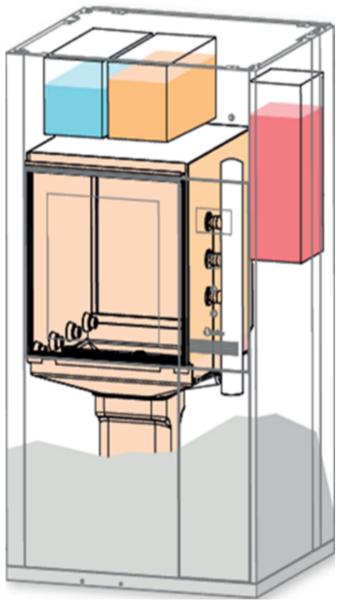

Figure 19. Instrument washer disinfector preheating tanks (Steelco, 2019).

Another example is the batch washer for clothes of the company Girbau (Girbau, 2019), a Catalan laundry equipment manufacturer. The batch washer has a washing capacity of 500 to 1000 kg of laundry per hour. The installation of the batch washer equipment features recovery tanks and an intercooler system, which allows savings of 70% of energy and 80% of water plus 40% of detergent and 90% labor. The wastewater from the last operation of the batch washer (pH neutralization) goes to a recovery tank and then it is used in the previous operation of rinsing. The wastewater from the rinsing operation (14ºC) passes through a filter and then through the intercooler where it is heated to 40ºC by the heat exchange with the wastewater from the pre-wash and wash operations, which are sent to the drainage. Finally, the clean water that has been heated in the intercooler, passes to a recovery tank and from there, when it is required, it feeds the water inlets for the pre-washing and washing operations completing with this the recovery cycle of water. The technology of control and recovery of the equipment allow maximum energetic efficiency and saving of water and of chemical product, with a consumption of water of only 4.3 l/kg of clothes. Figure 20 shows the batch washer with its energy and water recovery system.

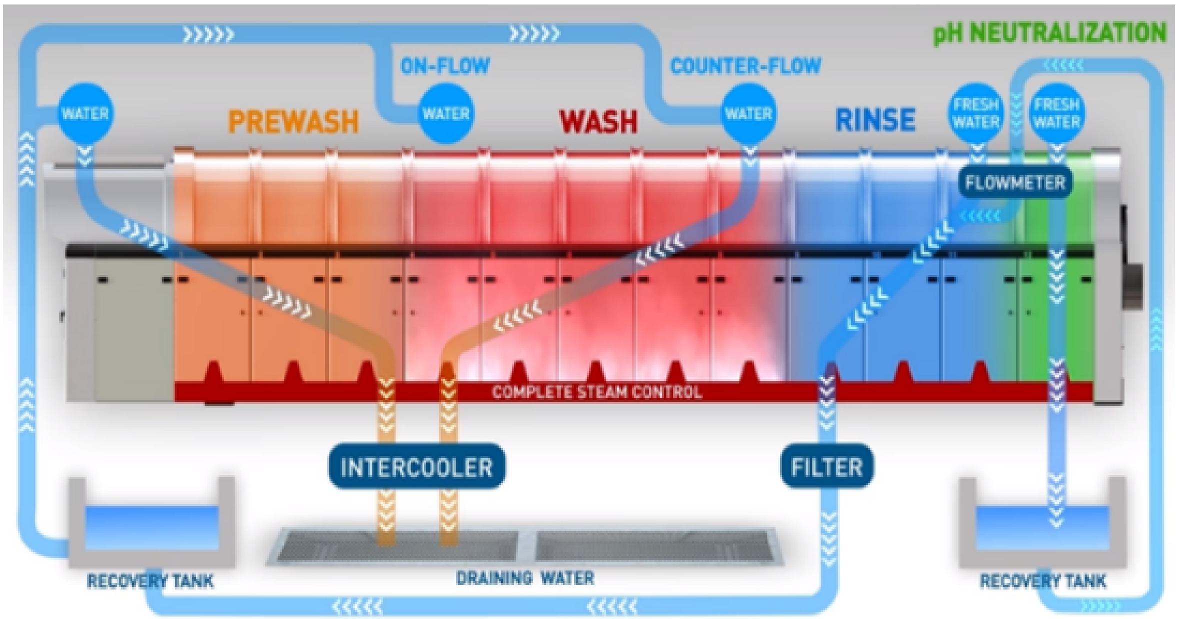

Figure 20. Batch washer energy and water recovery system (Girbau, 2019).

2.3 RESEARCH GAP

The review of the literature in the frame of reference evidence a body of existing knowledge both in the process-equipment system and in the sustainable innovation of production processes. In the first part of this chapter, the need of the holistic perspective when designing, improving, redesigning and innovating a technical system was described. Also, the importance that in the design of an equipment, the process where the equipment operates should be taken into consideration was explained. In the same way, the incursion of the diachronic and synchronic dimensions in the design of equipment has been emphasized. In the second part, the implementation of closed loops has been mentioned as one of the possible forms of sustainable innovation in production processes and how these can be achieved by the implementation of CP principles in production processes through CT that have the capacity to reuse emissions.

The analysis of the frame of reference shows that there is an opportunity to innovate the process-equipment system in a context of sustainability. The reuse of emissions between the equipment involved in the production process has not yet been explored either in the literature or in the industry, as is explained in Chapter 1. Therefore, the presented thesis focuses now on research what characterizes the sustainable innovations of processes and equipment in the industry through four case studies and a survey in Chapters 3 and 4, respectively, leading to the answers of the two research questions of the thesis described in Chapter 5 and 6.

3. RESEARCH METHODOLOGY

This chapter describes the research methodology adopted in the presented thesis starting with the choice of the research approach. Subsequently the research design and the data collection process are described. Finally, the chapter ends with a discussion about the reliability and validity of the research and a description of the process for the data analysis.

3.1 RESEARCH APPROACH

The research approach represents the research plans and procedures that include decisions from general assumptions to detailed methods for the collection and analysis of data (Creswell and Creswell, 2018). Ählström (2016) described three general considerations for deciding which research approach is the most suitable to answer the research questions: I) methodological fit, II) philosophical position and III) practical considerations in choosing a research approach.

3.1.1 Methodological fit

The *methodological fit* refers to the internal consistency between the elements of a research as the research question, the maturity of existing knowledge, the research approach and the contribution of the research (Edmondson and McManus, 2007). The revision of the literature presented in the frame of reference (Chapter 2) allowed to understand the process-equipment system as well as the advances in the sustainable innovation of production processes. Both topics have been studied previously, but there is a lack of studies focusing on the contribution of the equipment in the sustainable innovation of production processes. This turns the research topic of the presented thesis into a nascent theory within the maturity of existing knowledge. The nascent theory seeks to open new fields for research through suggestive models that require exploratory and theory-bulding studies in new contexts (Ählström, 2016; Edmondson and Mcmanus, 2005).

The research questions also depend on the maturity of the knowledge (Ählström, 2016). In this sense, nascent theory focuses on exploratory and descriptive types of research questions (Edmondson and McManus, 2007). Explorative and descriptive research questions are focused on "who, what, when and where". In contrast, descriptive research questions that are based on "how" and "why" questions (Yin, 2014). The first research question (RQ1) of the presented thesis seeks to "explore" how the process-equipment system can be innovated in a context of sustainability. The second question (RQ2) aims to “describe” what characterizes this type of innovation. For research questions focused on “how” and “what” the use of case research is preferable (Meredith, 1998; Yin, 2014). The answer to the research questions formulated in this thesis will contribute to the existing knowledge in the innovation of the process-equipment system in a context of sustainability, for which it was required to carry out descriptive and exploratory research. This means that the research is focused more on the know-how and the know-what rather than to understand the know-why.

3.1.2 Philosophical position

The research approach also needs to reflect the philosophical position of the researcher regarding the fundamental issues of ontology and epistemology (Åhlström, 2016). *Ontology* can be defined as the nature of existing reality (Saunders et al., 2009). *Epistemology* refers to what constitutes acceptable knowledge in a field of study through subjective experiences (Creswell and Poth, 2017). There are different ways to express these positions such as positivism, interpretivism, pragmatism, critical theory among others (Symon and Cassell, 2012). In Operation Management (OM), the positivism is the most dominant position (Åhlström, 2016). Unlike the interpretive research, which aims to develop an understanding of the social world and discover how people construct meaning in natural environments (Kiridena and Fitzgerald, 2006), the presented thesis has adopted the path of positivist research. This research aims to discover objective truth through results and conclusions that are reproducible, verifiable and generalizable (Åhlström, 2016). Karlsson (2016) mentioned that this generalization can be made through comparisons with theory and similar case studies.

3.1.3 Practical considerations in choosing a research approach

Finally, Åhlström (2016) mentions three practical considerations in choosing a research approach: I) gaining access to data, II) the consideration of institutional factors and III) the interests and skills of the researcher. Gaining access to data is critical (Symon and Cassell, 2012). Successful data collection directly depends on the ability of the researcher to negotiate access to the organization and to establish relationships and maintain agreements with participants (de Vos et al., 2011). In the presented thesis, access to the equipment company was obtained through a collaboration agreement, which offered to the company the implementation of Energy Management System (EMS). For its part, the company committed to provide all necessary access to facilities and information necessary for data collection during the project. In the same way, access to the research institute was also obtained through an agreement of an international doctoral stay for the realization of a well-established project that the institute required at that time. In both cases, access times to the entities were limited to the completion of the aforementioned projects.

The consideration of the institutional factors can also affect the selection of the research approach (Åhlström, 2016). The presented thesis is the result of cooperation between the Institute of Sustainability (IS-UPC) as well as the Center for Industrial Equipment Design

(CDEI-UPC) of the Universitat Politècnica de Catalunya (UPC) and the collaboration with the Matachana and the Institute of Production Engineering and Machine Tools (IFW) of the Leibniz University Hannover (LUH). The cooperation between the IS-UPC and CDEI-UPC allowed to establish to establish the research line of this doctoral thesis, the sustainability in the industrial equipment. Consequently, the type of entities where the research would be carried out was determined. It is worth mentioning, that most of the doctoral theses carried out within CDEI in recent years have been based on the development of methodologies for the design of industrial equipment based on the case research (Genovese, 2013; Llorens, 2015; Blanco, 2018). Finally, the consideration of the interests and skills of the researcher should not be underestimated (Ählström, 2016). The personal interest of the researcher may lead to research on certain topics and phenomena as well as influence the way in which the research question is framed and the context of the study (Rossiter, 2004). Also, the researcher needs to have good sales ability not only to gain access to the organization as mentioned above, but also social and people skills to establish relationships with people (Ählström, 2016). At the beginning of the presented thesis, the author had 10 years of professional experience in the manufacturing industry with direct contact to the production process as production supervisor, continuous improvement engineer and quality auditor. This experience allowed the development of job skills compatible with those of the case research commented by Ählström (2016), such as social-people, interview, analytical and presentation skills, etc.

Based on these considerations, in the presented thesis the case research approach was selected in combination with literature review in Chapter 2 in order to answer the research questions formulated in Section 1.2 and thus, achieve the objective of the research. Case research approach is one of the most important research methods used in OM in Europe for exploratory and theory building purposes (Boer et al., 2015). The case research approach uses case studies at its basis (Voss et al., 2016). *Case study method* is defined as “a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence” (Robson and McCartan, 2016). Considering that the innovation of the process-equipment system in a context of sustainability is a contemporary and complex phenomenon, the use of the case research approach can facilitate the management of the complexity involved in the study of production systems (Rösiö, 2012).

3.2 RESEARCH DESIGN

Once the research approach has been selected, the next step is the definition of the research design. The *research design* is the plan that guides the researcher in collecting, analyzing, and interpreting case study observations in order to answer the research questions

(Yin, 2014). There are different choices for conducting case research (Voss et al., 2016). The ones selected in the presented thesis are: the number of cases, the use of real-time or retrospective cases, the case selection and sampling as well as the unit of analysis.

3.2.1 Number of cases

Voss et al., (2016) mentioned that the fewer the number of cases, the greater the opportunity for depth of observation. However, there are different risks associated with this selection such as the limitation of the generalization of the conclusions, the misinterpretation and the exaggeration of easily available data from a single-case study. As mentioned at the beginning of this chapter, the lack of studies focused on the innovation of the process-equipment system in a context of sustainability makes the research purpose of the presented thesis as explorative theory building. For this purpose, the use of multiple-case studies provides a stronger base by creating a more robust and testable theory than by single-case research (Eisenhardt and Graebner, 2007; Yin, 2014). In addition, the use of multiple-cases can increase the external validity of the cases and help to prevent bias by the observer (Voss et al., 2015). Eisenhardt (1989) stated that, although there is no ideal number of cases, between 4 and 10 cases are recommended, since with less than 4 cases, it is difficult to generate a theory with a lot of complexity and, with more than 10 cases, the complexity and data volume can quickly become difficult (Eisenhardt, 1989).

3.2.2 Real-time or retrospective cases

The case research approach can be used to investigate a past or current phenomenon (Voss et al., 2002). The research contribution of the presented thesis is based on two real-time cases and two retrospective case studies with a total amount of 4 case studies. One real-time case study followed a continuous improvement project and the other an industrialization project in the same company. This type of cases allows real-time data collection. Thus, overcoming the problems associated with asking participants to recall particular events, addresses the biases associated with past events, and enables a flexible approach that allows investigation of interesting phenomena as they emerge (Vardaman et al., 2010). However, performing a real-time case study requires a large inversion of time by the researcher in the company, and part of that time is used to collect data from past events (Ählström and Karlsson, 2016). In addition, two retrospective case studies were conducted to follow one industrialization project in the same company and one industrialization project in a research institute. The synergy obtained by combining real-time and retrospective case studies reinforces the data collection process of one method, compensating a particular weakness or lack in the other, and increases the constructive, internal and external validity of empirical findings (Leonard-Barton, 1990).

3.2.3 Case selection and sampling

Another essential choice in the use of case research is the case selection and sampling. Miles and Huberman (1994) mentioned that two actions should be taken for correct sampling. The first is to establish limits to define the aspects of the case that can be studied and that connect directly with the research questions. As it has been mentioned, the innovation of the process-equipment system in a context of sustainability falls within a nascent or theory building in the maturity of existing knowledge. Voss et al., (2016) stated that, when a theory is built from multiple case studies, a literal or theoretical replication should be used in the case selection. The logic behind the use of multiple case studies is that literal replication can predict similar results and the theoretical replication can produce contrary results, but for predictable reasons (Yin, 2014). In the presented thesis, four different sampling criteria were used:

- The equipment manufacturing industry is under increasing pressure to reduce the resource consumption of the equipment that it produces, but also to reduce the resource consumption in the way that they manufacture these. Therefore, the selected entities have to be in search of complying with the increasing environmental requirements;
- The entities selected for the case studies should be industries that manufacture equipment or entities that are closely related to the equipment manufacturing sector and they should also be responsible for the design and development of equipment and production processes;
- The entities selected for the case studies must have an innovation department or should have experience in innovation projects;
- Since the objective of presented thesis is to develop knowledge that contributes to the innovation of the process-equipment system in a context of sustainability, it is essential that the selected entities integrate sustainable practices in their activities.

This selection of cases aims to capture the possible data coverage of process-equipment system innovation activities in the context of sustainability. This is in line with Pettigrew (1990) who defines *polar types* as cases studies with contrasted characteristics that make it possible to observe more easily contrasting patterns data of the studied phenomena (Eisenhardt and Graebner, 2007). Table 5 presents the selected entities and the case studies of the presented thesis.

During the development of the presented thesis, the sampling plan underwent different modifications. Following the recommendation of Miles and Huberman (1994), different tests were applied to each change to confirm the relevance of the conceptual framework and the research questions, the emergence of the phenomenon under study, its generalizability and feasibility, among others. In the same way and in line with Voss et al.,(2016), sampling controls to corroborate that the fundamental constant factors of the sampling plan (e.g. equipment manufacturing sector, improvement or innovation projects, sustainability practices) were implemented.

Table 5. Overview of the selected entities in the performed case studies.

Entity	Company			Research institute
Type	Equipment manufacturer			Production engineering and machine tools
Location	Castelldefelds, Spain			Hannover, Germany
Case type	Real-time	Real-time	Retrospective	Retrospective
Case	Sterilizer manufacturing	New equipment	Sterilization central	Grinding wheels
Acronym	SM	NE	SC	GW

3.2.4 Unit of analysis

Another essential choice is the unit of analysis of the cases studies. The *unit of analysis* represents the principal entity that the researcher analyzes in the case study and should be directly related to the research questions (Yin, 2014). The unit of analysis chosen for the real-time Case SM was the improvement of processes that occurred within the context of the implementation of an EMS in a company. The improvement of process refers to the activities carried out to improve the energy performance of the production process. Most of the improvement activities came from a program of ideas for continuous improvement of the employees of the production and quality departments and were implemented entirely by the same employees who generated them with some exceptions where the support of external service providers was needed. Since the presented thesis investigates the process-equipment system, special attention was paid to the activities to reduce the environmental resource consumption of the equipment involved the production process defining them as the sub-unit of analysis. The innovation of equipment within the context of the development of a new equipment was the unit of analysis for the other real-time case. The Case NE analyzed the environmental requirements in equipment design as a part of an innovation of equipment within a new equipment development project in the same company of Case SM but in another department. It is worth mentioning that during the development of the Case NE, the main innovation component of the new equipment was outsourced to an industrial equipment design center for which there was also the opportunity to observe the entire process of design and development of the component. For these reasons, the environmental requirements in the design of the equipment were the sub-unit of analysis of the Case NE.

For the retrospective Case studies SC and CW, the unit of analysis was an industrialization project within the context of a new product development in the same company and in a research institute for production engineering and machine tools. The industrialization project covered the acquisition of equipment, which became the sub-units of analysis for the Cases SC and GW. Table 6 presents an overview of the units of analysis of the case studies carried out in the presented thesis.

Table 6. Overview of the units of analysis in the performed case studies.

<table>
<tr><th>Case</th><th>Entities</th><th>Context</th><th>Unit of analysis</th><th>Subunit of analysis</th></tr>
<tr><td>SM</td><td rowspan="3">Equipment manufacturer company</td><td>EMS implementation project</td><td>Improvement of production process</td><td>Activities to reduce the environmental resource consumption of the equipment</td></tr>
<tr><td>NE</td><td>New product development project</td><td>Innovation of equipment</td><td>Environmental requirements in equipment design</td></tr>
<tr><td>SC</td><td rowspan="2">New product development project</td><td rowspan="2">Industrialization project</td><td rowspan="2">Environmental requirements in equipment acquisition</td></tr>
<tr><td>GW</td><td>Research institute</td></tr>
</table>

The real-time Case studies SM and NE can be compared with each other, as the units of analysis and sub-units of analysis of the two cases are related to the resource consumption of an equipment. Similarly, the retrospective Cases SC and GW share units and subunits of analysis, which is why they can also be compared with each other. Although there is a difference between the units of analysis of the four cases, it is possible to compare them since their subunits of analysis are similar.

a) Mixed method research

The use of other methods to complement data collection through case studies can increase the data collection efficiency and scope as well as strengthen the research validity (Voss et al., 2016). Mixed methods can help the researcher to collect richer and stronger evidence than can be collected by a single method (Yin, 2014). In the presented thesis the case study method was combined with the application of a survey to the Cluster of Equipment Manufacturing Companies in Catalonia (CEQUIP). The objective of the Survey C is to obtain more information about how the processes and equipment innovation occur in equipment manufacturing companies and how sustainable are these innovations.

3.3 DATA COLLECTION

The presented thesis was based on in two real-time Case studies (SM and NE), two retrospective Case studies (SC and GW) and the Survey (C). The data collection took place between 2013 and 2018. It was carried out using a combination of different methods such as, passive and active observations, semi-structured interviews, the analysis of documents and archives as well as questionnaires, which are explained below for each of the cases. Figure 21 illustrates the data collection process in a timeline.

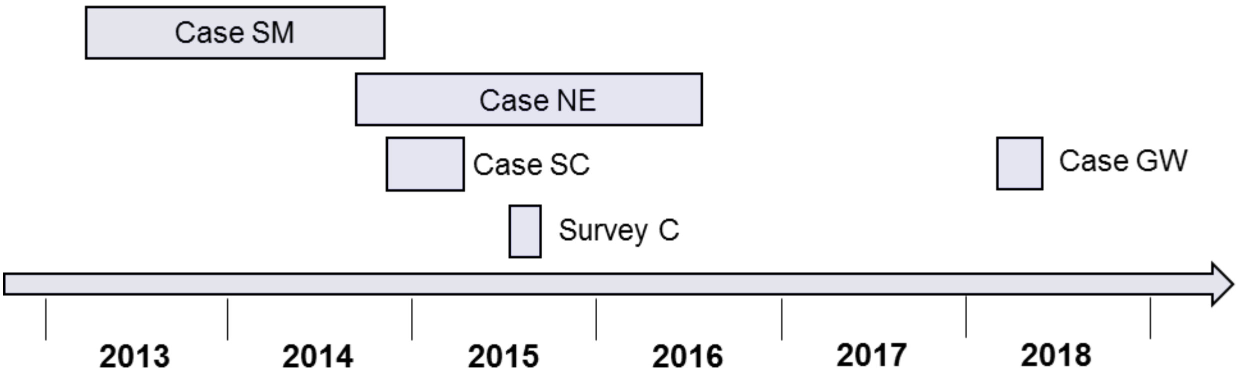

Figure 21. Data collection timeline.

3.3.1 Real-time case studies SM and NE

The cases were conducted in an equipment manufacturing company and aimed to understand how the innovation of the process-equipment system is developed in a company. For this, the improvement of processes in Case SM and the innovation of an equipment in Case NE were analyzed.

The Case SM was developed as a part of the implementation of an EMS, where the case focused on the improvement of production processes. Special emphasis was placed on activities to reduce the environmental resource consumption of the equipment involved in the production process. The empirical data collection for the Case SM started in March 2013 and finished in October 2014 (see Figure 21). The duration of the data collection of the Case SM was the same as the duration of the implementation of the EMS since improvement activities were implemented throughout the entire project as part of the continuous improvement of the EMS. During this time, all improvement activities could be observed as the author lead both the EMS implementation project and the Case SM. In the Case SM, data were collected by seeking triangulation of the data mentioned by Voss et al., (2016), through a combination of passive and participatory observations, semi-structured interviews, informal conversations and a documentary revision of different sources of evidence. Table 7 displays an overview of the data collection for the Case SM.

The data collection was carried out in three main stages: I) introduction, II) analysis, and III) improvement. The introduction stage I) began with a company-level project initiation meeting that marked the beginning of the EMS implementation project as well as the Case SM. At this meeting, the schedule, the approach, the implementation leader and the energy awareness course were presented to the staff of all departments including the personnel of the production area. This meeting facilitated the subsequently collection of data as the personnel of the company were already familiar with author and had a greater energy awareness. Another important activity in this stage was the documentary review made on the documents related to the production process. It is worth mentioning that, as part of the EMS implementation, full access was provided to the company's documentation system during the entire project.

In the analysis stage, a large number of passive observations and informal conversations were carried out in the production area. It was established a daily routine of visits to the production area that began with a passive participation of the author in the accountability meetings at the beginning of the shift and a subsequent tour through the production process. Remarkable is the disposition as well as the support for the realization of the process analysis of the personnel in the production area. The information collected in the process analysis complements the information collected at the plant level and allowed the realization of the energy review of the company. The presentation of the energy review results to the top management of the company allowed to understand what their significant energy uses were and where the improvement activities should be directed. For the improvement stage, the researcher became a participatory observer by implementing an improvement ideas program. It covered not only energy aspects, but also water consumption, quality and cost reduction. Improvement ideas proposed by the personnel were received, analyzed (cost-benefit) and implemented. It was always motivated to implement the improvement idea by the same employee who proposed it. The company provided the resources in time and, when needed, the necessary investment for the implementation of the ideas. Derived from the great amount of ideas received, an indicator was established on a monthly basis for the company to follow up the improvement ideas received and implemented. The feedback of the Case SM was given separately from the EMS implementation project feedback.

Table 7. Overview of the data collection for Case SM.

Technique	Frequency	Duration (min)	Types of data collected
Passive observations			
Production area	Daily	30-45	Information about the facilities, process type, operations, process equipment involved, product, quality tests and product packing.
Accountability meetings	Daily	15-20	Production orders, quality and material issues, Information about the product, process know-how.
Participant observations			
Kickoff meeting	1	30	Preliminary findings, opportunity areas for improvement, Environmental and Energy awareness course
Improvement ideas program	Daily	15	Collection of ideas, types of ideas, status of implementation
Management review, feedback meetings	Yearly, Monthly	60	Preliminary findings, opportunity areas for improvement, feedback
Interviews	32	30-60	Organizational chart, roles and responsibilities, energy and water billing, Respondents: Production manager, maintenance manager, engineering manager, R&D manager, manufacturing engineers, purchaser, production supervisors, quality technicians and production operators.
Informal conversation	Daily		Process know-how, feedbacks, opinions, continuous improvement ideas, project status
Documents	Full access		Process flow diagram, work instructions, procedures, sterilizer LCA.

The Case NE was carried out in the same company of the Case SM. The empirical data collection started in September 2014 and finished in July 2016. The case focused on the innovation of equipment, within the project of development of a new equipment of the company. Special emphasis was placed in the environmental design requirements when the company innovated an equipment.

In Case NE, data were collected through a combination of passive and participatory observations, semi-structured, informal conversations and a documentary revision. Table 8 presents an overview of the data collection for the Case NE. Before beginning the case, a previous time for data collection was invested in the study of documented procedures related to the topic of new product introduction in the company. The data collection was carried out during the three main stages of the project: I) design review, II) design verification and III) design validation. Most of the data was collected in the first stage of the project, as this is where the environmental design requirements are approved.

The Case NE began with a project initiation meeting. Here the objectives and schedule of the project, as well as the role of the author were presented. In the same way, a follow-up meeting was performed for each of the stages. In parallel, semi-structured interviews were conducted with the members of the project in order to know:

- Their responsibility in the mentioned development projects;
- Their experiences in the design and development of new products;
- Environmental requirements in equipment design;
- Opportunity areas observed during the introduction of new products.

One of the main outputs of the stage was the need to outsource the design and development of the main innovation component of the new equipment to an industrial equipment design center. The component development project started in December 2014 and ended in April 2015. During six months, the author attended six meetings as a participatory observer, as he was the link between the company and the industrial equipment design center. Once the outsourcing project was finished, this stage could be completed by approving the design and by the construction of the first prototype.

The design verification and validation stages were observed by the author, including the follow-up meetings, but in a passive manner. During the project, the possible results of the case study were discussed with the two supervisors of the company receiving feedback for the steps to follow in the data collection.

Table 8. Overview of the data collection for Case NE.

Technique	Frequency	Duration (min)	Types of data collected
Passive observations			
Project initiation meeting	1	60	Presentation of the project and the participating team, responsibilities, background and final objectives of the project.
Follow-up meetings	6	60-90	Status and progress of the project activities, environmental requirements achievement.
Participant observations			
Feedback meeting	Monthly	60	Preliminary findings of the case study, opportunity areas for improvement.
Informal conversations	Daily		Opinions, project status, opportunity areas for improvement.
Documents	Full access		Procedures, technical requirements check list, environmental requirements, follow-up acts.

3.3.2 Retrospective cases SC and GW

As a complement to the data collection of the Case studies SM and NE, two retrospective cases studies were conducted. Case SC in the same equipment manufacturer company and Case GW in a research institute or production engineering and machine tools. Empirical data were collected between October 2014 and April 2015 and between April 2018 and August 2018 respectively (see Figure 21). Both cases focused on an industrialization project and special emphasis was placed on the activities for the design of production processes and the environmental requirements in the acquisition of equipment.

The data collection in both cases occurred in a very similar way. A series of semi-structured interviews and a documentary review of the documents relating to each project studied in each case study were carried out. During 7 interviews in Case SC and 15 interviews in Case GW, an interview guide was applied through semi-structured interviews to the personnel of the different positions in relation to the projects studied in order to know:

- Overall process for the design and implementation of productions process;
- Their responsibility in the mentioned development projects;
- Environmental requirements in equipment acquisition;
- Their experiences in the design and implementation of production process;
- Opportunities observed during the design and implementations of production systems.

All interviews were conducted face-to-face by a single interviewer in the facilities of both entities, most of them in the production area. Each interview was started with the explanation of the purpose of the case study, followed by the application of the interview guide and concluding with the recommendation by the respondents of the possible steps to follow in the case study. All notes taken by the interviewer were subsequently transcribed. Table 9 and Table 10 presents an overview of the semi-structured interviews for the Cases SC and GW.

Table 9. Semi-structured interviews during Case SC.

Respondents	Position	Interview date	Duration (min)
1	Quality director	20.01.15	60
1	Engineering manager	22.01.15	90
1	R&D manager	29.01.15	90
2	Program managers	05.02.15	60-90
2	Manufacturing engineers	10.02.15	60

[redacted]

3.3.3 Survey C

The focus of the survey was to investigate how the innovation of the processes and equipment occurs in equipment manufacturing companies and how sustainable these innovations are. The survey questionnaire comprised 39 questions (see appendix E) and those were based on the literature reviewed in the Chapter 2 and in the preliminary empirical findings of the Cases SM, NE, SC. It is worth mentioning that the application of the survey was applied in Spanish and later translated into English for the presentation in this thesis.

The survey was sent to 25 equipment manufacturing companies through the online software Survey Monkey (SM, 2019). With the first notification from the system, ten complete questionnaires were received. With a second notification, four more questionnaires were received. It was necessary to contact the companies by telephone in order to receive two more questionnaires. Around 14 respondents design and manufacture process equipment, 1 company design and manufacture equipment for assembly lines and 1 company design and manufacture laboratory equipment.

3.4 RELIABILITY AND VALIDITY OF THE RESEARCH

The quality of the case study research can be judged through particular tests that allow the establishment of trust (Voss et al., 2016). Gibbert et al., (2008) defined these tests as: construct validity, internal validity, external validity and reliability.

3.4.1 Construct validity

The *construct validity* is the establishment of the correct operational measures for the concept studied (Voss et al., 2016). Construct validity in case research represents a challenge for the researcher since most of the time the establishment of correct operative measures falls on subjective judgments (Yin, 2014) and the use of inadequate definitions and measurements of the variables (Creswell, 2009). In this sense, different authors (Riege, 2003; Voss et al., 2016; Yin, 2014) have mentioned that the construct validity can be increased through the application of different methods as the use of multiple sources of evidence, the establishment of a chain of evidence in the case study and the revision of the case study draft by key internal informants

During all the case studies of the presented thesis, multiple sources of evidence including primary and secondary data sources were used (see Table 7, Table 8, Table 9, Table 10). Unlike the retrospective Case studies SC and GW, in which the obtained data were derived from semi-structured interviews and a documentary review, the real-time Case studies SM and NE included data derived from passive and participatory observations, informal conversations as well as semi-structured interviews and documentary reviews. The establishment of a chain of evidence allows the case study reader to follow the derivation of any evidence from the research question until the conclusions of the case study (Yin, 2014). Throughout the presented thesis, especially in Chapters 3 and 4, it was intended to maintain an implicit chain of evidence. Chapter 3 adequately presents the sufficient citation as specific documents, interviews, passive and participatory observations that allowed to arrive at the empirical findings presented in Chapter 4. Another way in which the chain of evidence was maintained was by explicitly indicating the circumstances in which the evidence was collected (place and time of semi-structured interviews and observations). Another method that strengthens the validation of the construct is the review of the case study draft by key internal informants (Voss et al., 2015; Yin, 2014). The final drafts of the case studies were presented to the two supervisors of the company (Cases SM, NE and SC) and to two supervisors of the institute (Case GW), with the aim of receiving feedback on possible empirical results and possible steps to follow to complete both case studies. In addition, Bruch (2012) used a combination of real-time and retrospective case studies, such as those presented in this research, to strengthen the construct validity in case study research.

3.4.2 Internal validity

Internal validity is the degree to which a researcher can establish cause-effect relationships in a case study (Voss et al., 2016). This means that the empirical findings in the case studies make sense and answer the research questions (Vincze, 2010). There are different methods to strengthen the internal validity in a case study. In the presented thesis the Chapter 3 was dedicated to demonstrate the logical causal relationship of the research through the documentation of the research framework (Voss et al., 2015). With the aim of avoiding the risk of post-rationalization of retrospective cases (Leonard-Barton, 1990), real-time Cases SM and NE were combined with retrospective Cases SC and GW to strengthen internal validity. Also, a pairs of case studies (SM-NE and SC-GW) were selected with the objective to cross-cases pattern matching and to have a multiple perspective in the verification of the findings in the subsequent enfolding literature as described in (Voss et al., 2015).

3.4.3 External validity

External validation is also known as generalization (Yin, 2014). This refers to the level at which the results of the case study can be generalized to other case studies (Voss et al., 2016). When theory building through multiple cases as in the presented thesis, a logical replication (theoretical or literal) should be used in the selection of cases (Voss et al., 2015). In real-time Cases SM and NE, a theoretical logical replication was used for the selection of the units of analysis. Contrary results were observed between the improvement of production process and the innovation of equipment innovation but for predictable reasons. The retrospective cases studies SC and GW were selected using a literal logical replication by analyzing the same unit and sub-unit of analysis predicting similar results. In addition, the use of retrospective cases also strengthens external validation in case studies (Leonard-Barton, 1990).

3.4.4 Reliability

Reliability in case study refers to the consistency and repetition of the procedures used in the investigation to obtain the same results (Yin, 2014). Reliability in a case study depends on documentation of the working procedures in an explicit research protocol and on the development of a case study database (Voss et al., 2016; Yin, 2014). Each of the case studies of the presented in this thesis were carried out using a standard work format. This allowed data collection between cases in a standardized manner. The standard work formats for each case were transcribed at the end of each case to avoid the missing of information by the loss of some format. One of the requirements of the entities where the case studies were carried out was to develop a database with all the information collected in each case study. For this purpose, a space was created within the internal server in the company and the institute, respectively. Table 11 shows the methods applied in the presented thesis to strengthen validity and reliability of the case studies.

Table 11. Methods to strengthen validity and reliability of case studies.

Test	Method	Case SM	Case NE	Case SC	Case GW
Construct validity	Key informants review	•	•	•	•
	Data triangulation	•	•	•	•
	Chain of evidence	•	•	•	•
	Data collection procedure	•	•	•	•
	Explanation of data analysis	•	•	•	•
	Research framework	•	•	•	•

Internal validity	Combination of real-time and retrospective cases	•	•	•	•
	Cross-cases pattern	•	•	•	•
	Enfolding literature	•	•	•	•
External validity	Replication logic in multiple cases	•	•	•	•
	Retrospective cases	•	•	•	•
Reliability	Case study protocol	•	•	•	•
	Case study database	•	•	•	•

3.5 DATA ANALYSIS

The *data analysis process* consists in the preparation and organization of the data for their respective analysis (Creswell and Poth, 2017). The data collected in the literature review of the frame of reference and in the case studies and the survey represented a large volume of data. In the presented thesis, the data analysis process was based on six steps as proposed Voss et al., (2016), I) documentation, II) coding, III) within-cases analysis, IV) cross-cases analysis, V) enfolding literature and VI) conclusions. Figure 22 shows the data analysis process used in the presented thesis.

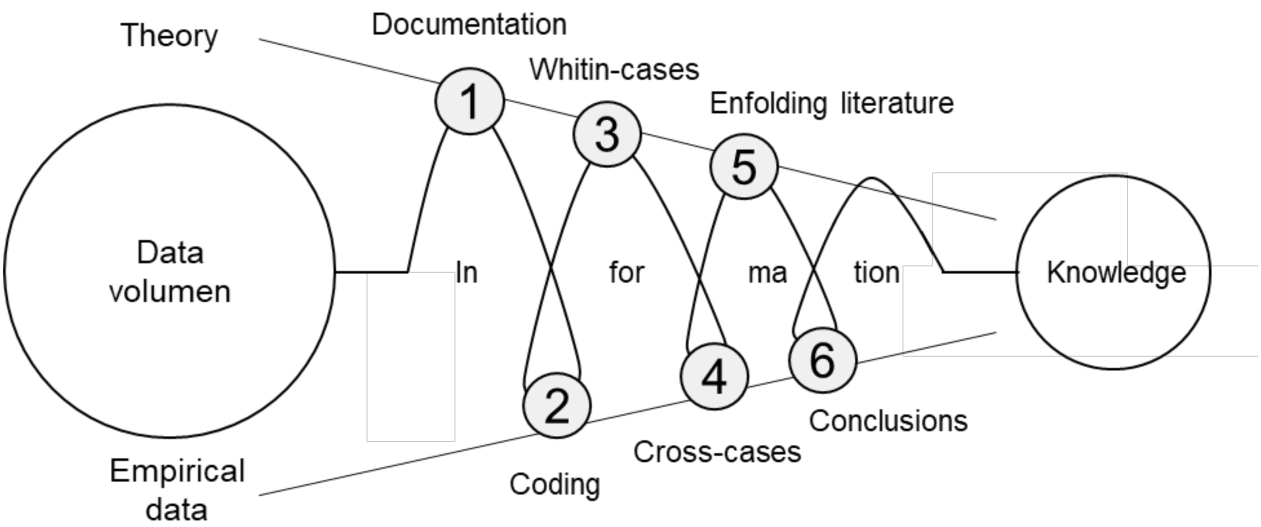

Figure 22. Data analysis process. Adapted and modified from (Bruch, 2012).

The first step of the data analysis process is the documentation. The data collected in the case studies were documented by interview and semi-interviews responses, notes, and recommendations and controlled copies of internal company documents and also, through the response formats of the survey carried out. It should be noted that all notes from the interviews were taken and subsequently transcribed, establishing with this a case narrative as described in (Voss et al., 2016). Particularly for the Case SM, the process improvement ideas generated by the employees were documented in paper format and in the electronic database as part of the EMS implementation.

The second step is the coding of the data. It is the action of attaching codes to the collected data to allow their analysis (Wicks, 2017) that is fundamental to an effective case study research (Voss et al., 2016). In this research, the collected data were organized according to the sub-unit of analysis of each study.

The third step is about the within-cases analysis. In this, the researcher analyzes each case separately by themes (Creswell and Poth, 2017) in order to become familiar with the cases and to identify unique patterns in each case (Eisenhardt, 1989). In this sense, in Section 3.3 and Chapter 4 all case studies and the survey were described in detail.

In the step four, a cross-case analysis was performed to identify (behavioral) patterns (Eisenhardt and Graebner, 2007). In the search for pattern matching, Cases SM and NE and subsequently, Cases SC and GW were analyzed. First separated by pairs of cases and then together in a cross-cases form because they had a very similar unit of analysis (Leonard-Barton, 1990).

In step five, in order to compare the findings of the case studies and the survey with existing literature in a enfolding literature form (Voss et al., 2002), the result of the analysis in step five was compared with the propositions found in the literature review in the frame of reference in Section 2.3 in the search to find out what is similar, what is different and for which reason (Eisenhardt, 1989).

Finally, the conclusions of the data analysis process are presented in the following Chapters 5 and 6, by answering the research questions presented in Chapter 1, Section 1.2.

4. EMPIRICAL FINDINGS

In this chapter the empirical findings from each of the real-time Cases SM and NE, the two retrospective Cases SC and GW and the Survey C are presented.

4.1. EQUIPMENT MANUFACTURER COMPANY

The Cases SM, NE and SC were carried out at Matachana in Castelldefels, Spain, a family-owned business company with a very solid reputation and prestige with more than 57 years of history. The company is the Europe's sterilization leader dedicated to the development of complete sterilization projects for hospitals, laboratories, research centers and industry in general. The company is responsible for the design, manufacture, marketing and technical service for sterilizers, washing machines and surgical units and has a worldwide presence through its own subsidiaries in Spain, France, Germany, Italy, USA, Argentina and Malaysia, as well as distributors in more than 110 countries.

In addition to manufacturing, the company designs and develops new products to meet the current and future needs of the market through its R&D department and as well as a competence center that designs and implements the installation of equipment. Figure 23 shows the facilities of the company.

Figure 23. Matachana production center, Castelldefels, Spain.

4.1.1 Case SM

The real-time Case study SM analyzed the activities to reduce the environmental resource consumption of the equipment as a part of an improvement of a production process within the implementation of an Energy Management System (EMS) in an equipment manufacturing company. The project consisted on the implementation of an EMS based on ISO 50001:2011 (ISO, 2018). The objective was to ensure the continuous improvement in the use of energy in the company through well-established procedures and methods. The implementation of the EMS was conducted by the author of the presented thesis. Once the project was in an advanced stage, an energy leader was designated by the company.

The EMS implementation followed the requirements established in the norm ISO 50001:2011 (ISO, 2018) and was conducted in all departments of the company but especially in the area of production with the support of the areas of quality, materials and engineering among others. The implementation was divided into five stages: I) energy policy, II) energy planning, III) implementation-operation, IV) monitoring-measurement-analysis and V) certification. The energy policy stage consisted in the realization of a process analysis, the identification and evaluation of the energy aspects, the definition of the energy policy and the revision of the legal and other requirements applicable to the company. At the energy planning stage, the energy review was carried out, and the energy baseline, the energy indicators (IDE´s), objectives, goals and action plans of the energy policy of the company were established. The implementation and operation stage consisted in the execution of the energy management action plans as the allocation of resources, functions, responsibility and authority, competence, training and awareness, communication, documentation and document control as well as organizational control. In the monitoring-measurement-analysis stage, the verification of the measures and the corrective actions including the monitoring and measurement, the compliance evaluation, the non-conformity, the corrective and preventive actions, control of records and the EMS internal audit were carried out.

An important activity within the EMS implementation that marked the beginning of the Case SM was the realization of the energy review at the energy planning stage. The energy review began with a process analysis through "go and see" of the process flow diagram to understand each of the operations and equipment involved in the operations and peripheral areas. In general, electricity followed by gas were found to be the most consumed types of energy and this consumption in three main areas: I) illumination, II) climatization and the III) production process. By focusing specifically on the production process the consumption is divided into three main areas: I) assembly, II) test area and III) packaging. The energy review established that the equipment in the assembly and packaging areas is essentially manual equipment and represents only 34% of total process consumption compared to 66% of the equipment consumption in the test area. The reason for this is that the test area offers the necessary conditions of electricity, water, steam and air pressure to simulate the operating conditions of the equipment through the realization of an end-of-line test. Figure 24 shows the assembly area of the production process of sterilizers in the manufacturing company.

Figure 24. Assembly area of the sterilizer production process.

Another important activity during the development of the Case SM was the implementation of improvement ideas by employees to cover communication requirement of the implementation and operation stage of the EMS. The process of ideas for improvement consisted in the filling of an improvement idea sheet (see appendix B) and its subsequent deposit by the employees in a mailbox established in a central point of the production area. Subsequently, the improvement ideas were collected, analyzed regarding its cost-benefit and then implemented or rejected. It was always motivated the implementation by the same employee that proposed the improvement idea. The company provided the resources as employee time, tools and, when it was necessary, the investment for the implementation of the ideas. Derived from the great amount of ideas received, an indicator was established on a monthly basis for the company to follow up the improvement ideas received. Figure 25 shows an excerpt from the improvement ideas tracking list. In general, a total of 117 ideas were collected and evaluated during the Case SM. The status up to the end of the Case SM was 65 improvement ideas implemented, 33 rejected and 19 were in the process of implementation.

#	Employee	Area	Proposal	Resource	Date of proposal	Action plan	Aproveed	Implementation
Improvement ideas implemented								
4	Miguel Garcia	Production	Regulate the lighting of luminaires in the morning on the production floor	Electricity	20-May-2014	Illumination Guideline		25 Mpoints
37	Germa Cuesta	Purchasing / Logistics	Reducing the contracted potency P1-P5 390 Kw to P1-P5 300Kw P6- 600 Kw to P6-451 Kw	Electricity	13-Jun-2014	Endesa (Download + IT Change)		520 Mpoints
25	Modesto Garcia	Test bench	Analyze the possibility of reducing the energy consumption of the test bench	Electricity / Water / Gas	14-May-2014	On standard machines reduce the number of programs that are tested		55 Mpoints
12	Eloi Peña	R&D	Installing a bicycle parking lot at the entrance enables us to give the company an ecological image and the employees can come to work without polluting the environment	Other	4-Apr-2014	Send a quotation and install a parking lot for 5 bicycles		30 Mpoints
28	Valentín Peláez	Production	Turn off the dining room light when not in use	Electricity	9-Apr-2014	Illumination Guideline		20 Mpoints
42	Jose Luis Fernandez	Purchasing / Logistics	Installation of shutters to minimize the temperature of the second floor distributor area	Electricity	14-Jun-2014	Request a quote for the installation and send it to management for approval		30 Mpoints
Improvement ideas in process of implementation								
8	Cristobal Risques	Production	Improve the company's heating by placing the heating rings above the two large doors. This is intended to create a wall of hot air that prevents cold air from entering the street when loading/unloading material	Electricity	4-Apr-2014	A quotation was requested		
22	Miguel Garcia	Production	Establish a color separation system for factory waste: cardboard, paper, metal waste, wood, etc. They can be separated on the production floor, sold and benefit from recycling	Waste	25-Apr-2014	Present a project of satellite areas at plant level		
14	Miguel Garcia	Production	Place curtains on the loading and unloading doors to prevent the entry and exit of air conditioned	Electricity	25-Apr-2014	A quote was requested for curtains		
20	Alonso Garcia	Production	Place sensors on the faucet of the factory bathroom sink to reduce water consumption	Water	25-Mar-2014	Quote sensor and propose places where they can be placed in the plant		
Improvement ideas not approved								
47	Ana Viñas	Quality	Turn off the servers on weekends and holidays, which would mean being able to turn off the air conditioning as well	Electricity	7-Jul-2014	Consult with management	Not approved by company policy. Servers must always be connected to allow access to the system	
13	Miguel Garcia	Production	Analyze the possibility of reusing the condensation water of air conditioners	Water	25-Apr-2014	Quote for recovery system	Not approved, because it is not relevant vs. Installation	

Figure 25. Follow-up to improvement ideas of the company

A total of 26 improvement ideas focused on reducing the consumption of electricity, gas and water in the equipment. Among these ideas for improvement, the most important were those aimed at reducing the consumption of manufactured sterilizers at the test area regarding the amount of resources consumed during the end-of-line test. Although different ideas were considered, two were the most important improvement ideas for the reduction of the consumption of resources. The first one was the reduction of the sterilization programs in the sterilizers at end-of line test. The need to test all sterilization programs that can be performed in the sterilizer in the mentioned test was eliminated as long as the first sterilizer of the shift or order passed all tests without any failure. The second improvement idea was the installation of a water recovery tank so that water emissions from a sterilizer could be reused by the next sterilizer to be tested. The main empirical findings of the Case SM can be summarized as follows:

- Equipment was the main consumer of resources in the production process;
- A reduction in the consumption of resources in the equipment resulted in a reduction of the consumption of resources in the production processes;
- The sterilizers manufactured by the company were able to reuse water emissions at the time of testing so that they could also reuse water emissions at the customers during their operational phase.

4.1.2 Case NE

The second real-time Case NE analyzed the environmental requirements in equipment design as part of an innovation of an equipment within a new equipment development project in the same company of Case SM but in a different area than the Case SM. The company had 57 years of experience in the design and development of new products. The project consisted in the design and development of a low-temperature steam formaldehyde sterilizer. The objective was to offer to the market a sterilizer equipment that consumed fewer environmental resources during its operation phase compared to the current production model at that time. The design and development of a new equipment was conducted by a project leader within the R&D department with the support of the engineering, production, quality and marketing departments among others.

The coordination of the product management and marketing departments communicated to the general director of the company that there was the need of the market and the opportunity to expand the range of products of the company through the innovation of a sterilizer equipment for the reduction of consumption of environmental resources in its operation. The directors of the engineering and R&D departments studied the feasibility of the project, considering not only technical or cost aspects but also related to competitive advantage, technological innovation and strategic importance. The design and development of a low-temperature steam formaldehyde sterilizer was proposed. The new sterilizer could reduce by 60% the environmental consumption compared to the current high-temperature steam model in production at that time by reducing the sterilization temperature from 134ºC to 69ºC on average, allowing a considerable reduction in the operating costs of the sterilizer. The project was accepted by the general direction of the company and proceeded to its design and development. Figure 26 shows the presentation of the new equipment development project to the departments involved.

Figure 26. Presentation of the new equipment development project.

The project followed the procedure established in the company for the design and development of new products and was divided into three stages: I) design review, II) design verification and III) design validation. At the design review stage, the adequacy of the design to the initial specifications, applicable standards, regulations, directives and established risk management was verified to validate the feasibility of the project. In this stage, the results of the Design Failure Mode and Effects Analysis (DFMEA) performed detected the possibility of leaks in the formaldehyde dispenser device which could generate evaporation and odors that could affect the operation of the sterilizer. In this sense, the design corrective actions contemplated the outsourcing of the design and development of the main innovation component of the new equipment to an industrial equipment design center.

The design and development of the formaldehyde dispenser device was carried out over a period of six months. The project followed the design center project management procedure and was divided into four stages: I) conceptual design, II) 3D design, III) prototype and IV) test. At the conceptual design stage, the operating principles of the component were determined (calculations and preliminary tests) as well as its basic architecture. Starting from the previous solution principle, in the 3D design stage, the global configuration of the design (layout) was determined by means of a 3D model. This model allowed to have an overview of the materials, shapes and dimensions as well as the manufacturing process of the dispenser. Based on the design and 3D model of the previous stages, in the prototype stage, the construction of the prototype of the component was carried out to later perform the functional tests in the test stage.

Once the outsourcing project was finalized, the sterilizer design review stage was completed by approving the design and the construction of the first prototype. In the design verification stage, the prototype was approved by verifying that it passed the tests and trials of the operating conditions defined in the technical specifications, thus obtaining a partial qualification of the new equipment for the launch of pre-series. Finally, in the design validation stage, the pre-series were approved by validating that the new equipment met the design specifications, was in accordance with the assessed risk management and satisfied the needs of the customer. Subsequently, the new equipment was released for standard production. Figure 27 shows the low-temperature steam formaldehyde sterilizer developed during the Case study NE.

Figure 27. Low-temperature steam formaldehyde sterilizer developed during the Case study NE.

In general, the analysis of the environmental requirements in the design of the equipment occurred during the whole project. Derived from a market need which required the production and commercialization of a more efficient sterilizer equipment in the consumption of environmental resources, the low-temperature sterilizer was developed. The main empirical findings of the Case NE can be summarized as follows:

- The company had environmental requirements for its equipment suppliers;
- The company´s decision to purchase the equipment was based on an analysis of the consumption of environmental resources of the equipment to be purchased;
- The company had experience in acquiring equipment that can reuse its own emissions.

4.1.3 Case SC

The retrospective Case SC analyzed the environmental requirements in the equipment acquisition from an industrialization project within a new product development project in the same equipment manufacturing company of Cases SM and NE. The project consisted of the design and implementation of a sterilization central. With this project, the company sought to expand the portfolio of products offered to its customers not only sterilizer equipment, but also the complete sterilization central, including other equipment different from those that the company manufactures. The design and development of a sterilization central was conducted also by a project leader within the R&D department also with the support of the engineering, production, quality and marketing departments.

The project followed also the procedure established in the company for the design and development of new products followed in Case NE and was therefore divided into three stages: I) design review, II) design verification and III) design validation. The design of the sterilization central was based on the initial specifications and revealed the need to acquire equipment external to those manufactured by the company. A contact was established with the different equipment suppliers and after the respective evaluation, a quotation was required following the procedure of purchase of the company. Once the equipment was acquired and received, the design of the sterilization central was verified and validated installing a prototype in one of the exhibition rooms of the company. Figure 28 shows the sterilization central prototype.

Figure 28. Sterilization central prototype.

Environmental requirements were sent to equipment suppliers through an advice letter from the purchasing department as part of the EMS implementation. In compliance with the requirements of the standard, the company informed to its suppliers in general that the purchase of energy services, products and equipment that have or may have a significant impact on the use of energy would be evaluated in part on the basis of energy efficiency, adding this criterion to the usual purchasing criteria such as quality, service, cost and delivery. For this, the supplier would have to provide the relevant information for the fulfillment of this requirement. Different proposals were received for the different types of equipment models and their capacities, highlighting the model of a thermo-disinfector washing machine that had the possibility of reusing its own emissions with the aim of reducing its energy consumption and the cycle time of the washing process, see Section 2.2.4, Figure 19. The main empirical findings of the Case SC can be summarized as follows:

- The company has environmental requirements for its equipment suppliers;
- The purchase decision of the equipment by the company is based on the analysis of the consumption of environmental resources of the equipment to be purchased;
- The company has experience in the acquisition of equipment that can reuse its own emissions which are already a reality in the market.

4.2 RESEARCH INSTITUTE

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4.3. CLUSTER OF EQUIPMENT MANUFACTURERS

4.3.1 Survey C

A survey method was conducted within the Equipment Manufacturer's Cluster of Catalonia (CEQUIP) which integrated a total of 42 entities related to the equipment manufacturing industry established in Catalonia. Figure 31 shows the companies that are part of the CEQUIP.

Figure 31. CEQUIP companies.

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This chapter summarizes the empirical findings of the cases studies and the survey carried out. The data collected in this chapter together with the data collected in the frame of reference (Chapter 2) will be analyzed as described in Section 3.5 Data Analysis. Based on this analysis, the following Chapters 5 and 6 will answer the two research questions (Chapter 1, Section 1.2).

5. EMISSIONS REUSE CLOSED LOOP THROUGH EQUIPMENT

This chapter answers the first research question (RQ1) How can the process-equipment system be innovated in a context of sustainability? developing a conceptual model for the implementation of emissions reuse closed loops through equipment.

5.1 DEVELOPMENT OF THE CONCEPTUAL MODEL

5.1.1 Conceptual model rationale

The rationale for developing the conceptual model described in this chapter is based on several concepts from the literature reviewed in Chapter 2 such as closed loops, CP as well as the diachronic and synchronic dimensions of the equipment. The proposed conceptual model combines the above mentioned concepts with the objective of establishing a basis for the development of a methodology for the sustainable redesign of production processes that allows the mentioned by Tonelli et al., (2013), that a redesigned production process should:

- Reduce material inputs and energy by 25% with the same added value;
- Use 90% of discarded materials;
- Implement the cradle-to-cradle concept in materials that can be reused;
- Recondition and reuse sophisticated and durable components;
- Imitate environmental ecosystems.

5.1.2 Cleaner production as a concept foundation

Gomes da Silva and Gouveia (2020) explained that the genesis of the CE and the CP seek to avoid the consumption of raw material via internal closed loops in order to extend the useful life of resources through the use of 4Rs tools (reduce, reuse, recycle and recovery). Therefore, to achieve the implementation of the emissions reuse closed loop in production processes, it is essential that the CE incorporates the CP tools that allow for the reduction, reuse, recycling and recovery of waste and emissions. *Recovery* of waste and emissions is the rate of material that can be recuperated from a waste stream (Worrell and Reuter, 2014). The *reuse* involves the repeated use of waste and emissions in a closed loop in the production processes (Nilsson et al., 2007). *Recycling* refers to the process by which material, which had previously been considered as waste or emissions is converted into new raw material (Jawahir and Bradley,

2016) to be used again in the same or another production process. Figure 36 shows how CE should incorporate CP tools to achieve emissions reuse closed loops in production processes.

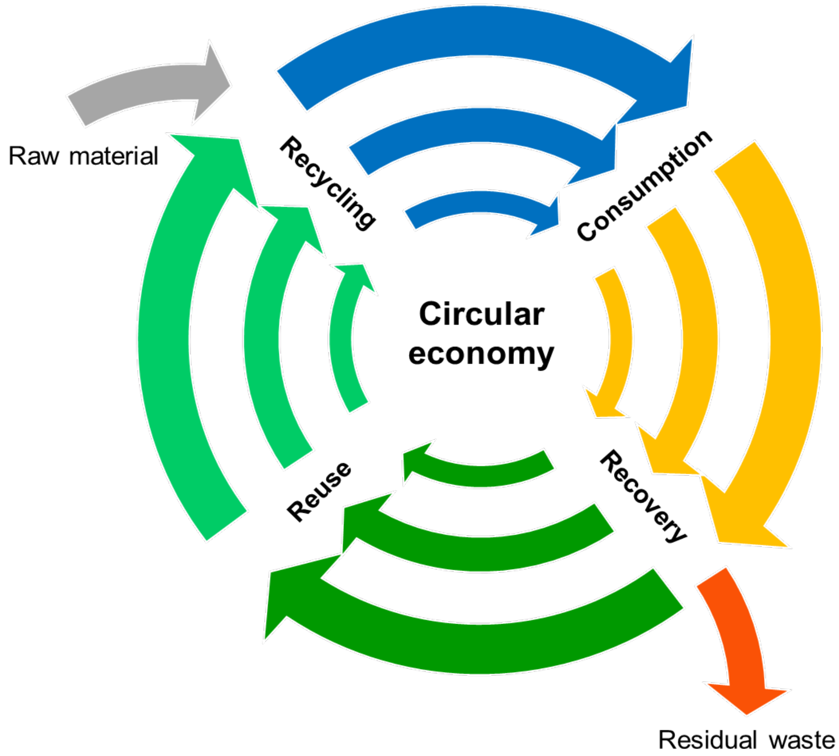

Figure 36. How CE should incorporate CP tools to achieve emissions reuse closed loops in production processes. Adapted from (Gomes da Silva and Gouveia, 2020).

The incorporation of CP tools by the CE allows the implementation of production processes as described by Graedel and Allenby (2002) as a quasi-cyclic resource flows closed loops with a certain high degree of cycling circulation of resources within the production process reducing the need for external resource inputs and the generation of waste and emissions.

Based on this, the presented thesis adapts the closed loop production system model presented by Prendeville et al., (2014) to represent the reduction, reuse, recycling and recovery of emissions in a closed loop in production process to reduce the generation of emissions to the natural environment as well as the decrease of the demand of raw material of the process. The proposed model focuses on the reuse of emissions as a central element of the model. The emissions (solid, liquid or gaseous) that are generated in the production process are recovered, reused and recycled in the same production process when possible. Figure 37 represents the proposed model for the emissions reuse closed loop in production processes.

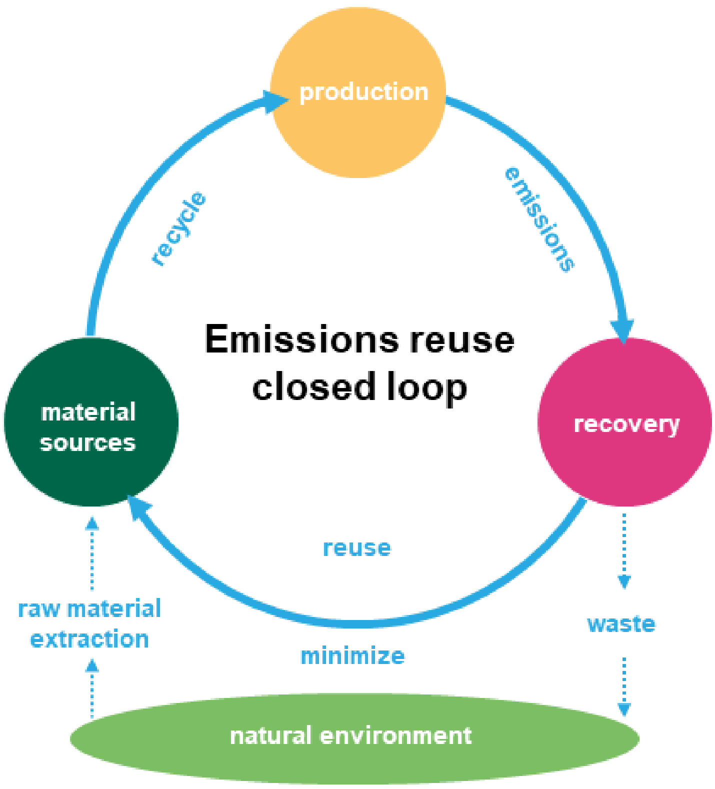

Figure 37. Emissions reuse closed loop. Adapted from (Prendeville et al., 2014).

5.1.3 Transverse analysis of the equipment diachronic and synchronic dimensions

Beyond the consideration of the life cycle of a process equipment (diachronic dimension), the analysis of its interaction with other equipment (synchronic dimension) constitutes an innovative perspective of great interest for the achievement of the emissions reuse closed loops in production processes. The transverse analysis of the principal assessments tools of the diachronic dimension (LCA) and the synchronic dimension (ARC) aim to identify the phase of the life cycle of the process equipment in which most resources are consumed and the amount of consumed resources in this phase as well as the relations of coexistence in aspects of energy, water, material, and emissions between process equipment. In this sense, there is a constant conclusion in the LCA performed for different equipment. The most important stage within the life cycle of an equipment is the operation phase (production process), since here the function for which the equipment has been designed takes place (Riba, 2002) and in which the majority of resources during the equipment life cycle are consumed (Mohammadi et al., 2014) and most of the emissions are generated (Jönbrink et al., 2011).

In a transversal way, the synchronic dimension of the equipment in the production processes holds that in the operation of a production process, all the equipment involved in the process concurs as part of a synchronization between the information, the resources to be consumed by the equipment and the emissions generated. Thus, the ARC result should show a detailed analysis of environmental consumptions and emission generations for each of the equipment that coexists and interacts in the production process. The objective is to evaluate the possibility of the implementation of an emissions reuse closed loop through the equipment emulating an eco-industrial system. Figure 38 represents the proposed conceptual model for the implementation of the CE emissions reuse closed loops in production processes.

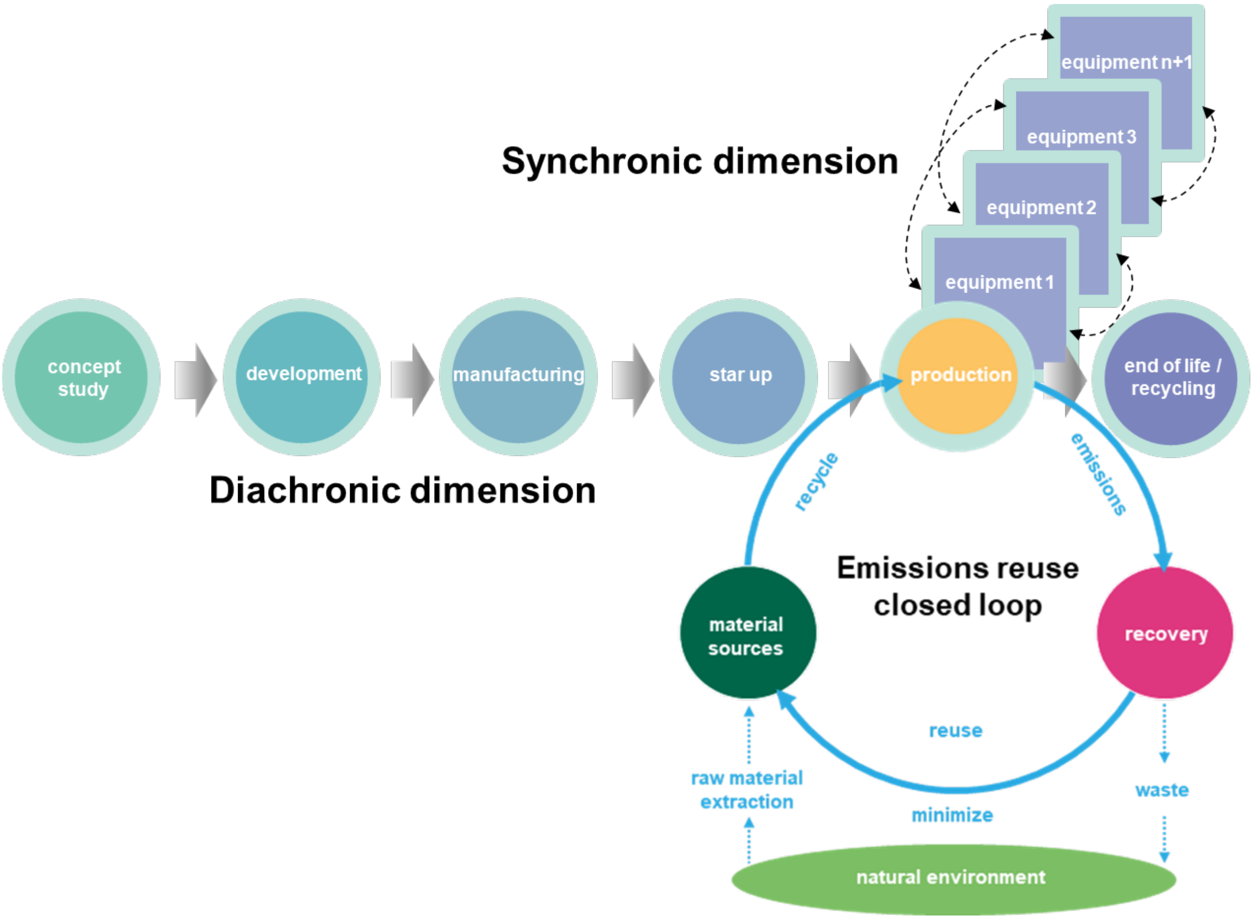

Figure 38. Emissions reuse closed loop in production process through equipment.

The proposed conceptual model allows answering the question RQ1, how the process-equipment system can be innovated in a context of sustainability by establishing the perspective to orient the change towards sustainable redesign of production processes. The characterization of the proposed innovation through a methodology for the sustainable redesign of production processes is the subject of the following Chapter 6.

6. R4ER METHODOLOGY

In this chapter, the answer for the second research question (RQ2), What characterizes the innovation of the process-equipment system in a context of sustainability? is synthesized into a methodology for the sustainable redesign of production processes.

6.1 METHODOLOGICAL APPROACH

The implementation of the proposed conceptual model will only be possible through the redesign of production processes (Camilleri, 2018). With the exception of Llorens (2015), which developed a methodology for redesigning the architecture of the range of equipment manufactured by a company, the different approaches relating to the term process-equipment analyzed in the frame of reference (Arinez and Cochran, 2000; Blanco, 2018; Riba, 2012; Riba et al., 2005) have explored the possibility of designing equipment through analysis of the process in which the equipment operates and not redesigning the process through analysis of the equipment.

The redesign of processes refers to a major effort to improve an existing process (Harmon, 2014). It consists in the modification or reduction of operations to remove non value activities and improve those that add value to the customers (Spring Singapore, 2013). The redesign of processes is an activity of industrial engineering. The basis for the redesign of processes was defined in Principles of Scientific Management from Frederick W. Taylor in 1911 (Serrano and Ortiz, 2012), by the creation of assembly lines divided into operations with different employees by Henry Ford in 1913 (Dooley and O'Sullivan, 2000), by the Structure Approach of Henry Fayol and in the Time and Motion Studies of the Gilbreth spouses in 1917 (Niebel and Freivalds, 2004). In addition, a very important contribution was the Systems Approach presented by Boulding in 1950 in which it was mentioned that the organization is more than the combination of unique elements and that their interaction is more important than the elements themselves (Dooley and O'Sullivan, 2000).

During the 1980s, different methodologies with a focus on quality were presented in order to emphasize the importance of meeting the customer's quality needs. Among the most important are the Statistical Process Control (SPC), Factory Focus, the Quality Circles, the Total Quality Management (TQM), Just in Time (JIT), ISO 9001 (ISO, 2015a) and the Benchmarking among others. Since 1990 different authors have published methodologies of process improvement that have made valuable contributions in the redesign of processes. Among the most remarkable is the contribution by Davenport and Short (1990), who introduced the Business Process Redesign (BPR) methodology. They focused on the concept of process descriptions and the definition and analysis of critical processes to reduce cycle time, to strengthen the value chain and to improve competitiveness. Business Process Management (BPM) is a structured and systematic way for the analysis, improvement, control and management of processes with the aim of improving the quality of products and services (Serrano and Ortiz, 2012). As part of the methodology Toyota Production System (TPS), The Value Stream Mapping (VSM) was presented in 1997. It is a lean manufacturing method for mapping and analyzing the production processes which support the redesign of processes and services (Serrano, 2007).

Harmon (2004) proposed a Business Process Change (BPC) methodology. The methodology is based on the improvement through process redesign due to the changes that can be experienced by the interactions of the staff, the management, IT systems, technology and the structure of the organization (Serrano and Ortiz, 2012). Recently, different authors have contributed to the existing body of knowledge on process redesign through the development of different methodologies for the redesign of process (Palma-Mendoza et al., 2014; Sanka Laar and Seymour, 2017; Venkataiah and Sagi, 2013). In the literature, step methodologies are the most used in the redesign of production processes. Figure 39 shows the sequence of the basic steps of process redesign methodologies.

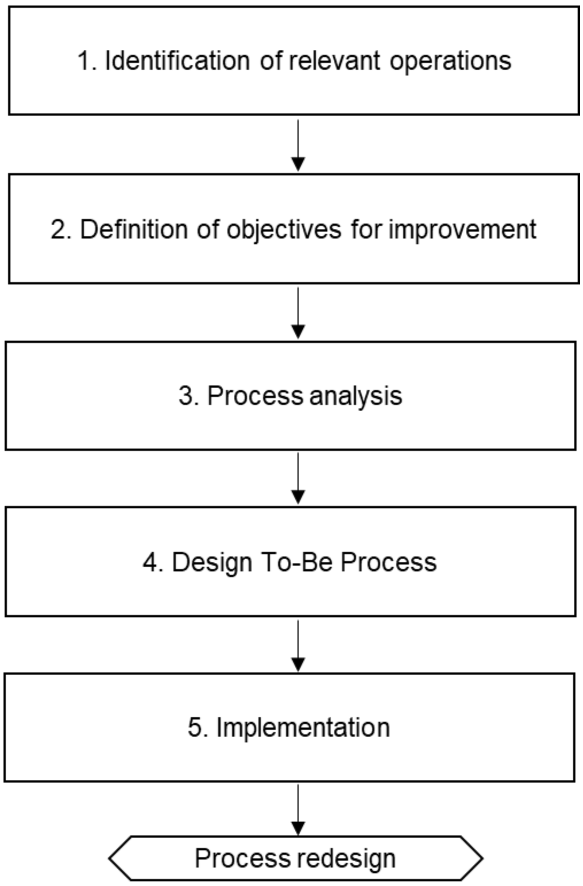

Figure 39. Steps of process redesign methodologies. Adapted from (Davenport and Short, 1990).

Taking into consideration, the current need for the industry to redesign its production process as described in the introduction (Chapter 1), in the frame of reference (Chapter 2) and in the empirical findings of the case studies and survey (Chapter 4), it is remarkable that there are no redesign methodologies in the literature that explore the possibility of reducing the resource consumption and emissions generation in the equipment involved in a process in order to reduce resource consumption and emissions generation in the production process.

All this justifies the proposal to redefine the general sequence of steps in production process redesign methodologies as presented in Figure 40. The redefinition introduces an analysis of the equipment involved in the production process to be redesigned in order to implement the conceptual model of emission reuse through the equipment, as proposed in Chapter 4.

To achieve this, it is necessary to:

- Reorder step 3 "Process Analysis" to position 1 emphasizing that the main output of the step is the identification of the equipment in the process;
- Rename the previous step 1 "Identification of relevant operations" by "Equipment review" and reorder it into position 2. The main result of this phase is to determine, which of the equipment identified in the previous step (1) consumes environmental resources in a significant way;
- Rename the previous step 2 "Definition of the objectives for improvement" by "Cost of the cycle of use" and reorder it into position 3. The result of this phase is to quantify the economic impact of the consumption of environmental resources during a specific period of time of the significant equipment identified in the previous phase (2);
- Finally, unify 4 "Design To-Be" with stage 5 "Implementation" into a single step 4 and rename it as "Emissions reuse". The output of this step will be the evaluation of the possibility of the implementation of an emissions reuse closed loop through the equipment emulating an eco-industrial system.

Following the proposed changes to the general sequence of steps in the production process redesign methodologies. Figure 40 shows the sequence of steps for the R4ER methodology.

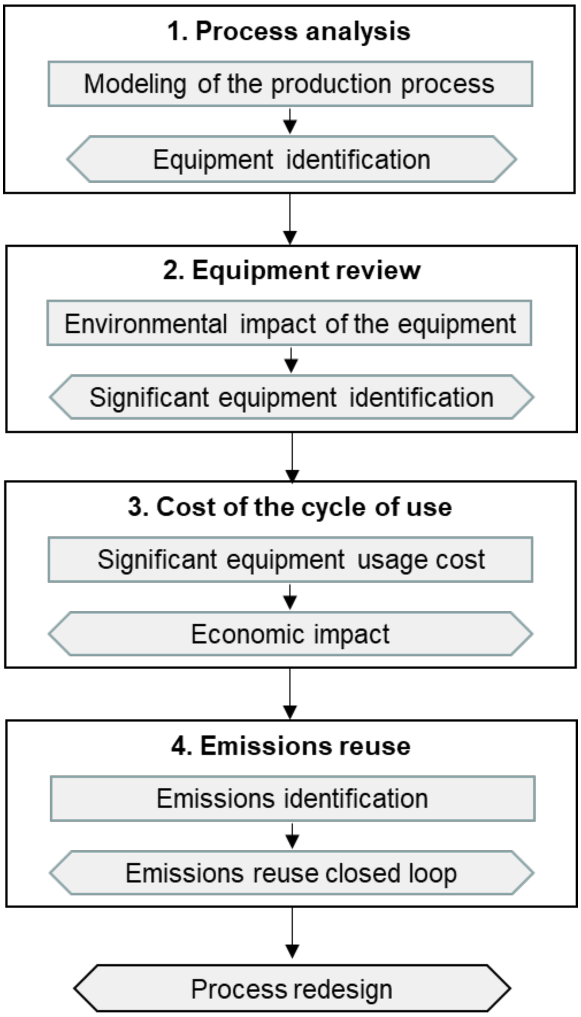

Figure 40. Proposal of steps of the process redesign methodology for the reuse of emissions.

6.2 DESCRIPTION OF METHODOLOGICAL STEPS

As shown in Figure 40, the proposed R4RE methodology consists of four main eps. In order to obtain the expected outputs of the proposed steps, it will be necessary to identify in the literature the supporting tools of each of the methodological steps. A detailed description of each of the steps and their respective support tools is presented next.

6.2.1 Step1: Process analysis

In order to analyze the production process and the identification of the equipment involved, it is necessary to carry out a representation model of the production process. The redesign of processes can be done through production process modeling (Lam and Hills, 2011). A complete survey (Kettinger et al., 1997) identified the Integration Definition for Function Modeling (IDEF0) as an important tool for the redesign phase of production processes. IDEF0 is an appropriate modeling method to describe process flows (Smith and Ball, 2012). The IDEF0 tool presents a structured description of activities in a process through the representation of their respective inputs, outputs, mechanisms and controls. The graphs in the IDEF0 diagram show the operations assigned to the different equipment in the form of boxes and the interfaces to or from the function in the form of arrows entering or leaving the boxes. This IDEF0 diagram should be performed to have a holistic view of operations, equipment, operators, material flows and their interactions within the production process in which the equipment operates.

6.2.2 Step 2: Equipment review

In the second step, it is necessary to perform or to know the results of the LCA for each of the equipment in the production process. The LCA is a method that allows the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006, p.10). LCA requires quantitative information of the complete life cycle (exploitation, production, use and end of life) of an equipment to reveal their environmental profile (Sakao, 2007) The LCA results validate the significant amount of resources consumed during the phase of use of the equipment and allow the identification of equipment significant for the reuse of emissions.

Adopted from the ISO 50001 (ISO, 2018) energy review, the Equipment Review (ER) step allows the identification of the equipment with a major environmental resource consumption in a process cycle. It is performed in the operations identified in the previous step. First, process operations are listed, the equipment involved in each operation and their number are identified. Second, the resource consumption per cycle are taken from the results of the previous equipment LCA. As is in the ISO 50001:2011, the consumption data can also be measured, calculated or estimated, in order not to limit the application of the tool to only measured or calculated data, but also to allow the use of estimated data for equipment consumption for which no real data are available. The name of the resource consumed, their coefficient, the unit of measurement and their percentage of contribution to the actual consumption of the process cycle are identified for each of the previously listed equipment.

Finally, based on the obtained data, it must be decided whether there is a potential for significant savings in the resource consumption and it is needed to identify the equipment and their subsystem on which improvement should be applied. Significance criteria should be established in order to prioritize which resource consumption in which equipment needs to be reduced, the criteria and their severity depend on the environmental needs and the purpose of these criteria that should balance the resource consumption of equipment in the production process.

6.2.3 Step 3: Cost of the cycle of use

In the next step, the cost of use of the significant equipment found in the previous step is calculated through Material Flow Cost Analysis (MFCA). MFCA is a “tool for quantifying the flows and stocks of materials in production processes in both physical and monetary units” (ISO, 2011b, p.3), in which water and energy can be included as materials (Christ and Burritt, 2016).

The MFCA follows the general procedure of the Plan-Do-Check-Act (PDCA) (Deming, 2000) and consists of ten steps. In order to know the cost of use of the significant equipment in the process, steps three until nine should be carried out. The definition of a boundary and a time period as well as the determination of quantity centers are included in steps three and four, for which, the analysis period and the operations involved need to be specified. In order to have a better overview of the flows and inventories of materials in the production process, it is advisable to analyze a month or a year of a production process (ISO, 2011). Steps five, six and seven are the identification of inputs and outputs for each quantity center as well as the quantification of material flows in physical and monetary units. For each operation, inputs (materials, energy) and outputs (products, material and energy losses) have to be identified and quantified in physical and monetary units (Schmidt et al., 2013). The last steps are MFCA data summary, communication of MFCA results and data interpretation.

The results of a MFCA can be very valuable in the search for opportunities to reduce material use and waste, to increase the efficient resource, and to decrease negative environmental impacts and associated costs (Kokubu and Tachikawa, 2013). MFCA can serve to present the economic impact of the resource consumption on the equipment in the production process.

6.2.4 Step 4: Emissions reuse

In the final step, the ARC presented by Llorens (2015) should be extended to the environmental analysis of the relations of coexistence of the equipment (EARC) in the production process. First, the resource consumption and the emissions generation in each of the equipment of the production process should be identified. For the consumed resources, it is necessary to identify their type and origin, coefficient of use, and the temperature, if applicable. For emissions generated, their type and destination, the coefficient of discharge and the temperature if it is applicable should be determined.

Second, the feasibility of reusing emissions as resources between equipment analyzed in the previous step should be evaluated in order to implement an emissions reuse closed loop emulating an eco-industrial system. Whenever possible, it should be sought that the emission outputs of one equipment become the resource inputs of another equipment within the same production process, without this representing an excessive expense for new installations or equipment such as filters, cooling systems or recovery tanks. The final output of the last step in the R4ER methodology is the suggestion to implement the conceptual model of emissions reuse closed loop through the equipment that is involved in a production process, as presented in Chapter 5. Figure 41 shows the proposed steps for the R4ER methodology with the recommended tools to be used at each step.

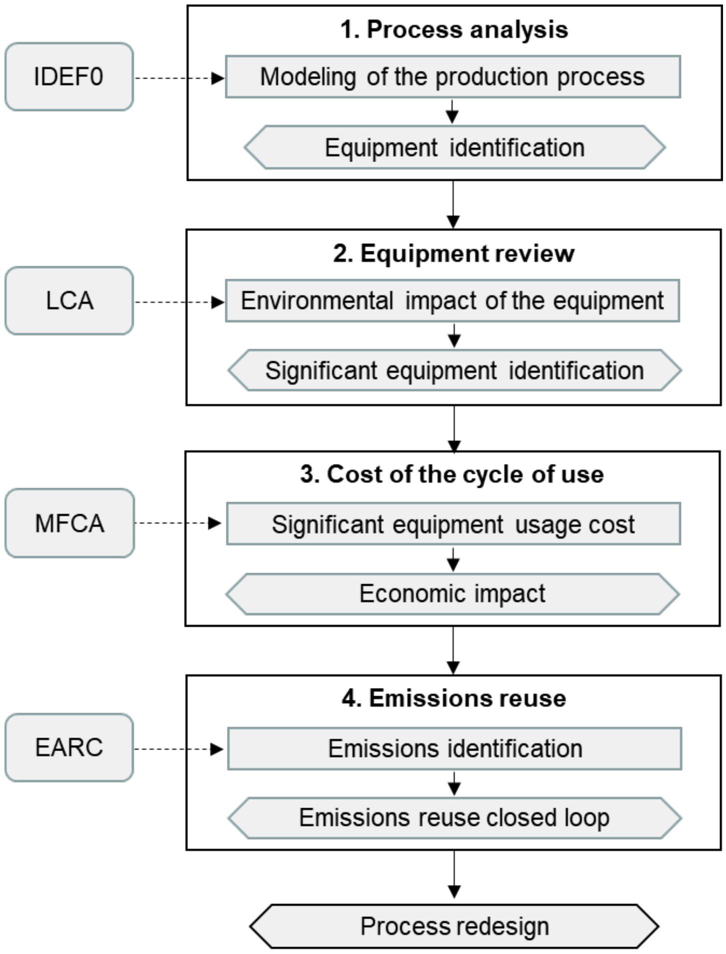

Figure 41. Proposed steps for the R4ER methodology.

7. R4ER IMPLEMENTATION

This chapter describes the general aspects of the implementation of the R4ER methodology presented in the previous chapter in a sterilization central in the manufacturing equipment company and in a grinding wheels production process in the research institute.

7.1 STERILIZATION CENTRAL

Step 1: Process analysis

First, a process model using the function modeling method IDEF0 for the sterilization central was elaborated. The following are the operations that were identified:

- Receiving: the surgical material is received after each surgical operation;
- Washing: the material received is washed in a washer-thermodisinfector machine;
- Preparing: the washed material is prepared in envelopes to be sterilized;
- Sterilizing: the prepared material is sterilized is a high temperature sterilizer;
- Storing: the sterilized material is stored waiting to be used in surgical operations;
- Ventilation: maintains sterilization area with continuous positive airflow.

Inputs

In this section, the input materials and resources before each operation were identified:

- Contaminated material;
- Contaminated material prepared;
- Water;
- Electricity;
- Detergent;
- Ink and printing paper;
- Thermal reactive.

Outputs

The output materials and emissions after each operation identified were:

- Contaminated material washed;
- Material sterilized;
- High temperature water;
- Dirty water mixed with soap;
- Saturated steam.

Mechanisms

Two types of operators were identified:

- Human operators: sterilization technician, instrumentalists and doctors;
- Technical operators: equipment.

Table 12 shows the equipment identified in the sterilization central.

Table 12. Equipment identified in the sterilization central.

Operation	Equipment
Traceability	Computer, monitor, scanner, labeler
Environmental controlled conditions	Air conditioning
Washing	Washing machine, ultrasonic washing machine
Prepare	Packaging machine
Sterilization	High temperature sterilizer

Controls

In the last part of the step, the work procedures, instructions and formats to perform each operation of the sterilization central as well as the regulations governed by this process were identified. Normally, every hospital, research center or laboratory has its own procedures. The procedures are based on the equipment manufacturer manual. A documentary review of work instructions and formats and manuals was carried out.

Regardless of the standards governing the manufacture (ISO 13485 (ISO, 2016a), ISO 9001 (ISO, 2015a), ISO 14001 (ISO, 2015b), ISO 50001 (ISO, 2018) and others) of the equipment involved in the sterilization central, the analysis focused on the standards governing the operation phase in the life cycle of the equipment, i.e. when the greatest amount of resources is consumed. In this implementation, two different standards were identified that directly affect the operation phase of the equipment life cycle of the sterilization central. Table 13 shows the standards identified in the sterilization central.

Table 13. Standards identified in the sterilization central.

Standard	Regulation
ISO 9001:2008	Quality management systems - requirements
UNE 171340-2002	Validation and evaluation of controlled environment rooms in hospitals

Figure 42 shows the IDEF0 for the sterilization central.

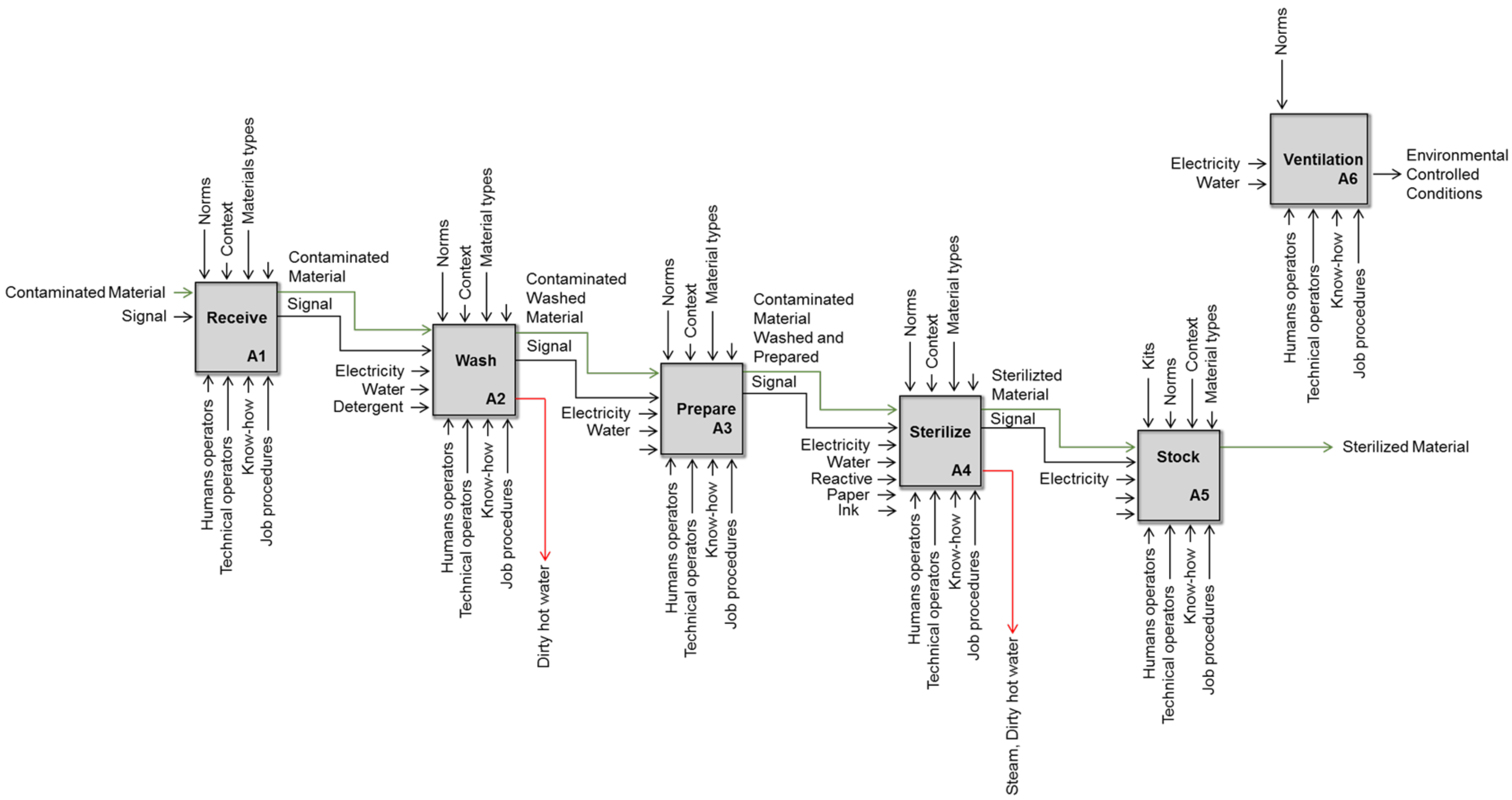

Figure 42. IDEF0 sterilization central.

Step 2: Equipment review

Second, an energy review (ER) of the operations and equipment identified in the previous step should be done. The ER was adapted from the ISO 50001:2011. The resource consumption was measured; the method for measuring the resource consumption was done by calculations and measurements of each equipment per process cycle.

These measurements were taken from the previous LCA of the equipment conducted by the equipment suppliers. The significance of the used criteria in this equipment review were:

Will be significant the equipment that consume more than 20% of the total consumed by the process per year

Under this criterion, the equipment and the consumption that exceed this percentage are:

- Air conditioning (electricity);
- Washing machine (electricity);
- High temperature sterilizer (electricity and water).

The air conditioning consumes a 30.43% of electricity and a 2.79% of water. The washing machine consumes 28.26% of electricity and 13.94% of water. The sterilizer needs 36.96% of the total electricity and 81.53% of the total water consumed in the sterilization central at full capacity with 160 kgs of surgical instruments. It was decided to take into consideration the washing machine and the sterilizer to continue with the methodology because they represent the most significant consumption of water that has to be heated by electricity. Table 14 shows the ER of the sterilization central.

Table 14. Sterilization central equipment review.

Operations		Equipment	Quantity	Measurement method	Real consumption per cycle				Source to improve	Cycles per year	Significance
					Resource	Coefficient	Unit	% of Total			
Global	Traceability	Computer	1	Calculated	Electricity	0.35	kWh	0.76%		Intermittent	
		Monitor	1	Calculated	Electricity	0.05	kWh	0.11%		Intermittent	
		Scanner	1	Calculated	Electricity	0.003325	kWh	0.01%		Intermittent	
		Labeler	1	Calculated	Electricity	0.06	kWh	0.13%		Intermittent	
	Ventilation	Air conditioning	1	Calculated	Water	16	l	2.79%	Cooling system	Constant	
				Calculated	Electricity	14	kWh	30.43%	Motor		X
Specifics	Wash	Washing machine	1	Measured	Water	80	l	13.94%	Vat	3155	X
				Measured	Electricity	13	kWh	28.26%	Motor		X
		Ultrasonic washing machine	1	Calculated	Water	10	l	1.74%	Vat	Intermittent	
				Calculated	Electricity	0.6	kWh	1.30%	Motor		
	Prepare	Labeler	1	Measured	Electricity	0.6	kWh	1.30%	Resistance	Intermittent	
	Sterilize	High temperature sterilizer	1	Measured	Water	468	l	81.53%	Vacuum system (Vacuum bomb, ejector)	3155	X
				Measured	Electricity	17	kWh	36.96%	Steam generator		X

Step 3: Process use cycle cost

The environmental resource consumed by the washing machine and the sterilizer had an economic impact. Table 15 shows the MFCA matrix of the sterilization central.

Table 15. MFCA matrix of the sterilization central.

Sterilized material (kg)	Water (l)	Water cost (€)	Electricity (kWh)	Carbon footprint (kg CO_2eq)	Electricity cost (€)	Total (€)
504,800	3,457,880	6,604.55	189,300	58,304.4	33,165.36	39,769.91
		16.61 %			83.39 %	100.00 %

The findings found through the MFCA matrix indicate that with 3155 sterilization cycles per year (wash and sterilize), the sterilization central can sterilize 504,800 kg of surgical material. This represents a consumption of 189,300 kWh with a cost of 33,165.36 euros. Electricity consumption represents 83.39% of the total cost per year of the operation of the sterilization central. Likewise, it is observed that the consumption of water is 3,457,880 l of with a cost of 6,604.55 euros. The water consumption represents 16.61% of the 39,769.91€ of the total cost of operation of the significant equipment in the process. The carbon footprint of the sterilization central represents a generation of 58,304.4 kg CO_2eq per year. Equations 1 and 2 were used for calculations.

$$Carbon\ footprint = Usage\ (kWh)\ .\ CO_2\,eq.\ Emission\ factor \quad (1)$$

$$Carbon\ footprint = Usage\ (kWh)\ .\frac{kgCO2}{KWh} \quad (2)$$

$Carbon\ footprint = 189{,}300\ kWh\ .\ 0.308$ (gentcat.cat, 2016)

$\mathbf{Carbon\ footprint = 58{,}304.4\ kg\ CO_2eq.}$

The results are presented visually using an e!Sankey program (IFU, 2019). Figure 43 shows the Sankey diagram for the sterilization central. The diagram provides an overview of the sterilization central behavior allowing to visualize the inputs and outputs of the water and energy flows through the equipment with significant consumption, two washing machines and two sterilizers in the areas of washing and sterilization respectively, that consume water and electricity and that discharge water mostly at high temperatures into the drainage.

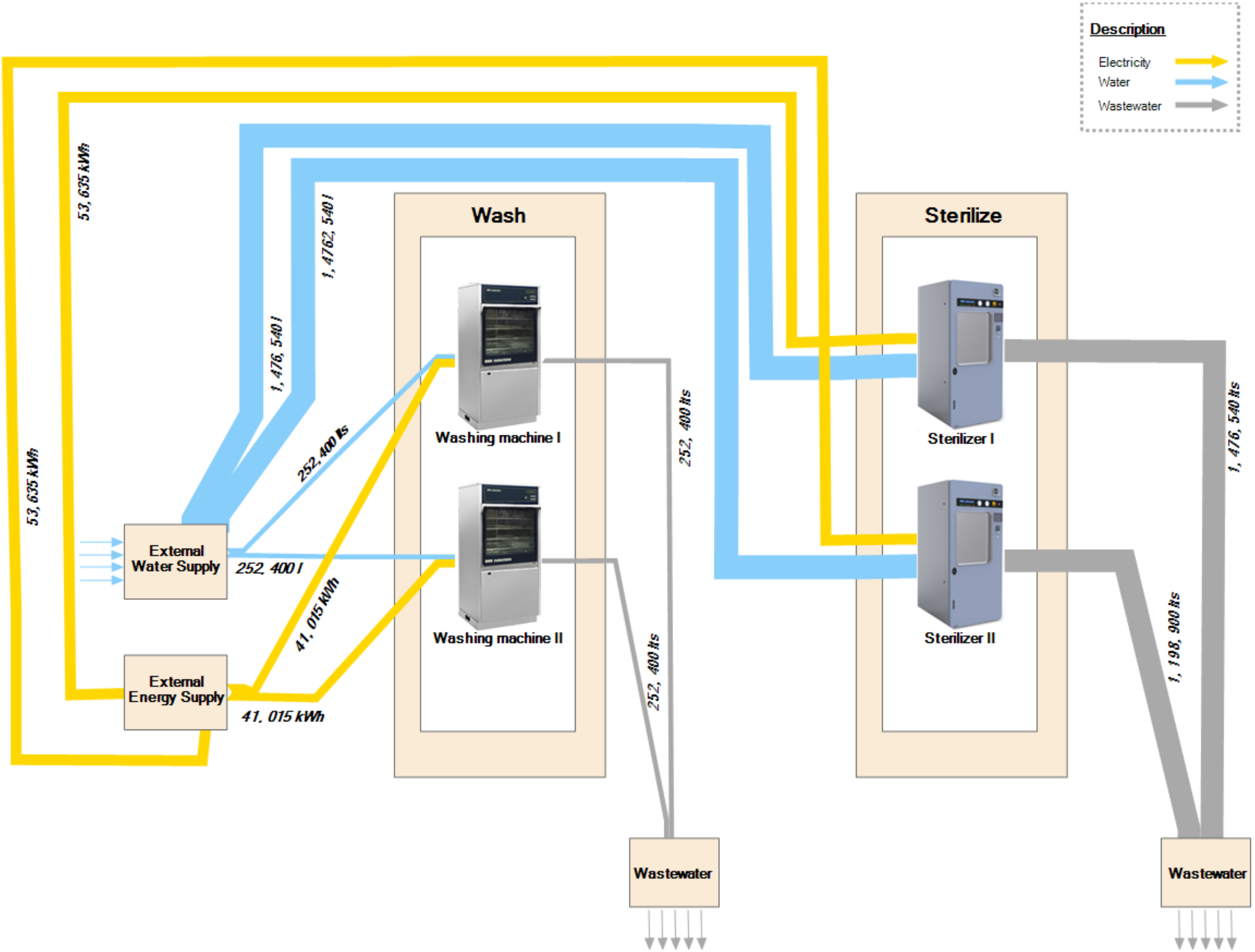

Figure 43. Sankey diagram of the sterilization central.

Step 4: Emissions reuse

An EARC of the equipment in the sterilization central was elaborated. Wastewater emissions of the significant equipment defined in the ER were identified. The EARC allowed to evaluate the reuse of emissions between the equipment and proposes its possible reuse between the equipment involved. Figure 44 shows the EARC of the sterilization central.

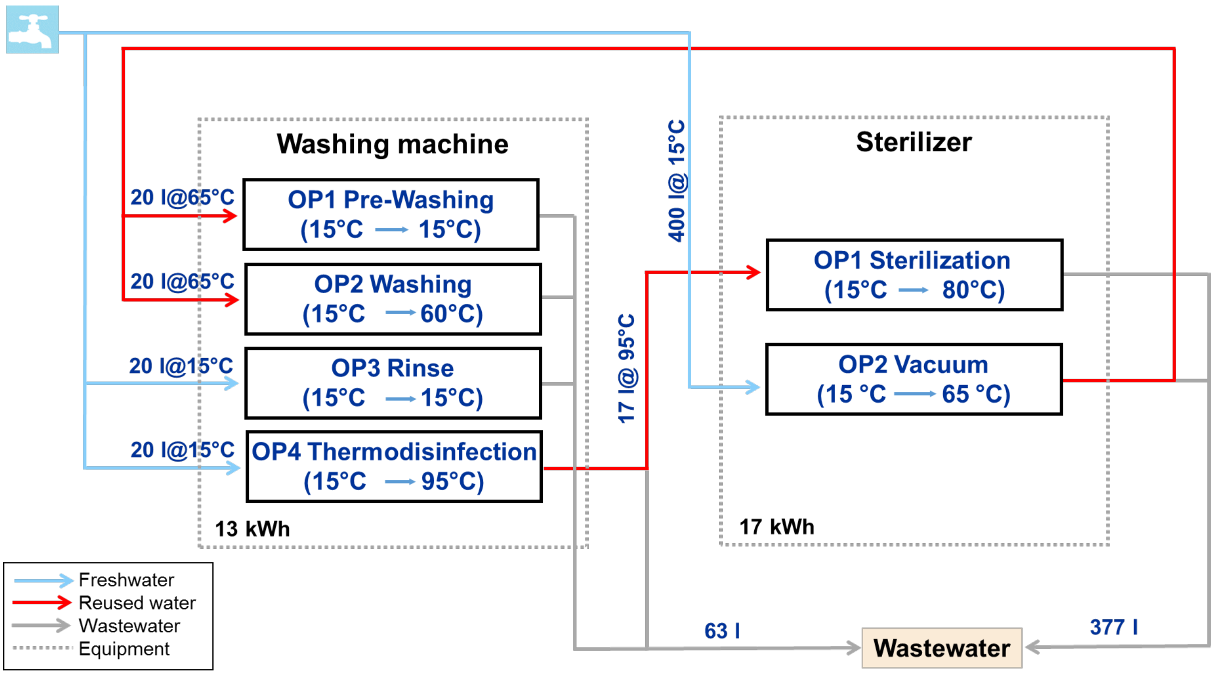

Figure 44. EARC of the sterilization central.

Sterilizer ⇨ Washing machine

40 l of the water emissions at 65°C for the Op2 (vacuum) of the Sterilizer (S) is reused in the operations Op1 (pre-washing) and Op2 (washing) of the washing machine (Wm) and the remaining (360 l) are discarded to wastewater. The water emissions outlet for the SOp2 have no contact with contaminated surgical material therefore, it is equal to the water inlet quality specification of WmOp1 and WmOp2, an external water supply quality. This does not represent an alteration in the results of operations WmOp1 and WmOp2. However, it represents a decrease in the water consumption of the washing machine. The temperature of the water emissions outlet for the SOp2 (65°C) is different to the water inlet temperature specification that WmOp1 and WmOp2 (15°C) need. This represents an improvement in the results of operations WmOp1 in cleaning the surgical material. In WmOp2 this difference in water temperature with respect to its specification, represents a decrease in the energy that is required to heat the water in WmOp2. At the end, the 40 l of the water emission outlet of

WmOp1 and WmOp2 are discarded to wastewater. Table 16 and equations 3-5 show the calculations performed.

Table 16. Sterilizer ⇨ washing machine water emissions reuse.

Sterilizer				
Op.	Water (l)	*T* Input (°C)	Water (l)	*T* Output (°C)
1	17	15	17	95
2	400	15	400	65

Washing machine				
Op.	Water (l)	*T* Input (°C)	Water (l)	*T* Output (°C)
1	20	15	20	15
2	20	15	20	60
3	20	15	20	15
4	20	15	20	95

360 l

Water improve:

$$\Delta S = Q_i - Q_o \qquad (3)$$

$$\Delta S_{S \to Wm} = (400\, l) - (360\, l)$$

$$\boldsymbol{\Delta S_{S \to Wm} = 40\, l}$$

Energy improve:

$$\Delta Q = m.c.(Tf - Ti) \qquad (4)$$

$$\Delta Q_{S \to Wm} = m.c.(Tf_S - Ti_{Wm}) \qquad (5)$$

$$\Delta Q_{S \to Wm} = (40\, kg).(1\, \frac{kcal}{kg.°C}).(Tf_{S\, Op.2} - Ti\,(\frac{Wm\, Op.1 + Wm\, Op.2}{2}))$$

$$\Delta Q_{S \to Wm} = (40\, kg).(1\, \frac{kcal}{kg.°C}).(65°C - (\frac{30°C}{2}))$$

$$\Delta Q_{S \to Wm} = (40\, kg).(1\, \frac{kcal}{kg.°C}).(65°C - 15°C)$$

$$\Delta Q_{S \to Wm} = (40\, kg).(1\, \frac{kcal}{kg.°C}).(65°C - 15°C)$$

$$\Delta Q_{S \to Wm} = (40\, kg).(1\, \frac{kcal}{kg.°C}).(50°C)$$

$$\Delta Q_{S \to Wm} = 2000\, kcal\, .0.001163\, kWh$$

$$\boldsymbol{\Delta Q_{S \to Wm} = 2.33\, kWh}$$

Washing machine ⇨ Sterilizer

17 l of the water emissions at 95°C for the Op4 (thermodisinfection) of Wm is reused in the operation SOp1 (sterilization) and the remaining (3 l) are discarded to wastewater. The water emissions outlet for the WmOp4 is an external water supply quality, but have contact with washed and thermodisinfected surgical material. However, according to the manufacturer, it does not represent an alteration in the results of operations SOp1 since this water is needed

to generate steam. The water inlet quality specification of SOp1 is an inverse osmosis quality. According to the manufacturer, the generation of steam by the sterilizer can be done also with external water supply, which has been preheated. The purpose is that in the course of heating the water begins to lose minerals. At 95°C water emissions outlet for the WmOp4 is almost at its boiling point, which represents a decrease in the energy required to generate steam by the sterilizer and in the water consumed because the loss of water when producing one liter of osmosis water is 1 l: 3 l. At the end, the 17 l of the water emission outlet of SOp1 are discarded to wastewater.

Table 17 and equations 6, 7, 8 show the performed calculations:

Table 17. Washing machine ⇨ sterilizer emissions reuse.

Washing machine				
Op.	**Water (l)**	***T* Input (°C)**	**Water (l)**	***T* Output (°C)**
1	20	15	20	15
2	20	15	20	60
3	20	15	20	15
4	20	15	20	95

Sterilizer				
Op.	**Water (l)**	***T* Input (°C)**	**Water (l)**	***T* Output (°C)**
1	17	15	17	95
2	400	15	400	65

3 l

Water improve:

$$\Delta S = Q_i - Q_o \qquad (6)$$

$$\Delta S_{Wm \rightarrow S} = (20\, l) - (3\, l)$$

$$\boldsymbol{\Delta S_{Wm \rightarrow S} = 17\, l}$$

Energy improve:

$$\Delta Q = m.c.(Tf - Ti) \qquad (7)$$

$$\Delta Q_{Wm \rightarrow S} = m.c.(Tf_{Wm} - Ti_S) \qquad (8)$$

$$\Delta Q_{Wm \rightarrow S} = (17\, kg).(1\, \frac{kcal}{kg.°C}).(Tf_{Wm\, op.4} - Ti_{S\, op.2})$$

$$\Delta Q_{Wm \rightarrow S} = (17\, kg).(1\, \frac{kcal}{kg.°C}).(95°C - (15°C))$$

$$\Delta Q_{Wm \rightarrow S} = (17\, kg).(1\, \frac{kcal}{kg.°C}).(80°C)$$

$$\Delta Q_{Wm \rightarrow S} = 1360\, kcal\, .0.001163\, kWh$$

$$\boldsymbol{\Delta Q_{Wm \rightarrow S} = 1.58\, kWh}$$

Equation 9 and 10 show the calculations performed for a total improve per cycle in a sterilization central.

Total improve per cycle:

$$Water = \Delta S_{S \to Wm} + (\Delta S_{Wm \to S} + inverse\ osmosis\ rejection\ 3:1) \quad (9)$$

$$Water = 40\,l + (17\,l + (17\,l\,.\,3\,l))$$

$$Water = 40\,l + (17\,l + (51\,l)$$

$$Water = 40\,l + 68\,l$$

$$\mathbf{Water = 108\,l\ per\ cycle}$$

$$Energy = \Delta Q_{S \to Wm} + \Delta Q_{Wm \to S} \quad (10)$$

$$Energy = 2.33\,kWh + 1.58\,kWh$$

$$\mathbf{Energy = 3.91\,kWh\ per\ cycle}$$

The findings found through the MFCA matrix after emissions reuse, indicate that with 3155 sterilization cycles per year (wash and sterilize) and with 504,800 kg of surgical material processed, the sterilization central experience a reduction of 4,322.54 euros in electricity consumption and a reduction of 1,301.61 euros in water consumption. The electricity consumed represents the generation of 50,705.4 kg CO_2eq.

$Carbon\ footprint = 164,628\ kWh\ .\ 0.308$ (gentcat.cat, 2016).

$\boldsymbol{Carbon\ footprint = 50,705.4\ kg\ CO_2eq}$

This represents a saving of 5,624.15 euros spent on electricity and water from the significant equipment of the sterilization central and a 7,599 kg CO_2eq. which will not be emitted to the environment. Table 18 shows the MFCA matrix after the redesign of the sterilization central.

Table 18. MFCA matrix after the redesign of the sterilization central.

Sterilized material (kg)	Water (l)	Water cost (€)	Electricity (kWh)	Carbon footprint (kg CO_2eq)	Electricity cost (€)	Total (€)
504,800	2,776,400	5,302.94	164,628	50,705.4	28,842.82	34,145.76
		15.53 %			84.47 %	100.00 %

Figure 45 shows the CE emissions reuse closed loop for the sterilization central. This figure shows the reuse of a part of the water at high temperatures from the emissions of the sterilizers to the washing machines and from these to the sterilizers as a closed loop, reducing the water discharge to the drainage and improving the efficiency of the sterilization central.

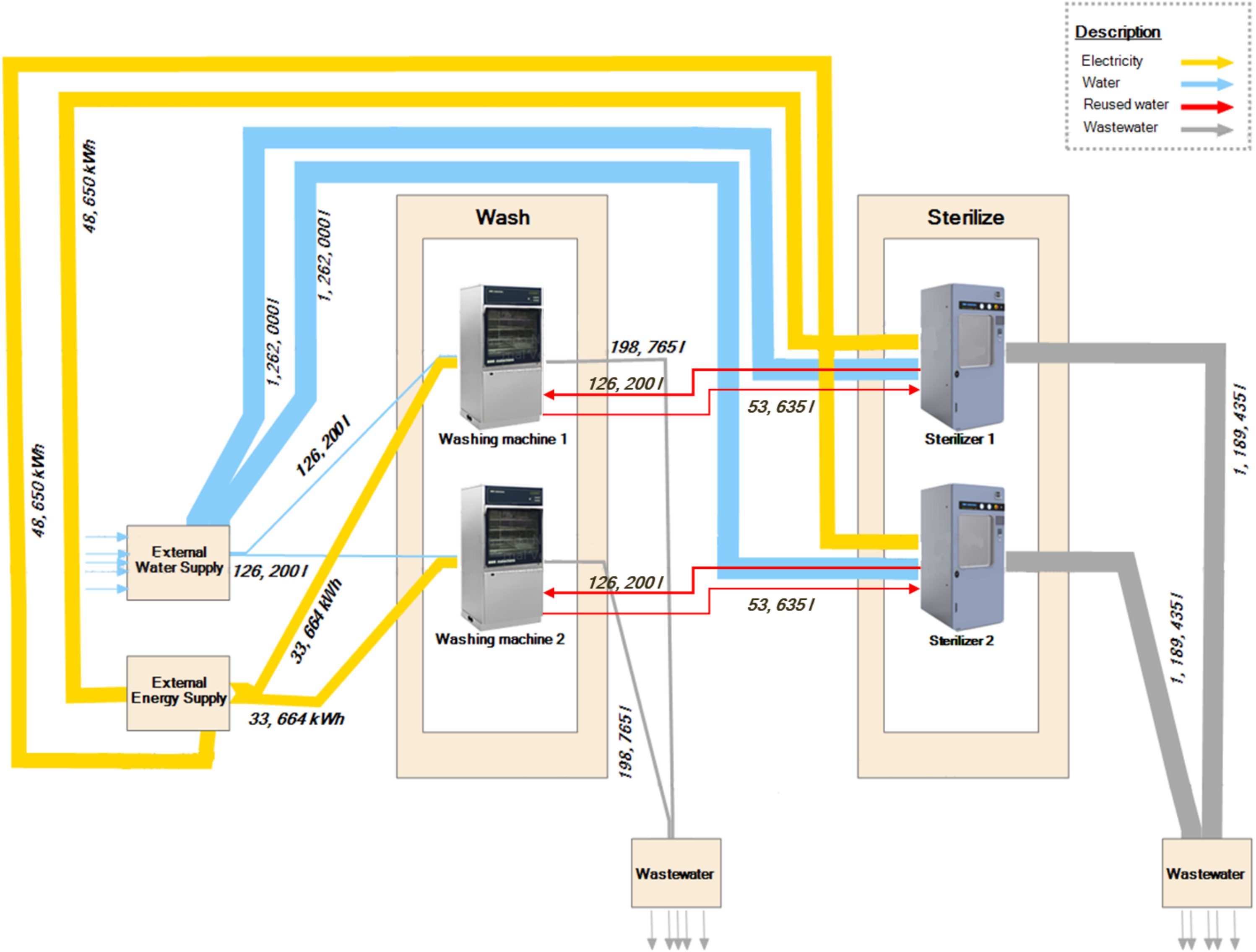

Figure 45. CE emissions reuse closed loop for the sterilization central.

8. DISCUSSIONS AND CONCLUSIONS

This final chapter presents the discussions of the implementations and the general discussion of the presented thesis. This chapter ends with the conclusion, the scientifically and industrial contributions and a proposal for future research.

8.1 DISCUSSION OF THE IMPLEMENTATIONS

The proposed methodology has been verified by the redesign of a sterilization central and a grinding wheels production process. The implementations of the R4ER methodology revealed:

- The methodology has effectively demonstrated that there is a direct relationship between the consumption of resources of the equipment and the production process in which the equipment are involved and support effectively the implementation of the emissions reuse CE closed loop trough equipment in production processes and services;
- The inputs and outputs of the IDEF0, LCA, MFCA and EARC tools are essential due to the synergy of the methodological steps. Absence of any of the inputs and outputs of the four tools mentioned is not effective. The IDEF0 output is the input of the LCA and the EARC. LCA results validate the significance of the equipment with more resource consumption in the ER and is the input of the MFCA and EARC;
- With the exception of the LCA for each equipment, the other three tools IDEF0, MFCA and EARC are relatively simple because they are based on common sense and can be used by process designers without extensive environmental experience;
- The methodology is broadly applicable to the redesign of any production processes or services in which equipment emissions are involved, independently of whether the emissions are continuous or discontinuous because no limitation to its implementation was found. For more complex production processes, the methodology would also be applicable. Rather, the methodology may be more effective in those processes or services where the consumption of resources and the generation of emissions are high.
- It would be necessary to implement the proposed methodology in the different production processes and services for the validation of their reliability. In addition, it is recommended that the proposed methodology should be verified by external verifiers through Environmental Technology Verification (ETV). ETV supports CE (EC, 2019e) and is applicable in verification to those innovative environmental technologies whose characteristics or performance cannot be assessed with the existing standards (ISO, 2016b).

8.2 GENERAL DISCUSSION

To innovate the process-equipment system in the current context of sustainability, in the presented thesis a conceptual model for the implementation of the CE emissions reuse closed loops through equipment was proposed and a methodology for the redesign of production processes for the reuse of emissions (R4ER) was developed.

The conceptual model (see Chapter 5, Figure 38) is based on several concepts from the literature review in the frame of reference in Chapter 2. The concepts were first, the reduction, reuse, recycling and recovery of emissions of the CP (Gomes da Silva and Gouveia, 2020) and second, the transverse analysis of the diachronic and synchronic dimensions of the equipment (Llorens, 2015) .The key point here is that this analysis should be performed in a transversal way in the operational phase of the equipment (production process) as a basis for the implementation of the emissions reuse CE closed loop through equipment. In the literature, the need to develop a CE closed loop material flow through technology has been stated (Jawahir and Bradley, 2016), but this issue has not been addressed by scientific and industrial experts with a successful implementation in the industry. Also, the importance of taking into consideration the diachronic and synchronic dimensions in the conception, design and development of equipment has already been mentioned (Llorens, 2015; Riba and Molina, 2006) but the focus was on the design of the equipment portfolio and the redesign of the architecture of the equipment range.

The possibility to develop a closed loop material flow through equipment was supported by the empirical results of the performed case studies. The Case SM revealed the possibility of reusing emissions in the equipment in the search for environmental improvement of a production process and Case SC confirmed that there is already equipment on the market that can reuse its own emissions (see Chapter 4, Sections 4.1 and 4.3). In addition, the results of Survey C (Section 4.5) showed that most of the external environmental requirements received by the equipment manufacturing companies were oriented to equipment and process improvements and that these mostly came from their customers.

On the other hand, the R4ER methodology (Chapter 6, Figure 41). is based on the proposed conceptual model (see Figure 38). The R4ER methodology includes four methodological steps: I) process analysis, II) equipment review, III) cost of the cycle of use and IV) emissions reuse. The realization of these steps is possible through the adoption of the IDEF0 (Smith and Ball, 2012), LCA (ISO, 2006), MFCA (ISO, 2011) and the EARC tool. In the literature, step methodologies are common for process redesign (Davenport and Short, 1990; Palma-Mendoza et al., 2014; Sanka Laar and Seymour, 2017; Venkataiah and Sagi, 2013). However, with the exception of Llorens (2015), no process redesign methodologies have been found that include specific analysis of the equipment involved in the production process within its methodological steps. Llorens (2015) identified the equipment involved in an operative process through a the IDEF0 and introduced the ARC in the search for innovation opportunities in the equipment. However, the methodology was limited to the redesign of the architecture of the equipment range and does not include in its analysis, the environmental aspect of the equipment in the production process as in the presented thesis.

The R4ER methodology has been verified through the redesign of a sterilization central in an equipment manufacturing company and a grinding wheel production process in a research institute. The application of the R4ER methodology resulted in a reduction of 20% of water, 13% of electricity and 14% of the operating costs a in a year in the operational phase of the sterilization central, representing a reduction of 7, 599 kg CO_2eq emissions to the environment in a year. [redacted]

These results demonstrated that the application of the R4ER methodology allows the reduction of the resource consumption and the generation of emissions to the environment as well as the reduction of operating costs of the production processes and services. However, unfortunately, the environmental improvements observed in the implementation of the R4ER methodology will not completely resolve the urgency of the industry's contribution to the fight against climate change as the results are more oriented towards eco-efficiency and not eco-effectiveness. Similarly, as mentioned in Section 2.1, the process-equipment system addressed in the presented thesis is a technical system where only the human factor is considered for its operational capacity of the equipment. This leaves aside its consideration as an element of the system, limiting the opportunity of improvement in the system as in the socio-technical systems.

8.3 CONCLUSIONS

Today more than ever, in the search to contribute to the current fight against climate change, the industrial sector needs to redesign its production processes as a way to accelerate its transition to the CE.

The presented thesis has demonstrated that the equipment has a critical role in the sustainable redesign of production processes and services through the implementation of the emissions reuse closed loops as a way to address the actual scientific and industrial gap in the implementation of the CE in production processes through technology.

The objective of the presented thesis is to develop knowledge that contributes to the innovation of the process-equipment system in a context of sustainability. In order to achieve the research objective, the following research questions have been formulated and answered.

The answer to the RQ1 reveals that there is a real possibility of implementing the CE emissions reuse closed loops through the equipment in production processes but for this, it is concluded that it is necessary to take into consideration the diachronic and synchronic dimensions of the equipment operating in the process. The answer to the RQ1 contributes directly to the achievement of the objective of the thesis by proposing how the process equipment system can be innovated in a context of sustainability.

The answer to the RQ2 identifies how this innovation can be carried out through 4 methodological steps that integrate a process redesign methodology for the reuse of emissions. The methodology steps are the process analysis, the equipment review, the cost of the cycle of use and the emissions reuse. The answer to the RQ2 contributes directly to the achievement of the objective of the thesis by defining what characterizes the innovation of the process-equipment system in a context of sustainability.

The answers to the RQ1 and RQ2 were summarized in a conceptual model for the implementation of the CE emissions reuse closed loops in production processes through equipment (see Figure 38) and a methodology for the redesign for emissions reuse (R4ER) of production processes (see Figure 41).

The results of the application of the R4ER methodology in a sterilization central and in a production process of grinding wheels have demonstrated that the R4ER methodology represents a structured practical guide on how companies could address the challenges posed by the large amount of resources consumed during the operational stage of equipment's life cycle involved in production processes or services and can be used in the long term, not only in the redesign of the current production processes or services, but also in their design as an another way to accelerate the transition from industry to the CE.

8.4 SCIENTIFIC AND INDUSTRIAL CONTRIBUTIONS

At the present time, CE is one of the main topics of discussion in the sustainability literature. It represents a worldwide opportunity to rethink and redesign the way our economy works by questioning our creativity and innovation in the quest to build a restorative economy. However, the implementation of the CE closed loops is still in an initial phase and focuses mainly on the recycling of products rather than the reuse of emissions in production processes. Likewise, early works on CE emphasized the need to implement an emissions reuse closed loops through technology, but this issue has not been addressed by scientific and industrial experts with a successful implementation in the industry.

At the scientific level, the presented thesis has contributed in resolving the existing knowledge gap of the technical aspects to achieve the CE closed loops through technology. This by proposing a conceptual model for the implementation of the CE emissions reuse closed loop in production processes through equipment. With regard to the field of process redesign methodologies, it is proposed a process redesign methodology for the reuse of emissions through the analysis of the equipment operating in the production or service, which is seldom considered in the literature on process redesign methodologies. In addition, the presented thesis continues with the research line developed through different doctoral theses during more than 20 years of research at CDEI-UPC.

At the industrial level, the thesis presented has contributed through a structured practical guide to accelerate the implementation of the CE emissions reuse closed loops in the industry as a way to facilitate the redesign of its production processes of the industry in the fight against climate change. The R4ER methodology will make it possible to address environmental impact and increase productivity, especially with regard to the often neglected interactions between the different operations of the processes within one company.

8.5 FUTURE RESEARCH

The presented thesis proposes a process redesign methodology for the reuse of emissions in production processes as a possible way to innovate the process-equipment system in the current context of sustainability. However, there are different opportunities for further research:

- Other production processes and services in other sectors: In the current context of sustainability it is necessary to implement the proposed methodology not only in the industries that manufacture equipment. The results of the implementation presented in Chapter 7 showed that it is feasible to implement the proposed methodology in the redesign of other production processes or services in other types of sectors;
- End-user equipment: The presented thesis refers only to industrial equipment, but it is also necessary to implement the reuse of emissions where this is possible for end-user equipment in other contexts such as commercial and domestic sectors;
- Standardization of the reuse of emissions in equipment: Finally, the reuse of emissions in equipment should not only be a specific case, as presented in Section 2.2.4, but should become a general characteristic of equipment that consumes resources and generates emissions. To this end, standardization of reuse of emissions should be implemented by the development of a technical standard at ISO level.

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APPENDIX A - RESEARCH PAPERS

sustainability

MDPI

Article

A Conceptual Tool for the Implementation of the Circular Economy Emissions Reuse Closed Loops through Process Equipment

Gregorio Ridaura [1,*], Sonia Llorens-Cervera [2], Carmen Carrillo [3], Irene Buj-Corral [4] and Carles Riba-Romeva [1]

[1] Centre of Industrial Equipment Design, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain; riba@cdei.upc.edu
[2] INN2-Innovació Industrial, 08024 Barcelona, Spain; sonia.llorens@inn2.cat
[3] Department of Mechanical Engineering, School of Industrial Engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya, 08028 Barcelona, Spain; ccarrillo@matachana.com
[4] Matachana Group, 08018 Barcelona, Spain; irene.buj@upc.edu
* Correspondence: ridaura@cdei.upc.edu

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Abstract: Nowadays industry is immersed in a transition to the Circular Economy (CE) as a way to achieve resource efficiency in production processes. However, the implementation of CE closed loops is still in an initial phase and it focuses mainly on the recycling of components of products instead of the reuse of emissions. The purpose of this study is to explore the possibility of accelerating the transition of the CE in production processes through a conceptual tool that allows the possibility of evaluating the reuse of emissions between the equipment involved in a process. The Environmental Analysis of Relations of Coexistence of the Equipment (EARC) tool is a novelty in the implementation of the CE emissions reuse closed loops at the company level. The EARC tool focuses on the identification and analysis of the equipment involved in a process and in the material inputs and emissions outputs of each of its operations with the objective of evaluating the possibility of reusing emissions among them. This paper presents a conceptual tool as the basis for the development of a redesign methodology for the reuse of emissions in production processes with the objective of reducing the consumption of resources and the generation of emissions as well as the reduction of production costs.

Keywords: circular economy closed loops; cleaner production; reuse of emissions in equipment; LCA; ARC

1. Introduction

In the present days, industry is immersed in a transition to the Circular Economy (CE) as a way to achieve resource efficiency in industrial processes. According to this research and derived from the large amount of concepts to define it [1], CE is "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops" [2]. The definition of CE involves the inclusion of the closed loop concept in the design of products and production processes. However, the implementation of CE closed loops is still in an initial phase and it focuses mainly on the recycling of components of products [3]. This situation is also reflected in the evolution of the definition of closed loop in manufacturing systems. Whereas, Sarkis [4] mentioned that the objective of the closed loops in production processes is the reuse of any kind of waste or by-products, emulating an eco-industrial system, Souza [5] defined closed loops as "supply chains where, in additional to typical forward flows, there are reverse flows of used products (postconsumer use) back to manufacturers".

Within the CE, Cleaner Production (CP) is a key concept for the implementation of closed loops at the company level [6], through focusing on the reduction of material inputs and the reduction of emissions in production processes [7]. CP is based on Eco-design, Environmental Management Systems, Best Available Techniques, and Cleaner Technologies [8]. Cleaner technologies refer to the use of novel technologies that provide economic and environmental benefits for source reduction and eliminating or reducing waste emissions [9]. In this sense, equipment with the ability to reuse emissions is an important approach to achieve the objectives of energy and emissions reduction in production processes [10]. The reuse of emissions in equipment is not a new concept; there are examples of equipment that reuse their own emissions on the market [11,12], but not in a generalized way in industry. Recent advances in equipment design have allowed for the incorporation of new methodologies and analysis tools in the design and development of process equipment. A good example of this is the Diachronic and Synchronic dimensions of the equipment, which integrate a transversal analysis of the Life Cycle Assessment (LCA) and the Analysis of Relations of Coexistence (ARC) of the equipment. The ARC allows for understanding the coexistence relationship of an equipment with other equipment or with a set of equipment which interacts in a production process [13] in the search for innovation opportunities. Taking into consideration that equipment is the principal consumer of resources and a generator of emissions in production processes [14], the extension of the field of application of the ARC towards environmental issues (EARC) has proven to be a good option for the reduction of the resources consumption in production processes.

This research paper presents a conceptual tool for the implementation of the CE closed loops in production processes. In the previous paper [14], a new systematic methodology for the redesign of production processes has been presented. The EARC tool had an essential role as the principal redesign methodological step, however it was not explained extensively. Therefore, a detailed description of the EARC is given here. The novelty of this conceptual tool is that it allows for evaluating the possibility of the reuse of emissions between the equipment that are involved in a production process with the aim to reduce the resource consumption, emissions generation, and the operating costs.

2. Methods

The research that is presented in this paper is part of a long-term investigation with the objective of proposing a conceptual tool for the implementation of the CE emissions reuse closed loops, and subsequently, a redesign methodology for the reuse of emissions in production processes. The first stage of this research consisted in the identification of the definitions and practices of the CE closed loops in the production processes that are described in the literature. "Closed loop in production processes", "closed loop in production systems", "closed loop in industrial processes", "closed loops manufacturing systems", "closed-loop supply chain", among others, were some of the search keywords. In the same way, initiatives, concepts, and tools that facilitate the implementation of the closed loops of the CE were explored in the literature. For the second stage, the literature was revised critically with the aim of finding the current concepts and tools for the closed loops implementation and its possible gaps in production process. As the third stage of this research, a conceptual tool was developed with the objective of filling the gaps that were found in the practices and implementation tools of the closed loops that were analyzed in the previous stage.

In stage four, the proposed conceptual tool in conjunction with other tools integrated the R4ER methodology. In the proposed model, this methodology had an essential role as the principal step. Finally, by validating the R4ER methodology in the redesign of a production processes, allowed in parallel the validation of the proposed conceptual tool was validated. Figure 1 shows the long-term stages for this research.

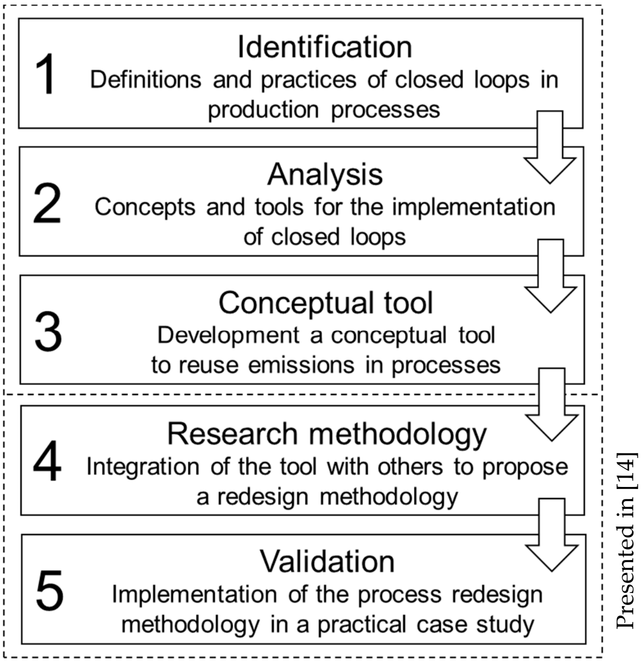

Figure 1. Long-term research stages.

3. CE Emissions Reuse Closed Loops and Process Equipment Relationship

3.1. CE Closed Loops

In the present days, industry is immersed in a transition to the Circular Economy (CE) as a way to achieve resource efficiency in industrial processes. CE is defined as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops" [2]. The definition of CE involves the inclusion of the closed loop concept in the design of products and production processes [4]. However, the implementation of CE closed loops is still in an initial phase and it focuses mainly on the recycling of components of products [3]. The actual definition of closed loops in production processes has been modified derived from the incorporation of concepts that share the closed loop idea within the CE [2]. For example, Kondoh et al. [15] defined a closed loop manufacturing system as "the manufacturing system that reutilizes modules, components and materials of post-use products in their production processes so as to minimize environmental impact of products as well as their manufacturing". This definition continues with the line of the reuse of products. Guide and Wassenhove [16] added the term supply chain management and defined the closed loops as "the design, control and operation of a system to maximize value creation over the entire life-cycle of a product with dynamic recovery of value from different types and volumes of returns over time". Later, Morana and Seuring [17] mentioned that "closed-loop supply chain management deals with all kinds of product return, both from unwanted products as well as from products at the end of their life-cycle". Finally, Souza [5] defined closed loops "which are supply chains where, in additional to typical forward flows, there are reverse flows of used products (postconsumer use) back to manufacturers". Figure 2 shows the current concept of closed loops in a production system.

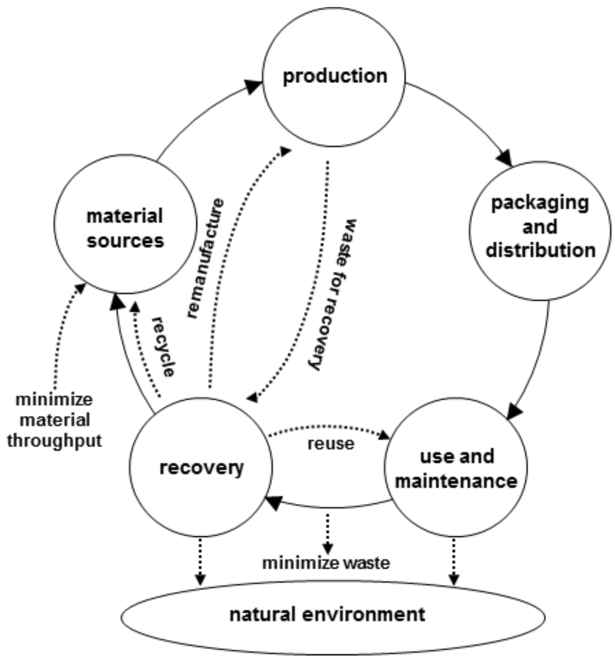

Figure 2. Closed loop production system. Modified from [18].

The tendency towards closed loops of products that are designed for multiple life cycles has also been supported by the development of tools for the implementation of closed loops of products in production systems. For example, the European Commission has developed different tools and instruments to facilitate the transition towards more CE products in Europe [19]. Another example of this is the collection of tools for the implementation of closed loop of products in manufacturing systems that were developed by the project Resource Conservative Manufacturing (ResCoM) [20].

The definitions and practices that were identified in the literature as well as the recently developed tools for the implementation of closed loops shows that most efforts focused on the reuse of products rather than the reuse of emissions. As an alternative approach to the closed-loop supply chain management practices presented above, the principal and essential step toward the final goal of CE in production processes is the achievement of a closed-loop operation [21] with the aim to reuse any kind of waste or by-products, emulating an eco-industrial system [4] that allows for the closed loop circulation of resources and emissions between the different actors of the production process. By the implementation of resource circulation closed loop within the production process, the consumption of resources can be minimized and the amount of related emissions can be reduced [22].

3.2. Emissions Reuse Closed Loops in Production Processes

The waste and pollution prevention which are the principals objectives of the CE closed loops in production processes (CE micro level) can only be achieved through Cleaner Production (CP) principles [3,23]. CP is "the continuous application of an integrated preventative environmental strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment" [24]. While the CE is observed as a set of global rules other norms that allow an economic system to regenerate through closed loops of materials and energy, the CP is a specific guide of principles and practices to achieve the CE objectives in the production processes. Implementation of CP principles to achieve emissions reuse closed loops focuses on five principal features of the process:

(1) Input materials—Material substitution can reduce dramatically the input and the use of natural resources (material and energy) through the reduction or eliminating hazardous materials and the exchange of recycled resources in the production process [6].

(2) Technology—Technological change include process and equipment modifications to reduce waste in production processes [25]. These may be changes in the process as an introduction of cleaner technologies or the redesign of equipment.
(3) Performance of the process—Good housekeeping refers to all of the procedures in a company to reduce waste. Examples of this can be a good management practice, material handling, loss prevention, and production scheduling, as well as energy and water efficiency in the process.
(4) Product—Product modification is about changing the characteristics of a product, such as its shape and material composition through eco-design [26] for the reduction of environmental impact.
(5) Waste and emissions—Reuse involves the repeated use of waste and emissions (closed loop for material and energy) and recycling occurs when a process is able to utilize the waste and emissions from another production process [25].

For the implementation of the mentioned principles in production processes, CP employs Eco-design, Environmental Management Systems (EMS), Best Available Technics (BAT), and Cleaner Technologies [8,27]. Eco-design (also called DFE) is used as a tool in the manufacturing processes for improving the sustainability of products. It is the integration into the product design stage (where most of the product impacts are determined) of the environmental aspects to reduce environmental impacts throughout the life cycle of a product [26]. Environmental Management Systems (EMS) refers to the part of the management system of the company that manages the environmental aspects with the objective to fulfill compliance governmental obligations and address environmental risk and opportunities [28]. Best Available Technologies (BAT) means the existing and coherent technologies or techniques that are the best for prevention and control of emissions and impacts on the environment [29]. BAT have a standard technological base that is applicable to different sectors of the industry and include the used technology as well as the design, construction, maintenance, operation, and decommission of installation [30].

Cleaner Technologies is considered as one of the most important methods for the application of the CP principles in production processes with the aim of achieving closed loops [27]. It refers to "a set of technologies that either reduces or optimizes the use of natural resources, whilst at the same time reducing the negative effect that technology has on the planet and its ecosystems" [31]. The objective for Cleaner Technologies is to prevent pollution by improving production efficiency through the adoption of innovative technologies that minimize or reduce waste [32]. In the equipment manufacturing industry, Cleaner Technologies are classified in: energy economizing, environment-friendly equipment, and resource conservation equipment [10]. The gradual incorporation of environmental concepts to the design and development of process equipment have allowed for the commercialization of equipment with the capacity to reuse their own emissions. There is different equipment available on the market that has this capacity. Examples of equipment that reuse their own emissions is the washer disinfector by the company Steelco, an Italian washer disinfectors and sterilizers manufacturer [11] and the batch washer for clothes of the company Girbau, a Catalan laundry equipment manufacturer [12]. The implementation of the reuse of emissions concept in process equipment implies the adoption of well-developed assessments tools as e.g., the Life Cycle Assessment (LCA).

LCA is a CP essential tool in the design and operation of process equipment [33]. LCA is a systematic method of the environmental analysis of products in general including equipment [34]. It is a comprehensive tool that gives to the equipment designers a better understanding of the environmental impact on the equipment use and provide valuable information regarding improvements of the environmental performance of the equipment [35]. LCA performs an inventory of energy and material that is consumed through equipment life cycle and evaluates the potential environmental impact that is derived from the identified resource consumption. The interpretation of the results had the objective to help equipment designers in decision making [36].

Other tools that have been adapted in the implementation of the reuse of emissions in process equipment are the input-output based analysis tools for environmental improvement in operations as the Green System Boundary Map [36]. It is a is material and energy balance at the company level, including all raw materials, energy, and water inputs and the product, waste, or emissions outputs. Material and energy balances data can be often obtained annually from accounts therefore they should be measured for more detailed balances [37] as in a process equipment.

CP concepts and tools for the implementation of closed loops in production processes (products and processes) are a well-defined practice, but it seems that they are not enough to support the transition of the closed loops of the circular economy in its entirety. The design and development of cleaner technologies that reuse their own emissions through LCA and Input-Output assessments are a reality but they focus on the gate-to-gate boundaries of an equipment (asynchronous vision). The implementation of emissions reuse closed loops requires the adoption of equipment design and operation tools that allows for the reuse and recycling of waste and emissions not only in an equipment, but also from an equipment to another or to others, considering all equipment working in the production process.

3.3. Diachronic and Synchronic Dimensions of the Process Equipment

The consideration of the life cycle of the equipment and the consumption of associated resources are one of the fundamental bases of the concurrent engineering [38]. One of its main premises is to emphasize in the diachronic dimension of the products through design of the life cycle. It is referred that the totality of the elements within the life cycle of an equipment, from functionality, manufacturing, use and maintenance, disposal, and recycling must be taken into consideration from the design phase of the equipment [39]. The LCA is an essential design tool in the diachronic dimension of the equipment [40].

Besides this first perspective, there is a second perspective in the concept and design of an equipment. The synchronic dimension considers the relationship of an equipment with other equipment or a set of equipment throughout its life cycle as a way to find innovation opportunities. In this sense, different authors have mentioned the importance of considering several equipment products in their design manufacture and use in order to obtain advantages when considering community, compatibility, standardization, and modularity [41–44]. Riba and Molina [38] described that, when an equipment is analyzed through the diachronic dimension (life cycle), the relationships between equipment in the origination and destination stages are especially relevant. The origination stages are the phases of the equipment life cycle through it is originated and that include the study of concept, design and development, and manufacturing. The destination is the phase of the life cycle to which the equipment is destined and include the use, maintenance, and the end of life. Table 1 shows the relationships between equipment through the equipment life cycle.

Table 1. Relationships between equipment through the equipment life cycle.

<table>
<tr><th colspan="2"></th><th>Equipment Life Cycle Phase</th><th>Relations between Equipment</th></tr>
<tr><td></td><td>Origination</td><td>Concept study
Design and development
Manufacturing</td><td>Equipment Family:
Equipment of a company that share elements in their origination</td></tr>
<tr><td></td><td>Destination</td><td>Use and maintenance
End of life</td><td>Equipment Portfolio:
Equipment of the market (or of a company) that share elements in their destination</td></tr>
<tr><td>Origination</td><td>Destination</td><td>Vision from an activity (beyond a manufacturing company)</td><td>Equipment Gamma:
Equipment of the market that share elements in their origin, and destination (eventually recycling)</td></tr>
</table>

Source: Author's elaboration. Modified from [38].

There is a relationship between equipment in the origination stage. The equipment family is the set of equipment of a company that coexist and interact, share architecture elements (modules and/or platforms) in their design and development as well as manufacturing. The objective of an equipment family is the use of resources in the origination in the most efficient way possible in order to save costs [38]. There is also an equipment relationship in the destination stage. The equipment portfolio is a set of equipment that a company offers to the market which coexist and interact in the destination stages as in use (process), maintenance and end of life phases. The objective is to optimize the offer of a comprehensive solution for the customer needs [13]. The equipment portfolio gets maximum of interest when the portfolio is extended to all the equipment offered by the market which interact in an activity [38]. There is a third type of relationship between equipment that covers the origination and destination stages. From the point of view of a company that designs, manufactures and sells equipment products, the equipment gamma is the set of equipment necessary for an activity that can be beyond those that a company manufactures and whose architecture is conceived to optimally solve the origination conditions, such as the optimization of the design and manufacturing resources and the destination opportunities in the search to offer the maximum satisfaction to the users [38].

The analysis of relations of coexistence (ARC) is a tool that allows for understanding the relationship between equipment (synchronic dimension) throughout the equipment's life cycle with emphasis on the use of equipment (operative process). The objective of carrying out an analysis of this type is to save costs, to facilitate manufacture, to manage complexity, and to optimize market response capacity and equipment functionalities [13]. The ARC of the equipment is relatively new. It was performed by Llorens [13] structuring a design methodology for the establishment of the architecture of gamma of equipment while considering an operational process in which a complete gamma of equipment coexist and interact. This work established a new framework for analysis and definition of the architecture of gamma of equipment through transversal visions of the LCA (diachronic dimension) and the ARC (synchronic dimension) for the equipment in the production process. The application of this methodology was based on a real case study in a Catalan laundry company, which designs and manufactures high complexity products, with medium-sized manufacturing, and a catalog of products with a certain maturity level. The case study included the definition of a new gamma of equipment architecture applied to an industrial laundry process [13].

3.4. Summary

Definitions and practices for closed loops in production processes as well as concepts and tools for their implementation have been reviewed in the literature. It is evident that there is a delay in the implementation of the CE emissions reuse closed loops in production processes since until now, this has been focused on the recycling of the components of products. On the other hand, when analyzing the methods and tools for emissions reuse closed loops implementation, there are cleaner production methods and tools that can help to accelerate this transition, such as cleaner technologies that reuse their own emissions, but they focus on the reuse of emissions from a single equipment, limiting the environmental improvement of the processes by not taking into account the environmental coexistence relationships of all the equipment involved in a process. This research aims to contribute to the availability of tools for the implementation of closed loops in production processes through the development of a conceptual tool for the emission of emissions between equipment.

4. Development of the Conceptual Tool

The conceptual tool approach that is proposed is based on the CP concepts of reuse emissions closed loops and on the transverse analysis of the diachronic and synchronic dimension of the process equipment in production processes.

4.1. Cleaner Production as a Base for the Conceptual Tool

To achieve the reduction of the environmental impact on the production processes, it is essential to implement CP strategies that allow for the reuse and recycling of waste and emissions in the production process. Figure 3 was adapted from the closed loop production system [18] to represent the recovery, reuse, and recycling of emissions in a closed loop production process. The emissions that are generated in the production process are recovered, reused, and recycled within the same process. Recovery refers to the extraction of the useful components of the waste for reuse. The reuse is the repeated use of waste and emissions in the production process and the recycling (internal recycling) occurs when one operation is able to utilize the waste from another operation or production process (input substitution) [25]. The application of the CP concepts that are described above allows for the reduction of emissions generation to the natural environment as well as the decrease of the demand of raw material of the process. Figure 3 represents a proposed model of emissions reuse closed loop in production processes.

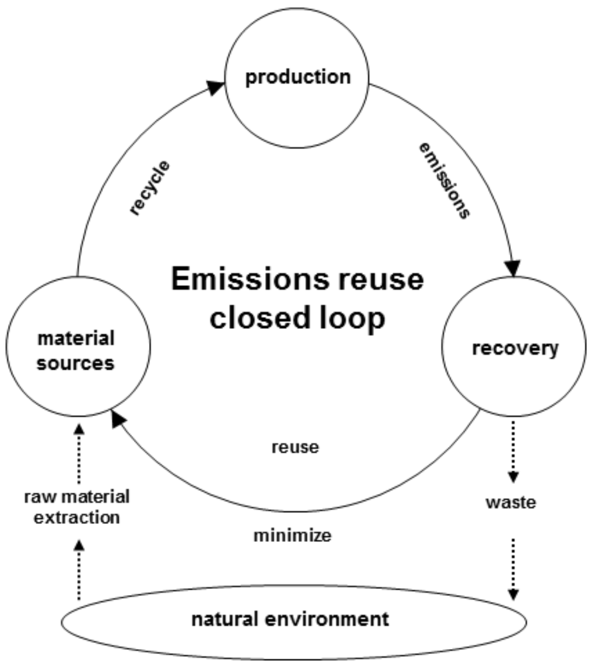

Figure 3. Proposed model of emissions reuse closed loop in production processes. Modified from [18].

4.2. Transverse Analysis of the Equipment Diachronic and Synchronic Dimensions

Beyond the consideration of the life cycle of a process equipment (diachronic dimension), the analysis of its interaction with other equipment (synchronous dimension) constitutes an innovative perspective of great interest for the achievement of the emissions reuse closed loops in production processes. The transverse analysis of the principal assessments tools of the diachronic dimension (LCA) and the synchronic dimension (ARC) aim to identify the phase of the life cycle of the process equipment in which most resources are consumed and the amount of consumed resources in this phase as well as the relations of coexistence in aspects of energy, water, material, and emissions between process equipment. There is a constant conclusion in the LCA that is performed for different equipment. The most important stage within the life cycle of an industrial equipment is the operation phase (operative process), since the function for which the equipment has been designed takes place [45] and in which the majority of resources during the equipment life cycle are consumed [14]. Equipment in production processes are used directly and predominantly for handling, storage, or conveyance materials and to act upon or effect a change in material to form a product and its subsequent packaging [46].

In a transversal way, the ARC should be extended to the environmental coexistence aspect of the equipment (EARC). The result of this analysis should show all possible environmental interactions between the equipment involved in the process. Equipment that coexist and interact in the production process must be identified. In the same way, all information regarding to the resources consumption and emissions generation per operation cycle of the production process as well as for each of the equipment must be collected. A detailed analysis of environmental consumes and emissions generations for each of the operations carried out by each of the equipment identified in the previous step must be performed. First, each of the operations for each of the equipment must be identified. Second, a subsequent analysis of resource entries and emissions outputs must be carried out. Again, for the resources, it is necessary to identify their type and origin, coefficient of use, and the temperature if applicable. For emissions, their type and destination, the coefficient of discharge and the temperature if it is applicable must be determined. Finally, the feasibility of reusing emissions as resources in operations between equipment analyzed in the previous step should be evaluated with the aim of emulating an eco-industrial system. Wherever possible, the reuse of emissions from one equipment's operations in the resource inputs of another equipment's operations is the aim. To carry out this last stage of the conceptual tool, the main rule for designing the emissions reuse model must take into accounts the common sense, always trying to propose a model of reuse of emissions that does not represent an excessive expense in new installations or in equipment link as filters, cooling systems, or recovery tanks, for example. The final output of this step is the proposal of a model of reuse of emissions between equipment that contributes to the implementation of CE closed loops in production processes. Figure 4 represents the proposed model for the CE emissions reuse closed loops in production processes.

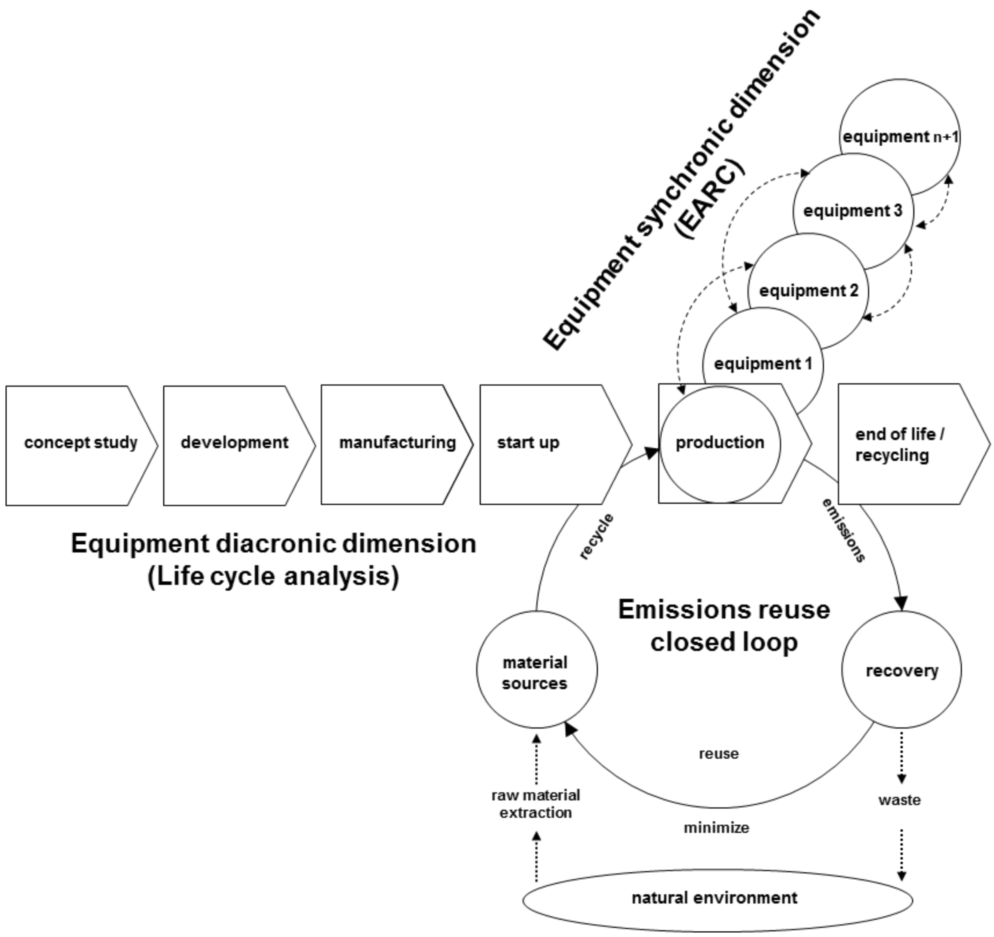

Figure 4. Proposed model of Circular Economy (CE) emissions reuse closed loop in production process.

5. Discussion

While the industry is immersed in a transition to the CE as a way to achieve resource efficiency in industrial processes, there is a difference in the interpretation about the closed loops in production processes. The identification in the literature of the concept under different terms, such as closed loop in production processes, closed loop in production systems, closed loop in industrial processes, closed loops manufacturing systems, closed-loop supply chain, among others, can be one of the main causes of delay of its complete implementation in the industry [3].

The moving towards sustainability in the industry requires accelerating the transition to the CE in production processes, not only in the reuse of products, but also in the reuse of emission. In this sense, CP has been recognized as a key concept for the implementation of closed loops at the company level through the reduction of material inputs and emissions in production processes [6].

The challenge of implementing CE emissions reuse closed loops in production processes requires changes in the way that equipment operate with the aim to reduce the generation of emissions to the environment. Equipment that reuse emissions are also considered to be cleaner technologies. This type of equipment already exists on the market [11,12] but not in a generalized way and when they are involved in a production process together with other equipment, the reuse of emissions is limited only to their own emissions (asynchronous vision).

The incursion of the design for life cycle (diachronic dimension) in the design of industrial equipment has allowed the incorporation of other perspectives for the conception and development of the equipment as the synchronic dimension [13,38]. It considers the relationship of an equipment with other equipment or a set of equipment throughout its life cycle. Taking into consideration that equipment is the principal consumer of resources and a generator of emissions in production processes [14], the authors recognize the opportunity to explore the implementation of the CE reuse emissions closed loops through an analysis of the relations of coexistence during the use phase (operative process) of equipment's life cycle involved in a production processes.

This research paper proposes EARC conceptual tool to analyze the feasibility of reusing emissions between equipment as an alternative to the CE emissions reuse closed loops implementation in production processes. The earlier works on reuse of emission in industrial processes [47] focuses on the link between operations, facilities, and buildings of a factory and not in the often neglected interaction between the equipment involved in a single production process, as is presented in this research.

A proposed model of CE emissions reuse closed loop in production processes was presented. The model integrates the concepts of recovery, reuse, and recycling of emissions of the CP and the transverse analysis of the diachronic and synchronic dimensions of the process equipment. The ARC should be extended to the environmental coexistence aspect of the equipment to show all possible emissions reuse interactions between the equipment involved in the process.

The presented conceptual tool complements the research for the development of a process redesign methodology. In a previous paper [14], the EARC has been applied successfully in conjunction with other tools (IDEF0, ER, MFCA) that integrate the redesign for emissions reuse (R4ER) methodology. The main objective of the R4ER methodology is the improvement of the environmental performance of the production processes through the redesign of the process that allows the reuse of emissions between the equipment. The validation of the R4ER methodology in the redesign of a sterilization process allowed for the reduction of 38% of water and 26% of electricity in the sterilization process per cycle and the reduction of 7599 kg CO2eq of carbon footprint, as well the reduction as 17.41% (6925.76 euros) of the cost of cycle of use in the sterilization process in a year [14].

6. Conclusions

The reuse of emissions between the equipment that is involved in a production process has been highlighted in this research paper to provide a new systematic tool to achieve the CE closed loops in production processes. An alternative model of CE emissions reuse closed loop in the production process is presented. The model is based on two principal initiatives. The first initiative is the CP operational concepts of waste and emissions recovery, reuse, and recycling. The second initiative is the transverse analysis of the life cycle and the environmental analysis of relations of coexistence of the process equipment. The EARC tool has been proposed to analyze the feasibility of reusing and recycling the emissions of equipment in another within a process. The EARC has been applied in conjunction with other tools that integrate the R4ER methodology in a sterilization process showing a potential reduction of resource consumption, emissions generation, as well as operating costs of production processes. Future work includes the implementation of the conceptual tool as a part the R4ER methodology in other kind of production or commercial processes.

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Full length article

Equipment suppliers integration to the redesign for emissions reuse in industrial processes

G. Ridaura[a,*], S. Llorens-Cervera[a], C. Carrillo[c], I. Buj-Corral[b], C. Riba-Romeva[a]

[a] CDEI-UPC, Centre of Industrial Equipment Design, Universitat Politècnica de Catalunya, Barcelona 08028, Spain
[b] Department of Mechanical Engineering, School of Industrial Engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya, Barcelona 08028, Spain
[c] Matachana Group, Barcelona 08018, Spain

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ABSTRACT

It is a fact that industrial equipment is the main consumer of natural resources, impacting considerably on companies' sustainability. In this context, the sustainable redesign of production processes is one of the main companies' challenges seeking to gain competitive advantage in an increasing sustainable environment. This research paper proposes a methodology for industrial application for the redesign of production processes in collaboration with equipment suppliers through resource efficiency based on Circular Economy (CE) closing loops. The redesign for emissions reuse (R4ER) methodology is a practical guidance on how manufacturing companies could address the challenges posed by the large amount of resources consumed during the operational stage of equipment's life cycle involved in production processes. The main results of this implementation are based on a real case study in a Catalan manufacturing company showing a reduction of 38% of water and 26% of electricity during the operational stage of a sterilization process in a year.

1. Introduction

For manufacturing companies involved in an increasingly sustain able environment, the reduction of the resource consumption of their production processes is essential to maintain the competitiveness but it is also crucial for the survival of the company. This is only possible when the industrial equipment use resources in a more efficient way reducing waste emissions or even reuse it as a new primary material resources (TU Delft, 2015). This is by no means a trivial task, it requires the integration of equipment suppliers to the redesign practice and the redesign of many production processes as well as the equipment in volved in them. Thus, it is essential that the process redesign considers simultaneously all of the equipment that operate in a production pro cess involved in it as part of a whole system where a modification or improvement in the equipment with the aim to reuse emissions, result directly in a reduction of resource consumption in the production process (Pisano, 1997).

The sustainable redesign for production processes require a funda mental readjustment of manufacturing companies with the aim of achieving a circular flow model (Swisher, 2006). The moving towards CE require a change in the way of the redesign of processes including the closed loop concept in the process redesign (Ferdousi and Qiang, 2016). For this, companies have to adapt their currents production processes and this adaptation must be supported by appropriate ana lysis and evaluation tools (Alves et al., 2016). The earlier works on process redesign have not especially focused on the reuse of resource emissions between equipment that operate in the same production process. The use of the function modeling method IDEF0 allows a holistic view of the process to be redesigned and the involved equip ment. Likewise, a transversal vision of the life cycle assessment (LCA) and the analysis of the relations of coexistence (ARC) for the equipment (Llorens, 2015) in conjunction with the material flow cost accounting (MFCA) is essential to achieve a CE closed loop.

This research paper proposes a methodology for industrial appli cation for redesigning production processes in conjunction with equipment suppliers with the aim to reuse the emissions between the equipment involved in the process. The main results of the metho dology implementation indicate the potential of sustainable innovation showing a decrease in the resource consumption in an operational stage of the sterilization process.

2. Frame of reference

2.1. The redesign of processes

The redesign of processes refers to a major effort to improve an

* Corresponding author.
E-mail address: ridaura@cdei.upc.edu (G. Ridaura).

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Nomenclature

ΔQ	Heat variation (kcal)
m	Mass (kg)
c	Specific heat constant $\frac{kcal}{kg.°C}$
Tf	Final temperature (°C)
Ti	Initial temperature (°C)
S	Sterilizer
Wm	Wash machine
ΔS	Stored water volume change (l)
Q_i	Total volume of input (l)
Q_o	Total measure volume of outputs (l)

existing process (Harmon, 2014). It consists in the modification or reduction of steps in processes to remove non value activities and improve those that add value to the customers (Spring Singapore, 2013). Including the delivery of production process with the capacity to respond efficiently to customer demands in a zero waste way (Alves et al., 2015). The redesign of processes is an activity of industrial engineering and it is not new. The basis for the redesign of processes was establish in *Principles of Scientific Management* from Frederick W. Taylor in 1911 (Serrano and Ortiz, 2012), by the creation of assembly lines divided into operations with different employees by Henry Ford in 1913 (Dooley and O'Sullivan, 2000), by the *Structure Approach* of Henry Fayol and in the *Time and Motion Studies* of the Gilbreth spouses in 1917 (Niebel and Freivalds, 2004). In addition, a very important contribution was the *Systems Approach* presented by Boulding in 1950 where it was mentioned that the organization is more than the combination of unique elements and that their interaction is more important than the elements themselves (Dooley and O'Sullivan, 2000).

During the 1980s, different methodologies with a focus on quality were presented in order to emphasize the importance of meeting the customer's quality needs. Among the most important are the Statistical Process Control (SPC), Factory Focus, the Quality Circles, the Total Quality Management (TQM), Just in Time (JIT), ISO 9000 and the Benchmarking among others. Since 1990, a variety of authors has appeared with methodologies of process improvement that have made valuable contributions in the redesign of processes. Among the most remarkable are the contributions of Davenport and Short who proposed the *Business Process Redesign (BPR)* methodology in 1990. They focused on the concept of processes description and on the definition and analysis of critical processes to reduce cycle time, to strengthen the value chain and to improve competitiveness (Davenport and Short, 1990). *Business Process Management (BPM)* is a structured and systematic way for the analysis, improvement, control and management of processes, with the aim of improving the quality of products and services (Serrano and Ortiz, 2012). As part of the methodology Toyota Production System, *The Value Stream Mapping (VSM)* was presented in 1997. It is a lean manufacturing method for mapping and analyzing the production process which supports the redesign of processes and services (Serrano, 2007). Harmon in 2004 proposed a *Business Process Change (BPC)* methodology. This methodology is based on the improvement through process redesign due to the changes that can be experienced by the interactions of the staff, the management, IT systems, the technology and the structure of the organization (Serrano and Ortiz, 2012).

2.2. Process equipment design relationship

The first record to understand the design relationship between existing industrial equipment and the production process in which they interact was introduced by Hubka and Eder (1988) presenting the *Theory of Technical Systems (TTS)*. They classified and categorized the knowledge of the technical equipment in a nature, structure, origin, development and empirical observations. The principal contribution of Hubka is that the analysis of the equipment must be based on the production process that reflects the activity where they operate (Riba et al., 2005).

Later, in the course of the GAMMA project (Riba et al., 2003) the necessity of a new design perspective is perceived that includes the equipment to be designed and the production process to which it contributes. Contrasting with the end user products that are used in situations where the relationship between the user and product is direct, the equipment for production processes operates in complex situations where different operators collaborate and many environmental factors contributes as resources availability, cultural and climatic conditions (Riba and Molina, 2006). Under this new perspective, the authors defined a new frame for the design and development of the equipment involved in the production processes named *Process Equipment* (Riba et al., 2005). While the previous design philosophies only accentuate the manufacture and the minimization of cost in the equipment, the *Process Equipment* philosophy is pronounced the usability and the effectiveness of the complete production process system (Riba et al., 2005). With the purpose of the implementation of this philosophy, the concepts of *Process Equipment Architecture and Portfolio Equipment Architecture* were defined (Riba and Molina, 2006).

For the purpose of complementing the terminology proposed during the GAMMA project, Llorens (2015) structured a design methodology for the establishment of the architecture of gamma of equipment redefining some concepts like a process family, architecture of process families, product family, product catalogue, gamma of equipment and the gamma architecture of equipment goods. The methodology to perform the design model contains five steps; 1. Identify, analyze and represent the operational process; 2. Identify, analyze and represent the existing contexts; 3. Get the scheme of the family of operational processes (based on existing context); 4. Analyze and represent the architecture of existing product gamma; 5. Redefine operational processes and architecture product gamma. It is performed considering an operational process in which there is a complete gamma of equipment that coexist and interact in the same production process. Llorens established a new framework for analysis and definition of the architecture of gamma of equipment through transversal visions of the life cycle assessment (*diachronic dimension)* and the analysis of the relations of coexistence (*synchronic dimension*) for the equipment in the production process.

Taking in consideration the increase of environmental requirements in the design of process equipment, in 2010, the CDEI UPC promoted a design methodology called *Design in blue*, which takes its name from the concept of the Blue Economy of Gunter Pauli. In contrast to the green economy, it advocated a simple change of unsustainable technologies for sustainable technologies accepting an increase in costs. The blue economy proposes a paradigm shift that eliminates the unsustainable production and consumption so that the good and innovative become competitive. It suggests that business models improve the quality of life of all evolving in harmony with ecosystems, using available resources and ensuring that process residues become resources for another process (Pauli, 2010). Based on this, Riba (2012) identified three lines of work in the methodology Design in blue that set the paradigm shift in the design and development of equipment; 1. The consideration of the operational process as the basis for analysis; 2. Assessment of energy consumption and environmental impact; 3. The consideration of social, cultural, natural environment and technological context. The consideration of the operational process as the basis of the analysis point of view should be extended from the equipment to the operating process including technical and human operators and all flows of materials, energy and information.

The different approaches and methodologies presented in the framework clearly illustrate a body of prior research activities that have enriched the redesign of processes practice. Process redesign is an evolving concept that will continue developing. The frame of reference also suggests the importance of the design relationship between the process and the equipment as a holistic view. In the actual situation of material, energy and resources shortage, process designers should include this consideration in their tasks and act accordingly in consequence (Riba, 2002). A production process is sustainable if they support the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources (US DOC, 2009) . The Circular Economy (CE) is "an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well being" (Murray et al., 2017). CE become a guide for the redesign of companies processes in the way to sustainability (Anttonen, 2017). It places emphasis on the redesign of production processes through the cycling of materials (Murray et al., 2017). The reuse of material and waste streams require the redesign of production processes (Tello and Weerdmeester, 2013).

The industrial equipment is the main consumer of resources in production processes. In order to continue with the line of research about the relationship of the process and the equipment, this research paper proposes a methodology for industrial application for the redesign of production processes in collaboration with equipment suppliers through resource efficiency between equipment that operate in the same process.

3. Research design

The empirical research of this paper is based on a real case study in a Catalan company that manufactures sterilizers.

3.1. Case study research method

The case study started in September 2014 and ended in July 2016. In order to follow up the activities of the development project and collect data in real time, a stay was allowed in the sterilizers company. The previous time for data collection was invested in the study of documented procedures and instructions related to the topic of new product introduction in the company. In order to know the company's background in collaboration with equipment suppliers, interviews were conducted throughout the entire organization. A total of 22 interviews were carried out with individuals in different positions as directors, departments managers, program managers and project engineers in different departments as quality, I + D, technical office, purchase, production, logistic, commercial department among others. The new component development project where the data to start the case study were collected, started in December 2014 and ended in April 2015. During the six months of the project, six meetings were attended (non participatory), the flow of information interchanged between manufacturing company and the equipment supplier was analyzed.

3.2. Current equipment supplier collaboration procedure

The case study targeted a new equipment that the company as in previous occasions, outsourced to an equipment supplier to design and to subsequent manufacture the new component. In this case, the equipment supplier was located in Catalonia but in another city about 140 km of distance. The process was carried out as in previous occasions, following an equipment supplier outsource activities plan:

- Background (Context, problem definition)
- Normative (Regulations applicable)
- Technical specification (Design and function requirements, process of operation description)
- Conceptual design (Determining system specifications from conceptual design in 3D drawings)
- Quotation (Materials, labor)
- First prototype (Partial design, manufacturing, assembly and functionality test in the developed prototype)
- Final prototype (Total design, manufacturing, assembly and functionality, reliability and durability test)
- Mass production (Quantity of order, delivery times, logistic plan)

Some of the most important aspects observed in the case study are: A single contact person between both sides was not assigned, since at the beginning of the process was observed that all project objectives were not well defined. Additionally, some system requirements were not defined, motivating design problems in the prototype stage were observed; *Computer assisted x* (CAx) systems compatibility between the equipment supplier and the client were not reviewed, causing significant loss of data at the time of conversion. The fact that the two companies were not in the same city, was sometimes reason for delay or rescheduling of follow meetings. The types of material to be used were taken into consideration, but not the energetic consumption of hazardous substances or the equipment used in the operation phase. All these situations brought a series of delays in project time, with an increased in the price of the projected initial investment. When asked about the regularity of these types of problems, the answer was that both parties experience this kind of problem with other companies regularly.

4. Proposed redesign methodology

Taking into consideration the literature review, a series of previous activities before the implementation of the methodology of production processes redesign were established.

4.1. Redesign for emissions reuse (R4ER) methodology steps

Step 1: Operative process knowledge

In order to analyze the production process and the identification of the equipment involved, it is necessary to carry out a representation model of the system. The redesign of processes can be realized through production process modeling (Lam and Hills, 2011). A complete survey (Kettinger et al., 1997) identified the IDEF0 as an important tool to the redesign phase in the innovation of processes. IDEF0 is a appropriate modeling method for describe process flows (Smith and Ball, 2012). This method, presents a structured description of activities in a system through the representation of their respective Inputs, Outputs, Mechanisms and Controls. The graphics of an IDEF0 diagram show the operations assigned for the various equipment's as a box and the interfaces to or from the function as arrows entering or leaving the boxes. This IDEF0 diagram must be performance in a way that equipment suppliers have a holistic view of operations, equipment, operators, materials flows and their interactions within the production process where the equipment they provide operates.

Step 2: Equipment review (ER)

In this step, it is necessary to perform or know the results of a life cycle assessment (LCA) for every equipment in the production process. The LCA is a method that allows the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006, p.10). LCA requires quantitative information of the complete life cycle (exploitation, production, use and end of life) of a product (equipment) to reveal their environmental profile (Sakao, 2007) The LCA results will validate the significant amount of resources consumed during the phase of use of the equipment and will allow to establish which equipment is significant to reuse emissions.

Adopted from the ISO 50001:2011 energy review, the ER allows the identification of the equipment with a major resource consumption in a process cycle. It is performed in the operations identified in the previous step. First, process operations are listed, the involved equipment in each operation and their number are identified. Second, the resource consumption per cycle are taken from the results of the previous equipment LCA or measurement. As in the ISO 50001:2011, the consumption data can be measured, calculated or estimated, in order not to limit the application of the tool to only measured or calculated data, but also to allow the use of estimated data for equipment consumption for which no real data are available. The name for the consumed resource, their coefficient, the unit of measurement and their percentage of contribution to the actual consumption of the process cycle are identified for each of the previously listed equipment. Finally, based on the obtained data, it must be decided whether there is a potential for significant savings in the resource consumption and it needed to identify the equipment and their subsystem on which improvement should be applied. Significance criteria should be established in order to prioritize which resource consumption in which equipment needs to be reduced. The number of criteria and their severity depend on the environmental needs and the purpose of these criteria that should balance the environmental consumption of equipment the in the process.

Step 3: Process use cycle cost

In this step, the cost of use of the significant equipment found in the previous step is calculated through material flow cost analysis (MFCA). MFCA is a "tool for quantifying the flows and stocks of materials in processes or production lines in both physical and monetary units" (ISO 2011, p. 3). In which water and energy can be included as term materials (Christ and Burritt, 2016).

The MFCA follows the general procedure for Plan Do Check Act and consists of ten steps. In order to know the cost of use of the significant equipment in the process, steps three until nine will be carried out. The *specification of a boundary and a time period* and the *determination of quantity centres are the steps three and four,* for which, the analysis time frame and the involved operations have to be specified. In order to have a better overview of the flows and inventories of materials in the process, it is advisable to analyze a month or a year of a production process (ISO, 2011). The steps five, six and seven are the *identification of inputs and outputs for each quantity centre,* the *quantification of* the material flows in physical and monetary units. For each operation, inputs (materials, energy) and outputs (products, material and energy losses) have to be identified and quantified in physical and monetary units (Schmidt et al., 2013). The last steps are MFCA data summary, communication of MFCA results and interpretation. The results of a MFCA can be very valuable in the search for opportunities to reduce material use and waste, increase the efficient resource, and decrease negative environmental impacts and associated costs (Kokubu and Tachikawa, 2013). MFCA will serve to present the economic impact of the resource consumption of the equipment in the process.

Step 4: Emissions reuse

Emissions from analyzed equipment operating in the production process must be identified. Subsequently, an analysis of the relations of coexistence (ARC) should be performed in order to reuse those emissions of resources turning them in the entrance of resources to another equipment within the same production process trying to convert the system in a closing loop. The ARC is a relatively new tool. In order to define a methodological basis for establishing the gamma of industrial equipment in an equipment manufacturing company, Llorens (2015) concludes that an equipment interacts in the production process in which it operates and also interacts with the other equipment. In this interaction, the relations of coexistence between equipment appears. Therefore, it is necessary to incorporate a new design perspective for industrial equipment, the design of an equipment based on the analysis of the relations of coexistence (ARC) with other equipment. This synchronistic perspective considers the interaction of the equipment and the set of equipment that operate in the process as well.

5. Application

5.1. Example

The case study consists of redesigning a complete sterilization process within the portfolio of products and services that are offered by the Catalan company to their customers. The operations washing and sterilization are both included in a complete sterilization process and are two major consumers of energy and water (significant amounts of water need to be heated). This section verifies the redesign methodology via application to the mentioned process. The results of the proposed methodology implementation are explained.

Suppliers of each of the equipment's involved in the project were in different countries: Spain, France and Italy. A face meeting was conducted at the beginning of the project in order to present the objective and expectations of collaboration. In this meeting, the roles and responsibilities for each of the sides were appointed. The person who led the project by the company knows the specifications and operation of equipment involved in the project, because previously he was supplier engineer and product engineer in the company. It was mentioned that this person would be the only responsible to send the information about the project to the equipment's suppliers, for this reason, a documented procedure was established with the respective formats of the project. CAx systems compatibility between the equipment suppliers were reviewed. A virtual meeting schedule was established for the follow up of the project milestones activities, regardless of communications via mail and by telephone needed day to day. The ecosystem builder visited one time each supplier in their plant. A total of 3 face to face follow up meetings were carried out, two in the first month of the project (presentation, brainstorm ideas) and one in the middle of the project, the face to face meeting to close the project continue pending.

5.2. Results

Step 1: Operative process knowledge

First, a process model using the function modeling method IDEF0 was elaborated in conjunction with the equipment suppliers. Fig. 1 represents the global operations like traceability and controlled environmental conditions as well as specific operations like receiving, washing, preparing, sterilizing, storing, distributing, operating and preparing and it shows their relationship for a sterilization process.

Inputs

In this section, the following were identified: i) The sterilized surgical material as a WIP (Working in process) and a signal showing the WIP status (Contaminated surgical material, contaminated surgical material washed, contaminated surgical material prepared and surgical material sterilized) after and before each operation. ii) The consumed of resources in the sterilization process (Water and electricity) and other materials necessary to perform the above process (Detergent, ink, printing paper, thermal reactive).

Outputs

The outputs identified in this section were: i) The sterilized surgical material as in the input section, and a signal showing its status, but after each operation. ii) The emissions generated in the sterilization process (high temperature, dirty water mixed with soap and some solid wastes, saturated steam and other kind of dirty water).

Mechanisms

Two types of operators were identified: i) human operators (Sterilization technician, instrumentalists, and doctors) ii) technical operators or better called equipment. The identified equipment, which is the focal point of this methodology, are listed in Table 1.

Controls

In this last section of the operative process knowledge step, the work procedures, instructions and formats to perform each operation of the

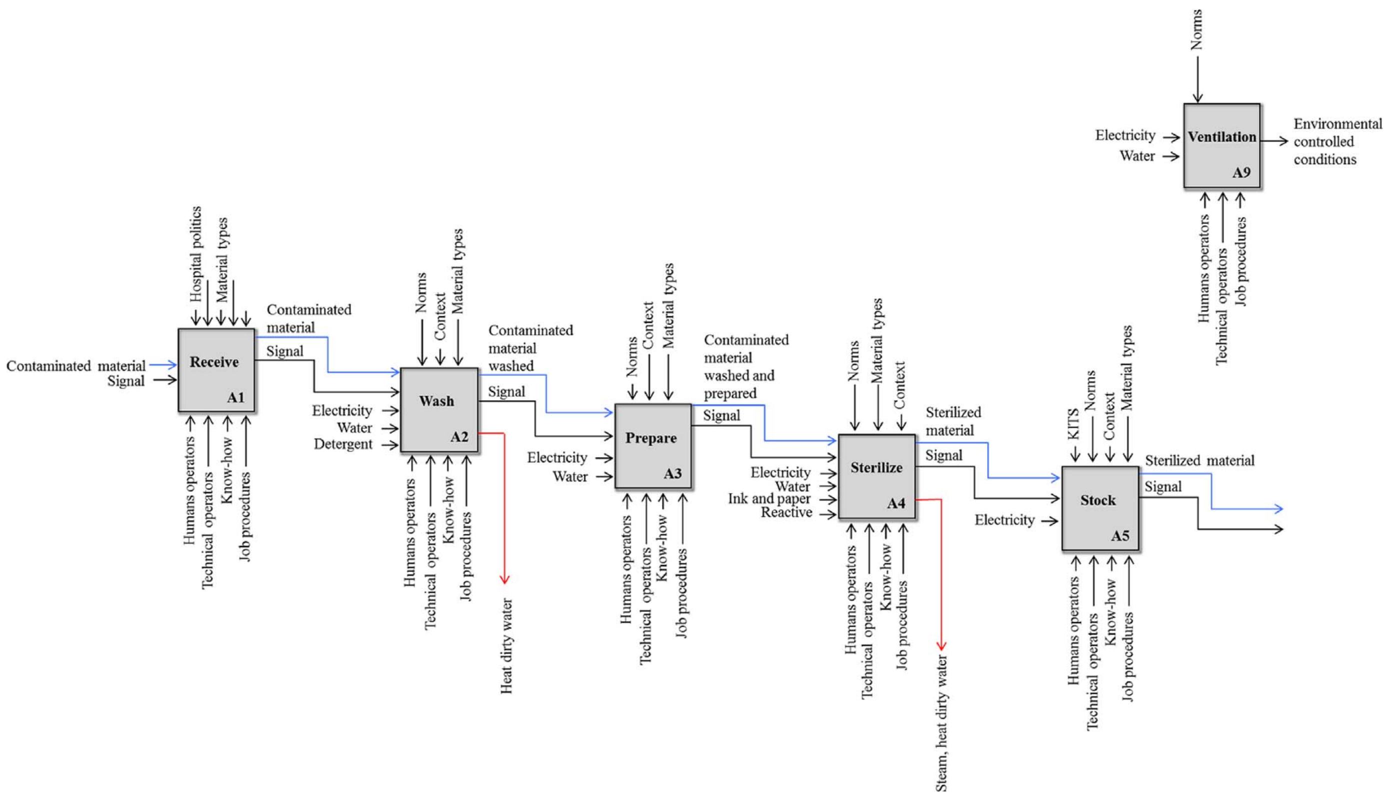

Fig. 1. IDEF0 Sterilization process.

Table 1
Identified equipment in a sterilization process.

Operation	Equipment
Traceability	Computer, monitor, scanner, labeler
Environmental controlled conditions	Air conditioning
Washing	Washing machine, ultrasonic washing machine
Prepare	Packaging machine
Sterilization	High temperature sterilizer

Table 2
Identified norms in a use phase of the sterilization process.

Norm name	Regulation
ISO 90001:2008	Quality management systems – Requirements
UNE 171340-2002	Validation and evaluation of controlled environment rooms in hospitals

sterilization process as well as the regulations governed by this process were identified.

Each hospital, research center, laboratory or anywhere else where the sterilization process is performed has its own procedures. They are based on the manuals of the manufacturers of the equipment and training that they receive from the equipment supplier in the purchase and installation phase. The way an equipment is used can affect their performance and therefore its consumption of resources. In this example, procedures, work instructions and formats were reviewed but no special emphasis was placed on them because they are based on the operation manuals and training by equipment suppliers.

Regardless of the regulations governing the manufacture (ISO 13485, ISO 9001, ISO 14001, ISO 50001 and others) of each involved equipment in the sterilization process, we will focus on the rules governing the phase of use in the life cycle of the equipment, that is when the greatest amount of resources are consumed. In this application example, two different norms that directly affect the use phase of the life cycle of the sterilization process equipment were identified (Table 2).

Step 2: Equipment review

First, following an energy review adapted from the ISO 50001 standard format, operations and equipment identified in the last step were listed. The resource consumption was measured; the method for measuring the resource consumption was done by calculations and measurements of each of the involved equipment per process cycle. These measurements were taken from the previous analysis of life cycle of the equipment conducted by the equipment suppliers (Table 3).

Electricity and water were the resources consumed by the sterilization process, the significance of the used criteria in this equipment review were:

Will be significant the equipment that consume more than 20% of the total consumed by the process per year?

Under this criterion, the equipment and the consumption that exceed this percentage are:

- Air Conditioning (Electricity)
- Washing Machine (Electricity)
- High Temperature Sterilizer (Electricity and Water)

The Air Conditioning consume a 30.43% of electricity and a 2.79% of water. On the other hand, the Washing Machine consume 28.26% of electricity and 13.94% of water. The Sterilizer needs 36.96% of the total electricity and 81.53% of the total water consumed in the sterilization process at full capacity with 160 kilos of surgical instruments. It was decided to take into consideration the Washing machine and the Sterilizer to continue with the methodology because they represent the most significant consumption of water that has to be heated by electricity.

Table 3
Sterilization process equipment review.

Operations	Equipment	Quantity	Measurement Method	Real Use per Cycle				Source to Improve	Cycles per Year	Significance
				Resource	Coefficient	Unit	% of Total			
Globals										
Traceability	Computer	1	Calculated	Electricity	0.35	k W h	0.76%		Intermittent	
	Monitor	1	Calculated	Electricity	0.05	k W h	0.11%		Intermittent	
	Scanner	1	Calculated	Electricity	0.003325	k W h	0.01%		Intermittent	
	Labeller	1	Calculated	Electricity	0.06	k W h	0.13%		Intermittent	
Ventilation	Air Conditioning	1	Calculated	Water	16	l	2.79%	Cooling System	Constant	
			Calculated	Electricity	14	k W h	30.43%	Motor		
Specifics										
Wash	Washing Machine	1	Measured	Water	80	l	13.94%	Vat	3155	
			Measured	Electricity	13	k W h	28.26%	Motor		
	Ultrasonic Washing Machine	1	Calculated	Water	10	l	1.74%	Vat	Intermittent	
			Calculated	Electricity	0.6	k W h	1.30%	Motor		
Prepare	Labeller	1	Measured	Electricity	0.6	k W h	1.30%	Resistance	Intermittent	
Sterilize	High Temperature Sterilizer	1	Measured	Water	468	l	81.53%	Vacuum System (Vacuum bomb, Ejector)	3155	
			Measured	Electricity	17	k W h	36.96%	Steam Generator		

Step 3: Process use cycle cost

The environmental resource consumed by the Washing machine and the Sterilizer had an economic impact (Table 4).

The findings found through the MFCA analysis indicate that with 3155 sterilization cycles per year (Wash and Sterilize), the sterilization process can processed 504,800 kg of surgical material. This represents a consumption of 189,300 kW h with a cost of 33,165.36 euros, which represents 83.39% of the total costs per year of the sterilization process. Likewise, it is observed that the consumption and loss of water is 3,457,880 l of water with a cost of 6,604.55 euros and that this represents 16.61% of the 39,769.91 euros spent on electricity and water annually from the significant equipment of the sterilization process.

The electricity consumed represents a generation of 58,304.4 kg CO_2eq

$$\text{Carbon footprint} = \text{Usage (kWh)}.\ CO_{2\text{emission factor}} \quad (1)$$

$$\text{Carbon footprint} = \text{Usage(kWh)}.\ \frac{kgCO_2}{kWh} \quad (2)$$

$$\text{Carbon footprint} = 189{,}300\ \text{kW h}.0.308\ \text{(gentcat.cat, 2016)}$$

$$\text{Carbon footprint} = 58{,}304.4\ kgCO_{2eq}$$

The results are presented visually using a e!Sankey diagram which allows to observe the flow of electricity and water in the sterilization process within four equipment in two operating areas (Washing and sterilization) (Fig. 2).

Table 4
Material flow cost matrix for water and electricity of the sterilization process.

Sterilized Surgical Material (year)	Water Consum (year)	Water Cost (year)	Energy Consum (year)	Energy Cost (year)	Total
504,800 kg	3,457,880 l	6604.55 € 16.61%	189,300 kW h	33165.36 € 83.39%	39769.91 € 100.00 %

Step 4: Emissions reuse

An analysis of the relations of coexistence (ARC) of the equipment in the sterilization process was elaborated (Fig. 3). Wastewater emissions of the significant equipment defined in the ER were identified and the reuse between them was proposed.

Sterilizer → Washing machine

40 l of the water emissions at 65 °C for the *Op2* (vacuum) of the Sterilizer *(S)* is reused in the operations *Op1* (pre washing) and *Op2* (washing) of the Washing machine *(Wm)* and the remaining (360 l) are discarded to wastewater.

The water emissions outlet for the *SOp2* have no contact with contaminated surgical material therefore, it is equal to the water inlet quality specification of *WmOp1* and *WmOp2*, an external water supply quality. This does not represent an alteration in the results of operations *WmOp1* and *WmOp2* however, it represents a decrease in the water consumption of the Washing machine.

The temperature of the water emissions outlet for the *SOp2* (65 °C) is different to the water inlet temperature specification that *WmOp1* and *WmOp2* (15 °C) need. This represents an improvement in the results of operations *WmOp1* in cleaning the surgical material. In *WmOp2* this difference in water temperature with respect to its specification, represents a decrease in the energy that is required to heat the water in *WmOp2*.

At the end, the 40 l of the water emission outlet of *WmOp1* and *WmOp2* are discarded to wastewater.

Figs. 4 and 5, Eqs. (3) (5) show the performed calculations.

Water improve:

$$\Delta S = Q_i - Q_0 \quad (3)$$

$$\Delta S_{S\rightarrow Wm} = (400l) - (360l)$$

$$\boldsymbol{\Delta S_{S\rightarrow Wm}} = (40l)$$

Energy improve:

$$\Delta Q = m.\ c.\ (Tf - Ti) \quad (4)$$

$$\Delta Q_{S\rightarrow Wm} = m.\ c.\ (Tf_S - Ti_{Wm}) \quad (5)$$

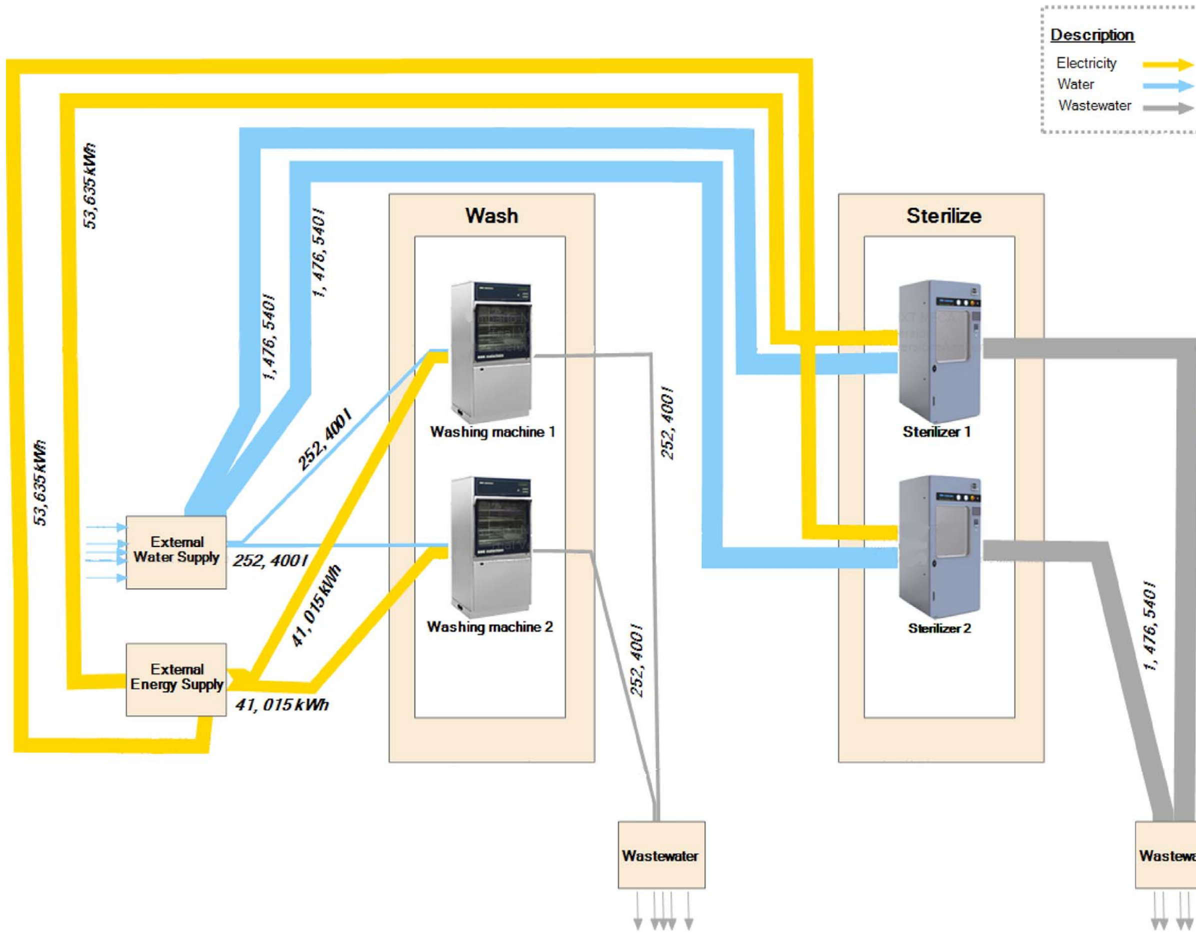

Fig. 2. Sankey diagram water and electricity of the sterilization process.

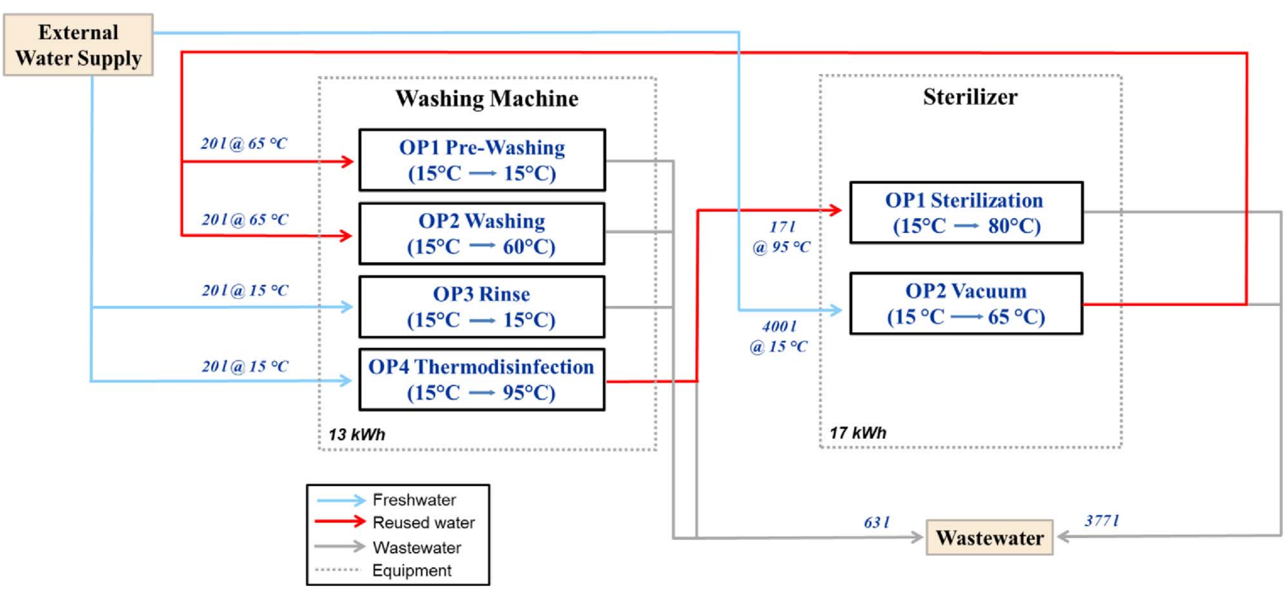

Fig. 3. Analysis of the relations of coexistence (ARC) of the sterilization process.

$$\Delta Q_{S\rightarrow Wm} = (40\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).\left(\text{T}f_S - \text{Ti}\left(\frac{WmOp.1 + WmOp.2}{2}\right)\right)$$

$$\Delta Q_{S\rightarrow Wm} = (40\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).\left(65°\text{ C}-\left(\frac{30°\text{C}}{2}\right)\right)$$

$$\Delta Q_{S\rightarrow Wm} = (40\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).(65°\text{ C}- 15°\text{C})$$

$$\Delta Q_{S\rightarrow Wm} = (40\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).(50°\text{C})$$

Sterilizer

Operation	Water	T Input	Water	T Output
Op. 1	17 l	15 ° C	17 l	95 ° C
Op. 2	400 l	15 ° C	400 l	65 ° C

Washing machine

Operation	Water	T Input	Water	T Output
Op. 1	20 l	15 ° C	20 l	15 ° C
Op. 2	20 l	15 ° C	20 l	60 ° C
Op. 3	20 l	15 ° C	20 l	15 ° C
Op. 4	20 l	15 ° C	20 l	95 ° C

360 l

Fig. 4. Sterilizer → Washing machine water emissions reuse.

$$\Delta Q_{S\rightarrow Wm} = 2000\ \text{kcal}.0.001163\ \text{kW h}$$

$$\boldsymbol{\Delta Q_{S\rightarrow Wm}} = 2.33\text{kWh}$$

Washing machine → Sterilizer

17 l of the water emissions at 95 °C for the *Op4* (Thermodisinfection) of *Wm* is reused in the operation *SOp1* (Sterilization) and the remaining (3 l) are discarded to wastewater.

The water emissions outlet for the *WmOp4* is an external water supply quality, but have contact with washed and thermodisinfected surgical material. However, according to the manufacturer, it does not represent an alteration in the results of operations *SOp1* since this water is needed to generate steam.

The water inlet quality specification of *SOp1* is an inverse osmosis quality. According to the manufacturer, the generation of steam by the sterilizer can be done also with external water supply, which has been preheated. The purpose is that in the course of heating the water begins to lose minerals. At 95 °C water emissions outlet for the *WmOp4* is almost at its boiling point, which represents a decrease in the energy required to generate steam by the sterilizer and in the water consumed because the loss of water when producing one liter of osmosis water is 1 l:3 l.

At the end, the 17 l of the water emission outlet of *SOp1* are discarded to wastewater.

Fig. 5 and Eqs. (6) (8) show the performed calculations:

Water improve:

$$\Delta S = Q_i - Q_0 \tag{6}$$

$$\Delta S_{Wm\rightarrow S} = (20\text{l}) - (3\text{l})$$

$$\boldsymbol{\Delta S_{Wm\rightarrow S}} = 17\text{l}$$

Energy improve:

$$\Delta Q = m.\ c.\ (Tf - Ti) \tag{7}$$

$$\Delta Q_{Wm\rightarrow S} = m.\ c.\ (Tf_{Wm} - Ti_S) \tag{8}$$

$$\Delta Q_{Wm\rightarrow S} = (17\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).\ (Tf_{WmOp.4} - Ti_{SOp.2})$$

$$\Delta Q_{Wm\rightarrow S} = (17\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).\ (95°\ \text{C}- 15°\text{C})$$

$$\Delta Q_{Wm\rightarrow S} = (17\text{kg}).\left(1\frac{\text{kcal}}{\text{kg.°C}}\right).\ (80°\text{C})$$

$$\Delta Q_{Wm\rightarrow S} = 1360\ \text{kcal}.0.001163\ \text{kW h}$$

$$\boldsymbol{\Delta Q_{Wm\rightarrow S}} = 1.58\ \text{kW h}$$

Eqs. (9) and (10) show the performed calculations for a total improve per cycle in a sterilization process.

Total improve per cycle:

$$\boldsymbol{Energy} = \boldsymbol{\Delta Q_{S\rightarrow Wm}} + \boldsymbol{\Delta Q_{Wm\rightarrow S}} \tag{9}$$

$$\boldsymbol{Energy} = 2{,}33\text{kW h} + 1{,}58\text{kW h}$$

$$\boldsymbol{Energy} = 3{,}91\text{kW h per cycle}$$

$$\boldsymbol{Water} = \Delta S_{S\rightarrow Wm} + (\Delta S_{Wm\rightarrow S} + \boldsymbol{inversis\ osmosis\ rejection}\ 3{:}1) \tag{10}$$

$$\boldsymbol{Water} = 40\text{l} + (17\ \text{l} + (17\text{l}.\ 3\text{l})$$

$$\boldsymbol{Water} = 40\ \text{l} + (17\text{l}+51\text{l})$$

$$\boldsymbol{Water} = 40\text{l} + 68\text{l}$$

$$\boldsymbol{Water} = 108\text{l}\ \ per\ \ cycle$$

The findings found through the MFCA analysis after emissions reuse, indicate that with 3155 sterilization cycles per year (Wash and Sterilize) and with 504,800 kg of surgical material processed, the sterilization process experience a reduction of 4,322.54 euros in electricity consumption and a reduction of 1,301.61 euros in water consumption (Table 5).

The electricity consumed represents is represents a generation of

Washing machine

Operation	Water	T Input	Water	T Output
Op. 1	20 l	15 ° C	20 l	15 ° C
Op. 2	20 l	15 ° C	20 l	60 ° C
Op. 3	20 l	15 ° C	20 l	15 ° C
Op. 4	20 l	15 ° C	20 l	95 ° C

Sterilizer

Operation	Water	T Input	Water	T Output
Op. 1	17 l	15 ° C	17 l	95 ° C
Op. 2	400 l	15 ° C	400 l	65 ° C

3 l

Fig. 5. Sterilizer → Washing machine water emissions reuse.

Table 5
Material flow cost matrix for water and electricity of the sterilization process after reuse of emissions.

Sterilized Surgical Material (year)	Water Consum (year)	Water Cost (year)	Energy Consum (year)	Energy Cost (year)	Total
504,800 kg	2,776,400 l	5302.94 € 15.53%	164,628 kW h	28842.82 € 84.47%	34145.76 € 100.00%

50,705.4 kg CO_2eq. Eqs. (1) and (2) were used for calculations.

$$\text{Carbon footprint} = 164{,}628\ \text{kW h}.0.0308\ \text{(gentcat.cat, 2016)}$$

$$\text{Carbon footprint} = 50{,}705.4\ \text{kgCO}_{2\text{eq}}$$

This represents a saving of 5,624.15 euros spent on electricity and water from the significant equipment of the sterilization process and a 7,599 kgCO_2eq which will not be emitted to the environment.

Fig. 6 present a proposal of the sterilization process closed loop model.

The closed loop model proposed for the redesign of the sterilization process is a continuous process of synchronous exchange of water emissions from one equipment to another. The company has developed software that controls and synchronizes this emissions exchange based on Digital Habitat Ecosystem Architecture (DHEA), which allows the monitoring of resource consumption and sends signals for the exchange of emissions when the equipment requires it. In case of a saturation in the system, emissions are released to the wastewater.

6. Discussing the application

The main results of this implementation indicate the potential of sustainable innovation. From the operational phase of the sterilization process was established:

- A reduction of 38% of water and 26% of electricity in the sterilization process per cycle;
- A reduction of 7,599 kg CO_2eq of carbon footprint of the sterilization process in a year;
- A reduction of 17.41% (6,925.76 euros) of the cost of cycle of use in the sterilization process in a year.

The case study presented has shown how manufacturing companies could address the challenges posed by the large amount of resources consumed during the operational stage of equipment's life cycle involved in a production process by following the proposed redesign methodology. As well as, the synergistic relationship between the inputs and outputs in three of the four tools was confirmed; The outputs of IDEF0 were effectively input to ER, while the output of ER was input to MFCA and ARC. An objective analysis performance was necessary for identifying all aspects in a sterilization process, which was achieved by adopting IDEF0. On the other hand, the knowledge of the consumption

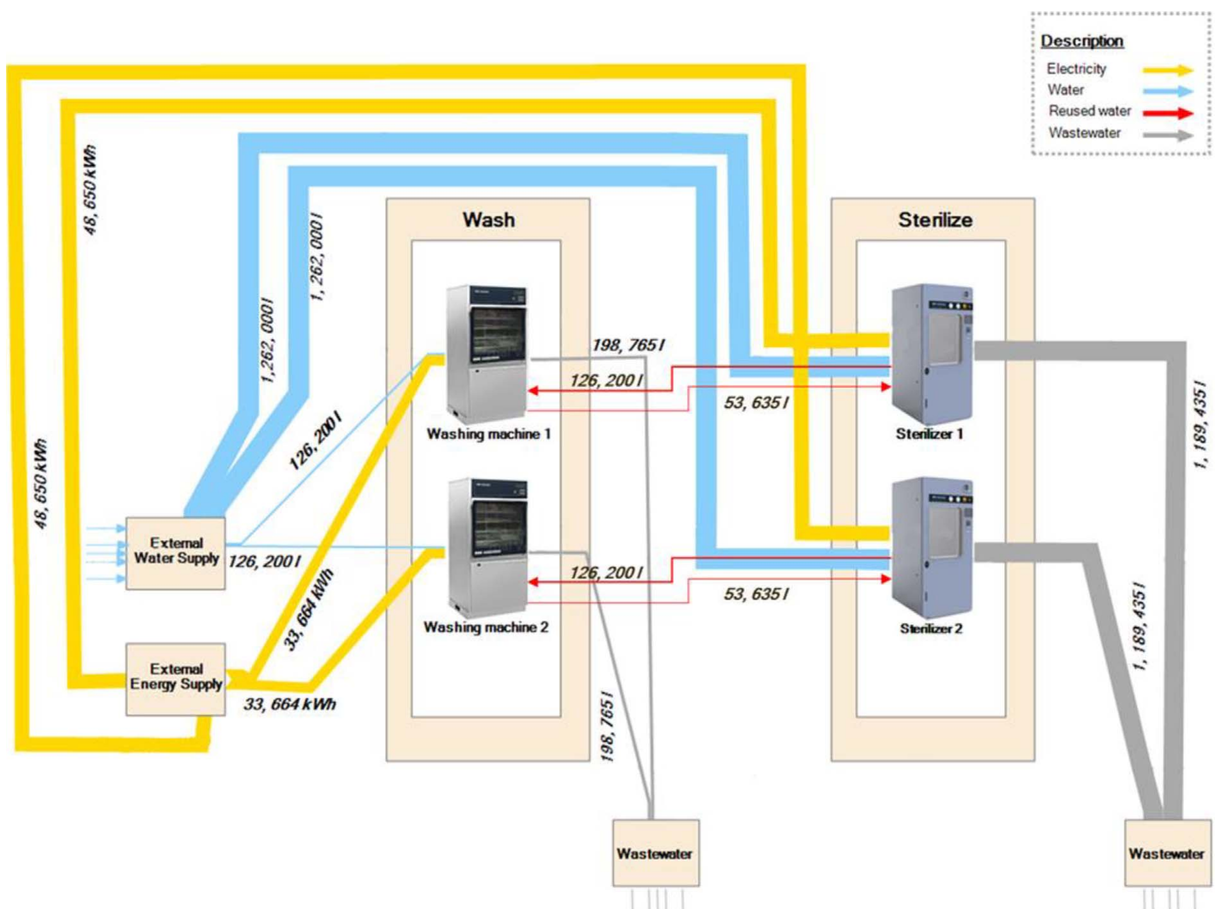

Fig. 6. Sankey diagram sterilization process closed loop model.

of resources of the equipment involved in the sterilization process is critical to identify which resource is used mostly and which are the equipment with the major consumes in the ER step. Additionally, it necessary to know the result of the LCA of the equipment performed by the equipment suppliers previously in order to verify its significance in the sterilization process.

The output of ER mentioned above was necessary as input of the next two tools. First, to perform the step of MFCA in where the con sumption of resources of the significance equipment in the sterilization process was critical to know the impact not only economically but also at the environmental level, generating concrete data, which can be helpful for process designers to understand the opportunity area to reduce consumes. To perform an ARC it is essential the use of a common sense and a systematic thinking with the purpose of reusing the emis sions of resources from one equipment in another.

7. Discussions

The application of the proposed methodology demonstrated in section five revealed:

1. The methodology effectively proved the essential relationship be tween the production process and the equipment involved in them not only in the design stage, but also in the relation of resource consumption and support of the sustainable redesign of industrial processes.
2. The inputs and outputs of the IDEF0, ER and ARC are essential, due to the synergy of the three tools. Absence of any of the three tools mentioned above is not effective. The LCA results must validate the significance of the equipment with more resource consumption in the ER.
3. With the exception of the previous LCA for each equipment, the other three tools IDEF0, ER, MFCA and ARC are relatively simple because they are based on common sense and can be used by process designers without the need for extensive environmental experience. This converts the methodology in a practical guidance on how manufacturing companies could address the challenges posed by the large amount of resources consumed during the operational stage of equipment's life cycle involved in a production process.
4. It is widely applicable to the redesign of any production process where industrial equipment is involved because any limitation on the applicability was found. In cases of production processes with more complexity, the methodology will be applicable, as well. Rather, the methodology may be more effective in such production processes where the resources consumption is higher.
5. The main objective of the redesign methodology presented in this research is to improve the environmental performance of the pro duction processes. As part of a number of innovative environmental solutions that have been appearing recently, it will be necessary to implement the proposed methodology in different production pro cesses and to validate its reliability for external verifiers. Environmental technology verification is a tool to support circular economy (Henry, 2017) " ETV is applicable to those innovative environmental technologies whose innovative features or perfor mance cannot be fully assessed using existing standards" (ISO, 2016). Along with the application in other processes, the mission of the ETV will be to certify that the proposed redesign methodology provides a solution to an environmental problem with the support of engineering and scientific principles (OECD, 1999).

8. Conclusion

This research presents a production processes redesign metho dology, which adopts IDEF0, LCA, MFCA and ARC tools. It has been verified through application to an exemplary sterilization process. From the application, it was shown that the proposed methodology effectively proved the essential design relationship between the pro duction process and the equipment involved in them and supports the sustainable redesign of production processes. The case study allows the integration of an equipment supplier to redesign the sterilization pro cess through the reuse of emissions between equipment, the integration of equipment suppliers to the circular economy resource efficiency. In its application, it was found out that the proposed methodology could be implemented in the redesign of any industrial process in which in dustrial equipment is involved.

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APPENDIX B - IMPROVEMENT PROPOSAL SHEET

matachana

Improvement Proposal Sheet

Employee(s): ____________________________________

Employee number(s) ______________________________

Date: _____/_____/_____ Area:_____________________

What is your idea?

Action plan:_____________________________________

____

Implementation date: _____/_____/_____

Supervisor's signature: _______________

No. 00025

Benefits

- ☐ Reduction electrical consumption
- ☐ Reduction gas consumption
- ☐ Reduction water consumptiona
- ☐ Reduction of waste

Impact of the improvement: ________________________

____

Cost ($): _______________________________________

APPENDIX C - CDEI-UPC INTERNATIONALIZATION PROCESS TO MEXICO

As part of the internationalization process initiated in 2012 by the CDEI-UPC, the author was responsible for the internationalization process to Mexico by organizing visits of different research centers and universities in the cities of Mexicali and Queretaro. As a result, the 1st Journey of Industrial Innovation in Mexicali was realized and a research agreement between CETYS and UPC was signed in Barcelona, Spain.

Mexicali, Baja California

CETYS University

Technological Institute of Mexicali

CENEER UABC

CANACINTRA

Queretaro, Qro.

CIDESI

CONCYTEC

CDEI Centre de Disseny d'Equips Industrials
UNIVERSITAT POLITÈCNICA DE CATALUNYA

Barcelona, Spain

CETYS - UPC Agreement

APPENDIX D - ISO 50001:2011 EMS IMPLEMENTATION

As part of a doctoral stay, the author was responsible for the implementation of an energy management system based on ISO 50001:2011 standard in the Matachana Company, Castelldefels, Spain. The following was the general schedule of the activities carried out during the implementation.

Energy Policy	Energy Planning	Monitoring / Measurement / Analysis	Implementation / Operation	Certification
-Process analysis; -Identification and evaluation of energy aspects; -Definition of the Energy Policy; -Legal and other requirements.	-Energy base line; -Indicators of energy efficiency (IDE's); -Objectives, goals and action plans to policy of the organization of energy.	- Implement energy management plans. -Resources, functions, responsibility and authority; -Competence, training and awareness; -Communication; -Control of documents; -Organizational control.	-Follow-up and measurement; -Evaluation of compliance; -No conformity, corrective and preventive action; -Control of records; -SGE Audit.	 -Phase 1 @09.09.2014 -Phase 2 @ 01-02.10.2014

September - December 2013 → **January - October 2014**

TÜVRheinland®

APPENDIX E - SURVEY C

1. ¿What equipment manufactures the company?

2. ¿What certifications has the company?

- ☐ ISO 9001:2008 (Quality Management System)
- ☐ ISO 14001:2004 (Environmental Management System)
- ☐ OHSAS 18001:2007 (Occupational Health and Safety)
- ☐ ISO 50001:2011 (Energy Management System)
- ☐ ISO 14006:2011 (Eco-design)
- ☐ Other (specify)

3. ¿The innovation of the equipment manufactured by the company has been encouraged?

☐ Yes ☐ No

4. ¿In which aspects the equipment manufactured by the company has been innovated?

- ☐ Cost reduction
- ☐ Security enhancements
- ☐ Ergonomics
- ☐ Reduction of environmental consumptions (water, energy, etc.)
- ☐ Other (specify)

5. ¿Has the company carried out collaborative projects with customers?

☐ Yes ☐ No

6. ¿What type of projects have been carried out?

- ☐ Product oriented
- ☐ Process oriented
- ☐ System oriented
- ☐ Other (specify)

7. ¿ What has been your experience in collaborations in with customers?

☐ Very good ☐ Good ☐ Regular ☐ Poor

8. ¿The projects carried out were supported by a grant or awarded a prize?

☐ Yes ☐ No

9. Have you, in the position of customer, carried out collaborative projects with equipment suppliers?

☐ Yes ☐ No

10. Returning to the case of collaboration with customers, how was the project organized?

- Face-to-face follow-up meetings
- Virtual follow-up meetings
- Other (specify)

11. ¿Who coordinated the project?

- The customer
- An external agent
- Other (specify)

12. On the customer side, were qualified resources and roles for project development established in advance?

 Yes No

13. ¿What position had the contact on the customer's side?

14. ¿What was the duration of the last project you remember?

15. ¿What was the level of autonomy that the company had in the decisions related to the project with the customer?

 High Medium Low

16. ¿Specific confidentiality contracts were formalized with the customer?

 Yes No

17. ¿What type of reports were submitted to assess project performance?

- Progress report
- Final report
- Other (specify)

18. ¿How often these reports were sent?

- On a regular basis (after each review)
- Exceptionally (derived from something not contemplated)
- Other (specify)

19. ¿ How detailed were the objectives of the project?

- Stage objectives
- Final objective
- Other (specify)

20. ¿What was the degree of detail of the project schedule?

- Per day
- Per week

- Per month
- Other (specify)

21. ¿How often the project schedule was reviewed?

- At every meeting
- At every end of stage
- Not reviewed

22. ¿How the work was formalized during the project?

- With working procedures
- With work instructions
- Control change documents
- Other (specify)

23. ¿What information the customer sent?

- Product Technical Specification
- Process Technical Specification
- Business strategy
- Context of the product or process
- Financial information
- Verification Information
- Other (specify)

24. ¿Was a single contact person designated by the client to send the project information?

- Yes
- No

25. ¿Are you satisfied with project performance?

- Very satisfied
- Satisfied
- Unsatisfied

26. ¿What was the degree of the customer's contribution to the company's strategic knowledge?

- High
- Medium
- Low

27. ¿There was some kind of extra reward from the customer linked to the performance of the project?

- Purchase contract
- Share patent
- Royalties
- Long-term strategic alliance
- Other (specify)

28. ¿ How you would describe the relationship between the overall project performance with the customer and the overall performance of the company's projects?

 Major Equal Minor

29. ¿What was the level of trust you have with the customer?

 High Medium Low

30. ¿What was the company's degree of commitment to the project??

 Very committed Committed Not committed

31. ¿At what level do you value the knowledge shared during the project with the customer?

 High Medium Low

32. ¿At what level do you think the client values the knowledge shared during the project with the company?

 High Medium Low

33. ¿To whom was the outcome of the project communicated?

- Internally
- Other clients
- Suppliers
- Government
- Other (specify)

34. ¿Receive the company external environmental requirements?

 Yes No

35. ¿From whom does the company receive these requirements?

- Customers
- Suppliers
- Government
- Other (specify)

36. ¿What type are these requirements?

- Product
- Process
- System
- Service

37. ¿What you would change to improve customer collaborations?

- Improve the common technical language
- Compatibility of CAD systems

- Improve control of specification changes
- Increase meetings
- Information in the same language
- Present the holistic vision of the project
- Other (specify)

38. ¿How you would change the information in order to improve customer collaborations?

- A single contact person
- Reduce the amount of unneeded information
- Complete information from the start of the project
- Updating information on time
- Other (specify)

39. ¿What would change if you were to collaborate again on a project with a customer?

APPENDIX F - CURRICULUM VITAE

Gregorio Ridaura Aldana

Industrial Engineer - MBA

PERSONAL INFORMATION

Address	Warstraße 7a, 30167 Hannover, Germany	Telephone	+4915115559195
E-mail	ridaura@cdei.upc.edu	Date of birth	09/17/1979, Mexico City

PROFESSIONAL EXPERIENCES

04 – 07/2018	**International Doctoral Stay in Sustainability** IFW-LUH Institute of Production Engineering and Machine Tools, Hannover, Germany. Implementation of the Circular Economy reuse emissions closed loops in the production of diamond grinding wheels.
03/2013 – 07/2015	**Internship as PhD Student in Sustainability** Matachana, Castelldefels, Spain. Development of case study doctoral thesis "Process-equipment model innovation in a sustainable context"; Implementation and certification (TÜV) of an Energy Management System based in the norm ISO 50001:2011.
02/2013 – present	**Professor of Design for Energy Efficiency** Mechanical Engineering and Industrial Equipment Master's degree, School of Professional & Executive Development, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain.
01/2012 – present	**Sustainability PhD Candidate** CDEI Center of Industrial Equipment Design – Sustainability Institute, UPC, Barcelona, Spain. Development of doctoral thesis "Process-equipment model innovation in a sustainability context"; Responsible for the internationalization process of the CDEI-UPC to Mexico; Coordinator of professional courses. **Achievements:** Research agreement signature UPC-Cetys Universidad.
11/2006 – 10/2011	**Quality System & Services Leader** Honeywell Turbo Technologies, Mexicali, Mexico. Internal and external ISO/TS 16949 audits; Management review coordinator; Corrective actions leader, Supervisor of metrology, document control, MRB, RTV, quality inspection and incoming inspection areas. **Achievements:** 2 external ISO/TS 16949 recertifications; Implementation of the corporate system of corrective actions (eCATS) at Mexicali site level (Turbocharger, heat exchangers and spark plugs plants); Implementation of the digitization project of quality records.
10/2004 – 11/2006	**General Production Supervisor** Honeywell Turbo Technologies, Mexicali, Mexico. Manufacture of Turbocharger assembly, turbine and compressor wheels machining (production numbers, quality PPMs, staff turnover, O.E.E, HS&E indicators for 2 shifts, 180 employees). **Achievements:** Honeywell Operating System (HOS) implementation in production area.
02/2004 – 09/2004	**Six Sigma Engineer** LG Electronics, Mexicali, Mexico. Instructor of the innovation school; Responsible for the six sigma groups and the continuous improvement ideas program. **Achievements:** Implementation of corporate training Innovation School (6 generations, 75 employees between managers, engineers, technicians).
07/2003 – 02/2004	**Quality Engineer** LG Electronics, Mexicali, Mexico. Suppler quality process and system audits, corrective actions follow up, first parts implementation (pre-production, trial-runs, MVTs, CETs plans) for DELL products; ISO 14001:2004 internal auditor. **Achievements:** DELL certification for the production of computer monitors.
01 – 06/2003	**Production Supervisor** Fetasa Industrial, Mexicali, Mexico. Manufacture of Fetapanel (production numbers, quality, staff turnover, HS&E indicators for 1 shift, 8 employees).
06 – 11/2002	**Internship as Manufacturing Engineer** Chromalloy, Mexicali, Mexico. Process engineering, process flow diagrams, inspection checklists, work instructions. **Achievements:** Implementation of a remanufacturing process for blade CFM56-5C.

EDUCATION

01/2012 – today	**PhD in Sustainability,** Sustainability Institute, UPC, Barcelona, Spain.
03 – 07/2013	**Master-Module: Design of Plastic and Elastomer Components in Industrial Equipment,** Mechanical Engineering and Industrial Equipment Master's degree, School of Professional & Executive Development, UPC, Barcelona, Spain.
01/2005 – 12/2008	**Master of Business Administration (MBA),** CETYS Universidad, Mexicali, Mexico Specialty: Top Management.
08/1998 – 12/2002	**Industrial Engineer,** Instituto Tecnológico de Mexicali, Mexicali, Mexico. Specialty: Manufacturing Topics.

SEMINARS AND CONFERENCES

02/25–03/01/2019	**The TEACHENER Social Sciences and Humanities Winter School,** Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany.
11/01 – 05/2015	**Global Cleaner Production and Sustainable Consumption,** Sitges, Spain. **Title:** Equipment Supplier Integration in Sustainable Processes and Services Redesign (poster presentation); **Title:** IES Industrial Equipment Symbiosis, The Future of Sustainable Industrial Equipment Design (oral presentation).
06/17–28/2013	**6th International Seminar on Sustainable Technology Development,** UPC, Vilanova i la Geltru, Spain. **Title:** Vision of the Renewable Energy and Community Participation in Catalonia (poster presentation).
07/25 – 27/2012	**Sustainability Analysis Tools for Energy Systems,** Universitat Jaume I, Castellón de la Plana, Spain.

PUBLICATIONS

10/27/2018	**A Conceptual Tool for the Implementation of the Circular Economy Emissions Reuse Closed Loops through Process Equipment.** Journal: Sustainability.
12/30/2017	**Equipment Suppliers Integration to the Redesign for Emissions Reuse in Industrial Processes.** Journal: Resources, Conservation & Recycling

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CERTIFICATIONS

10/2012	**IRCA ISO 50001:2011 Energy Management Systems Lead Auditor,** SGS, Barcelona, Spain
06/2011	**Formel Q Quality Capacity Process Auditor,** Volkswagen Institute, Mexicali, Mexico
02/2010	**RABQSA ISO/TS 16949:2011 Supplier Auditor Certification,** Plexus, Mexico City, Mexico
05/2008	**6 Sigma Green Belt,** Honeywell Turbotechnologies, Mexicali, Mexico
02/2007	**RABQSA ISO/TS 16949:2002 Supplier Auditor Certification,** Plexus, Monterrey, Mexico
07/2004	**6 Sigma Green Belt,** LG Electronics, Mexicali, Mexico
05/2004	**Lean Innovation School Leader,** LG Electronics, Kumy City, South Korea

CURSES

SPC Advanced, 6 sigma introduction, DELL Business process improvement, Document control, Internal auditor ISO 14001, APQP-PPAP-FMEA-Global-8D-FORD Specific requirements, GD&T, Economic development, VDA6.5 Product audit fundaments-Formel Q Management quality agreements, ISO/TS 16949:2009 Norm interpretation, Training to trainer.

METHODOLOGIES

Gage R&R, 7 Quality tools, OEE, F.M.E.A., D.O.E., 5S, Kanban, Pokayoke, Kaizen ideas, SMED, VSM, 7 Waste, VM, SW, 6 Whys, Andon, LCA.

LANGUAGES AND COMPUTER KNOWLEDGE

Spanish (Mother tongue), English (TOEFL: 624 points), Catalan (A2.2 level), German (B2 level)
Microsoft Office, Minitab, SAP R3.

Gregorio Ridaura Aldana

Barcelona, Spain, 16.01.2019