Proposal of a new process of products environmental assessment/ improvement on CAD phase

Raoudha GAHA[1], Bernard YANNOU[2], Abdelmajid BENAMARA[1].

[1] Ecole Nationale d'Ingénieurs de Monastir, Laboratoire de Génie Mécanique, Tunisie. raoudha.gaha@gmail.com ; abdel.benamara@enim.rnu.tn

[2] Ecole Centrale de Paris, Laboratoire de Génie Industriel, France bernard.yannou@centralesupelec.fr

Abstract – Most of methodologies, concepts and tools, which integrate Computer Aided Design (CAD) and Life Cycle Assessment (LCA) systems and aim at ecodesigning, are generally oriented to the environmental assessment. The environmental improvement is treated only in a few works; however it is a pivotal phase in the eco-design process. In this paper, we propose a new environmental improvement process based on the remaining Degrees of Freedom (DoFs) for CAD designer on which he can act to eco-design his/her CAD model. The originality in this process is the expression of a CAD model environmental impacts in function of CAD designer DoFs, aiming at help non environment experiment designer to eco-design products in CAD phase. For this, first, we present the concept of DoFs and we use it to identify the CAD designer action zone. Second, we establish the impact matrix of DoFs in each life phase, then; we develop the global impact matrix .The assembly of EIs by linear summation of the matrix columns shows the most impacting ones. Finally, we consider a case study to valid our proposed approach and results are shown in function of DoFs.

Keywords: Eco-Design / Environmental improvement / Degrees of Freedom / Impact matrix/CAD model.

1 Introduction

Most of methodologies, concepts and tools, which integrate Computer Aided Design (CAD) and Life Cycle Assessment (LCA) systems and aim at ecodesigning [1-5], are generally oriented to the environmental assessment. The environmental improvement is treated only in a few works such as "Solidworks sustainability" [6] that provides similar materials and the methodology proposed by Marosky [7] where she establishes guidelines for the improvement after products environmental assessment. CAD designers with CAD/LCA integrated tools can calculate the environmental impacts of their choices, but they can not act to improve environmental performances of their geometric models. Indeed, a non-expert designer in terms of environment has no ability to know on what parameters he can act. The question, here, is; is-it possible to have talking results which allow to the designer to reduce the environmental impacts of his/her choices? Hence, the answer is; yes and below we present a new methodology of environmental improvement to assist CAD designers to eco-design in geometric modelling phase. This methodology is based on two phases; the first one is identifying the most impacting DoFs and the second one is acting on the initial geometry by modifying DoFs identified. In this paper, first we present the concept of DoFs found in the literature and, also, our proposals how to use it in the environmental improvement. Second, we propose the DoF model and we describe how CAD DoFs can be linked to environmental impacts, then we propose the new environmental improvement methodology based on DoFs. Third, a case study to illustrate how the proposed approach works is presented. Results are shown and the most impacting DoF appears to the designer on which he can act to improve his product environmental performance. Finally, we conclude about the use of DoF model and its role in eco-design and we propose perspectives of this work.

2 The concept of DoFs oriented eco-design: Analysis and proposals

2.1 Overview of degrees of freedom in the design process

The notion of degrees of freedom (DOFs) during a design process is not new. Indeed, in the work of Andreasen and Hein [8] the notion of (DoFs) design, is a presentation of the design process in the form of a pyramid as shown in Figure 1.

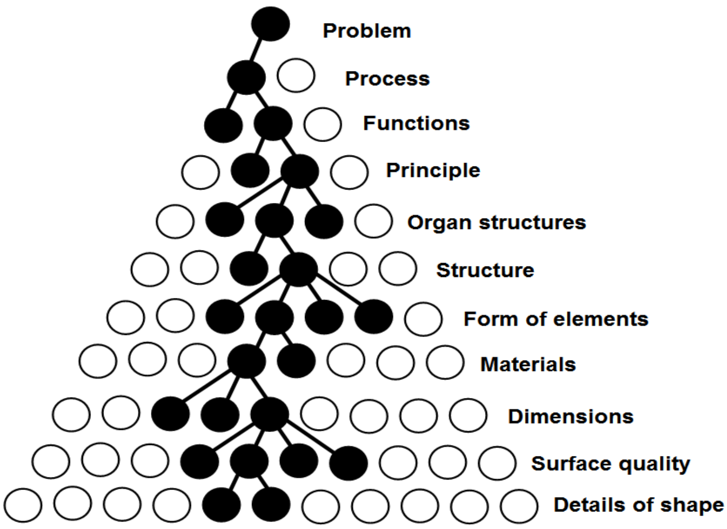

Figure 1. DoFs in the design process according [8]

These DoFs present the progress levels of the design process, where each level has a causal relationship with others and limiting a DoF influence the DoFs below. According to the pyramid, design process is accomplished when the lowest levels of the pyramid are set. Hence, the number of information about the system becomes increasingly important.

Using this pyramid, Bhander and Hauschild [9], offer a simplified generic environmentally conscious design process in relation with the DoFS (Figure 2). It is a generic design model called conscious Environmental Design (CED), which combines the "design features" given in [8] and the space of "environmental solutions".

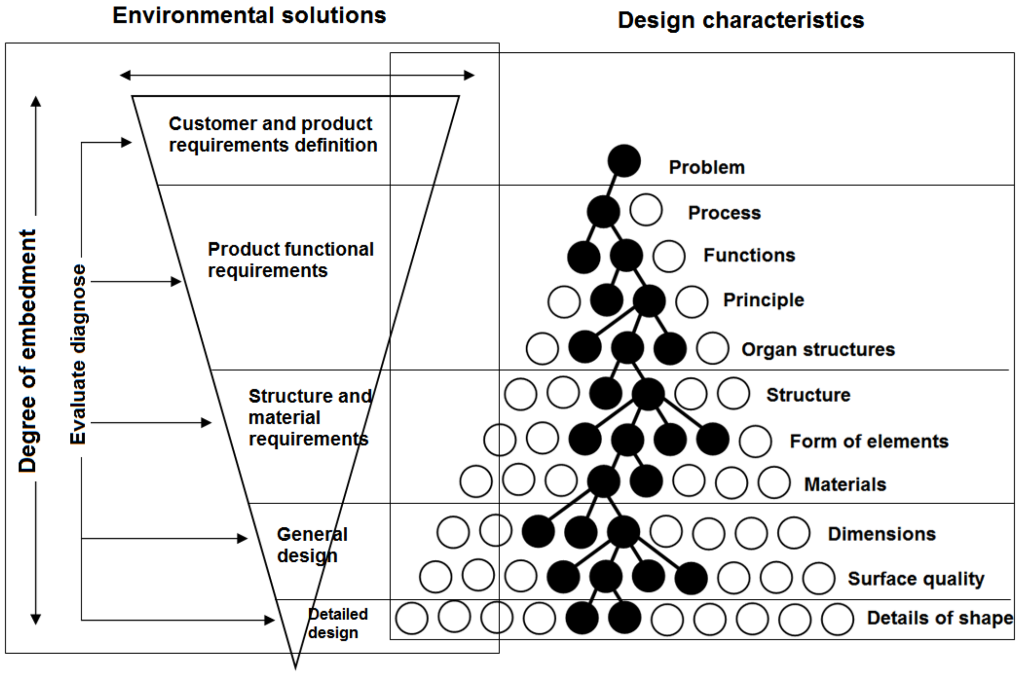

Figure 2. A simplified generic environmentally conscious design process Model [9]

2.2 Identification of CAD designer DoFs

Generally, to determine the CAD designer DoFs, it is necessary to model constraints throughout the design process. Establishing constraints leads convergence to the final solution and then the space of solutions which define CAD DoFs. For this, a multi-criteria approach should be developed to identify degrees of freedom related, first, to the company and subsequently the product, which is the object of our future work. However in this paper, the DoFs that we consider are relative to the company with which we collaborate. In detailed design stage, the CAD designer has a limited action area compared to the conceptual design phase. At this advanced stage, in the design process we identify 7 DoFs that we introduced in our previous work [10].

- DoF 1 : Forms
- DoF 2 : Dimensions
- DoF 3 : Materials

- DoF 4 : Volumes
- DoF 5 : production Process
- DoF 6 : Choice of « make or buy »
- DoF 7 : Thermal & surface treatments

2.3 Identification of impacting DoFs and definition of the action zone

In our research, we focus on the second phase of an eco-design process which is the environmental improvement [11]. The approach, that we present, in this paper, is for improving the environmental quality of a feature or a set of features environmentally evaluated by detecting various degrees of freedom in relation to the sources of impacts, to verify the possibility of action on these DoFs and improve the environmental performance of the geometric model under development. The location of DoFs sources of impacts allows the designer to act on the initial geometric model to eco-design it. Here, we process by a simplified method (a sort on Microsoft excel©) to classify DoFs in descending order. However, looking for the most impacting DoF could be made with other methods. For example:

- Experimental plans using the LCA tool but from well-defined DDL value.
- Advanced Optimization where DoFs are the variables with the constraints on their respective space, min IE function.

At this stage, the most CAD DoFs, influent environmental improvement of geometric model, are identified. Then, with reference to the product functional specifications and initial constraints, some DoFs can be eliminated and according to Andreasen and Hein work [8] there is a causal relationship between the DoFs, while eliminating one may influence others and a hierarchical representation of the interactions of the impacts of DoFs must be done to see the influence of each DoF and the possibility of action on the geometric model in order to eco-design it. Nevertheless, in this work the interaction between DoFs is not considered and we realize a simplified classification of impacting ones. Due to the importance of the detail design phase in eco-design and more specifically the choice of CAD DoFs, it is necessary to develop a model based on DoFs oriented eco-design for the environmental improvement. The development of this model is the subject of the next section.

3 Proposal of new environmental improvement process based on DoFs model

3.1 Presentation of a DoF model oriented ecodesign

A CAD feature presents a set of data such as material, dimensions, volume, etc. It may also carry other types of data when it is developed in an integrated CAX/ PLM / LCA system [10]. Figure 3 shows the relationship aspect between the parameters of a feature and CAD DoFs. The choice of DoFs implements an assignment of a feature. The environmental impacts that are associated with feature are then also linked to CAD DoFs. For this, we develop a model based on DoFs, which can detect those in relation with the impacting sources and allowing the designer to act on the initial geometric model to eco-design it. This model is based on the results of an environmental assessment practised previously on the CAD model. A feature carries a set of parameters (P_i) associated with the geometry such as type of material, density, volume, diameter, depth, etc. On the one hand, each of these parameters is related to one or more DoFs, as shown in Figure 3. On the other hand a DoF can be related to one or more parameters. Hence, as the number of DoFs (which are in number of 7 in our study), we divide the parameters into 7 groups (PG_i is the ith parameter group), ie the set of parameters which are related to a DoF are assembled into a group, knowing that the PG may interfere as a parameter which can be related to different DoFs.

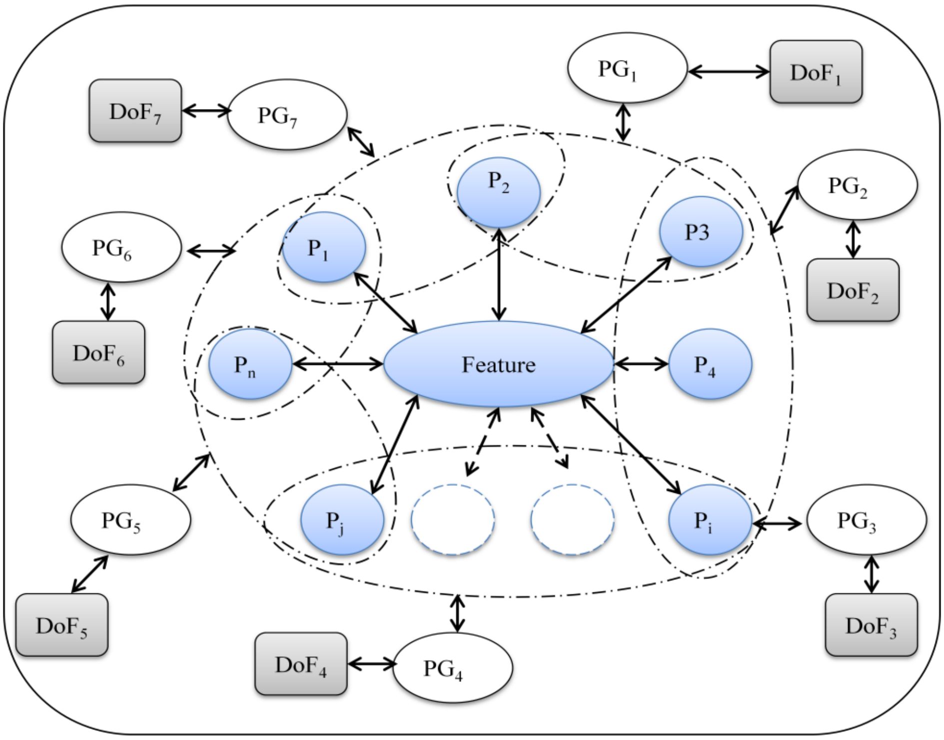

Figure 3. Relational model between feature parameters and DoFs

Sub-sets for the various feature life phases (such as subsets (SS); the manufacturing process and the energy used for the "production" phase) are related to DoFs. These subsets may be some DoFs, for example, in the "raw material" phase, the material is a subset and it is also the DoF_3. Hence, we establish a relational context between subsets of each phase and DoFs in the form of data lists. For example, if we have a cubic part (100, 100, 10) made on brass, for the extraction phase of the raw materials we can have the list shown in Table 1.

Table 1. Example of introduced data into an LCA tool for raw material phase

Data to introduce	Concerned DoFs	Data introduced
Type of material	DoF3 Brass (8500Kg/mm3)	Brass
Quantity of material used	DoF2, DoF3, DoF4 (100,100, 10) ; brass ; 105mm3	850g

By drilling a 10 mm diameter through hole, the part mass becomes 843,3g. Hence the energy must be calculated is the one required to remove 6.7 g by a drilling process. This energy is calculated based on the material, the amount of material to be removed. It therefore depends on DoF3, DoF2, DoF4 and DoF5. Similarly for the other parameters related to the stages of the life cycle, we establish their relationships with DoFs. The parameters for the raw material are expressed as follows:

SS_{1RM} = r(DoFs), SS_{2RM} = r(DoFs), ..., SS_{kRM}=r(DoFs); Where SS_{1RM} is the first subset to introduce into LCA software related to the first life phase of a geometric model which is the phase of extraction of raw materials and "r" is the relational aspect between them. In the same way, for the other phases of life, we establish the relationships between subsets and their related DoFs.

3.2 Process of linking environmental impacts to CAD DoFs

We suppose that the designer defines all DoFs allowed to him, before starting the geometric modelling. We want to have at the end the impact of each DoF to be able to act on the most impacting one, so it is necessary to link the EI each phase with DoFs. For simplification reasons, we consider, for a life phase subset, if one or more DoFs influence, then the EI of this subset will be divided between the related DoFs equally. Hence we suppose that all related DoFs have the same influence coefficient (for example whether for a phase production subset is found that the DoFs 1, 2, 3, 4 and 5 have an influence then the influence coefficient is 1/5). For other DoFs that do not influence this subset phase will assigned zero for their influence coefficient. Hence, equation 1 is established to express the EI of a given subset phase based on EI of each DDL with influence coefficients ($a_1 \ldots a_7$).

EI (subset of life phase) = a_1 x EI (DoF_1) + … +a_7 x EI (DoF_7) (1)

The link between the environmental impact of a given life phase to CAD DoFs can be represented in an impact matrix (8x7) (8 impact categories, used in the LCA toll "Bilan Produit", to consider and 7 DoFs). For example, the element of I_{MP11} impact matrix of the first material presents environmental impact N°1 of DoF_1 during the extraction phase of the raw material and the element has I_{MP87} environmental impact N°8 the DoF_7. This matrix M_{EIMP} can be expressed by Equation 2. $M_{EIMP} = \begin{bmatrix} I_{MP11} & \cdots & I_{MP17} \\ \vdots & \ddots & \vdots \\ I_{MP81} & \cdots & I_{MP87} \end{bmatrix}$ (2)

Similarly for each life phase we can obtain an impact matrix that can bind the environmental impact of a given phase to CAD DoFs.

From elementary matrices we develop global impact matrix which is presented by equation 3. It contains the environmental impact values of each DoF. The assembly of EIs by linear summation of the matrix columns shows the most impacting ones.

$$M_{IE}= \begin{bmatrix} I_{MP11}+I_{F11}+I_{U11}+I_{T11}+I_{FV11} & \cdots & I_{MP17}+I_{F17}+I_{U17}+I_{T17}+I_{FV17} \\ \vdots & \ddots & \vdots \\ I_{MP81}+I_{F81}+I_{U81}+I_{T81}+I_{FV81} & \cdots & I_{MP87}+I_{F87}+I_{U87}+I_{T87}+I_{FV87} \end{bmatrix} \quad (3)$$

We realize a hierarchical classification of generated impacts in function of DoFs. Then the most impacting DoF appears to the designer. In this step he can act on his CAD model aiming at improving its environmental performances. In order to look for the most impacting DoF, many methods could be developed such as experimental plan and muulti-criteria optimization. This work is limited to a simplified methodology that we propose to explain the concept of DoF model and its use for environmental improvement. We establish the algorithm of calculating DoFs environmental impacts which is presented in figure4.

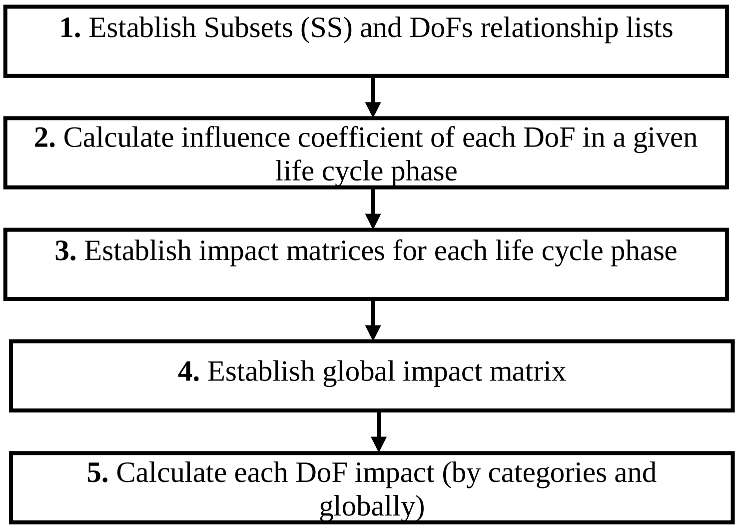

Figure 4. DoFs impact calculating algorithm

3.3 Proposal of the environmental improvement process

Based on DoFs model developed in previous sections, we propose a new environmental improvement process. The designer gets calculated environmental impacts expressed in function of DoFs. Hence, he has the action field necessary to improve the current CAD model. The proposed process is presented by the algorithm figuring in figure 5.

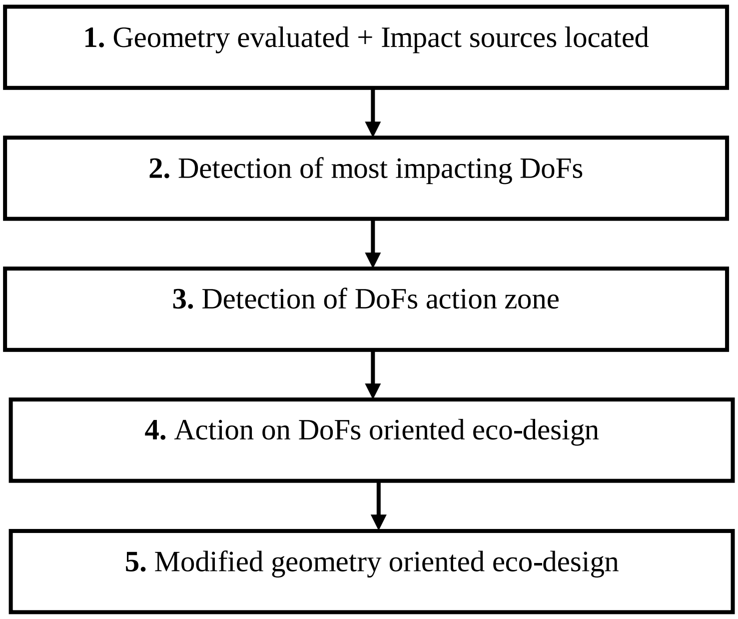

Figure 5. Environmental improvement process based on CAD DoFs

This process requires the presence of an evaluated geometric model in order to get an environmental improved one. It consists of three steps:

- Detection of most impacting DoFs
- Detection DoFs action zone
- Designer action on DoFs oriented ecodesign

4 Application on a case study (a basin mixer body)

4.1 Determining of the initial conditions to apply the proposed process

To validate our environmental improvement methodology based on DoFs model in CAD phase, we use an environmental evaluation of the basin mixer body case of our study shown in figure 6.

The LCA is practiced with the software “Bilan Produit”, developed by ADEME [12] to perform simplified LCA. The database used is developed in collaboration with EcoInvent Centre and the Swiss Centre for life Cycle inventories [13], aim at assessing the environmental impact. By using the CML method [14], calculated impacts are presented in the following categories life cycle phase: Energy consumption NR (MJ eq), Use resources (kgSbeq), Greenhouse GWP 100 mod (kg CO2eq), Acidification (kg SO2 eq), Eutrophication (air ground water) (kg PO4eq), Photochemical pollution (kg C2H4), Aquatic Ecotoxicity (kg1.4-DBeq) and Human toxicity (kg 1.4-DB eq). The results are expressed in points after practicing a normation because the impact indicators used are expressed in units incomprehensible by non environmental expert designer. The normation occurs by taking the ratio between the value of product’s impact and the reference value of the normation [15]. The normation retained in this software takes as reference the daily consumption of an average European. Other software can be used however we used here a simplified one in order to prove the feasibility of the proposed process. Hence the credibility of environmental evaluation results is not needed. Environmental evaluation results, of the basin mixer body used for the study, are shown in table 2.

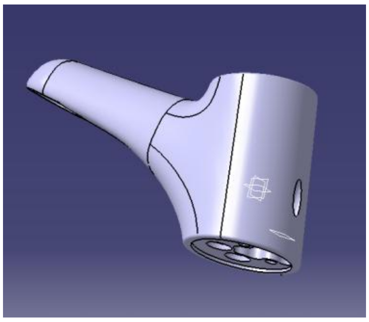

Figure 6. Basin mixer body

Table 2 The basin mixer body environmental impacts results of each phase by impact categories

Indicators	**Production Phase**	**Transports Phase**	**Use Phase**	**EoL Phase**	**Total indicators**
Energy consumption NR (MJ eq)	4,54E-01	4,55E-01	1,19E+00	-1,78E-01	1,92E+00
Resources consumption (kg Sb eq)	9,36E-01	8,63E-01	1,99E+00	-3,88E-01	3,40E+00
GreenhouseGWP 100 mod (kg CO2 eq)	4,50E-01	4,06E-01	1,02E+00	-1,77E-01	1,70E+00
Acidification (kg SO2 eq)	3,57E+00	3,55E-01	1,02E+00	-1,83E+00	3,11E+00
Eutrophication (kg PO4--- eq)	3,27E-01	8,07E-02	8,34E-02	-7,05E-02	4,21E-01
Photochemical pollution (kg C2H4)	1,10E+00	9,45E-02	4,56E-01	-5,62E-01	1,09E+00
Aquatic ecotoxicity (kg 1,4-DB eq)	2,71E+00	1,64E-01	1,62E+00	-1,13E+00	3,37E+00
Human toxicity (kg 1,4-DB eq)	4,49E+00	2,97E-02	9,77E-02	-2,22E+00	2,39E+00
Total phases	1,40E+01	2,45E+00	7,47E+00	-6,56E+00	1,74E+01

To establish the different impact matrices, it is first necessary to determine the various input data for each phase related to the body of the mixer. Here we present only for the production phase, how to establish the production matrix impact. Table 3 presents the input data of production phase used for the environmental assessment.

Table 3 Results Input production phase data in “Bilan Produit”

Noun	**Quantity**	**Unit**
Molding Brass	1,5	kg
Degreasing	0,045	m2
Black chrome on stainless steel	0,045	m2
Brass CNC Drilling	0,4	kg
Electricity high voltage Europe	0,5	kWh

4.2 Determining the impact production phase matrix depending on DoFs impacts

The determination of the impact matrix requires, first, the establishment of relational list between the parameters of the production phase and their related DoFs as shown in Table 4. Then, the influence equation derived from this relational list is developed to write thereafter the impact equation of the production phase in function of responsible DoFs impacts.

- EI (DoF2) = IE (DoF7) = b3 x EI (SE_3) +b4 x EI (SE_4); b3 et b4: influence coefficients as b3=b4=0.5.
- E I (DoF3) = EI (DoF4) = EI (DoF5) =c1 x EI(SE_1) + c2 x EI (SE_2) + c5 x EI(SE_5); c1, c2 et c5: influence coefficients as c1= c2= c5=1/3.

For the production phase, based on the impact equation in function of DoFs and impacts results shown in Table 5 of this phase generated by the LCA used tool, we establish the production phase impact matrix in function of DoFs for each considered impact category (equation 4). Similarly we can develop the impact matrix of each body basin mixer life cycle phase. Hence the global impact matrix can be deduced.

Table 4 Relational parameter list of the production phase and their related DoF

Life phase subsets	Data to introduce	Introduced data	Concerned DoFs
SE_1	Process type 1	Molding brass 1.5kg	DoF3 -DoF4-DoF5
SE_2	Process type 2	Brass CNC Drilling 0.4kg	DoF3 -DoF4-DoF5
SE_3	Treatment 1	Degreasing 0,045 m2	DoF7 –DoF2
SE_4	Treatment 2	Black chrome on stainless steel 0,045 m2	DoF7 –DoF2
SE_5	Energy type	Electricity high voltage Europe 0,5 kWh	DoF3 -DoF4-DoF5

Table 5 Impact results due to transport phase of parameters introduced body

Indicators	Molding Brass	Degreasing	Black chrome on stainless steel	Brass CNC Drilling	Electricity high voltage Europe
Energy consumption NR (MJ eq)	3,98E+00	7,61E+00	2,01E+00	5,86E+01	1,24E+01
Resources consumption (kg Sb eq)	1,77E-03	2,57E-03	4,65E-04	2,76E-02	4,59E-03
GreenhouseGWP 100 mod (kg CO2 eq)	2,37E-01	5,88E-01	7,13E-02	4,08E+00	6,19E-01
Acidification (kg SO2 eq)	1,02E-03	4,50E-03	3,89E-04	1,18E-01	2,76E-03
Eutrophication (kg PO4--- eq)	5,06E-05	1,85E-02	3,48E-05	5,22E-03	1,55E-04
Photochemical pollution (kg C2H4)	4,61E-05	1,60E-04	1,65E-05	4,46E-03	1,10E-04
Aquatic ecotoxicity (kg 1,4-DB eq)	7,65E-03	3,25E-01	2,59E-02	2,80E+00	3,49E-02
Human toxicity (kg 1,4-DB eq)	1,69E-01	7,37E-01	1,43E+01	6,35E+01	6,03E-02

$$M_{IEF}=\begin{pmatrix} 0 & 4{,}81E+00 & 2{,}50E+01 & 2{,}50E+01 & 2{,}50E+01 & 0 & 4{,}81E+00 \\ 0 & 1{,}52E-03 & 1{,}13E-02 & 1{,}13E-02 & 1{,}13E-02 & 0 & 1{,}52E-03 \\ 0 & 3{,}30E-01 & 1{,}65E+00 & 1{,}65E+00 & 1{,}65E+00 & 0 & 3{,}30E-01 \\ 0 & 2{,}44E-03 & 4{,}06-02 & 4{,}06E-02 & 4{,}06E-02 & 0 & 2{,}44E-03 \\ 0 & 9{,}27E-03 & 1{,}81E-03 & 1{,}81E-03 & 1{,}81E-03 & 0 & 9{,}27E-03 \\ 0 & 8{,}83E-05 & 1{,}54E-03 & 1{,}54E-03 & 1{,}54E-03 & 0 & 1{,}54E-05 \\ 0 & 1{,}75E-01 & 9{,}48E-01 & 9{,}48E-01 & 9{,}48E-01 & 0 & 1{,}75E-01 \\ 0 & 7{,}52E+00 & 4{,}35E+01 & 4{,}35E+01 & 4{,}35E+01 & 0 & 7{,}52E+00 \end{pmatrix} \quad (4)$$

4.3 Determining of the global matrix impact and identification of the most impacting DoF

The determination of the overall matrix impact requires the summation of different matrices previously calculated (equation 5).

Realized calculation shows that the most impacting DoF is DoF3 (Materials; 6,17E + 02), followed by DoF4 (Volume; 1,24E + 01), then the DoF6 (Choice "make or buy"; 7.3e 01), followed by DoF2 (Dimensions; 3,47E + 01), then the DoF5 (manufacturing Process; 1.56 + 01) followed by DoF7 (Treatment of materials; 5.33) and finally the DoF1 (forms; 0). In our case (mixer body), the form does not generate environmental impacts. However, for other products it may have an influence on their environmental performance.

$$M_{IE}= M_{IEMP+} M_{IEF+} M_{IEU+} M_{IET+} M_{IEFV} \quad (5)$$

0	3,13E+01	5,78E+02	1,15E+02	1,42E+01	6,85E+01	4,81E+00
0	1,46E-02	2,23E-01	5,19E-02	5,90E-03	2,90E-02	1,52E-03
0	2,09E+00	3,33E+01	7,21E+00	9,25E-01	4,13E+00	3,30E-01
0	8,02E-02	1,46E-01	1,33E-01	6,34E-03	1,70E-02	2,44E-03
0	1,19E-02	1,23E-02	7,24E-03	7,04E-04	1,21E-02	9,27E-03
0	3,01E-03	7,57E-03	4,94E-03	2,54E-04	5,62E-04	8,83E-05
0	1,28E+00	5,16E+00	2,20E+00	4,63E-01	3,29E-01	1,75E-01
0	5,10E+01	8,30E+00	6,53E+01	2,24E+00	8,08E+00	7,52E+00
0	3,47E+01	6,17E+02	1,24E+02	1,56E+01	7,30E+01	5,33E+00

5 Conclusion

To offer the designer an environmental assistance in geometric modelling by allowing him to calculate the environmental impacts does not help him to improve the environmental performance of his products, due to his lack of environmental knowledge. In this paper, we proposed a methodology to link DoFs remained in the design details to the results of calculated impacts to make them comprehensive. The DoF model proposed is oriented towards the second phase of the eco-design process, which is the environmental improvement phase. For this, relational parameter lists of life cycle phases and their related DoF are developed in order to link impact results to DoFs and then establish impact matrix. Each life phase has its elementary impact matrix. The addition of the five life phase matrices give, in the end, the part global impact matrix which shows the environmental impact of each CAD designer DoF. Several research axes are opened due to this work such as; the systematic identification of DoFs in a design process; the development of an expert system to find the greenest scenarios based on DoFs or optimize a greenest one by including constraints; and the development of a methodology that allows the location of the most impacting DoFs.

6 References

[1] Leibrecht, S., "Fundamental Principles for CAD-based Ecological Assessments," The International Journal of Life Cycle Assessment, Vol. 10, No. 6, pp. 436-444, 2005.
[2] Cappelli, F., Delogu, M., and Pierini, M., "Integration of LCA and EcoDesign Guideline in a Virtual Cad Framework," Proc. of LCE, pp. 185-188, 2006.
[3] Mathieux, F., Roucoules, L., Lescuyer, L., and Bouzidi, Y., "Opportunities and Challenges for Connecting Environmental Assessment Tools and CAD Software," Proc. of LCM 2005- Innovation by Life Cycle Management, 2005.
[4] Mandorli, F., Germani, M., and Otto, H. E., "CAD-LCA Data Migration Supported by Feature Technology and Attributed Structures," Proc. of Global Conference on Sustainable Product Development and Life Cycle Engineering," pp. 379-384, 2004.
[5] Morbidomi, A., "The EcoDesign Issue: Proposal for a New Approach, Methodology and Tools," Ph.D. Thesis, Dipartimento di Ingegneria Industriale e Scienze Matematiche Università Politecnica delle Marche, 2012.
[6]Solidworks, DS, Dassault Systems, "SolidWorks Sustainability, www.solidworks.com/sustainability.
[7] Marosky N., Challenges of data transfer between CAD and LCA software tools, 3rd International Conference on Life Cycle Management, University of Zurich at Irchel, August 2007.
[8] Andreasen, M.M. and L. Hein, "Integrated Product Development", IPU Institute for Product Development, 1987.
[9] Bhander, G. S., Hauschild, M., & McAloone, T. (2003). Implementing life cycle assessment in product development. Environmental Progress, 22(4), 255-267.
[10] Gaha, R., Yannou, B., & Benamara, A. (2014). A new eco-design approach on CAD systems. International journal of precision engineering and manufacturing,15(7), 1443-1451.
[11] Le Pochat, S. (2005). Intégration de l'éco-conception dans les PME: proposition d'une méthode d'appropriation de savoir-faire pour la conception environnementale des produits (Doctoral dissertation, Arts et Métiers ParisTech).
[12] ADEME, Bilan Produit 2008, http://www.ademe.fr/bilanproduit.
[13] Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Heck, T., Hellweg, S., ... & Wernet, G. (2007). Overview and methodology. Ecoinvent Rep, 1.
[14] Deja, M., and Siemiatkowski, M. S. (2012). Feature-based generation of machining process plans for optimised parts manufacture. Journal of Intelligent Manufacturing, 1-16.
[15] Guinée J., Heijungs R. (1992): Environmental life cycle assessment of products: Guide, CML, Leiden, The Netherlands, NOH report 9266.