

Innovative software platform for eco-design of efficient electric motors

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ABSTRACT

Electric motors are one of the most common electrical components used both in industrial and household applications. In order to reduce world energy consumption and environmental impact, electric motors need to be improved in terms of efficiency and eco-sustainability. For this reason it is necessary to improve environmental consciousness, favouring the application of eco-design guidelines in the design phase, which is the most important stage where “green” solutions can be rapidly ideated, evaluated and optimized. Different aspects have to be concurrently considered in order to achieve a high quality product in a short time to market. In this context, the present paper describes an innovative web-based software platform to configure and simulate customized energy efficient electric motors. The core of the platform is a knowledge-based system which aims to standardize the design process according to the rules which represent the company know-how and best practices. The platform integrates different software tools to support the development from conceptual design to detailed design, and from the configuration of design solutions up to environmental impact assessment and manufacturing cost evaluation. It also provides a collaborative area in order to improve the collaboration among remote users involved in the design process, thanks to the sharing of important design data and models. The presented practical case studies demonstrate the effectiveness of the platform application. The achieved results demonstrate the improvement of the configured solutions in comparison with the traditional adopted motors. The new motors exhibit both a considerable increase in energy efficiency and at the same time relevant improvement in product sustainability combined with acceptable production costs.

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1. Introduction

In modern society, problems such as energy consumption and related environmental aspects have become very important. The total world energy required has increased by approximately 2.5% in the last decade, and by 5.5% in 2010 (Enerdata, 2011). The European Commission has issued the communication “EUROPE 2020 – A strategy for smart, sustainable and inclusive growth” (European Commission, 2010), where one of the central subjects is the strategy for a 20% reduction in greenhouse emissions and a 20% increase in energy efficiency in comparison with 1990.

Electric motors consume roughly 40% of the electrical energy worldwide, being responsible for about 13% of the global CO₂ emissions (Ferreira and de Almeida, 2009). This result emphasizes the importance of electric motor energy efficiency improvement during ordinary working. For this reason, electric motors are one of the most important functional groups which need to be considered in order to achieve a considerable electrical energy consumption

reduction (European Commission, 1996). In addition, considering that almost all the lifecycle cost of an electric motor is determined by the electrical energy cost, it is clear that the improvement in energy efficiency leads to cost reduction of electrical equipment in the use phase of their lifecycle. Therefore, it is very important to implement energy efficiency standards for electric motors to reduce energy consumption growth in the industrial sector. An interesting example of standard application in a specific country is reported in Mahlia and Yanti (2010), where the relevant benefits are quantified.

Electric motors are one of the fundamental components of every manufacturing machine or industrial plant which has one or more primary or auxiliary electric motors. On the other hand, motors used in household appliances (such as refrigerators, freezers, washing machines, dishwashers and cooker hoods) have, in general, low specific energy consumption. However, due to their being found in almost every household, they are responsible for about 80% of domestic electric energy consumption. Therefore, the optimization of motor efficiency in all applicative fields, from low power motors used in domestic electrical equipment, to high power motors used for industrial applications, is fundamental in facing an increase in electrical energy consumption. For instance,

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the right sizing of electric motors can support the achievement of a meaningful energy saving (Ferreira and de Almeida, 2012).

The problem of environmental impact is closely correlated to energy consumption. In recent years this problem has become very serious, particularly due to the relevant increase in the worldwide population. For this reason the eco-design approach, a new manner to design products combining ecological and economical aspects, needs to be considered for sustainable development. This concept was defined over twenty years ago (United Nations, 1987) and has since been considered by numerous studies regarding for example, the sustainability in the development and manufacturing of new products (Kaebernick et al., 2003), eco-design guidelines (Luttropp and Lagerstedt, 2006) and the eco-efficiency of electrical products (Aoe, 2007). Furthermore, ISO (International Standard Organization) has issued a technical report (ISO-TR, 2002) and successively a standard (ISO, 2011) which focuses on the integration of environmental aspects into product design and development. Unfortunately, these concepts are not often applied by manufacturing companies, which tend to follow the classical criteria of the design process, such as costs, time or quality of final products. However, it is fundamental to take the variable “Environment” into account in the design process, in the same way as the other variables are normally considered.

In this context companies need to easily obtain the rapid idea-tion, configuration and assessment of “green” customized products. Only with continual and iterative improvements can companies extend their product life, adapting them to their customers’ needs and optimizing them in order to obtain energy efficiency and low environmental impact. In order to achieve this scope, companies need to manage multiple aspects and design alternatives and work in collaborative teams. For this reason, automatic configuration tools are essential tools to support designers in handling the huge quantity of knowledge involved in the design process, such as technical solutions, normative, standards and production processes.

The present paper proposes an innovative and integrated set of tools, oriented to the efficiency of the design process, called EROD Platform (Energy Reduction Oriented Design). It allows the standardization of the design process for electric motors and related machines. It simultaneously takes into account all aspects which influence environmental impact and energy consumption, and enables production cost to be controlled. It also enhances the synergic cooperation in all the product design chain and the company knowledge sharing.

The fundamental block of the platform is a Knowledge Based system containing the design rules and guidelines to achieve energy efficient products and to reduce their environmental impact. A web-based user-friendly interface allows designers to access all the functionalities of the system. It is able to share knowledge regarding electric motors and their applications to standardize the design process in a company. The different software packages permit the rapid configuration and simulation of innovative electric motors, considering the life cycle aspects from several viewpoints, from environmental to costs. The platform also fosters collaborative activities and data exchange among all design actors.

The following sections, after a brief review of research background, describe the tools and the whole platform. Then experimental case studies are reported to demonstrate the platform effectiveness.

2. Electric motor design process and related tools

From the analysis of electric motor design processes, both in literature and in practice, it emerged that a consolidated design methodology has not been formalized yet and neither is it easy to recognize (Hamdi, 1994; Pyrhonen et al., 2008). The process is

driven by individual designers’ experience. However, it is possible to recognize some common steps which are followed by experts and industrial practitioners.

The design of electric motors generally starts with the definition of technical specifications, mainly set by customers. At this stage one of the main significant problems regards data retrieval to support product design. In fact, it is common practice to configure a new customized electric motor starting from an old, previously designed solution. Electric motor documentation is usually not well organized, design methodologies belong to individual know-how and skill, and the design rules are not formalized or stored in any database which can be rapidly accessed by all process stakeholders. Considering this background, subjective expertise plays a crucial role in the identification and achievement of the best configuration. As a consequence, the success of the design solution is based only on the personal experience of the people involved. The result is an unavoidable extension of time to design customized electric motors and a delay in the overall time-to-market.

During the design process, conceptual and detailed design are generally supported by different software tools, such as 2D and 3D CAD (Computer Aided Design) systems, CAE (Computer Aided Engineering) software, worksheets and excel tables. These are general purpose tools, not oriented to electric motor design. Product models are progressively improved by iterative analysis and simulations. In the preliminary stage lumped-parameter software or spread sheets are used to evaluate the performances of the configured motor model. Optimization is carried out with the support of FEA (Finite Element Analysis) techniques, which allow the prediction of the electromagnetic dynamic behaviour of systems. Another common way to proceed in the design and optimization process is the “trial and error” methodology, which requires the creation and the test of numerous costly intermediate physical prototypes.

The main bottleneck of this traditional process relies on the number of repetitive operations to achieve a final design solution which respects all the required specifications. The increase in development time and in consequence in relative costs is also due to the lack of software tool integration and interoperability. In order to overcome these problems, it is necessary to rationalize the design process. One of the hypotheses of this work is that if designers can easily retrieve past solutions to similar design problems, store new case studies, operate with shared design rules and use a large set of integrated supporting tools, then the amount of time to develop a customized electric motor would decrease.

From the analysis of current practice in electric motor development, the collaborative nature of the design process emerges. The product complexity requires the involvement of multiple competences to face mechanical, electrical, electronic and software aspects. These competences are often distributed in different companies of the supply chain. Collaboration can be remote or synchronous, and take place in different places or in the same environment. Communication problems can emerge such as difficulty in data and model exchange due to the incompatibility of the format of files, low efficiency in documentation management, etc.

All these problems can cause an increase in time to market and a reduction of the process efficiency.

An additional issue in the state of the art of the current electric motor design process regards the control of production costs from the early design stages. Costs are usually estimated at the end of the development process, before starting the production phase. In some cases the achieved solution can provide high technical performance but cannot be economically feasible or convenient. As a consequence products may suffer from a lack of cost optimization. Their early estimation at the design phase allows the evaluation of alternative design solutions from an economical perspective,

rejecting any inconvenient solutions. Therefore, this can lead to the production of high quality and low cost electric motors.

Finally, it is not possible to avoid issues concerning the environmental aspects connected with the use of electric motors in machines, equipment, consumer goods, etc. The state of the art regarding environmental sustainability in manufacturing electric motors is poor. As far as the sector of electrical and electronic equipment is concerned, it is only in recent years that companies have been started to consider the environmental consciousness design. Regarding this, an interesting study (Platcheck et al., 2008) presents a methodology of eco-design for the development of more sustainable products. This study underlines the need to include the environmental aspect in all phases of the design process, from ideation to detailed project. In addition, in 2003, the European Community issued WEEE Directive (European Parliament and Council, 2002a), regarding the disposal and recovery of electric equipment, and RoHS Directive (European Parliament and Council, 2002b), regarding the restriction on the use of dangerous substances in the same products. Electric motors, which are the core of electrical and electronic equipment, are subjected to these directives. There are several available tools and methods for LCA (Life Cycle Assessment), but they are general purpose. Few experiences of application of environmental impact estimation techniques in the electric motor field can be found in literature (Torrent et al., 2011) and they are focused on specific motor typologies. From a normative point of view (de Almeida et al., 2008), specifications for the eco-design of electric motors have been set in the European Commission Regulation. Hence, it is essential to control the variable “Environment” at an early design stage, when a modification to the product is less problematic than in the successive development phases.

In the specific field of electric motors and machines, there is not an extensive state of the art regarding supporting systems for the whole design process (Scutaru et al., 2010; Jabbar and Yeo, 2000). The research is focused on physical or electromechanical principles and on product optimization to improve energy efficiency or thermal aspects (Fan et al., 2010; Saidel et al., 2010). Many research studies have also focused on innovative applications or on renewable energy production systems (Wu et al., 2007). In literature there is a lack of studies regarding the systematic design of electric motors and machines. In particular there are no examples of applying the eco-design approach in this particular sector or of applying the LCA methodology for the assessment of the environmental impact during all phases of electric motor lifecycle. A platform dedicated to the configuration and concurrent verification of various aspects of eco-efficient electric motors has never been presented. This highlights the novelty of the proposed platform, which also aims to encourage designers to take into account not only the classic economical and qualitative criteria, but also the environmental aspect of the entire product lifecycle, in order to develop more environmentally friendly electric motors.

3. Approach for efficient electric motors design and the EROD platform

The EROD Platform is a set of integrated software tools which aims to support electric motor designers throughout the complete design process. This platform can be used remotely and all functionalities can be controlled by a single user interface. The usability of user interaction favours easy data exchange and knowledge sharing along the different design departments and in the whole supply chain. A general architecture of the software Platform is proposed in Fig. 1. This innovative Platform can be used to develop electric motors in an efficient and sustainable way, in particularly to help small and medium companies to manage innovative projects and several aspects of the design process.

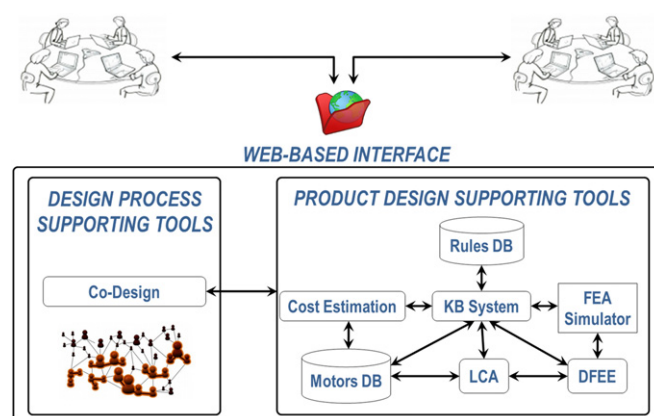


Fig. 1. EROD platform architecture.

The EROD Platform is composed of several interconnected systems and tools which manage different functionalities. The modules of the Platform guide designers in each phase of the product design process. A list of modules is reported below and described in detail in the following sections:

- Knowledge-based (KB) System.
- Design For Energy Efficiency (DFEE) Module.
- Life Cycle Assessment (LCA) Module.
- Cost Estimation Module.
- Co-Design Module.

Only authenticated user may gain access to the platform. This is an important feature which permits to differentiate the resources and functionalities (such as database or tools) provided by each user.

The well-organized and efficient design of sustainable electric motors are the main challenges of the EROD platform. The Knowledge Based system helps designers in all phases of the design process with the aim of ideating and configuring the new electric motor solution. The other modules, linked together, support the design activities with the simultaneous evaluation of electric energy consumption, energy efficiency, eco-sustainability and cost. Furthermore, these modules help the decision process to increase electric motor efficiency and sustainability. Dedicated systems for co-design activities facilitate the effective real-time involvement of different experts who can consider the simulation and assessment results.

3.1. Knowledge based system

The KB system is the core of the EROD Platform. It aims to support the configuration of customized electric motors by an efficient use of company knowledge. The KB System has a user-friendly graphic interface (GUI), developed using the ASP.NET technology (Active Server Pages on .NET software framework). This system is able to manage different data: firstly it highlights input parameters to be entered by the designers, and secondly, it collects the data retrieved from the different modules of the platform. The configuration tool guides designers in the whole design process, but requires some manual input for all phases. A general framework of the KB system is shown in Fig. 2.

The KB system has a central position in the Platform architecture and is linked to the other tools. In particular, due to the direct link with the virtual simulation tool, the designer can verify the electromechanical performance of the new configured electric motors. For this purpose an electromagnetic FEA Simulator is used. This commercial software tool is automatically controlled by the KB

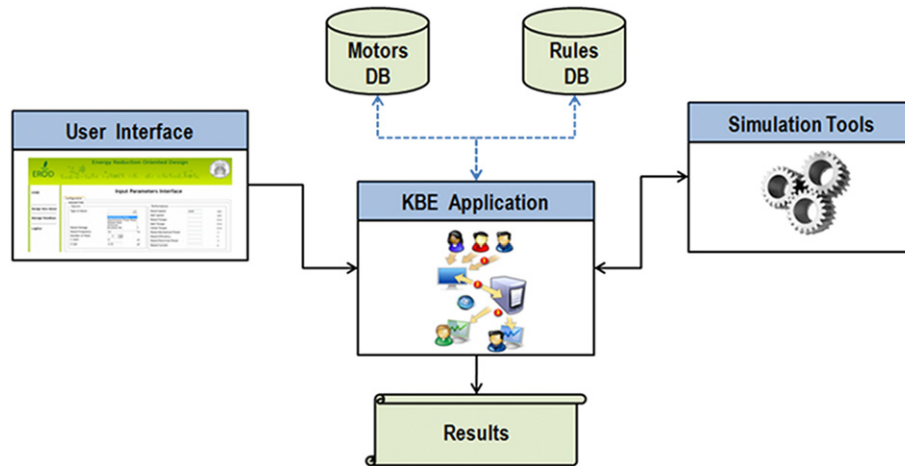


Fig. 2. EROD knowledge-based system framework.

system, thanks to the generation of appropriate scripts. The system builds a 2D CAD representation, sized according to the designer's input, and simulates the performance of the configured motor model, displaying the final results in the same interface. The result analysis of the virtual model, displayed in an organized way, suggests how to modify the input parameters (such as the geometric configuration of an electric motor) to maximize energy efficiency and sustainability. A new simulation highlights if the results have been reached or other adjustments are necessary. Therefore, the KB system provides Platform users with a structured design process to define and optimize electric motor design.

As highlighted in Fig. 2, the KB system is built on two distinct databases which contain useful data and configuration rules for electric motor design. The two repositories are developed using Microsoft SQL Server and comprise:

- *Motors DB* which stores the documentation about previous solutions, such as geometrical models, data sheets or bills of materials;
- *Rules DB* which collects best design practices and company rules.

A brief procedure of the design activities achieved by the use of this module is reported. The first phase of the new electric motor configuration is the definition of technical specifications and design constraints. Subsequently, designers can easily search past solutions and case studies from the EROD Platform database (*Motors DB*) according to the design specifications. This retrieved information is the starting point for the new motor design. When the solution which best fits the design requirements has been identified, the KB system guides the user step-by-step in entering proper input parameters and in configuring the design solution. The simulation of the configured model behaviour allows the assessment of the electromagnetic performance. The automation of the simulator is essential to reduce the development time, which is usually long in this phase due to the necessary iterative simulations. By using the Platform, all repetitive phases, such as the resizing of a component, are completely automatic. The designer has only to enter parameter values in a user-friendly interface. When the final design solution has been found, the KB system stores the new optimized motor in the database and permits the creation of the final product model. Technical datasheets and all documents useful for production and assembly phase are then generated.

3.2. LCA module

The environmental performance of appliances containing electric motors is becoming an important feature to be considered in the new market context. The possibility to mark products which use electric motors with a "green" label can develop new business scenarios and satisfy communitarian legislations.

The LCA Module is an environmental evaluation tool integrated into the general framework of the EROD Platform. The purpose of this module is to estimate the environmental impact of electric motors during the early design stage. The impact assessment is carried out following the well-known LCA methodology described by ISO 14040 series (ISO, 2006a,b). The environmental impact analysis determines the damage to the ecosystem as a result of human activities related to the product under analysis in all phases of its lifecycle. The LCA method comprises 4 distinct phases:

- The goal and scope definition;
- Inventory analysis (LCI - Life Cycle Inventory);
- Impact assessment;
- Interpretation.

The main goal of this module is to give designers the possibility to quickly estimate the environmental impact of electric motors in two phases of the product life-cycle: the production/manufacturing phase and the use phase. These two phases are, in fact, the most critical to analyse in the design process of electric motors from an environmental point of view.

Another great advantage compared to the current state of the art is the possibility to easily and automatically retrieve information for the LCI phase. In fact, a dedicated repository of this module stores useful data for the LCI phase, such as the components used in the motor, the type of materials, the mass, the manufacturing processes, etc.

The evaluation method used for impact assessment is the Eco-indicator (EI-99). This method permits to obtain a weighted and normalized value of environmental impact in three major categories of environmental damage:

- Resources;
- Ecosystem quality;
- Human health (Goedkoop and Spriensma, 2000).

The fact that only few and simplified indicators are managed makes the interpretation of results very easy. Another advantage is

the comparison of alternatives for what concerns different solutions configured.

Impact calculation regards both materials and manufacturing processes to produce electric motors and relative components. The framework of the developed environmental impact estimation tool is presented in Fig. 3.

The information is collected in two separate databases, the *Materials DB* and the *Processes DB*, which have been developed in Microsoft SQL Server. The processes can be personalized, expanded and modified considering the characteristics of electric motors and related manufacturing technologies. Otherwise, existing manufacturing processes, modelled for the specific company, can be stored in the database and automatically selected by the system for a certain typology of electric motor. The LCA Engine System consists of a certified open-source database from the European Commission (ELCD DB) (European Commission, 2011) and an Impact Calculator which carries out the environmental impact evaluation. The original environmental impact flows are collected in the ELCD repository of the European Commission which is linked to the Material and Process repositories.

Estimating the environmental impact of electro-mechanical products requires extending the analysis beyond the production phase. It is important to distinguish the impacts the electric motors have during the production phase and in the use phase. In particular, in the use phase, when most energy is consumed, the product sustainability is directly related to the electrical power consumption and to the average utilization lifetime.

Both environmental impacts in production and in use phases (LCA production and LCA use) are considered and estimated independently. Therefore, the evaluation becomes useful for companies in order to improve the manufacturing processes in terms of sustainability, and also for final users of electrical machines and equipment, who can be informed by producers about the damage to the environment caused during the use phase of the purchased product. With the innovative LCA Module of the EROD Platform the environmental impacts can be assessed rapidly, as early on as in the first design stages. This is very important information for designers since they can then consider the environmental aspects during the design process and if necessary change some input parameters, such as materials, in order to improve the sustainability of the configured electric motor.

3.3. DFEE module

The increasing need to reduce global energy consumption has recently brought about the issue of an international regulation regarding the efficiency classification of electric motors (IEC, 2008; IEC/TS, 2009). Furthermore, the European Commission has issued some directives regarding the use of efficient electric motors and efficient electrical equipment (European Parliament and Council, 2005, 2008, 2009) for the purpose of forcing manufacturing companies to produce and distribute only energy efficient

products, especially in household appliances and industrial applications.

The DFEE Module supports designers in developing energy efficient motors. A general framework of the proposed module is shown in Fig. 4 and described below.

The module is built to give rules and guidelines for the best configuration of electric motors with the scope to increase efficiency, reduce losses, and as a consequence improve the performance of products in which they are used. In particular the system guides engineers in the geometrical modification of the electric motor model, in selecting materials for a specific component, and in designing windings. In other words, the tool provides solutions to reduce the energy consumption of the entire system (motor with its load) in use, for a specific working point. Thanks to the link with a 2D FEA Simulator the DFEE tool allows the losses to be assessed and subdivided into 3 major groups:

- *Iron losses* due to hysteresis and parasitical eddy currents in laminated stator and rotor cores;
- *Winding losses* caused by the current flowing through windings;
- *Other losses* (IEC/TS, 2009).

The statistical analysis of the estimated losses performed by the DFEE engine is the starting point for the successive phase of the model modification.

The system provides an efficiency classification of the electric motors according to the information stored in the DFEE database. The electric motor classification is built starting from the European standards and directives (IEC, 2008; European Parliament and Council, 2005). In particular, the electric motors are divided into 5 groups (shaded poles, induction 3-phases, induction single-phase, brushless PM and synchronous reluctance) and for each group 4 different efficiency classes have been created (EFF0, EFF1, EFF2 and EFF3). The system also makes it possible to modify the thresholds for each efficiency class according to the specific application of electric motors and the evolution of communitarian directives. The classification is an important feature of the system in terms of eco-design, because this software tool allows designers to easily control the efficiency class of the new developed product, fostering in this way the optimization of the electric motors in terms of energy efficiency. The designer is guided into the reconfiguration of the electric motor to reduce losses in the various components. Depending on the predominant loss in the motor, the DFEE user interface helps designers with proper modifications. For example, for the reduction of losses in laminated steel rotor and stator cores, one of the possible proposed modifications is using materials with better magnetic properties. The results are available in a graphic report and can be saved in the repository of the module as a final report or as a starting point for a new configuration.

As in the Knowledge Based configuration system, the model is automatically rebuilt and then simulated again by the 2D FEA software. This phase usually requires a long calculation time and more than one iteration to obtain maximum efficiency and good quality results.

Another relevant characteristic of the DFEE tool is the full integration with the above described LCA module to carry out a rapid evaluation of the environmental impact of the new modified model, especially in the use phase. As a consequence, designers can improve the energy efficiency and the closely correlated impact during the use phase. But designers can simultaneously hold in check the impact of the production phase, avoiding for example the use of materials which are rare, difficult to mine, or to manufacture.

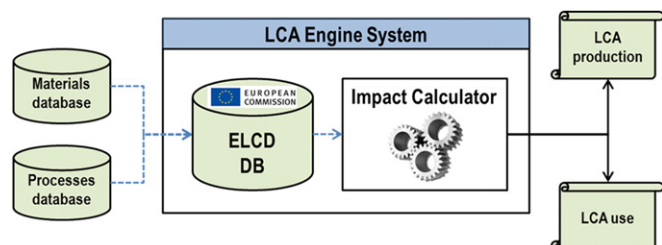


Fig. 3. EROD LCA module framework.

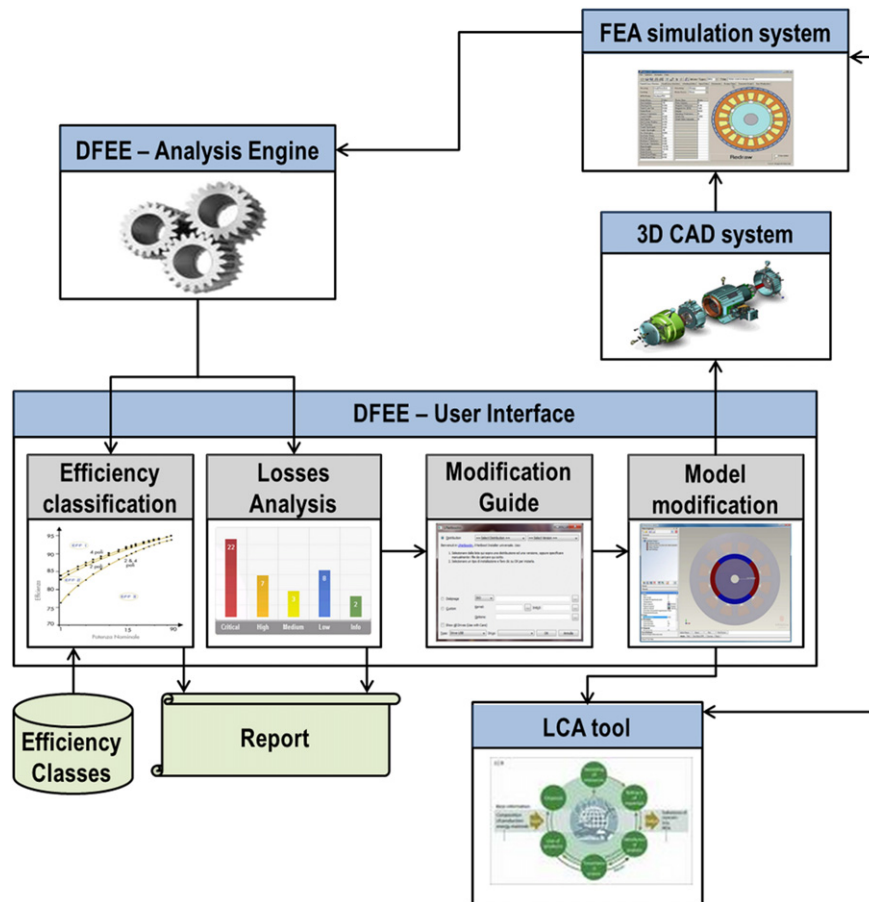


Fig. 4. EROD DFEE module framework.

3.4. Cost estimation module

Most product and component costs are set during the industrialization or production phase, when the detailed design has been completed. The cost estimation activity is affected by a lot of conditions which are in constant and rapid evolution. For these reasons it is very difficult to predict the real production cost of the electric motors in the early design phases. However, a rapid analysis of cost items can be useful for designers in these preliminary phases and can affect their choices.

The Cost Estimation module is used to evaluate the manufacturing costs of electric motor components during the early phases of design process. The general framework of the integrated module is depicted in Fig. 5.

The cost estimation tool is based on the determination of materials, cycles and times for the production of the electric motor components. This information is stored in Costs the database.

The module is composed of several packages. The first package is a CAD Interface which allows mass and constituent material to be assessed for each component. Other important data can be retrieved by the Company PDM (Product Data Management) database which stores the actualized value of cost items (such as the cost of materials, quantity in stock, etc.). These database are constantly maintained by companies due to the rapid variation of material costs and availability.

The Process Allocation package is able to recognize a list of potential manufacturing processes which can be used for component production. The Cost Calculator Engine is the package which performs the estimation of the production costs, according to the

information retrieved by the modules previously described. The package summarizes the cost items and shows an indicative value of cost estimation for each component. The costs are classified as:

- *Raw material costs* due to the acquisition of starting materials;
- *Production cycle costs* due to operations of transformation required for the component manufacturing;
- *Auxiliary component costs*.

The goal of this tool is to provide an indicative value of production costs for the electric motors under design and orientate designer choices. Cost is not the main driver which affects the efficiency and the environmental sustainability of electric motors, however cost monitoring is necessary during the development process of new efficient motors.

3.5. Collaborative design module

The Collaborative Design module is developed to efficiently support the design activities among different users involved in this process. This module enables real-time collaborative design among remote designers/engineers with a high level of interaction. The Collaborative Design module is developed to fill the most critical shortfalls design communication of electric motors, in particular:

- Virtual environment for CAD model visualization, import, comparison and measurement.
- CAD data sharing tool for the simultaneous interaction of more than one user in the same model.

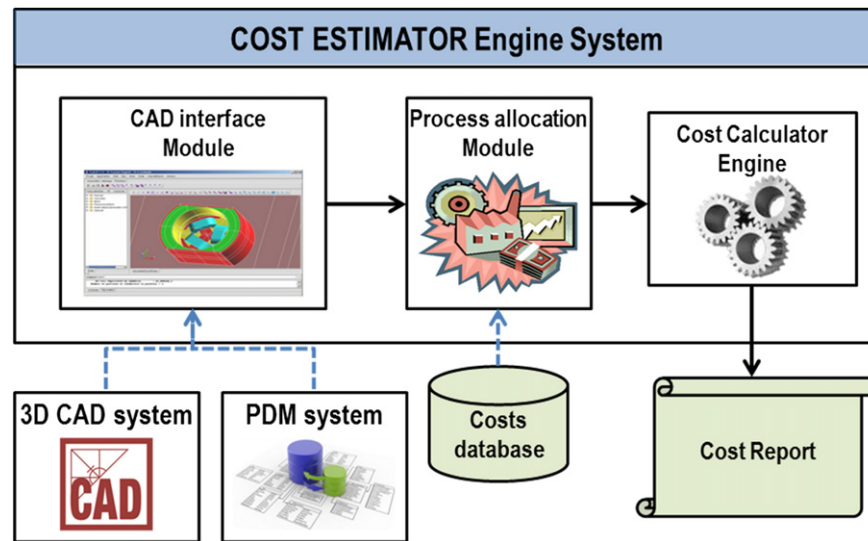


Fig. 5. EROD cost estimation module framework.

- Digital mock-up tool to add attributes and characteristics to 3D models.
- Documentation management tool for rapid information exchange with versioning management and modification traceability.
- Audio-video communication tool to open virtual conferences among members in different places.

The Collaborative module of the EROD Platform provides all these functionalities. The collaborative session can be also useful to involve environmental experts or specialists in energy efficiency of electric motors in the project evolution. The integration of this module and all the related functionalities in the EROD Platform makes the design process of electric motors complete and efficient.

4. Results and discussion

The EROD platform is currently being used to support the design process of five Italian companies involved in the production of new energy efficient electric motors for different applications: cooker hoods, washing machines, air cooler evaporators, electric vehicles and machine tools. The developed electric motors are innovative solutions in each of the industrial and domestic fields considered. From this testing phase it is clear that the use of the EROD platform leads to considerable improvements in the new solutions, in terms of energy efficiency and sustainability.

The obtained results are presented in Table 1 which compares several motors which are currently used in the European market and new efficient motors which are developed using the EROD platform to substitute the presently used motors. The improvement in electrical efficiency of the new motors for all the considered applications is an important aspect.

In particular, the increase is relevant for small motors such as those used in cooker hoods, whereas the introduction of Brushless PM motors should double the efficiency of the motor. This is a very common application and for this reason this important improvement leads to a considerable reduction in energy consumption. However, it is also very important to note that high power motor efficiency has improved more than 10%, since the industrial sector is currently the largest electric energy consuming field.

Table 1 also shows the reduction of environmental impact between presently used and new motors, calculated by the LCA module of the EROD platform. In this table only the use phase of each motor is displayed because it represents the most critical phase. In fact, in all electrical appliances approximately 90% of the environmental impact is caused by energy consumption during the use phase of its lifecycle (Ashby, 2009) and the results obtained with the experimentation of the EROD LCA module have confirmed the validity of this assertion also for electric motors. The chosen indicator for the environmental impact estimation is the amount of CO₂ emitted into the air. The results demonstrate that the new efficient motors have a low impact compared to the currently used motors. Of course the difference is more evident for high power motors used in electric vehicles and in machine tools. These results highlight the increase in sustainability of the innovative motors and are very important particularly when considering the regulations and the directives issued by National and European Governments to reduce greenhouse emissions and to consequently reduce the global warming.

In the following section two test cases are presented in detail.

4.1. Application 1: cooker hoods

In the cooker hood sector the currently used electric motors have very low efficiency. In particular the most common solutions

Table 1
Comparison between currently used and new motors.

Application	Currently used motor	New motor	Efficiency improvement	CO ₂ saving per 1 h of use [kgCO ₂ eq.]
Cooker Hoods	Single-phase asynchronous	Brushless PM	+35%	0.126
Washing machines	Three-phase asynchronous	Synchronous reluctance	+20%	0.0366
Air cooler evaporator	Shaded poles	Brushless PM	+31%	0.0594
Electric vehicles	Three-phase asynchronous	Wound rotor synchronous motor	+12%	1.8
Electric spindles	Three-phase asynchronous	Brushless PM	+13%	0.82

are the shaded poles motor and the asynchronous single phase motor. Though these motors provide an efficiency of 30–35% at most (about 25% for shaded poles), they are widely used due to their very low production costs.

In recent years, the European Parliament has issued some directives and regulations regarding the production and commercialization of only high efficient EuP (Energy using Product) to reduce the global energy consumption and gas emissions. The scope of these directives is the introduction of an Energy label for every domestic application. Since the electric motor is the most energy consuming component in cooker hoods, improving the efficiency of electric motors is fundamental to elevate the efficiency class of the entire product.

In this context, the EROD Platform has been tested to design a Brushless PM motor for high quality cooker hoods. The new configured motor has a double efficiency in comparison with the current most used motors.

The first stage of the design process is the evaluation of four different solutions: Brushless PM motor with interior magnets, External rotor Brushless DC motor with surface magnets, Synchronous reluctance motor and Brushless PM motor with surface magnets.

Thanks to the Knowledge Based system, the evaluation of the above design solutions is rapid. The platform is able to configure the 2D model automatically, recovering information from the databases. The user only needs to set several parameters into the web-based interface (Fig. 6), such as materials or geometrical dimensions of the stator, of the stator slots and of the magnetic rotor. When configuration of the model has finished, the FEA simulator, which is completely controlled by the platform, automatically evaluates the electromagnetic performances of the new motors. In this case the best solution is obtained with the External rotor Brushless DC motor with surface magnets.

The DFEE module of the EROD platform is used to optimize this solution. The evaluation of the losses in the various parts of the electric motor permits the main causes of these losses to be understood. For this motor the main causes of losses retrieved by the system are stator and rotor losses. The variation of some input parameters, such as type and thickness of lamination steel and height of the stator core, allows the required performances to be reached and improves energy efficiency, which reaches 73.38% at

2400 rpm, a remarkable value considering the small size of the motor.

From an economical viewpoint, one of the greatest costs of Brushless PM motors is related to the materials and in particular to the hard magnet used in the rotor. The cost analysis performed by the integrated Cost Estimation module permits a rapid evaluation of the production costs for more than one solution. In this case the solution adopted is using a Ferrite magnet, which has worse magnetic characteristics in comparison with other materials such as rare earth magnets, but a reasonable cost.

Finally the Co-Design module is used for a collaborative session among subjects involved in the above described design process. The CAD data sharing session (Fig. 7) permits the configured model to be evaluated, not only independently but also integrated in the whole cooker hood.

4.2. Application 2: washing machine

The second case study is another important domestic appliance: the washing machine. In this sector the energy label has been applied for many years, but now it has become increasingly necessary to eliminate the less efficient products from the market. Nowadays, the tendency is to abolish the low class labels (B and C) and to offer final users not only A-class products but also A-30% or even A-50% washing machines.

The energy consumption of a washing machine is affected by many factors (washing efficiency, water temperature, etc.). However, the efficiency of the electric motors has a fundamental importance, considering the reduction of water temperature and of cycle time in recent years. Therefore, it is necessary to design new efficient motors to improve the performance of the currently used universal motor and asynchronous three-phase motor.

The new design solution, configured with the EROD platform, is a synchronous reluctance motor. The use of the Knowledge Based system combined with the integrated FEA software permits the evaluation and simulation of an innovative kind of motor with a permanent magnet (Ferrite magnet) in the flux barriers of the rotor. The use of the DFEE tool for the evaluation of the various kinds of losses in the motor model allows the optimization of the dimensions of flux barriers in order to obtain further improvement in efficiency. A successive structural analysis confirms the resistance of the rotor laminated structure. The electromagnetic

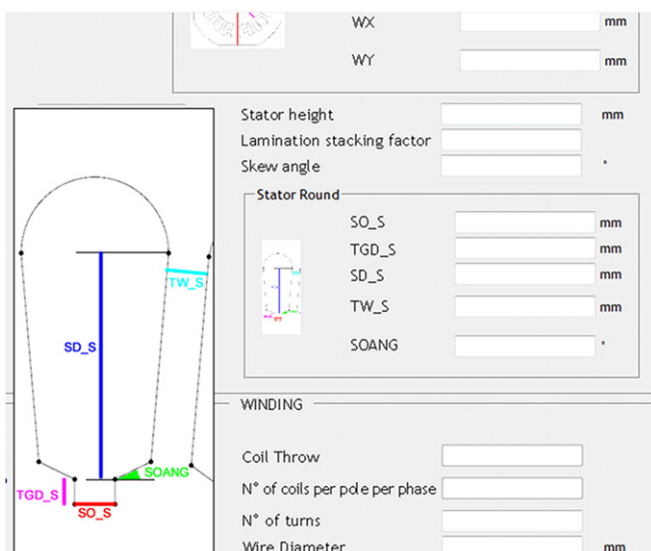


Fig. 6. EROD platform user interface.

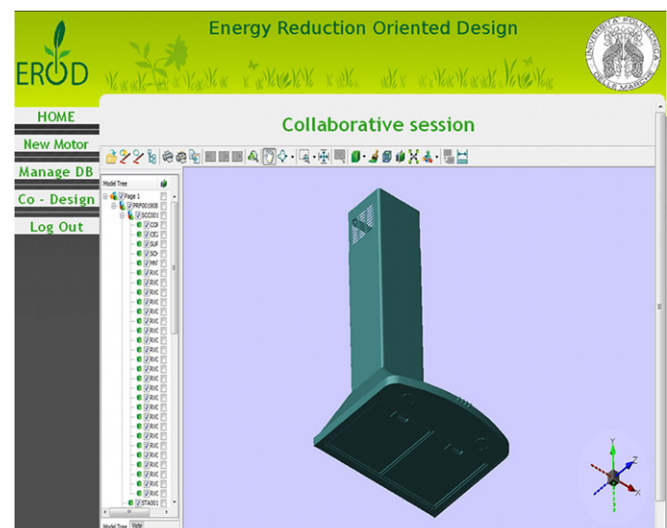


Fig. 7. CAD sharing session of a cooker hood 3D model.

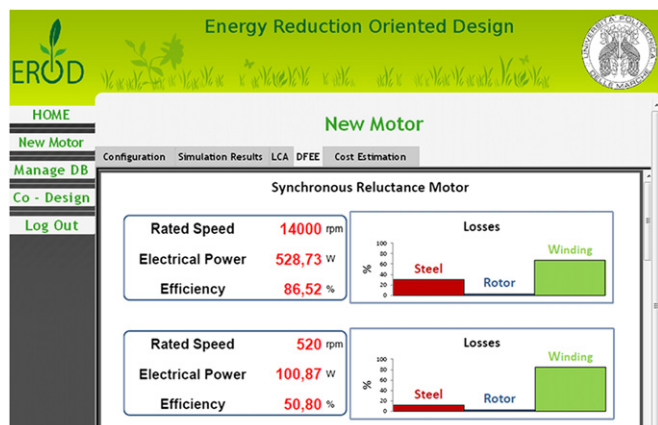


Fig. 8. Performance and loss evaluation of the synchronous reluctance motor.

performances obtained for the optimized motor in different work points (14,000 rpm for spin-dryer and 520 rpm for washing) is presented in Fig. 8.

In addition, the use of the LCA module permits the evaluation of the environmental impact of the innovative motor, both in production and in use phase (Fig. 9). In the following diagrams the indicators chosen for the impact estimation are the consumption of Fossil Fuel and Mineral Resources and the quantity of CO₂eq emitted into the air.

4.3. Discussion

The two test cases, explained above, show the potentiality of the EROD platform in the development of new efficient and sustainable motors.

In order to demonstrate the effectiveness of the EROD platform, a comparison between the “traditional” design process, commonly applied by electric motor manufacturers, and the EROD methodology is provided in Table 2.

The first important advantage of the EROD methodology is the possibility for companies to easily introduce the concept of Design for Environment into their product development process. In fact, the LCA Module and DFEE Module are respectively dedicated to the sustainability and to the efficiency of electric motors.

Even if the focus of the EROD platform is on sustainability, another relevant aspect is the full integration of several tools in the same user-friendly interface. This certainly makes the design

Table 2

Comparison between “traditional” design process and EROD methodology.

	“Traditional” design process	EROD methodology
Sustainability	General purpose tools	LCA module dedicated to electric motors
Efficiency	General purpose tools	DFEE module dedicated to electric motors
Integrated approach	Tools not integrated	Full integration of several tools
Usability	User interfaces of commercial tools	Univocal user-friendly EROD web-based interface

process faster compared to the traditional one, on account of the reduction of errors and repetitive iterations in the optimization phase, and finally increases the quality of new products, which can be simultaneously analysed from different point of view. Moreover, this design process is repeatable because the company know-how is shared among all designers and among design departments.

The main advantages in the use of the EROD methodology can be summarized as:

- Efficient documentation sharing and time-to-market reduction;
- Engineering expertise conservation;
- Repeatable design process;
- Full storage of documentation (files, CAD models, reports, etc.);
- Integration of several analysis tools to increase the sustainability of new products and to control other aspects (performance, costs, ...);
- Quality improvement;
- Cost reduction of design activities.

5. Conclusions

Electric motors and machines are one of the most important functional groups which need to be considered to obtain a significant global electrical energy consumption reduction. The design of electric motors needs standardization to eliminate the inefficiency and improve the quality of configured products. Furthermore, there is an increasing need to also consider the environmental aspects right from the early design stage in order to obtain electric motors optimized not only in terms of performance but also in terms of environmental sustainability.

For this reason this paper proposes a semi-automatic web-based platform called EROD which aims to support the whole design process of eco-efficient electric motors. The main focuses of the system are the efficiency and the sustainability of electric motors. However, the integration of 5 modules in the same user-friendly GUI permits rapid configuration and simulation of new products, the simultaneous verification of other important design aspects such as costs, and facilitates the collaboration among remote users involved in the process.

The proposed test cases demonstrate the robustness of the developed software system, which enables environmental aspects to be integrated in the traditional design process and also makes a considerable saving in terms of time, and in consequence, of costs correlated to the design activities. The innovative motors, designed for application in cooker hoods and in washing machines, exhibit relevant improvements in terms of energy efficiency and also sustainability, in comparison with the motors currently used for the considered applications.

Future developments will be dedicated to integrate new tools for the verification of other important design aspects, such as noise or thermal aspects which are very important in the field of electric motors. Also a new software tool for the analysis of End of Life

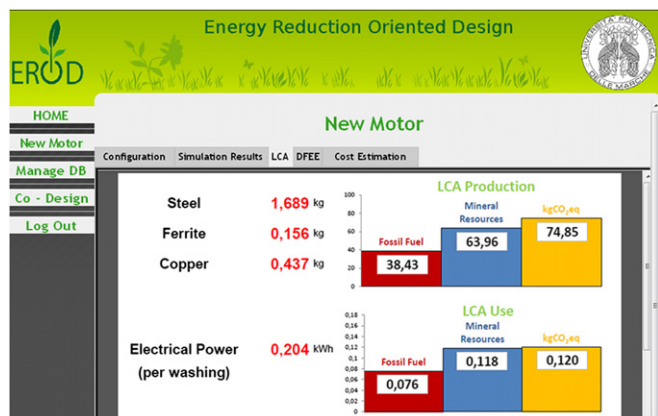


Fig. 9. LCA evaluation of the synchronous reluctance motor with interior permanent magnet.

strategies dedicated to the electromechanical product and the related electric motors will be integrated, to favour the closed-loop lifecycle. Finally, further experimentation in the context of further complex real design processes will allow the identification of the software modules to be optimized.

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References

- Aoe, T., 2007. Eco-efficiency and ecodesign in electrical and electronic products. *J. Cleaner Prod.* 15, 1406–1414.
- Ashby, M.F., 2009. *Materials and the Environment – Eco-Informed Material Choice*. Butterworth-Heinemann, Oxford, United Kingdom.
- de Almeida, A.T., Ferreira, F.J.T.E., Fong, J., Fonseca, P., 2008. EUP lot 11 motors final Report February, Coimbra, Portugal.
- Enerdata, 2011. Global energy statistical yearbook. www.yearbook.enerdata.net (accessed 20.10.11).
- European Commission – Motors Study Group, 1996. *Actions to Promote Energy-efficient Electric Motors*. Brussels, Belgium.
- European Commission, 2010. *EUROPE 2020 – A Strategy for Smart, Sustainable and Inclusive Growth*. Brussels, Belgium.
- European Commission – Joint Research Centre, 2011. ELCD core database version II. lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm (accessed 03.08.11).
- European Parliament and Council, 2002a. Directive 2002/96/EC on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union.
- European Parliament and Council, 2002b. Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). Off. J. Eur. Union.
- European Parliament and Council, 2005. Directive 2005/32/EC establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council. Off. J. Eur. Union.
- European Parliament and Council, 2008. Directive 2008/28/EC amending Directive 2005/32/EC establishing a framework for the setting of ecodesign requirements for energy-using products, as well as Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC, as regard the implementing powers conferred on the Commission. Off. J. Eur. Union.
- European Parliament and Council, 2009. Directive 2009/125/EC establishing a framework for the setting of ecodesign requirements for energy-related products. Off. J. Eur. Union.
- Fan, J., Zhang, C., Wang, Z., Dong, Y., Nino, C.E., Tariq, A.R., Strangas, E.G., 2010. Thermal analysis of permanent magnet motor for the electric vehicle application considering driving duty cycle. *IEEE Trans. Magn.* 46, 2493–2496.
- Ferreira, F.J.T.E., de Almeida, A., 2009. Large-scale downsizing of induction motors requiring stator rewinding as a low-cost strategy to save energy and extend motors lifetime. In: *Proc. of the Inter. Conf. on Energy Efficiency in Motor Driven Systems (EEMODS'09)*.
- Ferreira, F.J.T.E., de Almeida, A.T., 2012. Induction motor downsizing as a low-cost strategy to save energy. *J. Cleaner Prod.* 24, 117–131.
- Goedkoop, M., Spriensma, R., 2000. *The Eco-indicator 99-A Damage Oriented Method for Life Cycle Impact Assessment Methodology*, second ed. PRé Consultants B.V., Amersfoort, Netherlands.
- Hamdi, E.S., 1994. *Design of Small Electrical Machines*. Wiley, New York, United States.
- IEC 60034-30, 2008. *Rotating Electrical Machines – Part 30: Efficiency Classes of Single-speed, Three-phase, Cage-induction Motors (IE-code)*.
- IEC/TS 60034-31, 2009. *Rotating Electrical Machines – Part 31: Guide for the Selection and Application of Energy-efficient Motors Including Variable-speed Applications*.
- ISO/TR 14062, 2002. *Environmental Management – Integrating Environmental Aspects into Product Design and Development*.
- ISO 14006, 2011. *Environmental Management Systems – Guidelines for Incorporating Ecodesign*.
- ISO 14040, 2006a. *Environmental Management – Life Cycle Assessment – Principles and Framework*.
- ISO 14044, 2006b. *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*.
- Jabbar, M.A., Yeo, S.W., 2000. A new architecture of design software for electric motors. In: *Proc. Canadian Conf. on Electrical and Computer Engineering*, pp. 360–364.
- Kaebnick, H., Kara, S., Sun, M., 2003. Sustainable product development and manufacturing by considering environmental requirements. *Robot. Com. Int. Manuf.* 19, 461–468.
- Luttropp, C., Lagerstedt, J., 2006. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *J. Cleaner Prod.* 14, 1396–1408.
- Mahlia, T.M.I., Yanti, P.A.A., 2010. Cost efficiency analysis and emission reduction by implementation of energy efficiency standards for electric motors. *J. Cleaner Prod.* 18, 365–374.
- Pyrhonen, J., Jokinen, T., Hrabovcova, V., 2008. *Design of Rotating Electrical Machines*. Wiley, New York, United States.
- Platcheck, E.R., Schaeffer, L., Kindlein Jr., W., Cândido, L.H.A., 2008. Methodology of ecodesign for the development of more sustainable electro-electronic equipments. *J. Cleaner Prod.* 16, 75–86.
- Saidel, M.A., Ramos, M.C.E.S., Alves, S.S., 2010. Assessment and optimization of induction electric motors aiming energy efficiency in industrial applications. In: *Proc. of the XIX Int. Conf. on Electrical Machines (ICEM)*, pp. 1–6.
- Scutaru, A., Negoita, R., Ionescu, R.M., 2010. Three-phase induction motor design software. In: *Proc. of the IEEE Int. Conf. on Automation Quality and Testing Robotics (AQTR)*, pp. 1–4.
- Torrent, M., Martinez, E., Andradá, P., 2011. Life cycle analysis on the design of induction motors. *Int. J. Life Cycle Assess.* 17, 1–8.
- United Nations – World Commission on Environment and Development, 1987. *Our Common Future*. Oxford University Press, London, United Kingdom.
- Wu, S., Song, L., Cui, S., 2007. Study on improving the performance of permanent magnet wheel motor for the electric vehicle application. *IEEE Trans. Magn.* 43, 438–442.