Management and Production Engineering Review
Volume 9 • Number 3 • September 2018 • pp. 79–89
DOI: 10.24425/119537

RECYCLING-ORIENTED ECO-DESIGN METHODOLOGY BASED ON DECENTRALISED ARTIFICIAL INTELLIGENCE

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Received: 6 August 2018
Accepted: 6 September 2018

Abstract

In recent years, due to the growing importance of eco-design and tightening EU regulations entrepreneurs are required to implement activities related to environmental protection. It influences the development of methods and tools enabling the implementation of eco-design into practice, which are increasingly used by modern information technologies. They are based on intelligent solutions that allows them to better match the requirements of designers and allows for the automation of processes, and in some cases they are able to do the work themselves, replacing designers. Details are useful in areas that require calculations, comparisons and making choices, which is the process of eco-design. The paper describes methodology of pro-ecological product design oriented towards recycling, based on agent technology, enables the design of environmentally friendly products including recycling. The description of the methodology was preceded by a literature analysis on the characteristics of tools supporting eco-design and the process of its development was presented. The proposed methodology can be used at the design stage of devices to select the best product in terms of ecology. It is based on the original set of recycling indicators, used to evaluate the recycling of the product, ensure the ability to operate in a distributed design environment, and the use of data from various CAD systems, allows full automation of calculations and updates (without user participation).

Keywords

eco-design, methodology, decentralised artificial intelligence, agent-based technology.

Introduction

There are two aspects to environmental policies carried out by manufacturers: environmentally friendly products, made of renewable materials, free from harmful substances, recyclable or reusable, and environmentally friendly manufacturing processes, with efficient energy management, low emission of gases, liquids and dust, and appropriate waste management.

The need for environmentally friendly products has driven the development of tools supporting life cycle assessment and environmental impact. It was acknowledged that environmental aspects should be considered early – in the phase of designing the product. Such an approach to design is referred to as eco-design. This paper includes a review of relevant literature and presents the author's own work in this field. From the definition of eco-design through a description of its main characteristics, the author moves on to a review of methods, tools and software supporting eco-design and environmental impact assessment, to finish with a presentation of an original eco-minded product design methodology oriented at recycling.

Eco-design and its main characteristics

Eco-design is considered a design strategy congruent with the concept of sustainable development

[1–4], or a proactive approach to management, which supports product development oriented at reducing the environmental impact yet without compromising such qualities as performance, functionality, appearance, quality or cost [5–7].

Eco-design is also referred to as design for environment, green design, and design compliant with the principle of sustainable development.

The term of eco-design is used in Europe; in the United States, it is referred to as design for environment. Luiz and others [8] note that research into eco-design markedly intensified at the end of the 1990s, with more consideration given to product life cycle and environmental impact [9, 10]. It coincided with an increase in awareness of environmental issues in New Product Development (NPD). Eco-minded product development was acknowledged to be an important part of environmental protection [8, 11]. In 2000, eco-design was for the first time defined as a research area and an organisational practice [4, 12, 13]. At the same time, political and strategic aspects of eco-minded product development [14, 15], as well as product management in the context of the ISO 14000 environment management systems [16, 17], gained momentum. Research into traditional environmental protection-related issues, such as selection of materials [18], consumption of resources throughout the product life cycle, reuse, reconditioning and recycling [19, 20], was paralleled by research into design and use of eco-minded methods and tools [21, 22].

Eco-design has not yet become a common approach adopted in enterprises. In their research into barriers to the implementation of eco-design, Dekoninck and others [23] note that one of the underlying problems is integration of eco-design into the NPD process. Other issues include prioritisation (more pressure is put on reducing costs rather than implementing eco-design), low motivation and resistance of in-house beneficiaries. Implementation of eco-design is hindered by a lack of related cooperation, expertise or eco-design supporting tools. Another barrier is created by the fact that eco-minded designs are far more complex than traditional ones. Their development is more time-consuming, more information is required at the development stage, and there is a higher level of uncertainty of results [8, 24].

As a design strategy, eco-design expands the area of focus of the designer. Apart from functionality, the designer must consider the entire product life cycle, from the concept through to disposal. The design must be developed taking into consideration reduction of energy consumption, elimination of harmful substances, and possible reduction of the use of materials. Product life cycle must be expandable through possible repairs. The product must be made of recyclable materials and designed in a way supporting disassembly (joints must facilitate quick and easy disassemble). Moreover, compatibility of materials in terms of recycling must be taken into consideration [25, 26]. An important constituent of eco-design is maximum possible reduction of the environmental impact in the phase of manufacturing and use [27], taking into consideration the manufacturing system, servicing, overhauls, repairs, etc.

All in all, eco-design is a complex process which requires appropriate management and tools supporting both managers and designers.

Tools supporting eco-design

The "eco-design supporting tool" is defined on an individual basis, depending on the context [21, 28]. Baumann and others [12] define eco-design supporting tools as "any systematic means clustering for dealing with environmental issues during the product development process", i.e. as any method or procedure aimed at integrating the environment into the system (product or service) design.

There exists ample literature on eco-design supporting tools. Pigosso and others have described tools for assessment of the environmental impact throughout the life cycle [5]. Le Pochat, Bertoluci and Froelich have classified and characterised seven basic groups of eco-design supporting tools: LCA, Simplifild LCA, Eco-matrix, Checlist, Eco-parametric tool, Guidelines and Maual [29]. They have also developed the original EcoDesign Integration Method for SMEs (EDIMS) supporting the implementation of eco-design in enterprises.

Of special importance is the life-cycle assessment (LCA). It supports a "cradle to grave" [30] analysis of environmental hazards, including documentation of environmental impact and prioritisation in the process of product improvement, and makes it possible to compare various solutions to a problem [31].

A review of eco-design supporting tools is available in [4]. The authors present tools supporting industrial designers at early stages of product design. A dozen or so eco-design tools are presented and compared in [21]: ABC-Analysis [32, 33] the Environmentally Responsible Product Assessment Matrix (here called ERPA) [34], MECO [35], MET-Matrix [36], Comparing tools Philips Fast Five Awareness [37], Funktionkosten [38], Dominance Matrix or Paired Comparison [32], EcoDesign Checklist [32], Econcept Spiderweb [32], Environmental Objectives Deployment (EOD) [39], LiDS-wheel [36], The Morphological Box [36], Prescribing tools Strategy List [32], Ten Golden Rules [40], Volvo's Black List, Volvo's Grey List, Volvo's White List [41]. The tools are analysed for usefulness in the environmental impact assessment and comparison of various versions in search for the one which best meets environmental requirements. The analysis focuses on simple tools which do not require complex quantitative data; however, their user must be familiar with environmental issues.

One of the latest publications in the "Eco" field is "Eco-tool-seeker" [28]. It reviews tools, methods, standards and directives which may be found useful across company departments in an effort to improve environmental standards. As many as 629 tools are presented and described, grouped into categories and assigned to various business areas (Purchasing, R&D and Product development; QSE (Quality, Safety, Environment), Management and Sustainable Development; Production and Manufacturing; Legal, Sales, Marketing and Communication).

An important part of eco-design support are software tools, reviewed in [25], grouped into two categories: autonomous and CAD system-integrated. The former are databases supporting the work of designers. Most of them require onerous implementation of product structure; those which do not take into consideration product structure, contain only general eco-design guidelines.

The latter are CAD system-integrated analytical tools. They use CAD model-based data for the environmental assessment or product analysis. CAD/LCA integration methods were proposed by [42], who developed an algorithm for data transfer between CAD (SolidEdge) and LCA (SimaPro), and by Gaha et al. [43], who developed a system for data integration based on a database of environmental impact parameters.

The literature describes many prototype tools using CAD-based data for the environmental impact assessment. One of them is DEMONSTRATOR, developed by Mathieux and others [44], which combines the CATIA (CAD) system with the EIME (SLCA) software. Others include EcoFit, developed by Jain [45] – a 3DSmax overlay combining the system with EcoIndicator99 (EI99), or EcoCAD, designed by Cappelli and others [46], which uses CAD-based product structure data for the environmental analysis. DeforDis is a software tool supporting environmental analysis based on the product structure, taking into consideration disassembly. It generates sets of assessment indicators, such as the product or part disassembly indicator [47]. CAST [48] makes it possible to integrate the LCA, including the product life cycle cost analysis, into PLM systems. EcologiCAD, developed by Leibrecht [49], supports assessment of the environmental impact of the product virtual prototype [50].

Commercial CAD systems use dedicated eco-design modules. For example, Sustainable Materials Assistant® from Autodesk Labs, designed to work with Autodesk Inventor® 2009, supports the process of material selection aimed at reducing the environmental impact through ensuring defined performance parameters [51]. SolidWorks Sustainability, one of the applications in the SolidWorks package [52], provides process models and life cycle assessment databases, and works with LCA-based GaBi software [53]. The examples presented above show that CAD software developers have admitted the necessity of taking into consideration environmental aspects at early stages of product design. However, the applications are simply modules closely associated with respective CAD software.

Recycling-oriented product design methodology

Environment-oriented tools and methods are being continuously updated and developed. The number of 150 various methods and tools identified in 2002 [12] soared to 629 in 2017 [28]. It must be noted here, however, that – as defined by Baumann and others [12] – tools include legal acts, standards and legislative acts. The increase has been driven by the tightening up of environmental regulations on one hand and the broadening of environmental awareness of enterprises on the other. A need for efficient yet simple tools supporting assessment of product recyclability has been noted.

The author's original methodology presented further in this paper has been developed to support enterprises designing new products or improving existing ones. Based on decentralised artificial intelligence, and more specifically – on an agent system, it assists in the process of designing environmentally friendly household appliances required to meet specific environmental standards. It may as well be used for designing of other types of products. The solution is one of the CAD system-integrated analytical tools. An analysis conducted by the author demonstrates that these tools are advanced databases of standard guidelines, environmental attributes, data on materials, etc., which support assessment of the environmental impact of the designed product on the basis of CAD system-provided product parameters [49]. Being complex in use, their application is hindered by the required expertise in eco-design from users and multiple functionalities offered [54, 55]. Most of them require manual data transfer from the CAD system, or data transfer is handled by a third-party application [56].

The methodology developed by the author is free from all the above mentioned hindrances. It offers the following functionalities and qualities:

- an original set of recycling indicators designed to assess recyclability,
- operation in a distributed environment and utilisation of data from various CAD systems,
- fully automated computing and updates (without user intervention),
- prompts assisting in the selection of the best product version (in terms of recyclability),
- indicating product components critical for recyclability, comparing various product versions and suggesting the one which offers the highest recyclability potential.

An advantage of the proposed methodology is also support for the recycling cost analysis.

The methodology has been developed based on an original approach consisting of the following steps:

1. analysis of the design process of a selected product taking into consideration environmental aspects,
2. development of the eco-design procedure,
3. specification of the methodology,
4. specification of requirements for the IT system,
5. development of the IT system ontology,
6. design and programming of the agent-based technology IT system,
7. testing and verification of the system.

Ad.1. In the first step, the process of designing an eco-friendly household appliance was analysed. The design process consists of the following phases: *concept and idea, technical design, analysis, construction and testing of the prototype, verification of costs, documentation, manufacturing of the sample batch and product inspection.*

Various factors are taken into consideration in the phase of *concept and idea*, such as market needs, future product development potential, operational and design-related qualities of the product, as well as costs of manufacturing, production volume, and manufacturing technologies. Ideas for the product are generated, analysed and assessed, and a detailed concept is developed. To a certain degree, eco-design is part of the phase, as data on the legislation concerning environmental aspects of designing and construction of products are collected and analysed.

In the phase of *technical design*, which includes the development of the industrial design, construction and technology, the eco-minded approach is manifested through:

- improvement of "material efficiency" through reduction of material consumption, use of materials of low environmental impact or renewable raw materials,
- reduction of energy consumption or use of renewable energy, i.e. improvement of energy efficiency,
- taking into consideration recycling of the product,
- marking of harmful substances.

The aspect of recycling is accommodated into the product design through minimalisation of harmful gases, oils and greases in the product. They are extremely difficult to dispose of and increase the overall cost of the recycling process.

In the process under review, the *analysis* consists in a review of assumptions made for the technical design against guidelines and checklists concerning materials, information on assembly and disassembly, and the database of materials. The product is verified for easy disassembly and marking of materials.

The *construction and testing of the prototype* and *verification of costs* are aimed to identify any possible construction errors, estimate the value in use of the designed product, test the construction in the future operating conditions, assess the construction in terms of the technological load, make the final selection of input materials (taking into consideration the above mentioned recycling requirements), structure and qualities of the surface of particular parts, specify the method and conditions of assembly, and analyse costs of the applied solutions. In order to launch the production of the *sample batch*, it is necessary to collect and develop the design, manufacturing process and environmental *documentation* of the product.

The *sample batch* is manufactured in order to verify whether the manufacturing process compromises any of the product's qualities, as compared to the prototype. The final verification of the design and production process documentation is conducted. In the *inspection* phase, information is prepared for future product users and the manner of disposal of the product at the end of its life cycle is defined.

It follows from the analysis that, to a certain degree, environmental qualities of the product are taken into consideration in the designing phase. In the example presented above, no formal procedure or tools are applied to support the environmental assessment. Instead, focus is put on meeting the general environmental requirements of the design. Considering that product recyclability assessment is the weakest link in the eco-design procedure, further study focuses on eco-minded product design oriented at recycling.

Ad.2. Based on an analysis of the design process and the regulatory requirements following from relevant standards and directives, the author has developed a recycling-oriented eco-design procedure (Fig. 1).

The procedure includes evaluation of all the attributes necessary to conduct an assessment of the product recycling opportunities, such as recyclability of materials, their compatibility and identification, materials incompatible for recycling, harmful and hazardous materials, availability of materials in the product's structure, types and variability of joints, time and cost of disassembly, as well as tools necessary for disassembly. As part of the procedure, aggregated indicators are determined to be used for verification of the product's parameters against applicable eco-design standards, and assessment of recyclability. If need be, the design can be altered during the assessment to achieve the best possible results. The procedure has provided guidelines for the development of an eco-design methodology.

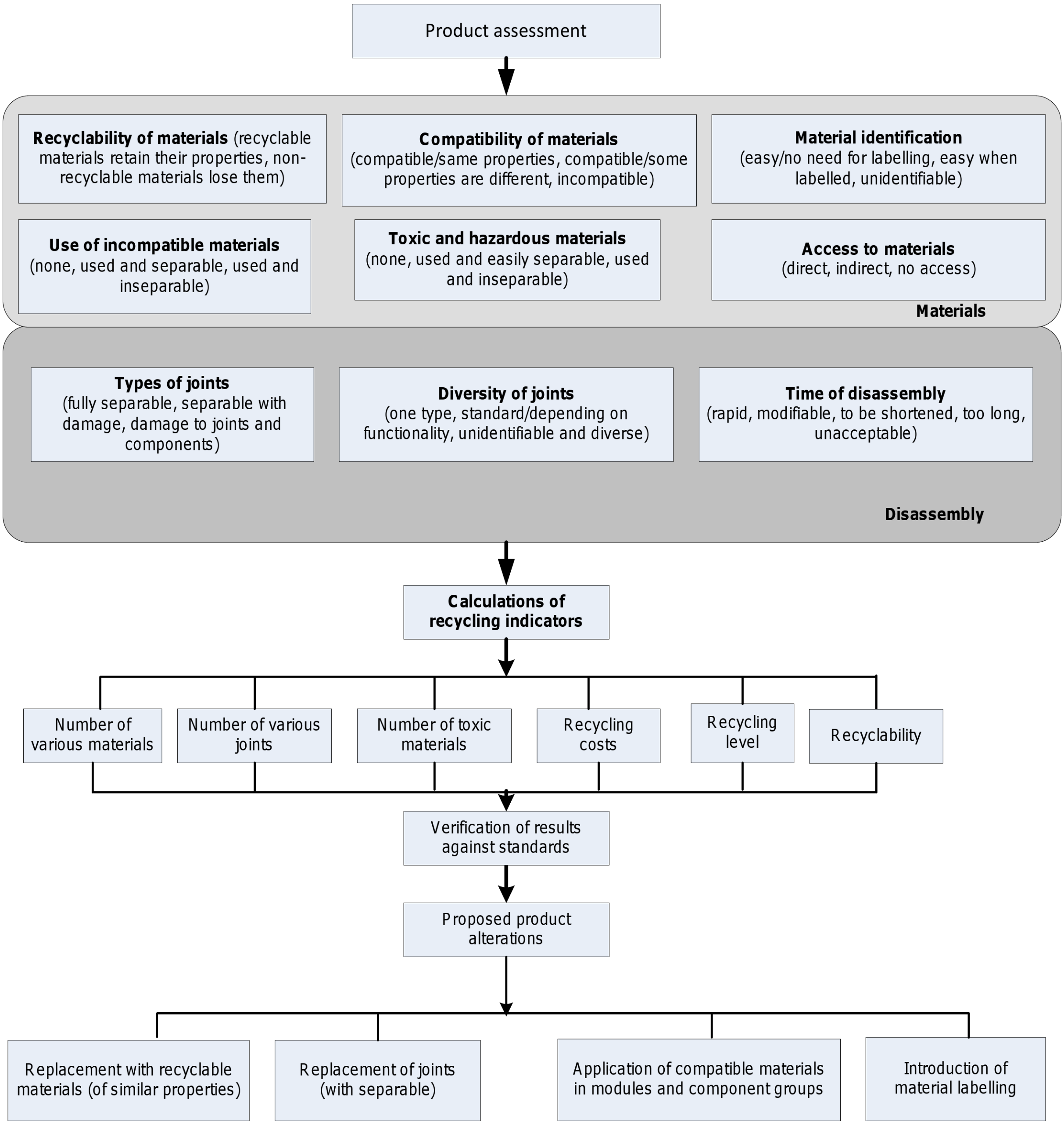

Fig. 1. Recycling-oriented eco-design procedure.

Ad.3. The developed methodology provides for:

- unique recycling assessment measures (or recycling indicators) and calculation of the costs of recycling,
- recycling assessment automation, i.e. prompts and suggestions to improve the recycling parameters during the design process.

The functionalities mentioned above have been implemented into an IT system based on decentralised artificial intelligence (or agent-based technology) [25].

The recycling assessment implemented in the system is based on the unique total recycling indicator (CWR), which is a sum of three constituent indicators: diversity of materials (WRM), diversity of joints (WRP), and recycling level (WPR). The constituent indicators are minimants – the lower the value, the easier the recycling (1)

$$\mathrm{CWR} = \mathrm{WRM} + \mathrm{WRP} + \mathrm{WPR}. \tag{1}$$

The diversity of materials (WRM) indicator is based on the assumption that the smaller the number of different materials, the easier the recycling of the product is.

The diversity of joints (WRP) indicator is based on the assumption that the fewer joints of various types are used, the easier and faster, thus less expensive, the recycling of the product is. Moreover, products with a smaller number of different joints are easier to disassemble, owing to the smaller number of tools necessary for the disassembly.

The recycling level (WPR) indicator shows the proportion of recyclable (reusable) weight of the product to its total weight. It has been defined taking into consideration the recommended minimum recycling levels set forth in Directive 2012/19/EU on waste electrical and electronic equipment [57].

The costs of recycling (income or loss) are estimated according to formula (2). It has been assumed that income is the difference between the total profit from sale of recyclable (reusable) materials and the total costs of disassembly and disposal and utilisation or storage of other materials. If the difference is a negative value, a loss is incurred

$$\mathrm{INCOME\ (LOSS)} = \sum_{i=1}^{n} \mathrm{PROFIT} - \sum_{i=1}^{n} \mathrm{COSTS}. \tag{2}$$

Two decisions taken in the design process are supported automatically as part of the recycling assessment: replacement of materials for given product components, and replacement of a fixed joint with a dismountable joint. On the basis of the total recycling indicator (CWR) and classification of product components, the system singles out components whose replacement can improve the overall recyclability. The components suggested for replacement are non-dismountable or made of materials which are incompatible with those of adjacent components. The suggested solution combines a prompt resulting from a static analysis of the product and the behavioural data from the history of suggestions utilised by the designer. All the suggestions previously utilised by the designer serve as useful data for prioritising the generated prompts. For example, the system may prompt to replace material M of component C with one of the recycling-compatible materials X, Y, Z. It follows from the historical data that designers have replaced M with X 10 times, M with Y – 5 times, while M has never been replaced with Z. Therefore, the highest priority will be assigned to the suggestion to replace material M with X. The suggestion to replace material M with Y will be assigned secondary priority, while the replacement of M with Z will be only a prompt.

Ad.4. The procedure presented above has been implemented into the IT system supporting designers in recycling-oriented eco-design. Considering that:

- design-related tasks are often performed by designers working in various physical locations,
- information on components of the product being designed is obtained from particular design team members and forwarded to different locations,
- during the design process, the concept for the product is often modified; therefore, adjustments of the environmental requirements must be made online, and
- automation of certain tasks related to the assessment of product recyclability and the gathering of relevant data has been assumed,

the system has been designed based on decentralised artificial intelligence, or agent-based technology. The basic unit of the system is the agent. There is no clear-cut definition of the term "agent". One of the most popular and acceptable definitions was proposed by Nick Jennings and Michael J. Wooldrige: "[...] an agent is a computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives" [58]. The interpretations of the agent's role are diverse [59, 60] but undoubtedly have the following common features: observation, autonomy, mobility, communication and intelligence [61]. To perform the task it was assigned, each of the programmed agents must have a certain level of intelligence. Specific features of the agents are used in communication technologies [62, 63, 64], data acquisition, aiding operations in distributed environments [65] and decision-supporting systems [66, 67]. Agents were also implemented for modelling and simulation of production systems [68, 69] and for integration of activities in specific manufacturing areas [70].

Considering the above mentioned features of an agent as well as the existing practical applications of agent-based technologies, it seems appropriate to implement the technology in an eco-design supporting system.

Ad.5. The design of the system was preceded by research into the construction of an agent system ontology. A knowledge model was developed, containing a set of definitions describing the state-of-the-art of recycling-oriented eco-design. The process of ontology construction consisted in actions aimed at: identifying notions (defining classes), constructing structures of notions (arranging classes in hierarchical structures) and modelling relations as attributes of classes (defining qualities and sets of values for particular classes). The ontology was built to facilitate data acquisition and utilise the knowledge gathered in the performance of eco-design projects. Owing to the ontology, basic information necessary to design an environmentally-friendly product is readily available and easily accessible.

Answers to a defined set of questions facilitated defining the field of ontology and ensured that software agents can perform certain actions aimed to conduct the recyclability assessment. The ontology served as a basis for the design of the agent-based system.

Ad.6. The main functionalities of the agent-based system comprise:

- analysis of the product structure, taking into consideration logical correctness of joints between product components,
- automated calculation and updating of the weight of product components,
- automated identification of user-introduced alterations,
- calculation of statistics and recycling indicators for the entire product and its components, including the costs of disassembly,
- detection of changes to the recycling level and recycling indicator – a functionality identifying alterations to the product design which have an impact on improvement or deterioration of the recycling level and recycling indicator values or make the values go below the permissible minimum,
- detection and indication of components which are part of non-dismountable joints and are incompatible with one another,
- detection and indication of components which have the highest negative impact on the recycling level,
- generation of numerical lists of materials and types of joints used,
- detection and warning of use of hazardous materials,
- automated generation of prompts and suggested alterations to materials or joints, aimed at improving the recycling parameters of the designed product,
- generation of lists and reports.

The agent-based system provides the following information for each component of the designed product: recycling indicators, weight, information on disassembly and compatibility of materials among connected components (including information on whether it is possible to disconnect components). Figure 2 presents a sample screenshot from the agent-based system with a calculation of recycling parameters in the process of design of a household appliance.

The agent-based system conducts analyses on the basis of data from any source or any CAD 3D system.

The system's software supports eighteen types of agents. Each agent has a strictly defined role. The functions of several selected agents are presented below:

- the interface agent – responsible for monitoring the designer's work, traces the designer's activity, detects alterations to the CAD 3D-based design, transfers data for analyses,
- the conversion agent – converts data from the CAD 3D to the agent-based system,
- structural agents – a team of agents which scan the tree of the designed product and update its recycling parameters,
- measure agents – calculate particular measures of the product (the recycling level agent, joint diversity agent, material diversity agent),
- design alteration agent – compares the current and previous versions of the design and generates lists of alterations,
- prompt agent – conducts algorithmic analyses and generates lists of possible alterations to the design aimed at improvement, etc.

The agent-based system interface has been developed in two language versions, Polish and English.

Ad.7. In order to test the system, the Recycling-based Product Model (RmW) has been developed, based on the CATIA CAD 3D software. The RmW consists of a standard 3D geometrical model, an extended product structure, extended material attributes, dismounting attributes (data on the dismounting process) and the product categorisation data. The RmW and the data implemented in the agent-based system have provided sufficient informa-

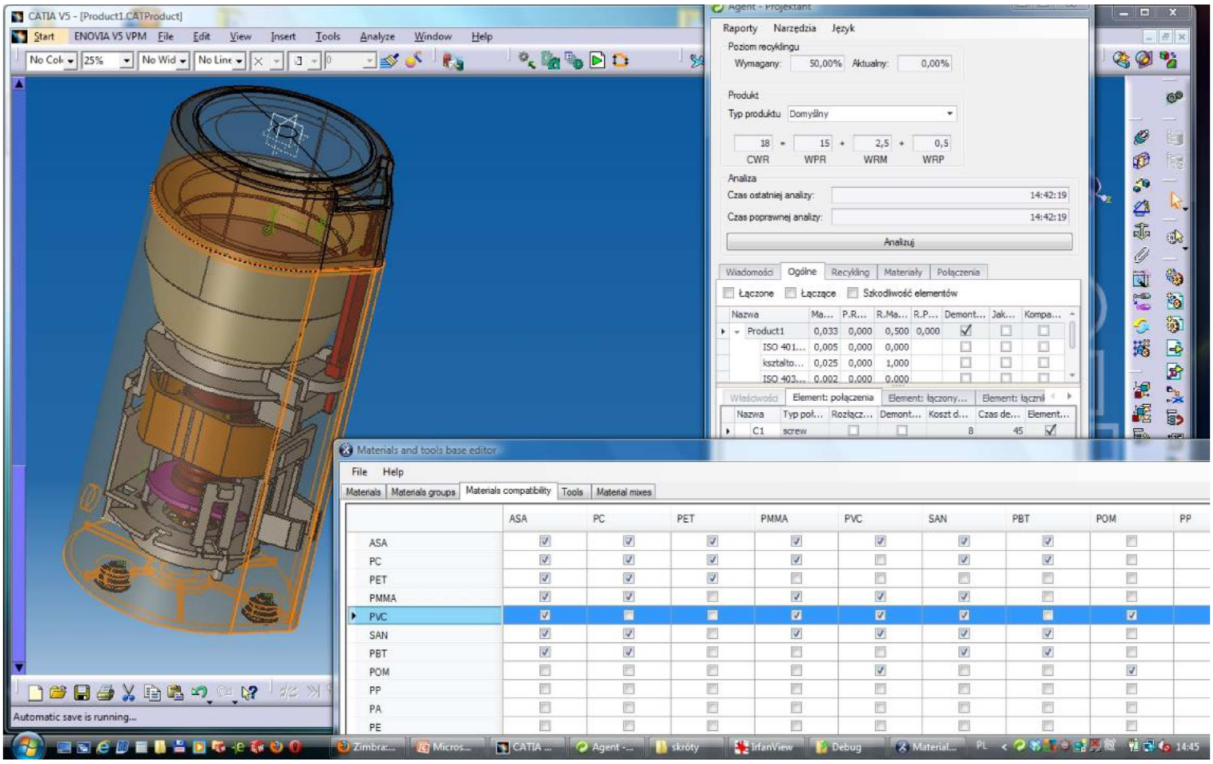

Fig. 2. Sample screenshot from the agent-based system.

tion to conduct an assessment of the product's recyclability. The developed system has been tested with the use of real data provided by manufacturers of household appliances. It has been implemented for one of Poland's leading household appliance manufacturers. The system has been tested for usefulness, reliability, speed (support of advanced product designs) and simplicity of operation.

Its main advantages and new features, as compared to other existing systems, include: ongoing (online) supervision of recycling parameters, support of online comparison of various versions of the product, automated prompts and suggestions aimed to improve recycling parameters, no need for manual data implementation, analysis on the basis of data acquired from various sources (cooperation with various CAD systems).

Conclusion

A review of literature on eco-design tools has demonstrated a demand for new solutions targeted at designers' requirements. The eco-design product methodology presented in this paper is the resultant of a number of research projects in the eco-design area. It introduces a new approach to design, which takes into consideration environmental issues related to the recycling assessment. Based on artificial intelligence, it works autonomously thus saving the designer's time. The agent-based technology applied provides for easy expansion of the system. New functionalities can be added through programming new agents for cooperation with the existing ones.

Further works on the development of the methodology will be focused first on functional expansion of the IT system, and next on evaluation of opportunities for its application in the area of disassembly, with the use of augmented reality.

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