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

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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.

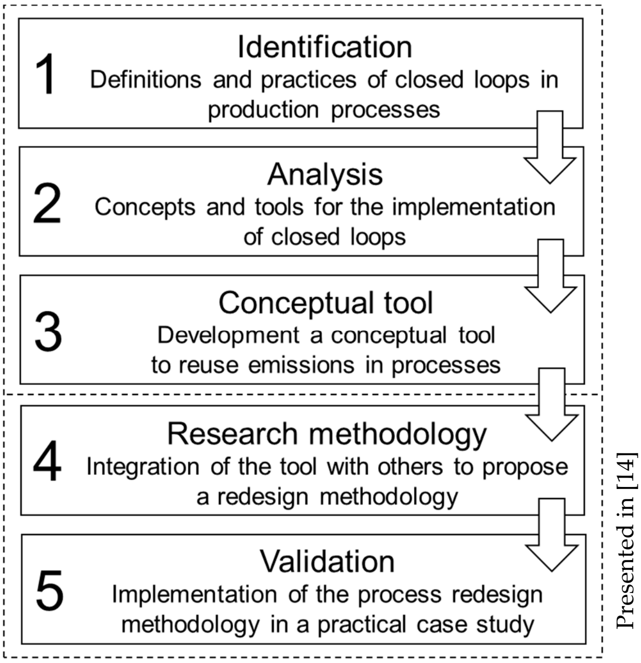

Figure 1. Long-term research stages.

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.

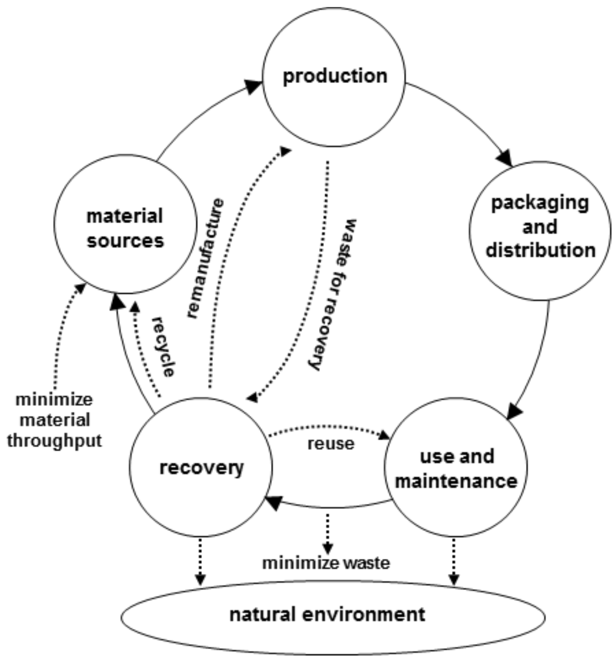

Figure 2. Closed loop production system. Modified from [18].

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.

		Equipment Life Cycle Phase	Relations between Equipment
	Origination	Concept study Design and development Manufacturing	*Equipment Family*: Equipment of a company that share elements in their origination
	Destination	Use and maintenance End of life	*Equipment Portfolio*: Equipment of the market (or of a company) that share elements in their destination
Origination	Destination	Vision from an activity (beyond a manufacturing company)	*Equipment Gamma*: Equipment of the market that share elements in their origin, and destination (eventually recycling)

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.

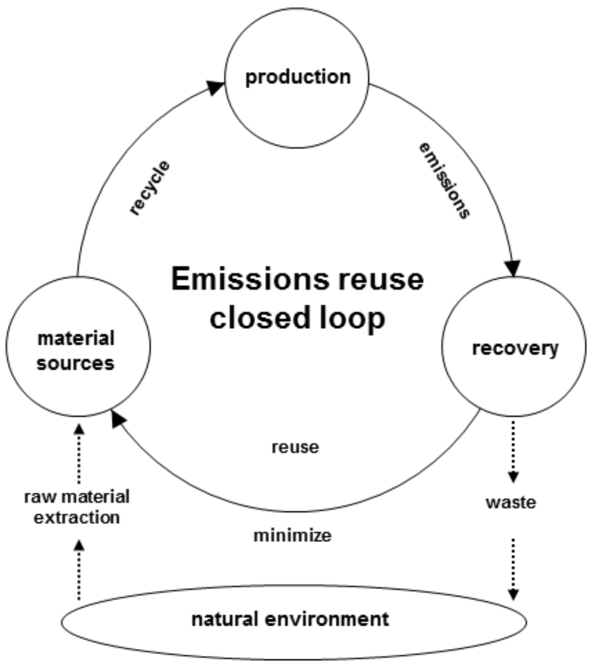

Figure 3. Proposed model of emissions reuse closed loop in production processes. Modified from [18].

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.

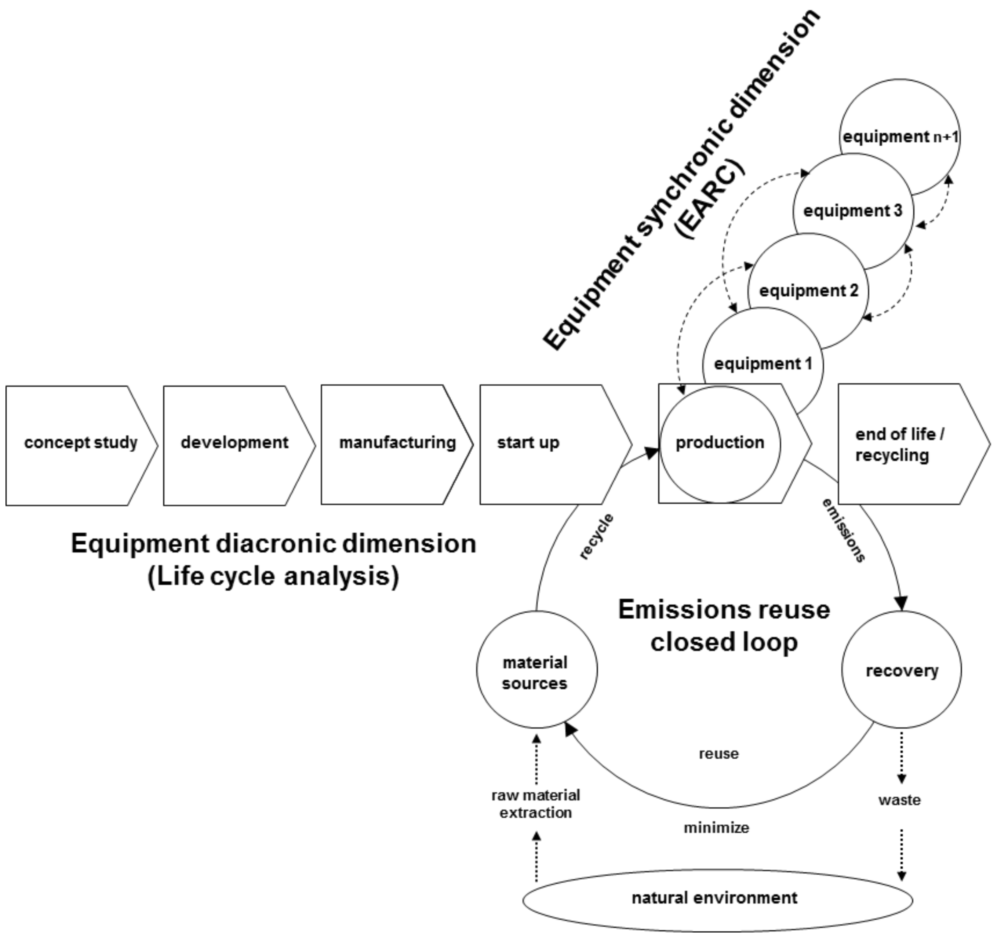

Figure 4. Proposed model of Circular Economy (CE) emissions reuse closed loop in production process.

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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