CONDITIONS OF USING STEEL PRODUCTS FOR THE PRODUCTION OF STEAM TURBINE BLADES – ECODESIGN IMPLICATIONS

BARAN Jolanta

Silesian University of Technology, Gliwice, Poland, EU, jolanta.baran@polsl.pl

Abstract

Ecodesign of blades used in steam turbines is the example of integrating environmental aspects into the process of designing and development of a product during life cycle. The life cycle of blades begins with extraction of raw materials and manufacturing steel products used as material charge in the process of their production. Among the activities that can decrease environmental impact of blades during life cycle is considering the environmental profile of used steel. The aim of the article is identification of environmental impacts connected with alternative ecodesign variants created during modeling of using different steel products to manufacturing the blades and also determining potential and needs connected with elaborating environmental profile of blades life cycle. Environmental aspects concerning using different steel products are considered in relation to various forms of material and types of steel. The design variants are analyzed basing on LCI data concerning steel, taking ecodesign approaches and principles into account. The usability of specific LCI databases and LCIA methods was also considered. The analyzed problem can lead to determine possibilities of integrating environmental aspects concerning steel into design of blades, also in context of life cycle management. Presented considerations can be helpful in improving logistic chains and in making decisions connected with elaboration and implementation of eco-innovations.

Keywords: Ecodesign, Life Cycle Inventory, steel products, steam turbine blades, eco-innovations

1. INTRODUCTION

The turbine together with the components – blades – this is one of the elements of the energy system influencing on the environment throughout the life cycle from pre-production phase through manufacturing and using phase until waste management including recycling.

Usually the impact of energy on the environment is considered in the context of fuel to production electricity and heat, which is the basis of all production processes. The extension of this approach can be achieved by estimating the environmental impact related to the manufacturing of the turbine components as well as their modernization and repairs. Minimization of this impact can be achieved among others by increasing turbine efficiency and also by reducing the influence of the life cycle elements of turbines on environment. The significance of this problem is expressed in quantitative scale – steam turbine plants remain the most common type of systems used for combined production of electricity and heat [1]. Additionally steam turbine blades are the critical component in power plants, especially low pressure blades are generally found to be more susceptible to failure [2], so they need to be produced constantly. Existing power plants are equipped with old, even 50-years-old turbines working based on old and inefficient technologies. That is thus field for research to achieve both higher efficiency and performance as well as reducing the environmental impact.

In this paper the attempt of considering the environmental impact of the pre-manufacturing and manufacturing phases in turbine blades production is made. Different steel products are considered as input for manufacturing process as well as potential and needs related to elaborating environmental profile of blades life cycle is determined. The procedure of ecodesign is applied to define the best variant taking the environmental profile into account among the other criteria.

2. ECODESIGN OF STEAM TURBINE BLADES – INSPIRATIONS AND POSSIBLE SOLUTIONS

Blades that are used in stationary energy industry are elements of thermal turbines in professional and industrial power plants and in combined power plants. Since one of the elements of innovation implementation in a company is identification of the needs and opportunities to implement innovations using the network of cooperation and relations with clients [3], the inspiration for ecodesign of blades was the option of using the results of analyses related to various environmental parameters in B2B relations.

Within planning of the design process possible ecodesign approaches were considered. It was decided to begin ecodesign in the range of material efficiency improvement, energy efficiency improvement and durability increase. Those approaches can be particularized (according to ISO/TR 14062 [4]): minimization of the materials consumption, use of materials with lower environmental impact, use of recycled materials, consideration of total energy consumption in the whole product life cycle, consideration of long product lifetime and consideration of environmental improvements resulting from new technologies. Taking these approaches into account the possible ecodesign solutions can be identified (**Table 1**).

Table 1 Ecodesign solutions for steam turbine blades

Ecodesign approaches		Possible ecodesign solutions for the blades
Material efficiency improvement	Minimization of the materials consumption	Selection of constructional variant with lower consumption of steel
	Use of materials with lower environmental impact	– Use of steel that has the lowest environmental impact – Cooperation with suppliers of materials in range of reduction of the environmental impact
	Use of recycled materials	Use of steel with the high recycling rate
Energy efficiency improvement	Consideration of total energy consumption in the whole product life cycle	Minimization of energy consumption on different stages of life cycle
Durability increase	Consideration of long product lifetime	Looking for the optimal constructional solution taking into account failures reduction
	Consideration of environmental improvements resulting from new technologies	Looking for the optimal constructional and technology solution

As we can see in **Table 1**, the possibilities of reducing the environmental impact of blades in the range of selected ecodesign approaches, relate mainly to the three stages of life cycle – acquisition and processing of raw materials, manufacturing of blades and waste management. The first phase of blades life cycle is acquisition of raw materials and processing them in the process of manufacturing the steel products. By using steel that has the lowest environmental impact, the designer can influence on the environmental profile of blades life cycle.

On the other hand the possibility of inclusion of the environmental criteria in blades life cycle design depends strongly on the supply chain condition, beginning with the steel producers. Steel industry has significantly limited its environmental impact in the recent years, but eco-innovative solutions still need to be developed and implemented in numerous areas [5]. Moreover the steel industry is development-oriented sector. There are continually developing new types of steel for specific applications as well as there are R&D departments in the steel plants working [6, 7]. Thus the developing potential can be the other inspiration for including the stage of steel manufacturing in this study.

3. ECODESIGN VARIANTS OF STEAM TURBINE BLADES

Making the choice of specific ecodesign solutions it is necessary to achieve a reasonable balance between the various environmental issues and other relevant aspects such as safety and health, technical requirements, functionality, quality, performance, and economic aspects, including manufacturing costs and marketability, while complying with all relevant legislation [4, 8].

Taking the above into account, searching for the eco-innovative solution was preceded by initial assumptions formulation and defining technical parameters, criteria related to safety, manufacturing and environmental requirements (see [9]). Finally two constructional variants of possible solutions have been identified – (A) stator blade – spacer and shroud made separately (standard solution) and (B) stator blade – spacer and shroud made of one piece of material (innovative solution) (**Fig. 1**).

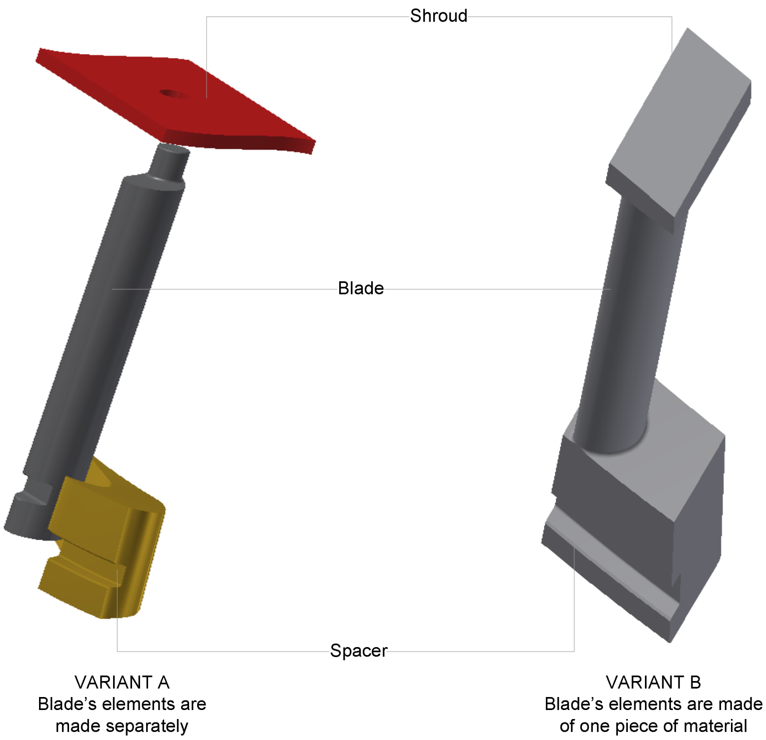

Fig. 1 CAD models of stator blades – two analysed variants in ecodesign

Working conditions of blades installed in turbine (high temperature, high stress and vibrations) determine the necessity of taking the strength and other important parameters of material into account. Material for blades manufacturing should be stainless steel for example the grades X12Cr13, X20Cr13. For the analysis the constructional and material variants were selected (**Table 2**).

Table 2 Constructional and material variants of analysed solutions

Constructional variants	Variant A	spacer and shroud made separately
	Variant B	spacer and shroud made of one piece of material
Material variants	Variant 1	X12Cr13
	Variant 2	X20Cr13

4. ENVIRONMENTAL EVALUATION OF VARIANTS OF STEAM TURBINE BLADES

Within integration of environmental aspects into design process designers need to have reliable information concerning environmental impact of considered solutions. Such information can be provided by the quantitative analysis, mainly through the use of Life Cycle Assessment LCA [10]. For the designer developing the ecodesign solution the real difficulty is gaining the data and carrying out the life cycle impact assessment of the pre-production phases that are outside of the enterprise control, especially if the acquisition and processing of raw materials in order to obtain material for production is so complex process such as steel production, even if it is supported with the software and databases.

In the case of blades the life cycle assessment was carried out for the functional unit equals 100 blades, taking two phases of life cycle into account into account – (1) acquisition and processing of raw materials, (2) manufacturing of blades. Due to the lack of the data concerning steel grades that are considered as the input material for blades manufacturing, the available data from databases were used. The data come from the ecoinvent database (in SimaPro) as well as from International Stainless Steel Forum and in both cases concerns 304 steel grade. The results of the LCA are presented in **Table 3**.

Table 3 Comparison of LCIA (characterisation, ReCiPe Midpoint H) of two constructional variants of blades with using different data sources concerning steel

Impact category	Unit	Variant A	Variant B	Variant A	Variant B
		Data on steel from ecoinvent 2 (chromium steel 18/8 (Europe))		Data on steel from ISSF (world mean)	
Climate change	kg CO_2 eq	2717.92	2011.61	2665.58	1960.88
Ozone depletion	kg CFC-11 eq	0.00005	0.00004	0.00004	0.00003
Human toxicity	kg 1,4-DB eq	1719.88	129081	1650.66	1223.85
Photochemical oxidant formation	kg NMVOC	6.20	4.64	6.10	4.54
Particulate matter formation	kg PM_{10} eq	5.01	3.91	4.18	3.11
Ionising radiation	kg U235 eq	108.42	90.28	51.88	35.58
Terrestrial acidification	kg SO_2 eq	14.44	10.61	15.26	11.41
Freshwater eutrophication	kg P eq	2.38	1.76	2.25	1.64
Marine eutrophication	kg N eq	0.70	0.52	0.68	0.50
Terrestrial ecotoxicity	kg 1,4-DB eq	0.13	0.11	0.11	0.09
Freshwater ecotoxicity	kg 1,4-DB eq	54.59	44.70	33.79	24.58
Marine ecotoxicity	kg 1,4-DB eq	54.64	44.95	33.25	24.26
Agricultural land occupation	m^2a	51.03	38.88	43.97	32.05
Urban land occupation	m^2a	12.43	10.06	8.25	6.01
Natural land transformation	m^2	0.11	0.09	0.08	0.06
Water depletion	m^3	12.22	9.08	10.42	7.34
Metal depletion	kg Fe eq	839.24	810.12	6.27	4.46
Fossil depletion	kg oil eq	737.85	548.69	705.35	517.25

The obtained results indicate that the lower environmental impact corresponds to the constructional variant B that is manufacturing of blades elements of one piece of material. It is associated with another processing method, differences in the technology. The differences between the same constructional variants analysed using different data sources concerning steel in this case don't affect the proportion of the comparison.

The further research focused on answering the question if it is possible to acquire data unequivocally indicating the best solution from the acceptable material variants. The set of environmental parameters of a few steel grades (among others for material variants) is presented in **Table 4**.

Table 4 Energy Demand and Carbon Footprint of selected steel grades

Steel grades or types	AISI	CED[1] [MJ/kg]	Carbon Footprint (or Global Warming Potential) [kg CO_2 eq./kg]	Source of data
1.4006	410	83.6	4.5	[11]
1.4021	420	89.8	4.9	
1.4016	430	28.5	1.9	[12][2]
1.4301	304	31.7	2.0	

[1]CED – Cumulative Energy Demand – in this column are presented the data calculated as CED or PED (Primary Energy Demand) – according [13] this is the same indicator differing in names and compatibility to databases and/or software.
[2]Characterisation factors for these results come from CML-IA Characterization factors. Leiden: Leiden University.

Table 4 shows that the better variant of the two possible materials in blades manufacturing taking the environmental aspects into account is using the X12Cr13 steel (AISI 410) because it is the steel grade characterised by lower energy requirement and lower GHG emissions relating to the same functional unit. Data for two other steel grades are presented for comparison. It should also be noted that the difference between the CED for 410 and 420 grades of steel and 304 steel grade for which the analysis was taken above is more than 2.5 times, which is a substantial disparity.

Using as input material the various forms of steel may also influence on the final balance of life cycle environmental impact. Using the matrix forgings for blades manufacturing contributes to reducing the consumption of material, energy and tools (basing on qualitative assessment). Using hot rolled steel bars and forged bars in this respect is worse solution, although it would be necessary to determine the environmental impact associated with the whole life cycle.

Practitioners in the design teams need to have the data and information facilitating inclusion of ecodesign parameters in their work. The needed data can be searched in LCI databases, such as data accessible from World Steel Association (LCI for 15 main finished products of the steel industry but there is no data for engineering steel and stainless steel products), Eurofer (European stainless steel study available for grades 304, 316, 430 and 2205 Duplex) as well as from International Stainless Steel Forum ISSF (for grade 304). Another source of data concerning steel is ecoinvent (above 340 records concerning the steel, including stainless steel) and European reference Life Cycle Database ELCD shared by JRC (datasets also concerning stainless steel). Apart from the above mentioned data sources the designers can also use data in scientific publications as for example [12, 14]. However many practical problems related to the use of data on steel result from the differences in datasets versions and updates. The similar situation is relating to use of the LCIA methods. Among many LCIA methods that are using in studies on steel we can indicate ReCiPe, CED, IPCC, CML, IMPACT2002+, EPS, Eco-indicator 99. In [15] authors describe five LCIA methods taking different criteria like value choices and assumptions, scientific and technical validity, applicability into account. They stated that there are many problems in using and interpretation of the LCIA methods. Using CED method in this study is simple but there are methodological intricacies that can be another barrier for practitioners.

5. CONCLUSIONS

Presented study can be illustration of carrying out the ecodesign modelling of the solutions and inclusion of the wider perspective of the product life cycle in design process. Based on the conducted analysis it is stated that the best solution is production of integrated blades (constructional variant B) using the X12Cr13 steel. But simultaneously the difficulties in gaining the data, their interpretation and selecting the appropriate methods were evident. To stimulate the elaboration and implementation of eco-innovations the support in ecodesign process is highly needed. For steel considered in ecodesign of the products further research concerning databases integration and unification of methodology should be conducted.

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