Introduction of environmental aspects in designing of machines

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Abstract. Until now, in designing, an engineer's main task was to find solutions for practical problems including limitations of mainly material, technological and economical nature. Recently it was stated that environmental aspects need to be included as well in any design algorithm to provide low environmental impact profile of any technical object. In this paper, the example of use of the tool oriented at environment impact analysis – Life Cycle Assessment (LCA) – in the design stage of technical objects, is presented. The environmental analysis is done on the wrapping machine, with the special interest given to its gear transmission. Using LCA, environmental profiles and environmental indices for different constructions of gear wheels are elaborated and on this basis, an environmentally optimal combination of materials for elements of transmission gear: shaft, gear wheels and body is proposed. The analysis of results brings interesting observations and conclusions, important and useful for both machine designers and producers.

Keywords: ecodesign, eco-decisions, LCA, materials, food processing machine

1 Introduction

Designers can play a crucial role, by using proper algorithms – design algorithms – based on ecobalancing methods, in minimizing the environmental impact of technical objects. Usually, an engineer's main task was to find solutions for practical problems taking into consideration conditions of mainly material, technological and economical nature. In last years, aspects, which could be named as ecological or environmental, need to be included as well in any design algorithm to provide low environmental impacts of any technical object (machine, device, technological line etc.) at earliest stages of its life cycle [1, 2, 3]. Due to legislative pressure, customer requirements or even manufacturer's environmental policy, ecodesigning is currently gaining in popularity in many industrial sectors. Although a lot of product environmental impact assessment and Design for Environment (DfE) tools already exist, environmental aspects are unfortunately rarely routinely integrated into product development process in the industry [4].

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Ecodesigning is a process of designing products and product systems in order to minimize environmental impacts over the total product life cycle (ISO 2002). Most environmental impacts are “locked in” at the design stage, which is when key decisions are made on materials, manufacturing methods and how the product will be used and maintained. Addressing environmental impacts at the design stage will produce solutions that are likely to be environmentally positive and cost effective [5]. The syllable "eco” refers to both economy and ecology [6]. This introduces additional dimension to traditional design. Still, important part is played by such aspects as: functionality, safety, ergonomics, endurance, quality and costs. The additional criterion is a project estimation taking into account its environment influence [7].

Although it is not the only parameter to be considered in ecodesign, material selection obviously plays an important role in the developing the environment-friendly products. Material choices have an impact on costs, manufacturing, recyclability, etc. The main factors upon which the designers rely when considering materials choice are: the relationship between materials specifications and technical, economic and environmental performance of the product and the practice of industrial design embedded in the product and its functionality [8].

This paper aims to show the use of the Life Cycle Assessment methodology in the decision process concerning design of elements, subsystems and systems of an exemplary food processing machine. First, chosen elements will be assessed against a possibility to improve the environmental profile of the machine. Then the subsystem and the system will be considered, and a complex assessment will be possible and the most favorable solution chosen. The stated problem is important in the area of pro-environmental development of technical objects (e.g. required by certain EC directives) and in the specific area of food production sector, in area of the industrial processes.

2 Object of analysis

The machine considered in this paper is a wrapping machine dispensing pasty products into cubes, including butter, lard, cottage cheese, minced meat, ice cream or baker’s yeast. All the functions related to package shaping, product portioning, wrapping a cube and passing it to bulk package are performed automatically. Applied cam drive allows for reliable work in even very hard conditions and yields high output that can be accordingly reduced. The machine allows for packaging products in parchment or aluminum foil and uses stamp for coding single units with necessary information including date of production or factory code. By default, the machine is equipped with butter cube sized units, but it can be easily refitted for a range of package dimensions. Basic technical information on the machine are presented in Table 1.

Table 1. Basic characteristics of the exemplary machine

Output	Up to 90 pcs/min
Butter, lard, cottage cheese and ice cream cube size - 250 g cube - 125 g cube	 100×75×35 mm 75×50×35 mm
Margarine cube size - 500 g cube	 120×83×54 mm
Overall dimensions	2800×2800×1900 mm
Bulk weight	2500 kg

In the design process, the designer makes many decisions on which durability, economic and environmental costs of the designed object are decided. Decision making process is dependent on many different factors, like: designer's knowledge and experience, available construction materials, machining methods (accessible technologies), environmental protection regulations etc. Basic decisions are always made, irrespective of problem type and complexity, other are helpful when solving unusual problems and happen very rarely. Some actions in the decision making process are one-time, others are recurrent, until a specified result is achieved. To systematize these activities, algorithmic methods have been found useful. They give the designers a possibility to ergonomically design machines and appliances. A design of a given object needs to be characterized first of all with a capability to meet basic needs to produce it in a possibly optimal way with no redundancy. It is not only connected with economical savings, but also with increased environmental friendliness of an object [9].

A tendency towards low environmental profile of a machine expressed by its future users can be recently observed. The industry tries to include this requirement right from the beginning of the conception process, finding and neutralizing possible areas where the environmental impact could prove to be highest, for example by using:

- appropriate selection of materials needed to manufacture given machine part,
- choice of adequate technological processes, providing lower energy consumption and in effect, minimizing the formation of toxic chemicals etc.

That is why not only the whole concept of the designed object is important, but also the concept of individual parts, mechanisms and nodes. Those, after passing through applicable environmental procedures, contribute to the machine as a whole, becoming more environmentally friendly.

In the presented example, various decisions need to be made, concerning different elements of the transmission, some of those are listed below:

1) Transmission type: choice between belt drive, chain transmission and gear transmission. Environmental consequences are connected with vibration levels, noise emission, danger of lubricant spill, energy consumption. Gearing transmission was chosen, in spite of worst environmental performance (large dimensions, need to lubricate and precise machining of elements). This is due to some advantages that other types of drives do not possess, like high precision, high efficiency (~99%) and known high reliability and durability. In general, the choice of transmission was decided mostly by operating conditions of the designed machine.

2) Gearwheel type: choice between homogenous and modular wheel. Environmental consequences are connected with energy consumption during the machining processes and noise levels during wheel operation. Homogenous wheel was chosen because of its better mechanical characteristics and endurance. However, some aspects need to be taken into account, like more complicated disposal (presence of minerals and basic elements in cast alloys). On the other hand, the machining process for modular wheels takes more time to complete, consumes few times more energy and leaves various pollutants (like heavy metals) that due to their toxicity need to be neutralized quickly. One of the reasons to support the decision for using cast steel wheels is their smaller cost when produced in larger numbers.

3) Gearwheel material: choice between steel, cast steel and polyamide. Although polyamide does not corrode, it is not resistant to high temperatures (melts at 180-250 °C). As many plastics, it originates from petroleum, and petrochemical processes tend to produce very high environmental impacts. When it comes to damping vibrations that occur in operating transmission, cast steel and polyamide are known to work like that and steel only serves as propagator of vibrations. All the materials can be easily recycled. The decision which material to choose is therefore dependent on technological aspects of designed machine operation processes. Assuming moderate workload and corrosive environment, polyamide

would be a good choice, but it is a material that generates higher environmental loads during transformation processes than steel or cast steel.
4) Body type: choice between homogenous or compound. The decision is based on responsibility of designed transmission: if it is crucial to the machine operation, cast steel homogenous body should be used. In other cases, compound body made of easily accessible and cheaper materials is an optimal solution. It also creates lower environmental loads.
5) Body material: choice between cast steel and aluminum alloy. In this case, various factors need to be taken into account by the designer to provide high durability of the construction, low price and environmental impact. These factors, among others, are: mechanical characteristics of the material, its cost, availability, ease of treatment and influence on human and environment health. Cast steel, possessing higher endurance than aluminum allows to create smaller and more durable constructions. On the other hand, it is more susceptive to corrosion and needs to be protected from it. When taking into account operating conditions, if they are stable and moderate, aluminum can be used. This results in lower mass of the construction and easier disposal (aluminum scrap is more desirable), although aluminum processing creates higher environmental impacts than in the case of cast steel.

3 Methodology

There are many methods that support the pro-environmental design or designing of an object or a process. A few can be named, for example: EIA (environmental impact assessment), SFA (substance flow assessment) or TA (technology assessment). Among those the Life Cycle Assessment (LCA) is the best, focused on a single object, following it through its whole life cycle, from the resources gathering up to disposal, representing so called cradle-to-grave approach. LCA's inherent feature to calculate and compare environmental indicators that can be put into measurable values is especially convenient in relation to the stated characterization of an object through the materials its elements consist of.

According to the ISO 14040 and 14044 standards, a Life Cycle Assessment is carried out in four distinct phases that are often interdependent, in that the results of one phase will inform how other phases are completed [10, 11]: goal and scope definition, inventory analysis, impact assessment and interpretation.

4 Results

The structure of the following chapter reflects subsequent phases of Life Cycle Assessment procedure as stated above, in relation to the exemplary object.

4.1 Goal and scope definition

In the presented application of LCA, only the gear transmission with simple gear wheels was analyzed. The reason for choosing this subsystem is its universality and widespread use in food processing machines. As it was presented above, first and basic problem a designer comes across is the gearwheel itself. The decision problem at his stage is the choice of its type and material it is made of. Chosen solution causes consequences on the next links of the kinematic chain in the considered transmission. It is not only changes in dimension and mass of elements, but also specific, measurable environmental impacts.

4.2 Inventory analysis

In this phase of analysis, which is important from the methodological point of view, gathering of available data concerning transmission is performed. Elements on which the data are gathered include: a pair of gearwheels, two shafts on which the wheels are set and the body in which the shafts are installed. Modifications, including 12 different materials used for these elements, will be taken into account in the LCA. This way, a large number of possible combinations will be available to choose from in the design process.

In the presented calculation case, each of possible transmission solutions works in the same conditions and bears the same workload. It is assumed that because of the distances between gearwheels, the distances between shafts have to be the same. This limitation causes the diameters of coworking wheels to be the same, with only possible alterations in the width of the wheels.

To allow a comparison of environmental impacts generated by different versions of the transmission, its elements were created from different construction materials from the same group of stainless and acid-proof steel and cast steel: 1H18N9T, 3H13, 3H17M, 2H13, 2H17N2, 1H13, 0H18N9, H17, 00H17N14M2, 0H13J and GX12Cr14, GX5CrNi19.

The choice of material solutions affects the changes in design of the whole model of transmission. Strength characteristics of selected materials result in different width of gearwheels to carry the same workload. The change in width results in increase of dimensions and mass of elements. All these alterations cause different environmental impacts.

As all the selected materials are from the same group, the durability calculations were not taken into account, because chemical composition of chosen materials did not vary too much.

To eliminate a very great number of possible material combinations, sample analyses (in reference to 1 kg of each material) were conducted at the beginning. After verification of environmental impacts of chosen materials, those that are characterized with extreme (high and low) and mean environmental impacts have been chosen for further analysis, as well as those typically used for construction of food processing machines. Achieved results are presented in relation to the environmental point unit (Pt) and its 10^{-3} aliquot (mPt) as presented in ISO standard [10].

4.3 Impact assessment

Achieved LCA results allow for multi-aspect comparison of gearwheels in respect of generated environmental impacts and in turn, formulating the following conclusions:
1) Values of environmental indicators for each of proposed material solutions indicate that the use of 1H13 steel results in the lowest environmental impact (17.1 mPt), the second lowest is coming from the 2H13 steel (19.9 mPt) and GX12Cr14 cast steel (20.0 mPt). The complete results are presented in the graph (see Fig.1).

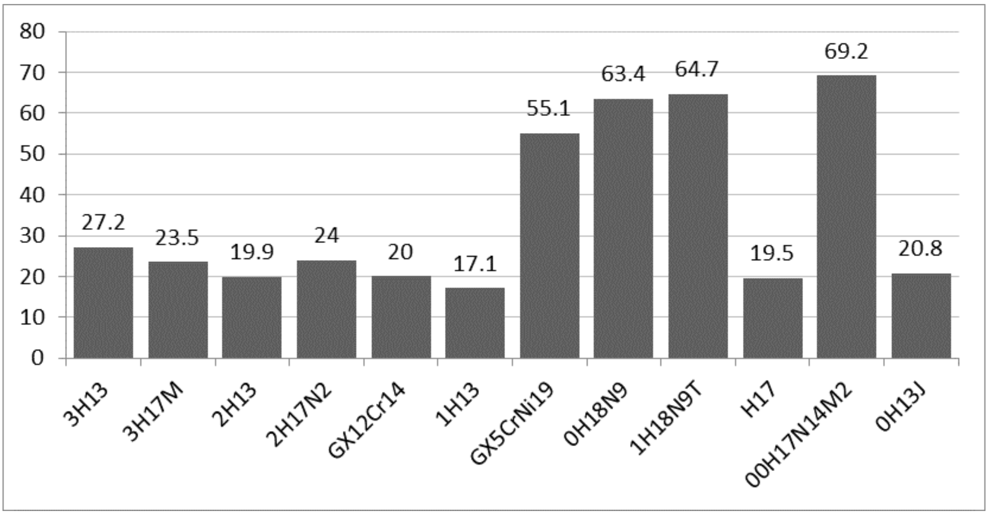

Fig. 1. Comparison of environmental indicators (in mPt) for selected steel and cast steel gearwheels

2) Detailed analysis of the assessed gearwheels environmental profiles identifies as dominant the result of their use – ecosystem destruction (soil acidification) induced through emissions of sulfur compounds, nitric oxides and ammonia in their life cycles. Group of materials with highest environmental impacts include: 00H17N14M2, 1H18N9T, 0H18N9 and GX5CrNi19, the remaining having five times lower impact levels. Another crucial consequence is the human health hazard, induced mostly by dusts and the emission of sulfur dioxide (impact levels similar as in the case of soil acidification). Also important to note is the aspect connected with creation of heavy metals in the life cycle of chosen materials, which is similar in all cases. Impact levels in remaining categories (greenhouse effect, eutrophication, carcinogens and summer smog) are low when compared to discussed categories.

Achieved LCA results for the most and least favorable solution of cooperation between shaft, body and gearwheels allow to draw the following conclusions:

1) Total environmental impact of transmission using 3H13 steel shaft and body (most favorable solution from the environmental point of view) is 0.06236 Pt. Small differentiation between impact values can be observed in case of the shaft and the body while using different gearwheels – it is 0.00596 Pt and 0.0564 Pt respectively (see Fig. 2 and Fig. 3).

2) Total environmental impact of transmission using 00H17N14M2 shaft and 1H18N9T body (the least favorable solution in means of environmental impact) is 0.4748 Pt. Also in this case small differences can be observed when compared against different proposed gearwheels – 0.0188 Pt and 0.456 Pt respectively (see Fig. 4 and Fig. 5)

3) Among the environmental impacts generated by a transmission composed of 3H13 shaft and body (most favorable solution in means of environmental impact), heavy metals creation is the category that burdens the natural environment the most. About half of that is generated in connection with soil acidification. Other categories have marginal impact.

4) Most of the environmental burdens when using 00H17N14M2 shaft (least favorable solution in means of environmental impact) are connected with soil acidification due to the emission of sulfur compounds, nitric oxides and ammonia in the life cycle. It can also be observed that when using 0H13J, 3H17M and (what is somewhat surprising) 3H13 steel leads to 20-30% higher level of environmental impacts than in the remaining impact categories. Essential categories of impact in terms of volume include also the creation of heavy metals and winter smog; all the other categories are insubstantial.

5) In case of using 1H18N9T body in the transmission (least favorable solution) impact levels are high in soil acidification and winter smog categories, with other categories having only slight importance.

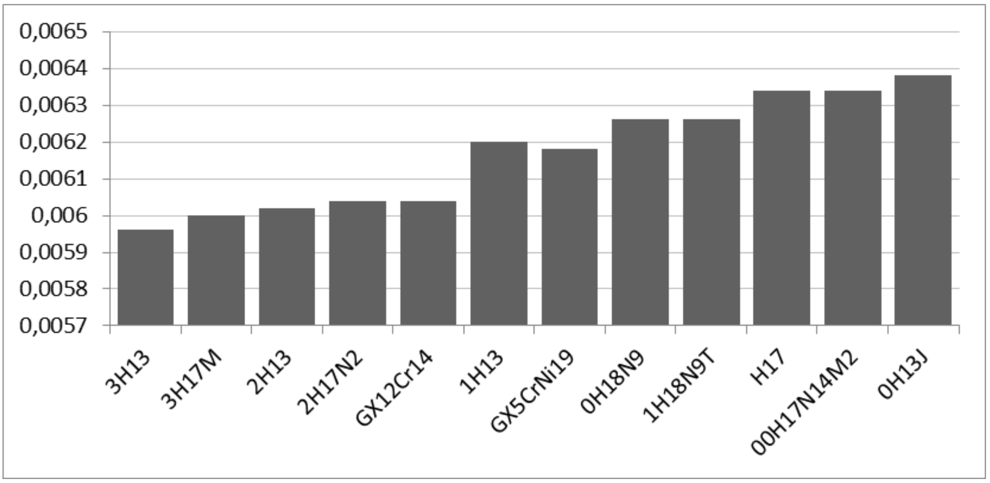

Fig. 2. Comparison of environmental indicators (in Pt) generated by 3H13 shafts in transmissions using different gearwheels (most favorable solution)

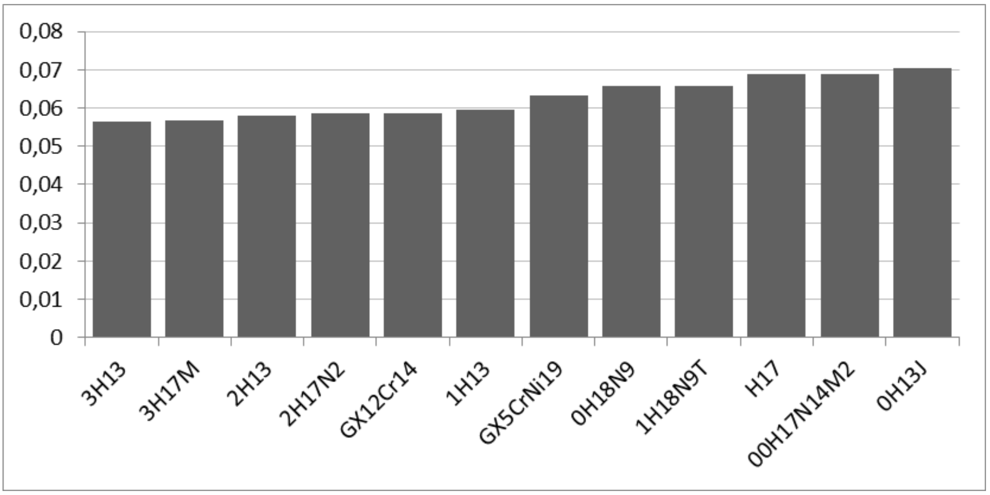

Fig. 3. Comparison of environmental indicators (in Pt) generated by 3H13 bodies in transmissions using different gearwheels (most favorable solution)

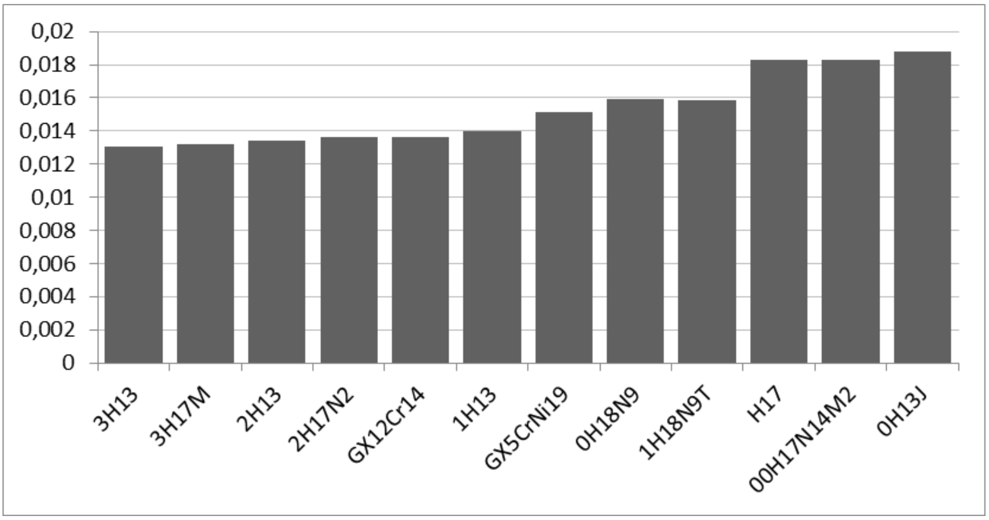

Fig. 4. Comparison of environmental indicators (in Pt) generated by 00H17N14M2 shafts using different gearwheels (least favorable solution)

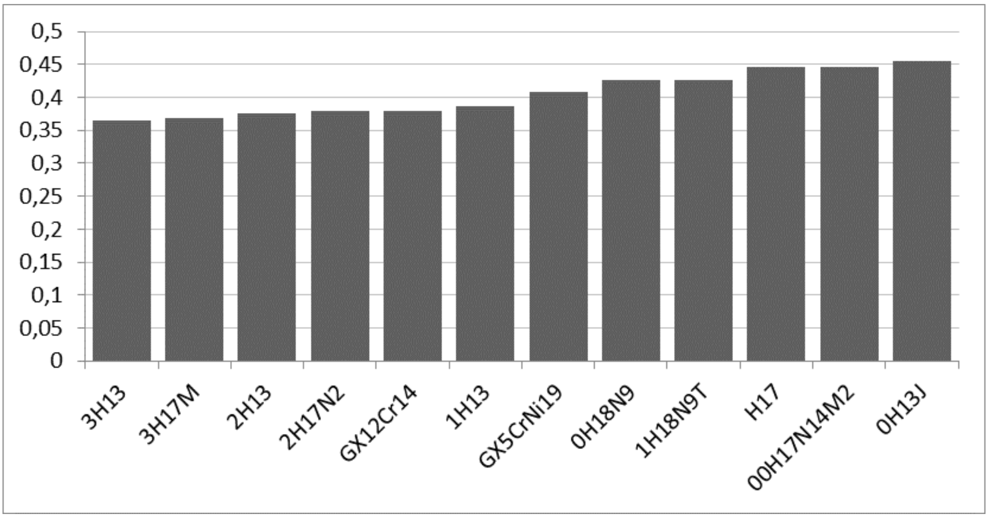

Fig. 5. Comparison of environmental indicators generated (in Pt) by 1H18N9T bodies using different gearwheels (least favorable solution)

4.4 Interpretation of results

After the ecobalance analysis of transmission elements and versions, environmental impacts for proposed combinations can be presented. This includes the most and the least favorable in terms of environmental impacts as well as a typical one used in the food processing machines. Criteria for choosing three specifications were based on results of previous LCA analyses of chosen variants, and those three are:
1) 1st transmission – 00H17N14M2 gearwheels and shafts, 1H18N9T body (the least favorable solution in means of environmental impact)
2) 2nd transmission – 2H17N2 gearwheels and shafts, 1H18N9T body (typical)
3) 3rd transmission – 1H13 gearwheels, 3H13 shafts and body (the most favorable solution in means of environmental impact)

The aggregated LCA results for the chosen variants are presented in Table 2.

Table 2. Comparison of chosen transmissions models environmental profiles /unit: points/

No	Impact category	Most favorable solution 1H13/3H13/3H13	Typical solution 2H17N2/2H17N2/1H18N9T	Least favorable solution 00H17N14M2/00H17N14M2/1H18N9T
1	Climate change	0.00761	0.0156	0.0203
2	Ozone layer depletion	5.553E-05	7.11E-05	5.91E-05
3	Soil acidification	0.0241	0.23	0.334
4	Eutrophication	0.00267	0.00392	0.00491
5	Heavy metals	0.0412	0.0416	0.0423
6	Carcinogens	0.00887	0.00773	0.00956
7	Winter smog	0.0108	0.134	0.197
8	Summer smog	0.00118	0.00143	0.00181
Eco-Indicator		0.0966	0.434	0.610

Achieved results allow for multi-aspect comparison of three transmission variants being under consideration and in turn, formulation of conclusions:
1) Environmental indicator values for each proposed material solution of a transmission show that using 1H13 steel for gearwheels and 3H13 steel for shafts and body results in the lowest environmental burden (96.6 mPt). Nearly four times worse (434 mPt) is the result for a typical solution used by designers in food processing machines: 2H17N2 steel gearwheels and shafts with 1H18N9T steel body. The least favorable solution, earning 610 mPt is the use of 00H17N14M2 steel for gearwheels and shafts with 1H18N9T steel for the body.
2) Detailed analysis of proposed solutions environmental profiles identifies the destruction of the ecosystem due to emissions of sulfur compounds, nitric oxides and ammonia as the dominant negative aspect of their application in the manufacturing as well as other life cycle phases.

5 Final conclusions

Most important conclusions, from above presented research, are:
1) Undertaken analysis shows that implementation of environmental aspects in the design process can substantially reduce the environmental impacts of any technical object. This was presented on the case of a transmission system installed in a food processing machine, but it is also valid for any other element, subsystem or a system of the object.
2) In the analyzed case, the manufacturing of transmission bodies has the greatest share in negative environmental implications of the life cycle of a transmission system. It also shows that the levels of environmental impact may vary greatly according to the type of material used, reaching up to 300% in the exemplary case (e.g. comparing 1H13 to 1H18N9T steel).
3) Among the most important factors influencing the environmental impact of materials, two can be distinguished: the selection of materials and intake of energy for the manufacturing processes of machine elements.
4) What is important in the context of food processing industry is that existing solutions of subsystems may have, as shown in the exemplary comparison of transmission system, as much as four and a half times more negative environmental impacts than the most favorable of the presented combination of materials. This only gives an idea of how much there is to do in the field of ecological awareness when choosing material composition of machines and appliances.

Identification of environmental impact sources in relation to every element, subsystem and system of a machine should lead to undertaking actions aimed at improvement of

current situation. This relies on the increase of interest of designers and technologists in including the ecobalancing methodology in their work, which in turn would result in:
1) research and application of eco-friendly materials that guarantee the creation of lightweight, durable elements and systems; this can be done by proper selection of materials (e.g. composites instead of metals, due to their near-immunity to corrosion, they can be reused),
2) minimization of energy input to technological processes, mainly accompanying the machining of elements,
3) use of environmentally friendly lubricants that reduce friction resistance in kinematic nodes of a machine and allow easier dismantling of elements.

All these activities should be supported by popularization of the idea of quantitative characterization of environmental impacts caused by technical objects. This should result in easier access to the related data, allowing designers to use them to create environmentally friendly machines and appliances or to improve existing solutions.

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