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

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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.

Keywords: Redesign of processes; IDE0, LCA; MFCA; ARC; Emissions reuse.

1. INTRODUCTION

For manufacturing companies involved in an increasingly sustainable 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. It 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

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The equipment involved in them. Thus, it is essential that the process redesign considers simultaneously all of the equipment that operate in a production process 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 fundamental 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 analysis 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 equipment. Likewise, a transversal vision of the life cycle assessment (LCA) and the coexistence relationships analysis (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 application 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 methodology 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 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, 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 important 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). Elzinga (1995) and Zairi (1997) defined *Business Process Management (BPM)* as 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, presents *The Value Stream Mapping (VSM)* 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 complement the terminology proposed during the GAMMA project, Llorens, 2015 structured a design methodology called *Family, Catalog, Gamma and 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 eliminate 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. Department of Comerce, 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 manufacturing company.

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 star the case study were collected, started in December 2014 and ended in April 2015. During the six month 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; 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 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 appropiate 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, calculate 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 decide 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, Llores (2015) concludes that an equipment interacts in the production process in which it operates and also interacts with the other equipment. In this interaction relationship 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 coexistence relationships (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's involved in the project, because previously he was supplier engineer and product engineer in the company. It was mentioned that this person will be the only responsible to send the information about the project to the equipment's suppliers, for this reason, a documented procedure is 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. Figure 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.

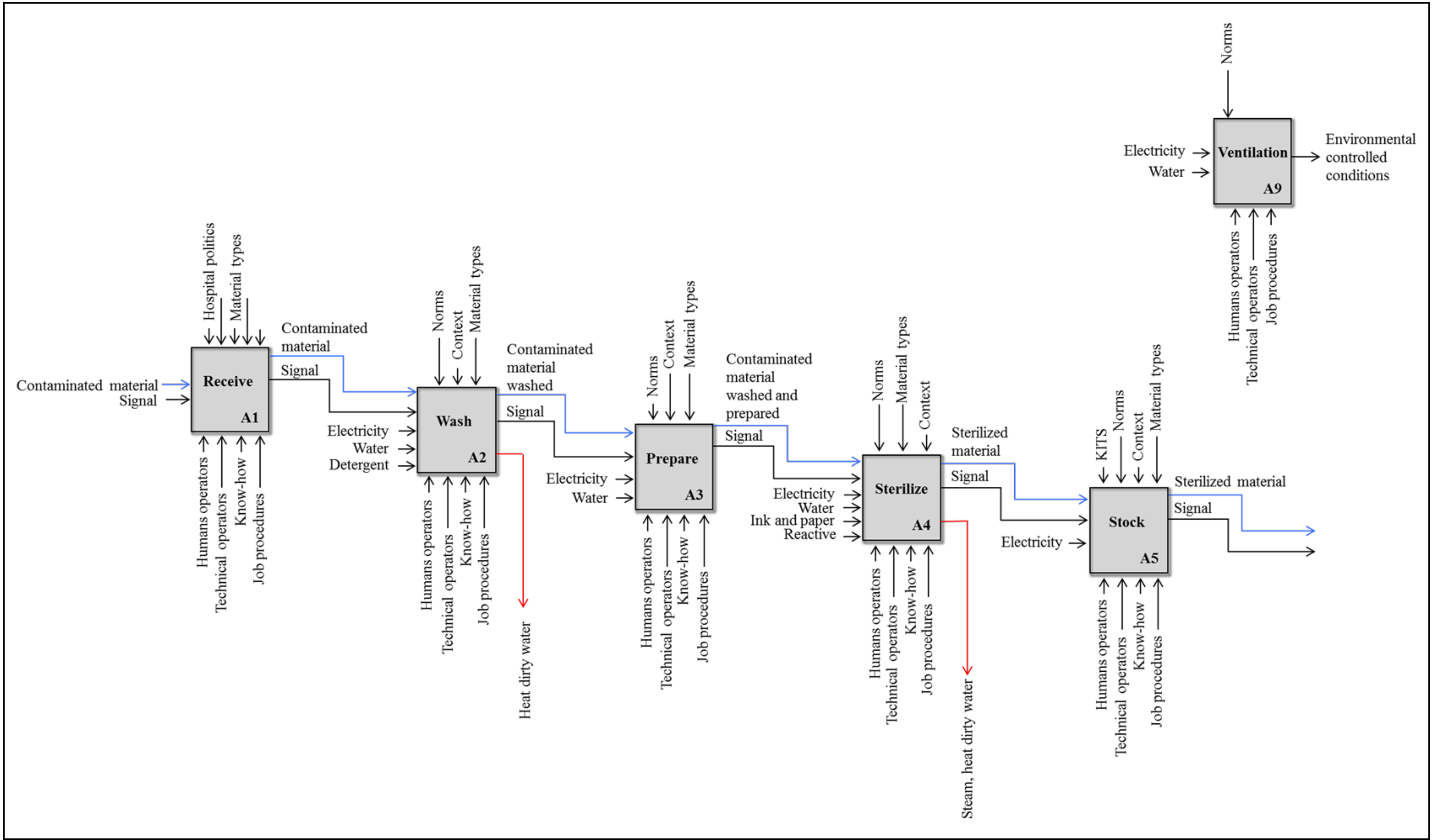

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Figure 1: IDEF0 Sterilization process.

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.

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 machin
Prepare	Packaging machine
Sterilization	High temperature sterilizer

Controls

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

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

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).

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	*kWh*	0.76%		Intermittent	
		Monitor	1	Calculated	Electricity	0.05	*kWh*	0.11%		Intermittent	
		Scanner	1	Calculated	Electricity	0.003325	*kWh*	0.01%		Intermittent	
		Labeller	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		
Specifics	Wash	Washing Machine	1	Measured	Water	80	*l*	13.94%	Vat	3155	
				Measured	Electricity	13	*kWh*	28.26%	Motor		
		Ultrasonic Washing Machine	1	Calculated	Water	10	*l*	1.74%	Vat	Intermittent	
				Calculated	Electricity	0.6	*kWh*	1.30%	Motor		
	Prepare	Labeller	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	
				Measured	Electricity	17	*kWh*	36.96%	Steam Generator		

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 criteria, 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.

Step 3: Process use cycle cost

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

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 €	189, 300 kWh	33165.36 €	39769.91 €
		16.61 %		83.39 %	100.00 %

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 kWh 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 $C0_2$eq

$$Carbon\ footprint = Usage\ (kWh) \cdot CO_{2\ emission\ factor} \tag{1}$$

$$Carbon\ footprint = Usage\ (kWh) \cdot \frac{kg\ CO_2}{kWh} \tag{2}$$

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

$$Carbon\ footprint = 58,304.4\ \text{kg}$$ C02eq

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) (Figure 2).

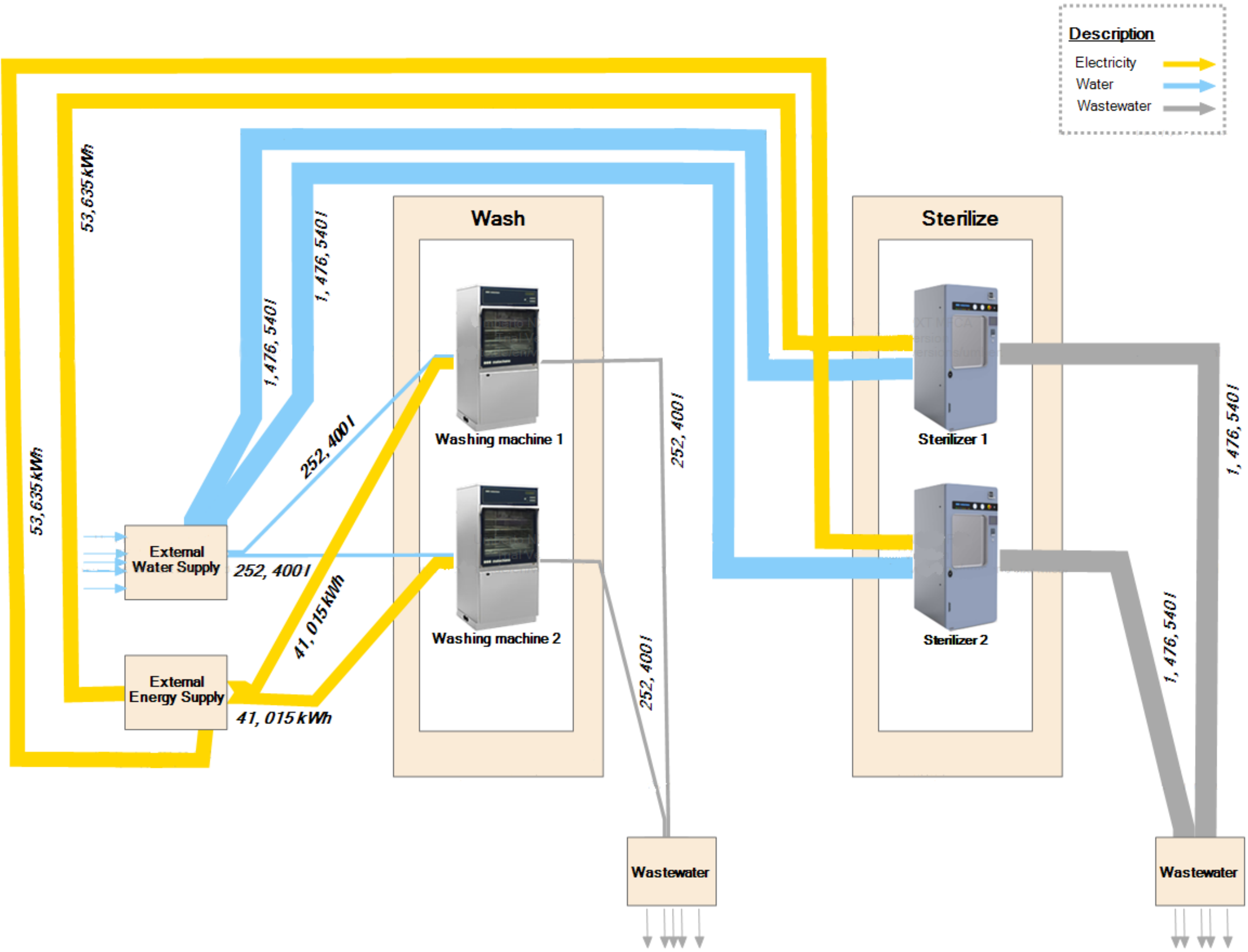

Figure 2: Sankey diagram water and electricity of the sterilization process.

Step 4: Emissions reuse

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

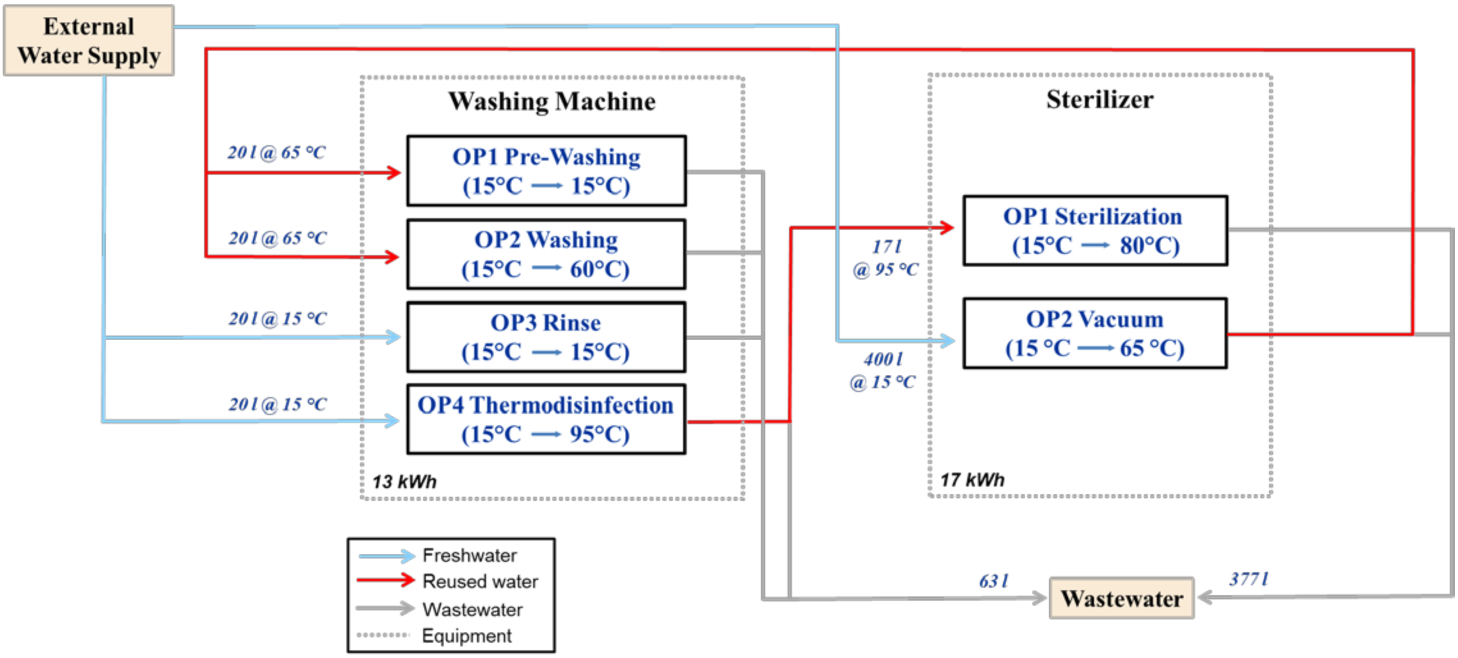

Figure 3: Analysis of the relations of coexistence (ARC) of the sterilization process.

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.

Figure 4 and, Figure 5, Equations 3, 4, 5 show the performed calculations.

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

Figure 4: Sterilizer → Washing machine water emissions reuse

Water improve:

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

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

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

Energy improve:

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

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

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

$$\Delta Q_{S \to Wm} = (40\ kg) \cdot (1 \frac{kcal}{kg \cdot {}^{\circ}C}) \cdot (65\ {}^{\circ}C - (\frac{30^{\circ}C}{2}))$$

$$\Delta Q_{S \to Wm} = (40\ kg) \cdot (1 \frac{kcal}{kg \cdot {}^{\circ}C}) \cdot (65\ {}^{\circ}C - 15^{\circ}C)$$

$$\Delta Q_{S \to Wm} = (40\ kg) \cdot (1 \frac{kcal}{kg \cdot {}^{\circ}C}) \cdot (50\ {}^{\circ}C)$$

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

$$\Delta \boldsymbol{Q}_{S\rightarrow Wm} = \mathbf{2.33}\ \boldsymbol{kWh}$$

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.

Figure 5 and Equations 6, 7, 8 show the performed calculations:

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

Figure 5: Sterilizer → Washing machine water emissions reuse

Water improve:

$$\Delta S = Q_i - Q_0 \qquad (6)$$

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

$$\Delta \boldsymbol{S}_{\boldsymbol{Wm\rightarrow S}} = \mathbf{17}\ \boldsymbol{l}$$

Energy improve:

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

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

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

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

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

$$\Delta Q_{Wm \to S} = 1360\,kcal \cdot 0.001163\,kWh$$

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

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

Total improve per cycle:

$$\textbf{\textit{Energy}} = \boldsymbol{\Delta Q_{S \to Wm} + \Delta Q_{Wm \to S}} \qquad (9)$$

$$\textbf{\textit{Energy}} = \boldsymbol{2.33kWh + 1.58kWh}$$

$$\textbf{\textit{Energy}} = \boldsymbol{3.91\,kWh}\ \textbf{\textit{per cycle}}$$

$$\textbf{\textit{Water}} = \boldsymbol{\Delta S_{S \to Wm} + (\Delta S_{Wm \to S} + inverse\ osmosis\ rejection\ 3{:}1)} \qquad (10)$$

$$\textbf{\textit{Water}} = \boldsymbol{40\,l + (17\,l + (17\,l \cdot 3\,l))}$$

$$\textbf{\textit{Water}} = \boldsymbol{40\,l + (17\,l + 51\,l)}$$

$$\textbf{\textit{Water}} = \boldsymbol{40\,l + 68\,l}$$

$$\textbf{\textit{Water}} = \boldsymbol{108\,l}\ \textbf{\textit{per cycle}}$$

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 €	164, 628 *kWh*	28842.82 €	34145.76 €
		15.53 %		84.47 %	100.00 %

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.

The electricity consumed represents is represents a generation of 50, 705.4 kg $C0_2eq$. Equations 1 and 2 were used for calculations.

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

$Carbon\ footprint = 50,705.4\ \text{kg}$ $C0_2eq$

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.

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

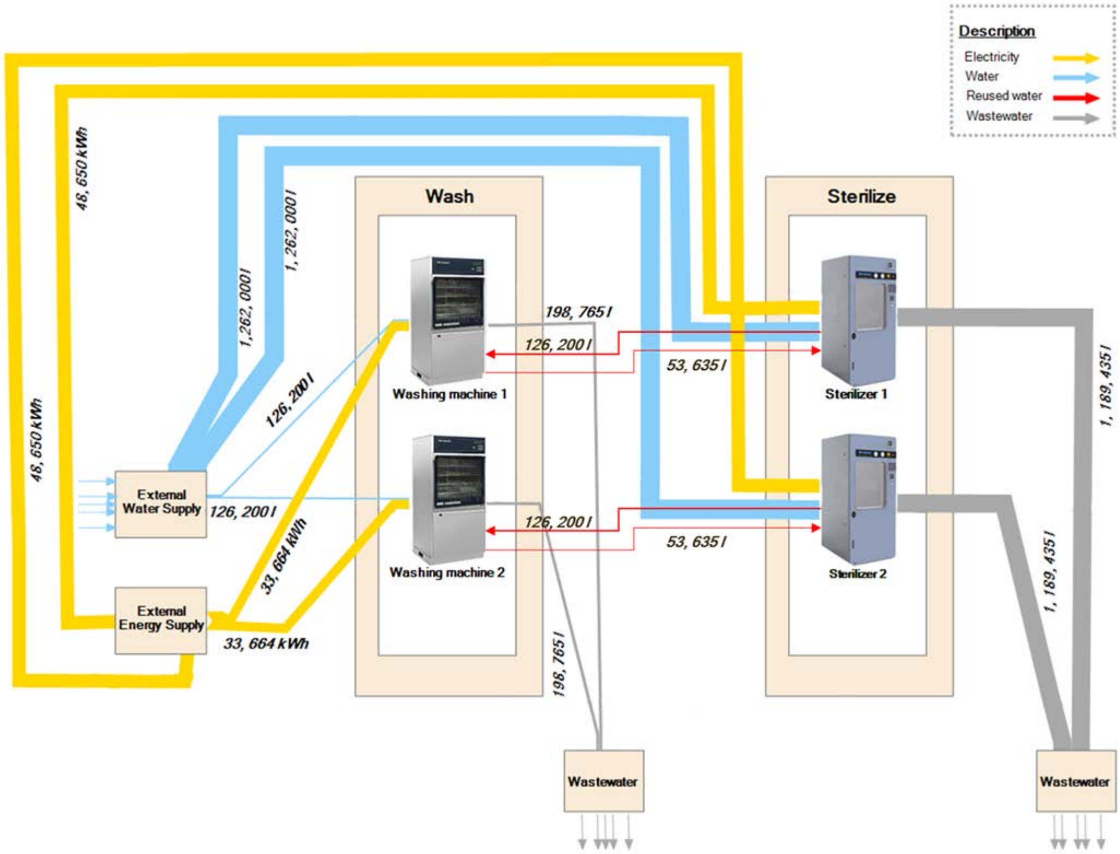

Figure 6: Sankey diagram sterilization process closed loop model.

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 kgCO_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 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 consumption 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 a ARC it is essential the use of a common sense and a systematic thinking with the purpose of reusing the emissions 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 between the production process and the equipment involved in them not only of design stage, but also 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 essentials 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 production 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 processes 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 performance 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 methodology, 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 production 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 process through the reuse of emissions between equipment's, 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 that industrial equipment is involved.

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NOMENCLATURE

$\Delta Q =$ *Temperature change (˚C)*

$m =$ *Mass (kg)*

$c =$ *Specific heat constant* $(\frac{kcal}{kg \cdot {}^\circ C})$

$Tf =$ *Final temperature (˚C)*

$Ti =$ *Initial temperature (˚C)*

$S =$ *Sterilizer*

$Wm =$ *Wash machine*

$\Delta S =$ *Stored water volume change (l)*

$Q_i =$ *Total volume of inputs (l)*

$Q_0 =$ *Total measure volume of outputs (l)*

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