

Models of Impact for Sustainable Manufacturing

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Abstract. Design for Sustainability (D4S) and LifeCycle Assessment (LCA) methods usually focus on one single aspect of sustainability at a time (e.g., environmental issues, ergonomics or costs) and are usually applied when the industrial system is already created, so that only corrective actions can be taken. In this context, the present research highlights the need of predictive methods to design sustainable system, able to provide an early holistic assessment from the early conceptual stages, and defines a set of models of impact able to assess all aspects of sustainability (i.e., environmental, economic and social) by proper key performance indicators (KPIs) from the early design stages. An industrial case study is presented to show the application of the proposed models on industrial manufacturing systems and demonstrate their validity in estimating the global impact on sustainability, including also human factors.

Keywords. Design for Sustainability, Design Methods, Sustainable Manufacturing, Human Factors, Lifecycle analysis, Key Performance Indicators (KPIs).

Introduction

In numerous countries the actual economical growth is triggering environmental and social problems, pushing companies to adopt Design for Sustainability approaches (D4S). However, according to modern Sustainability Assessment (SA) practices, companies are called to optimize the use of any kind of resources and consider the mutual impacts of their choices on three dimensions: profit, planet, and people [1]. However, application of SA in industry is mainly based on ex-post analyses to monitor the existing conditions on the basis of Life Cycle Assessment (LCA) or Discrete Event Simulation (DES) [2]. As a consequence, actions are usually taken after the design stage, when products and/or processes are already developed [3-4]. In this context, the paper presents a set of key performance indicators (KPIs) and models of impact for early SA to be applied from the early conceptual stages, according to an analytic estimation approach. Indeed, industrial systems are particularly challenging due to the numerous aspects integrated into a single product and the transdisciplinary nature of problems. The goal is providing a quick and easy methodology to support designers in early SA of their products and systems in order to easily identify optimization actions to make the products more sustainable. The main paper contribution is the definition of structured models and KPIs to carry out a transdisciplinary SA, merging economical, environmental and human aspects, from the initial design stages in order to prevent low sustainable solutions by their timely optimization. The main challenge is to carry out

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such analysis from the early stages of product development, where systems are not already created so few information are usually available. Up to now, the models have been defined for manufacturing and production stages, but the same approach could be extended also to the other product lifecycle stages (i.e., use, end of life).

1. Research background

A broad range of different approaches is described in literature about SA. Based on evidences from real world, companies are pushed towards Sustainable Manufacturing (SM), based on the balance among environmental, economic, and social objectives [5]. Nevertheless numerous examples demonstrated how the adoption of sustainability principles can gain competitive advantages for companies [6], concrete benefits can be achieved only when the SA is introduced during the preliminary design stages, before product creation, optimizing the solutions in short time, and avoiding numerous engineering changes and optimization loops [7]. One of the most common approaches to SA is Life Cycle Design (LCD), which considers the entire lifecycle 'from cradle to grave' and the related impacts at each phase, from resources extraction through pre-manufacturing, manufacturing, transportation, use, recycling, and ultimately, disposal. Usually LCD includes the definition of key indicators to assess performances (e.g., functionality, manufacturability, serviceability, environmental impact) [8]. Different methods have been developed for these purposes: Life Cycle Assessment (LCA), that sums the environmental impacts generated during all phases of product lifecycle [9-10]; Life Cycle Cost Analysis (LCCA), that associates total cost to all lifecycle activities [11]; Social Life Cycle Assessment (sLCA) addressing the social dimension [12]. Some researches have coupled LCA, LCCA and sLCA analyses in different industrial sectors [13-15] and faced different aspect, such as lifecycle cost or human-related aspects [16]. In this context, several studies demonstrated the importance of adopting a holistic approach including the three areas of sustainability (i.e., plant, profit and people) in order to increase product quality, customers' satisfaction, and global competitiveness in order to increase the market shares [17]. However, a literary review about SA in industry, especially in manufacturing, highlighted the lack of robust frameworks for early assessment to be applied from the preliminary design stages. Considering the publications on international journals during the last ten years on Scopus databases, we found that the majority of research works refer to environmental-related aspects, and a good number refer to cost assessment. Only few works deals with social and human-related aspects. Four main methods for SA have been also compared: Environmental Impact Assessment (EIA), Human Development Index (HDI), Environmental Footprint (EF), and Life Cycle Assessment (LCA) [18]. A framework for the integration of different SA methodologies has been recently proposed [18]: it considers Multi-Criteria Analysis (MCA), Cost Benefit Analysis (CBA), EIS, Strategic Environmental Assessment (SEA), LCA, LCC, sLCA, European Social Impact Assessment (EuSIA) and Life Cycle Sustainability Assessment (LCSA).

Furthermore, numerous indicators have been defined during the years about SA of industrial products. A comprehensive overview has been recently provided by [19]. Few studies considered contemporarily the three areas of sustainability, but proposing a late assessment on existing plants and projects. Only Morbidoni et al. [20] proposed an early SA, but analysis is limited to costs. About social aspects, an interesting study [16] estimated the impact by considering injured worker's rehab, replacement of the

operator with a new employee, and know-how dispersion in case of replacements. About physical stress analysis, the most common methods are REBA, RULA, NIOSH for the static tasks, OCRA and OWAS for the repetitive tasks. In most cases Discrete Event Simulation (DES) is used to segment the activities performed into sub-activities whose harmful level can be easily inferred. However, such methods generally require high level of detail and real process monitoring, which exclude their application to preliminary design stages and make it difficult and time-consuming for industry. From the literary review, two main issues in early SA have been identified:

- lack of practical guidelines to merge environmental assessment with cost and human-related issues assessment;
- lack of practice method to anticipate the assessment to the preliminary design stages, since impacts are usually evaluated “ex-post” on real plants or systems, once they have been already created and usually are currently working.

2. The research approach for sustainable manufacturing

The study proposes an analytic approach for the early SA of industrial products and systems based on a set of KPIs and a feature-based approach to fasten the assessment and make it suitable for industry. Indeed, it is based of the analysis of 3D product models features and their association to manufacturing and assembly processes, necessary to realize that shapes, in order to fasten and automatize the SA and make it possible also from the preliminary design stages. The approach combines three analyses: Early Environmental Assessment (EEA), Early Human Assessment (EHA) and Early Cost Assessment (ECA). For each of them a different set of KPIs is defined, and a set of models of impact for the KPIs measurement.

In particular, the early assessment is based on the recognition of the manufacturing processes started from the analysis of the product features. It is based on a quantitative estimating technique and, in particular, adopts the feature-based analytic approach as proposed by [21]. Such an approach allows to link geometric and non-geometric features to technological and assembly features in order to predict the following manufacturing process. Recognition is based on the decomposition into basic features and the correlation between geometrical features and process features. Thanks to this association, the product design can be analyzed and related processes can be inferred according to a set of pre-defined list of sub-processes. This association is possible thanks to a proper formalization of the process knowledge and the merge between geometrical data and logical information (i.e. design requirements, system configuration, technical specification, plant features, company best practices, etc.). Such an approach can be adopted manually or, more conveniently, automatically by a proposer software toolkit. Finally, processes are matched with machines’ tasks, operators’ actions, etc. thanks to a set of scenarios (respectively for manufacturing, use and end-of-life phase) that represent how the entire value chain (made up of the company, suppliers and customers) will behave. Assessments are based of a set of “models of impacts” that relate the process parameters (as estimated) and the selected KPIs. For each sustainability area, a set of KPIs is defined. A set of models of impacts is defined on the basis of process parameters, as described in the following section, which values usually vary from company to company, and from sector to sector. Also this step can be executed with excel-based tools or more advanced ICT toolkit.

2.1. KPIs for sustainability assessment

For each early assessment (i.e., EEA, EHA and ECA) described in the previous section, a set of KPIs and models of impacts for their calculation is defined. Table 1 shows the selected indicators (KPIs) for each assessment, how to measure them, and the main involved parameters. Specific models of impacts combining the identified parameters are then used to evaluate the KPIs.

About EEA, selected KPIs are Energy consumption (E) and Environmental impacts vector (V), that consider the impact as done by LCA applications, but having an estimation in the early design stage for a preventive assessment. Indeed, by a proper knowledge management about workstations, operators and logistics conditions, a set of pre-defined scenarios can be defined and used for an early assessment. About EHA, KPIs refer to the assessment of the quality of human actions by predicting postures, conditions and durations. In particular, a dedicated assessment method is applied based on: 1) Static Risk Score (SRS) to get a risk factor by summing the Rapid Upper Limb Assessment (RULA) impact and the Rapid Entire Body Assessment (REBA), and 2) Job Exposure Score (JES) that considers the effect of task frequency by means of OCRA checklist [22]. About ECA, KPIs consider Production Costs (C_{PROD}) and Investment Costs (C_{IN}) and exploit company knowledge about processes, machine operations characteristics, standard operators' actions, and hourly costs. Table 1 summarizes the KPIs and the parameters considered for each assessment.

In the following paragraphs the three above-mentioned assessment models are described in details. Each assessment is represented as a "logical function" where inputs, constraints, resources and output are indicated.

Table 1. KPIs for sustainability early assessment.

Assessment	KPIs	Unit of meas.	How to measure	Parameters
EEA	Energy consumption (E)	kW	$EEA = (\bar{V}_{ws} + \bar{V}_{op} + \bar{V}_l) + (\bar{E}_{ws} + \bar{E}_l)$	\bar{V}_{ws} = env. impact produced by workstations involved \bar{V}_{op} = env. impact produced by operators involved
	Environmental impact vector (V)	gr or lt	$\bar{E} = [kW]$ $\bar{V} = [CO_2eq; SO_2eq; NO_xeq; H_2O]$	\bar{V}_l = env. impact produced by logistic operations \bar{E}_{ws} = energy consumed by workstations involved \bar{E}_l = energy consumed by logistic operations
EHA	Static Risk Score (SRS)	No.	$EHA = \bar{H}_{ws} + \bar{H}_l$ $\overline{CHKP} = [FRC; REC; RIP]$	\bar{H}_{ws} = human impact on workstations \bar{H}_l = human impact during logistic operations \overline{FRC} = force exertion score
	Job Exposure Score (JES)	No.	$\bar{H} = [SRS; JES; \overline{CHKP}]$	\overline{REC} = recovery score \overline{RIP} = repetitivity score \overline{CHKP}_l = checklist score according to OCRA
ECA	Production cost (C)	euro	$ECA = \bar{C}_{ws} + \bar{C}_{rw} + \bar{C}_{op} + \bar{C}_l$ $\bar{C} = [C_{PROD}]$	\bar{C}_{ws} = cost for processes on workstations \bar{C}_{rw} = cost for raw material \bar{C}_{op} = cost for operators \bar{C}_l = cost for logistic operations

2.2. Models of impact for sustainability manufacturing

For each above-mentioned assessment the knowledge-based models of impact are described, where input and output are highlighted. In particular, the *EEA* needs as input parameters the product geometry and properties (e.g., shapes, material, mechanical properties), the electric furniture information, and the factory process knowledge. Furthermore, it needs machines' parameters and facility working-capacity as constraints and resources. The *EHA* requires information about product geometry, tools availability, product components positions and postures assumed by workers, and workers capabilities as input parameters. At the same time, the human resources characteristics (e.g., height, force, gender, nationality) are considered as constraints. The knowledge about the handling and moving actions (e.g., lifting, moving, turning, precision positioning) and supporting devices (e.g., screwdriver, electrical screwdrivers, use of trolleys) are considered and modeled properly to describe the operations carried out by workers during the process stages. About the *ECA*, information about the product geometry and properties as well as machines working cycle are considered as input data, data about human resources, energy consumption and fuel consumption for logistics operation are used as resources. The following sections described the models adopted for each assessment. The sustainability assessment presented below focuses on the production stage and do not considers the other lifecycle stages, but it could be easily extended also to other product lifecycle stages.

2.2.1. Early Environmental Assessment

Hereafter some examples of models of impact are provided. About manufacturing operations, two different machine states are defined: *online time*, when the workstation is currently in an active running mode, and *offline time*, when workstation is running but is not active on the production. For each state, a certain energy consumption rate is defined. The operative power specific consumption $P_{ON,k}$ and the power consumption $P_{act,k}$ can be assessed as indicated by Eq. (1) and Eq. (2) respectively:

$$P_{ON,k} = P_{n,k} * \frac{V_{t,k}}{V_{t,k}|_{max}} * \frac{s_k}{\eta_{mecc,k}} \quad (1)$$

$$P_{act,k} = \frac{[t_{ON,k} * P_{ON,k} + (t_{set} + t_{OFF})_{k} * P_{OFF,k}]}{60} \quad (2)$$

where $t_{ON,k}$ is the interval of time where operation is effectively performed of the k workstation or machine, and depends on the specific operation and process, $P_{ON,k}$ is the electrical power absorption (in the ON state) of the specific k workstation or machine, $t_{OFF,k}$ is the interval of time where the k workstation or machine is not working, and depends on the specific operation and process, $P_{OFF,k}$ is the electrical power absorption (in the OFF state) of the specific k workstation or machine, and η_{mecc} is the workstation mechanical efficiency. About $t_{ON,k}$ Eq. (3) indicates an example for milling process:

$$t_{ON} = \left(\frac{L+E}{VA} \cdot Np \cdot Nw \right) \quad (3)$$

where L is the depth of the operation, E is the extra-stroke, VA is the machine speed, L is the length to be processed, Np is the number of runs in deep direction (along z axis), Nw number of runs in length direction (along y axis). Finally for logistic operations assessment, a database can be created by coupling the company historical knowledge with environmental impact data (from LCA standards for instance) to estimate the emissions impact according to Eq. (4):

$$V_i = \zeta_{emis} * N_{trk} * D \quad (4)$$

where ζ_{emis} is the specific emission per kilometer, N_{trk} is the number and type of transport involved, and D is the distance to cover in kilometers.

2.2.2. Early Human Assessment

The *EHA* focuses on risk for the human beings involved in the different operations. According to RULA, REBA and OCRA Checklist assessment, the most human effort is calculated for each i action considering also the activity duration, frequency and rest phases. The model merges a static posture assessment, obtained by combining REBA and RULA analyses, with dynamic assessment based on OCRA Checklist. The Total Score (*TS*) for each activity can be calculated by Eq. (5):

$$TS_i = SRS_i + JES_i \quad (5)$$

where SRS_i is the static risk score for the i action and JES_i is the Job Exposure Score for i action that considers the effect of repetitiveness (frequency of actions). A set of pre-defined postures for workers are defined considering the most common ones: standing, seating, crunching, kneeling, tiptoed, etc. For every type of posture, effect of distances is also considered. SRS_i is assessed by a manual or an automatic application of the RULA and REBA scoring, while JES_i is defined by Eq. (6):

$$JES_i = Int[Dm_i * (SRS_i + CHKP_i) * FW_i] \quad (6)$$

where *Int* is a math operator that indicates that the nearest entire number must be taken into account, Dm_i is a *Duration multiplier coefficient* that considers the task frequency and the FW_i is the fraction of time during which the operator works on the workstation for the i action, and $CHKP_i$ is the OCRA Checklist score. FW_i is measured by Eq. (7) whereas $CHKP_i$ is measured by Eq. (8)

$$FW_i = tc_i / WS_i * 100 \quad (7)$$

$$CHKP_i = FRC_i + REC_i + REP_i \quad (8)$$

where tc_i is the cycle time for the i action, and WS_i is the total time on the specific workstation. FW_i takes into account that breaks are usually required to have an active anti-fatigue effect. In Eq. (8) FRC_i is the score for force exertion, REC_i is the score for the recovery (the major the score is the less recovery possibility is), and REP_i is the score for the number of actions per minute recorded.

2.2.3. Early Cost Assessment

ECA is carried out by estimating the final cost for the entire manufacturing process C_{PROD} , that considers the costs for manufacturing on workstations or machines (C_{ws}), the costs for raw materials (C_{rw}), the costs for human resources involved into the process (C_{op}) and the costs for logistics operations (C_l). They are determined by Eq. (9), Eq. (10) and Eq. (11) respectively.

$$C_{ws} = [\sum_{k=1}^M Q * (t_{ON} + t_{OFF} + t_{set})|_k + t_{acc}] * c_{ws} + E * c_{kwh} \quad (9)$$

$$C_{rw} = Q * c_{raw} \quad (10)$$

$$C_{op} = [\sum_{k=1}^M Q * (t_{ON} + t_{OFF} + t_{set})|_k + t_{acc}] * c_{hr} * w \quad (11)$$

$$C_l = \zeta_{cons} * c_{fuel} * N_{trk} * D \quad (12)$$

where Q is the quantity of product produced, t_{acc} is the time for the equipment, t_{set} is the time needed for the setup, c_{wS} is the hourly labour cost for machines, E is the amount of electricity spent, c_{kWh} is the cost for each kWh, c_{raw} is the cost for raw material, w is the number of workers involved, c_{hr} is the hourly labor cost for human resources, ζ_{Cons} is the fuel-consumption rate [lt/km] according to the type of truck deployed, c_{fuel} is the fuel-cost per litre, N_{trk} is the number of trucks per type involved in the transport and D is the distance covered [km].

3. Case study

3.1. Case study description

The case study was developed in collaboration with a machine builder for the packaging sector. The proposed models of impact were applied to assess the sustainability of a high-automated filling machine that processes a flat web of packaging material to create closed packages of pre-defined shapes. The desired shape is obtained by pushing the packaging material into a forming section, made up of a set of so-called “forming rings”, constituted by a sequence of tangent rollers. Usually designers create a first guess of the forming section on the basis on CAE results and their own experience. Since the machine manages liquids, both tolerances and surface roughness are very stringent and the manufacturing process is complex and difficult to assess. In the paper, the attention is paid to one of the most critical components of the system, the so-called “forming ring” (Fig.1), which has high cost and elevated human efforts for handling and assembling.

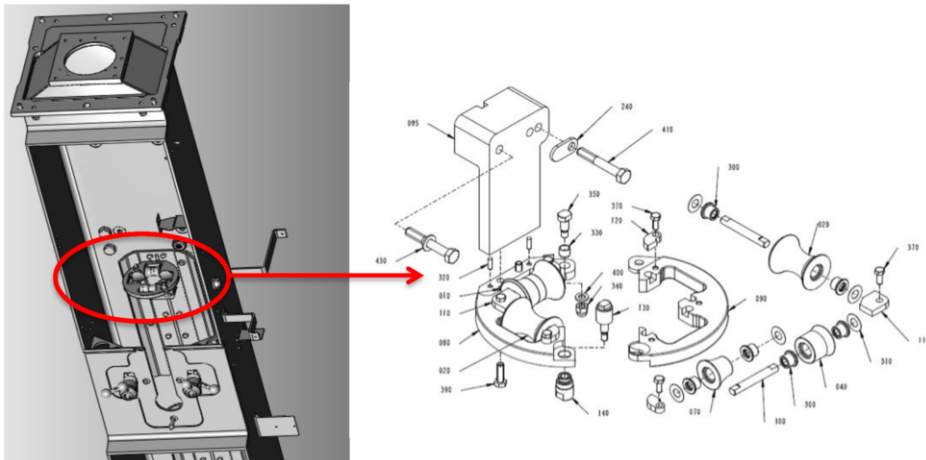


Figure 1. The forming ring (analyzed during the case study).

The models of impact were also applied to the entire machine and analyses are still in progress. Due to space limit, in the paper only results about the forming ring are reported. The main actions taken to assess the sustainability of the forming ring (hereafter “the product”) were as follows:

1. Analysis of the machines adopted in the production stage: all the machines involved in the production were analyzed by collecting the necessary parameters required by the models of impacts;

2. Early definition of the production cycle: both manufacturing, assembly and logistics operations were investigated and a production cycle estimated from the analysis of the product geometry and properties as well as the assembly requirements;
3. Application of the EEA, EHA and ECA models of impact: data necessary for the three assessments were collected and the models applied.

The results about the early definition of the production cycle and the manufacturing times, supporting the following assessment, are presented in Table 2.

Table 2. Estimated production cycle and times for the forming ring (main components).

Component code	Q	n° Op.	Workstation/Machine	t _{on}	t _{off}	t _{setup}
Xxxx1	1	1.1	Bandsaw FORTE	15	0	5
		1.2	Mazak Nexus 250-500	0,3	0	5
		1.3	GravoGraph LS 900	2,4	0	0
Xxxx2	1	2.1	Mazak Nexus 250-500	3,5	0	15
		2.2	Bandsaw FORTE	0,3	0	5
		2.3	GravoGraph LS 900	2,4	0	0
Xxxx3	2	3.1	Mazak Nexus 250-500	5	0	15
		3.2	Bandsaw FORTE	0,3	0	5
		3.3	GravoGraph LS 900	2,4	0	0
Xxxx4	1	4.1	Mazak Nexus 250-500	0,96	0	10
		4.2	Bandsaw FORTE	0,79	2,42	52,4
		4.3	GravoGraph LS 900	2,4	0	0
Xxxx5	1	5.1	Mazak Nexus HCN 6800	54	0	45
		5.2	Bandsaw FORTE	5	0	1,5
		5.3	Tumbler di Maio BVC 16	3	0	0
Xxxx6	1	6.1	Mazak Nexus HCN 6800	50	0	30
		6.2	Bandsaw FORTE	5	0	1,5
		6.3	Tumbler di Maio BVC 16	2,4	0	0
Xxxx7	1	7.1	Mazak VTC 560/25	31,15	0	120
		7.2	Bandsaw FORTE	5	0	2
		7.3	Tumbler di Maio BVC 16	2,4	0	0

3.2. Early assessment results

The early assessment is based on EEA, EHA and ECA results. In particular, for each product component, emissions for raw materials processing and energy consumption of the involved machine are collected by existing eco-databases such as GaBi software databases [23]. As far as the energy furniture, since the company and its supply chain were located in Italy, the energy supply profile was taken directly from ENEL data [24], according to which energy is entirely generated from thermo-generation. According to the proposed models, EEA, ECA and EHA were calculated for the main components as presented in Figure 2.

Such assessments allow to anticipate product criticalities into the production process and to support the machine design in order to optimize the potential problems. For instance, from the analysis of the early assessment result, it is possible to highlight the most expensive operations (i.e. code Xxxx3) that could be optimized, and the most risky activity (i.e. lifting pieces from rack) that could be improved. It supports the design optimization according to the sustainability principles.

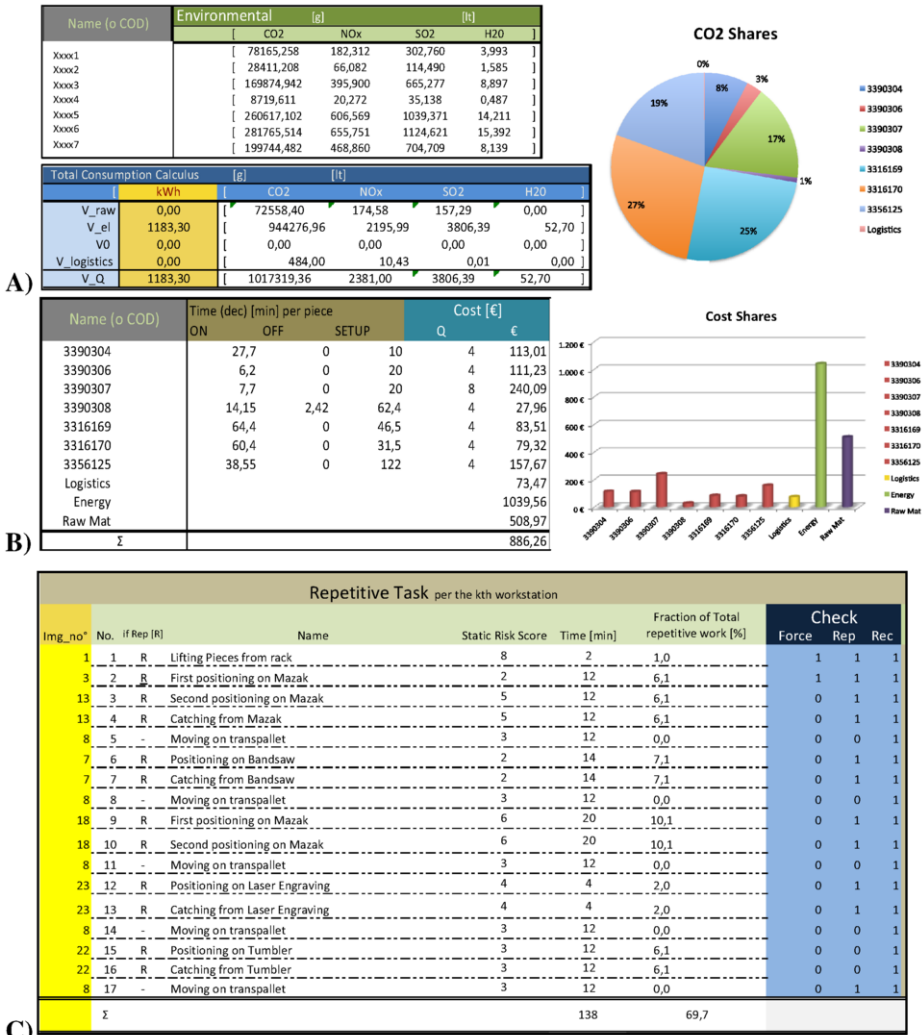


Figure 2. Results for EEA (A), ECA (B) and EHA (C) for the forming ring.

4. Conclusion

The paper proposed a set of models of impacts to evaluate the level of sustainability of manufactured parts, groups of parts or systems, to support the design of sustainable products and processes. The models have been applied to an industrial case study in the packaging sector demonstrating how the validity of the proposed method to drive the design choices by identifying the less sustainable processes in terms of costs, environmental impact and human efforts. Future works will be addressed to extend the proposed models to a wider range of manufacturing processes and to the entire lifecycle, including use and end-of-life phases.

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