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SPECIAL SECTION

End-of-life design aid in PLM environment using agent technology

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Abstract. End-of-life oriented product design (design for recycling, disassembly, remanufacturing) is considered an emerging area in modern approach to product lifecycle. Numerous tools aiding the design process have been developed, but many of them work as independent computer applications. The presented solution is strictly integrated with typical design environment: CAD 3D and PLM systems. This paper presents the application of agent technology operating in the PLM environment to support the design process. The architecture of the proposed solution is shown. A method of product assessment, based of three indicators, is described. The example analysis of real household appliance is presented.

Key words: design for end-of-life, agent technology, PLM.

1. Introduction

For many years, the transformation of manufacturing companies has been shaped by the global economy and customer market. The demands put on the modern manufacture range from product diversity (multiple variants, wide product selection) through the reduction of cost and lead times to the improvement of product quality. Modern manufacturing companies need tools supporting quick decision-making, e.g., regarding new product concepts. One type of such tools are the product lifecycle management (PLM) systems. There are a lot of ways in which manufacturing companies can benefit from the implementation of a PLM system, such as:

- supporting market analyses and new product concept development,
- ensuring legal and safety compliance,
- mitigating the risk inherent in the marketing of new products,
- improving efficiency of R&D employees,
- supporting management of product design and manufacture processes,
- reducing time and costs of the design and marketing of new products while maintaining or even improving quality,
- building a product information database,
- enabling close collaboration of constructors, process engineers, suppliers, co-operators and customers, aimed at improving business and marketing strategies.

Implementation of a PLM system in an enterprise requires complex and tedious configuration of the system individually for every end user. Many enterprises design unique PLM systems customised to their needs. Some of the preconditions for successful implementation of a PLM system include the definition of data flow processes and identification of data. In principle, PLM systems encompass all enterprise areas. However, individual implementations usually cover selected functional areas. Some functional areas of an enterprise are more likely to be supported by a PLM system than others [1]. One of the areas in which PLM support is hardly ever considered is end-of-life of a product (recycling, disposal of reuse) – an area of crucial importance for the management of data indispensable for decision-making. Properly defined and sorted data on, e.g., product recycling or disposal can be used as early as at the design stage to improve sustainability. This paper proposes to expand the functionality of a PLM to include end-of-life aspects, with the use of agent-based technology. PLM system is used for conducting recycling analysis at the design stage of product lifecycle. Its main task is to collect data on designed product and results of analysis conducted by agent system supporting ecodesign [2]. These data are collected and stored by program agent that cooperates with other agents of the recycling assessment system.

2. End-of-life design in product life cycle

The term eco-design, also known as, e.g., ecological or green design, or design for environment, has been in use since the 1990s [3]. Eco-design consists in identifying the environmental aspects of the designed product and including them in the design process at an early stage of product development [2, 4]. This approach to design is aimed at reducing the product's environmental footprint across its life cycle. An eco-designed product is supposed to be sustainable and socially acceptable, and meet environmental requirements [3]. Eco-design enables the reduction of costs of product manufacture and operation, helps improve products and technological processes, drives the reduction of material and energy consumption by products and packaging, helps meet customer expectations as well as create new needs and requirements, and facilitates the reduction

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of costs owing to early verification and modification of the product concept [5]. Eco-design is applied for a wide variety of reasons – from the environmental approach underpinned by high environmental awareness through to the mundane obligation of legal compliance. Nevertheless, the underlying purpose of eco-design, whether indirect or direct, main or secondary, is to mitigate the environmental impact of the product across the life cycle. The sooner it is pursued, i.e., the earlier the life stage at which environmental aspects are considered, the sooner it is achieved. Designers have a range of tools, methods and indicators (e.g. life cycle analysis – L31, life cycle management – LCM, life cycle cost – LCC, control chart, material input per service unit – MIPS, MIT, etc.) based on eco-design guidelines [6]. If those guidelines are followed at early stages of product development, the environmental impact of the product can be reduced by 70 to 90% [7]. What is more, modification of product design and manufacturing process at early stages of product life cycle generates costs low enough to enable multiple changes aiming to achieve the best possible outcome. It should be stressed that the initial 20% of decisions made (those concerning costs and other matters) determines up to 80% of the ultimate results [8]. In the eco-design process, the environmental impact of materials and resources, as well as the length of life, are taken into consideration. The designer needs to make choices and take decisions at early stages of the design process to minimise the product's environmental footprint. Decisions made at early stages of the design process determine the product's properties and operation, as well as the costs generated at subsequent stages of its life cycle. The ability to explore all the important aspects at the product development phase is crucial for the achievement of the desired results (such as reduction of the environmental and financial costs of production processes, mitigation of the environmental impact at product retirement, etc.) [9].

One of the approaches to eco-design is the end-of-life design, aimed to maximise the reuse of materials after product retirement. Waste from retired products can be utilized in one of the following ways:

- multiple reuse of the product following regeneration,
- reuse of raw materials without altering their composition or state,
- reuse of raw materials with alteration of their composition or state,
- end-of-life design.

End-of-life design is of great relevance to the environment, as it reduces the amount of waste on one hand, and decreases the consumption of natural resources on the other. The term "end-of-life design" is used alternately with "design for recycling".

3. PLM system in the project life cycle

Data management across the product life cycle can be supported by a product lifecycle management (PLM) system. In principle, PLM systems provide functionalities in four key areas [10]:

- idea, specification, technical requirements and concept (area 1),
- product design, testing and analysis (area 2),
- implementation (area 3),
- after-sales service and maintenance (area 4).

An alternative approach to the product life cycle takes into consideration eco-friendliness and environmental protection [11]. The environmental management practices utilize the product life-cycle assessment, defined by the US Environmental Protection Agency as an objective technical tool to evaluate the environmental impact of a product, process or activity holistically, across its entire life cycle [12]. The areas listed above can encompass eco-design. In areas 1 and 2, eco-design may concern the selection of material (e.g. secondary or regenerated raw materials) or technology – designing a technological process so as to minimise energy and water consumption and reduce waste, flue gas or other by-products harmful to the environment. End-of-life design, as part of eco-design, facilitates quick and environmentally-friendly disassembly of the product. Eco-design also relates to area 4, which can be expanded to include disposal at the end-of-life. Here, the task is to create a product which can be still utilized at its end-of-life, i.e., dismounted so that certain components can be reused, worn out parts – recycled, and dangerous waste – disposed of safely. A close link between areas 1 and 2 is obvious. The existing PLM systems do not support environmental assessment or suggest environmentally friendly design solutions; in other words, they do not support end-of-life design.

The functionality of PLM systems extends far beyond data management. The systems are used to support activities undertaken as part of global cooperation, allowing for the achievement of competitive advantage. Typically, the functionality of a PLM system is described as the support of businesses in the process of product development from concept through design to production. PLM systems enable the management of product portfolio and production process, creation of product concept and design of the product, as well as management and analysis of legal compliance [13]. The 2017 research shows that the number of organisational departments which were accessible through a shared platform of data made available by a PLM system increased significantly: design 41%; development 51%; production preparation 40%; production 35%; maintenance 34%; marketing 36%. The challenges posed by Industry 4.0 make further development of PLM systems inevitable. The systems are bound to be transformed into product innovation platforms facilitating efficient cooperation, a holistic approach to the production process, and integration of quality and service data. An analysis of the PLM systems described in the literature shows that the environmental aspect is left out. As the name suggests, a product lifecycle management system, in terms of its functionality, should take into consideration all data regarding product life cycle, including the environmental data, especially those which enable the design and manufacture of an environmentally friendly product.

This effect can be achieved through an extension of the PLM system's functionality to include the product's end-of-life. For successful product life cycle management, communication and cooperation among all parties engaged in the product creation, especially in the management (control) of the process flow, are of utmost importance. Regardless of importance or type, each piece of information in the form of a document should have a place assigned in the system. Each piece of data should be accessible by anyone who needs it to proceed with their work. These objectives can be achieved with a single database, accessible to authorised users from various locations, facilitating the workflow design for better control and safety. This is especially important when data created at one stage of the design process are used for decision making at a subsequent stage – as in the case of eco-design. End-of-life attributes properly defined at the design process will be used for the decision-making at the end-of-life. In view of the above, an attempt has been made to implement attributes describing the environmental properties of a product in a PLM system.

The solution proposed in this article is an attempt to extend the functionality of a PLM system to include environmental data management. Taking into consideration the current trends in the development of the PLM systems, the objective has been achieved with the application of intelligent agent-based IT technologies.

4. Overview of program agents

In the proposed solution, agent system technology was used. The beginnings of research into program agents date back to the 1990s, when it accompanied the development of distributed decision support systems. The subject matter of agents and multi-agent systems remains relevant today and research work into agent-based technologies is still underway. Multiagent systems owe their popularity to the Industry 4.0 concept, based on the assumption of system integration and creation of networks integrating human beings and digitally controlled machines with the application of the Internet and information technologies. The idea underpinning Industry 4.0 is the unification of the world of machines with the Internet and information technologies. Agent systems can speed up the practical implementation of Industry 4.0 [14]. Program agents are capable of making autonomous decisions and taking goal-oriented actions in many applications [15–17]. Applications based on agent technology may range from small, customized systems, such as email filters, to huge, complex systems [18, 19] utilized in, e.g., air traffic control [20–22]. Agent systems are aso applied in management and process control, i.e. business processes [23]. Multiagent solutions have a huge potential for solving various problems that are not directly connected with the given industry, i.e. formation control [24] or population-based global optimization meta-heuristics [25, 26].

The word "agent" originates from the word "agency", defined as the capacity to take autonomous action oriented at the achievement of one's objectives [27, 28]. There is no explicit definition of the agent; the existing definitions are context-dependent and focus on various aspects of the agent-based technology. One of the most commonly referred to definitions of the agent is the one provided by Wooldridge and Jennings [29], who described the agent as a computer or hardware system characterized by autonomy, social ability, reactivity and pro-activeness. According to Wooldridge and Jennings, the agent is "a computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives." According to IBM, the creator of many software programs utilizing the agent-based technology, "intelligent agents are software entities that carry out some set of operations on behalf of a user or another program with some degree of independence or autonomy, and in so doing, employ some knowledge or representation of the user's goals or desires" [30].

Work [31] refers to a number of other definitions of the agent, which contain descriptions of some of the desired features of an intelligent agent. The author has computed how often the agent's features considered as desired occurred in a number of selected definitions (see Table 1).

Table 1
Occurrence of particular agent's features [31]

Occurrence	Feature
9	Reactivity
9	Autonomy
8	Computer program
7	Drawing conclusions
7	Acting intentionally
6	Cooperation
5	Taking long-term action
3	Adaptability

It follows from the data in Table 1 that the most desired features of the agent are reactivity and autonomy. Reactivity is the agent's capability to take action resulting from changes in its environment. The agent needs a picture of the surrounding reality and effectors capable of reacting to changes. The picture of the surrounding reality can be built in two ways: by means of various sensor monitoring the agent's environment, or by means of an environment model (embedded in some agents). The model describes the way in which the agent's environment changes (both independently of the agent and under the influence of its actions). The model takes over for the sensors, building a picture of the environment that includes those parts of the environment which are beyond the sensors' field of view at a given moment. The effectors utilized by the agent for affecting the environment vary depending on the type, structure and intended use of the agent. They may be represented by simple algorithms operated in certain situations, as well as by, e.g., robot's pinchers grabbing and moving objects as required. The autonomy of the agent, the second most frequent feature, enables the agent to perform tasks assigned to it independently of the ordering party. Agents are capable of achieving the assigned objectives without any intervention from the environment, through autonomous analysis of possible decisions and choice of optimal, in their view, solutions. Autonomy is considered one of the main features differentiating agents from ordinary computer programs. The word "program" appears in the definitions of intelligent agents nearly as often as "reactivity" and "autonomy" – rightly so, in the case of program agents, as every program agent is a program (however, not every program is a program agent) [32]. The ability to draw conclusions is inherent in intelligent agents. It consists in making the most reasonable decisions based on an analysis and observation of the current state of the agent's environment as well as on the archival states, a knowledge base and its ability to predict the effects of future actions. "An agent is perceived as an intermediary, a representative, an entity acting upon authorisation, for the benefit of a third party" [33]. Therefore, many definitions refer to its ability to act intentionally.

The features of agents discussed above, in particular autonomy, reactivity and ability to act intentionally, have been utilized in the management of data, information and knowledge to make them available in the process of eco-design, in view of the entire product life cycle. Design is one of the first stages of the product life cycle, where the Design for X (DfX) assumptions are made. The environmental aspect of the designed product should be taken into consideration at every stage of the product life cycle. Design for environment (eco-design) provides for determining the utilization of the product after its retirement.

5. Proposed solution

The agent technology is used in the solution to support decision-making in the design of recycling-oriented products. The multi-agent system is to conduct a recycling-oriented assessment of a product designed in a CAD 3D (as the part of PLM environment), based on data from a special kind of product model (RpM – recycling product model) made in a CAD 3D system. The role of PLM system is to store the selected group of data necessary for preparation of RpM and integrate the results of the design process with regard to environmental issues connected with the product.

The system for recycling-oriented product assessment is based on the recycling product model (RpM), which was implemented into the CAD 3D system and in the agent system. The authors implemented the recycling-oriented product assessment into the agent system. Agents follow the work of the designer in the 3D CAD system, monitor the changes made in the design, assess their impact on the parameters relevant to recycling, and provide suggestions of product improvements to facilitate recycling. The use of the agent technology and RpM in the application enabled automatic support for the recycling aspect of designing directly from the product model, without having to manually aggregate the parameters relevant to the adopted method of product recyclability evaluation, and to reintroduce them to third party systems [34].

The recycling assessment implemented in the system is based on the unique total recycling indicator CWR, defined as:

$$CWR = WRM + WRP + WPR$$

where:

WRM – diversity of materials indicator,
WRP – diversity of joints indicator,
WPR – recycling level indicator.

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 [35]. All of the indicators are minimants – the lower the value, the easier the recycling.

The main task of an agent system is to support designers in the design process taking into account the end-of-life.

The following agents have been defined in the system:

- designer agent – monitors the designer's operations for changes in the product model,
- hints agent – performs algorithmic analysis of the design and draws up a list of possible changes to improve the product,
- suggestions agent – qualifies hints as suggestions based on the history of accepted hints,
- suggestion history agent – records hints used by the designer,
- materials agent – searches the materials base (embedded in the PLM system) extended to include attributes relevant to the end-of-life, and generates information on compatibility of materials,
- report agent – creates reports based on analysis results,
- knowledge base agent – records knowledge resources required for the generation of hints and suggestions.

The structure of the system is shown in Fig. 1.

For the PLM system to serve as a knowledge base, additional attributes in the classes existing in the PLM system must be defined. The attributes which are missing in typical implementations of the PLM system represent data required for product assessment in terms of its end-of-life. The attributes refer to:

- assigning the product to a particular group of equipment in terms of legal compliance [36], and the required and achieved levels of recyclability and re-usability,
- the parameters of materials relevant to the end-of-life (density, tensile strength, elongation at yield point, processing temperature, dielectric constant, dielectric strength, Young's modulus, water absorption, environmental toxicity, recycling costs).

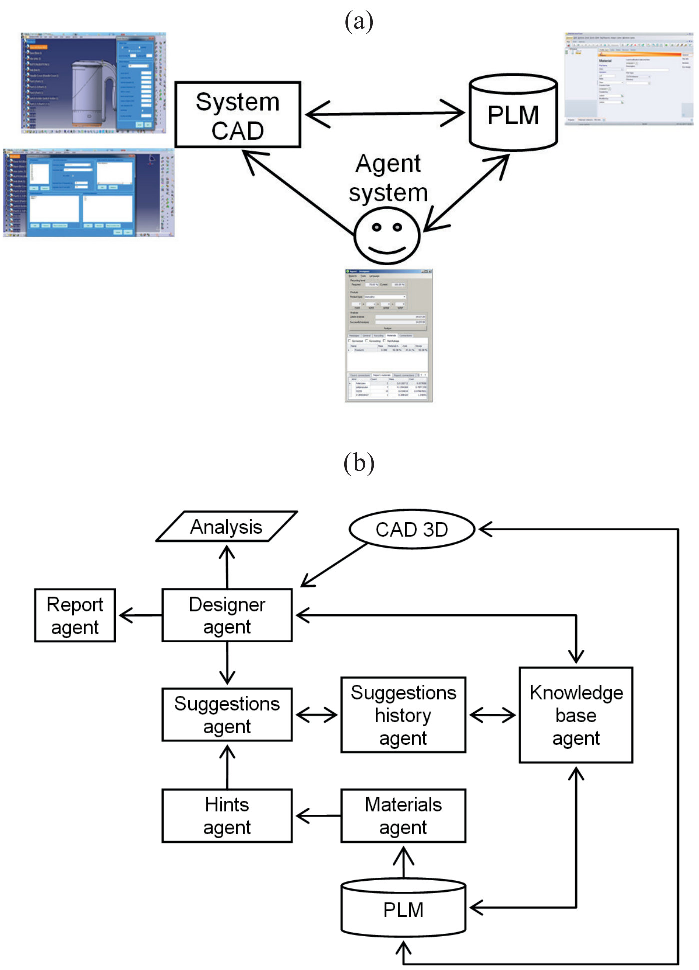

Fig. 1. General (a) and detailed (b) structure of agent system

An example of implementing additional attributes in the PLM Enovia SmarTeam environment is shown in Fig. 2.

The data described above, implemented to RpM, are the basis for the analysis conducted by the agent system. The agent system supporting green, recycling oriented design features the following functions:

- analysis of product structure, including the logical correctness of the defined joints between elements (in order the analysis to be conducted all the parts have to be included in the structure of joints),
- automatic calculation and updating the weight of components,
- detection of changes made to the product model by the designer (generally: user),
- calculating statistics and recycling assessment indicators of the entire product and its individual elements,
- detecting changes in the recycling rate and recyclability indicator – thanks to this feature, the user can see which changes in the product structure caused the increase, reduction or exceeding of acceptable levels and rate of recycling,
- detecting and identifying inseparable and incompatible elements,
- detecting and identifying elements that have the greatest negative impact on the recycling rate,
- creating summary of the used materials and types of joints,
- detecting the use of hazardous materials and warning the user,
- suggestions and tips on changing materials or joints to improve recyclability parameters of the designed product.

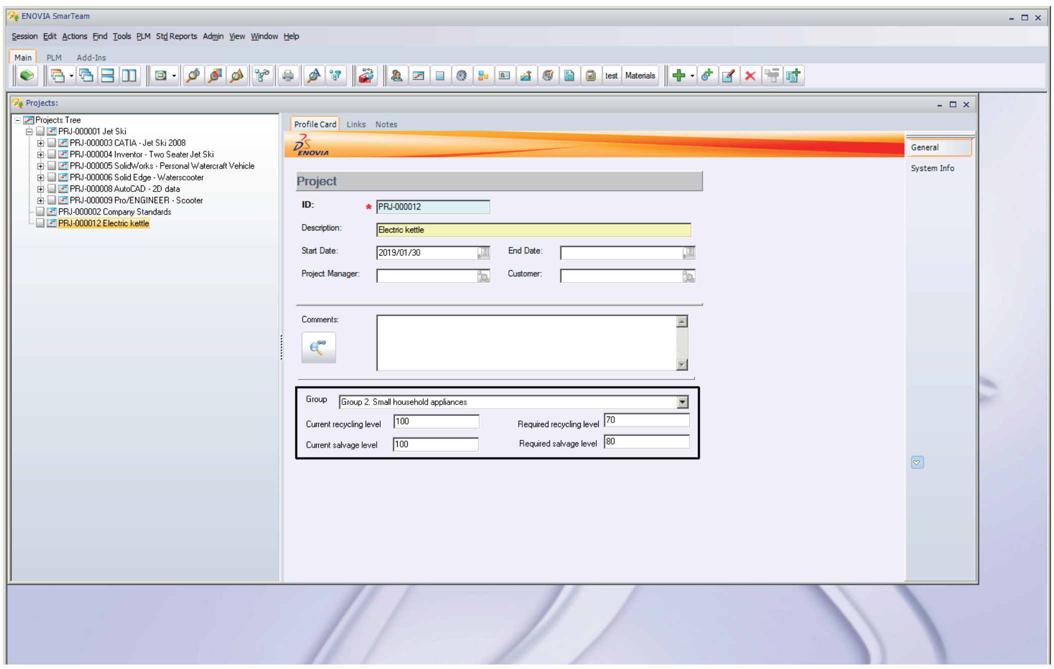

Fig. 2. General view of the project profile card with implementation of additional attributes describing the product in terms of legal compliance (in accordance with [36])

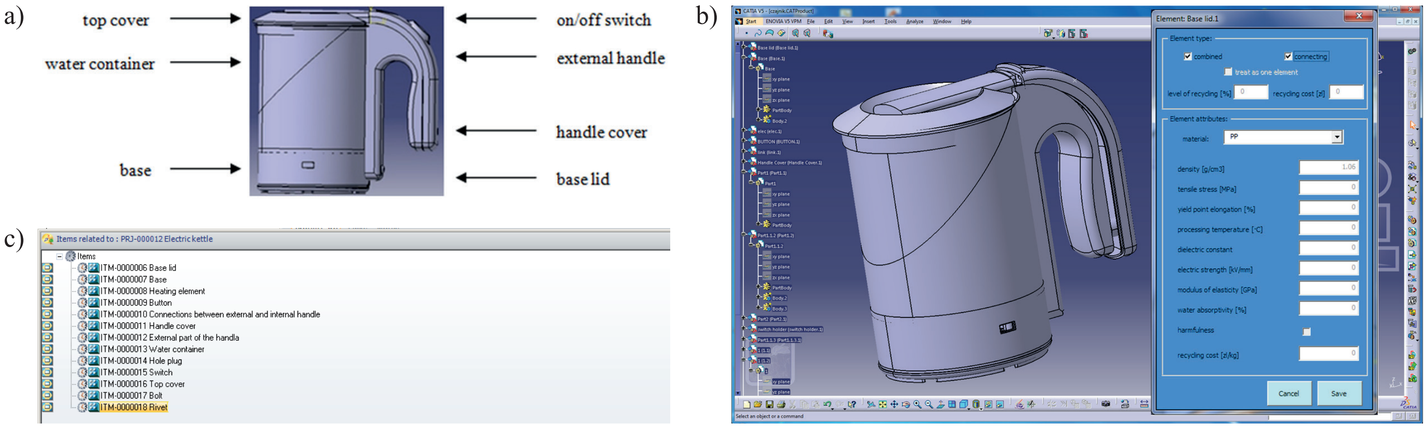

Fig. 3. Assessed product: a) general view with main parts [37], b) model in CAD 3D system while defining the connection between parts [37], c) part list in PLM system

6. Recycling-oriented assessment of a real household appliance

The use of the proposed solution will be illustrated with an example of analysis of a designed product (electric kettle) in terms of its recycling properties. In order to conduct the analysis, it was necessary to create a RpM model of the product. The preparation of RpM model includes establishing of typical CAD 3D product model and defining all necessary attributes that define recycling properties in the meaning of RpM. It includes the definition of all the joints in the product and assigning extended material attributes to all the parts in the model.

The designed product model consists of 13 parts. The construction of the appliance is shown in Fig. 3. The set analysis was conducted based on that.

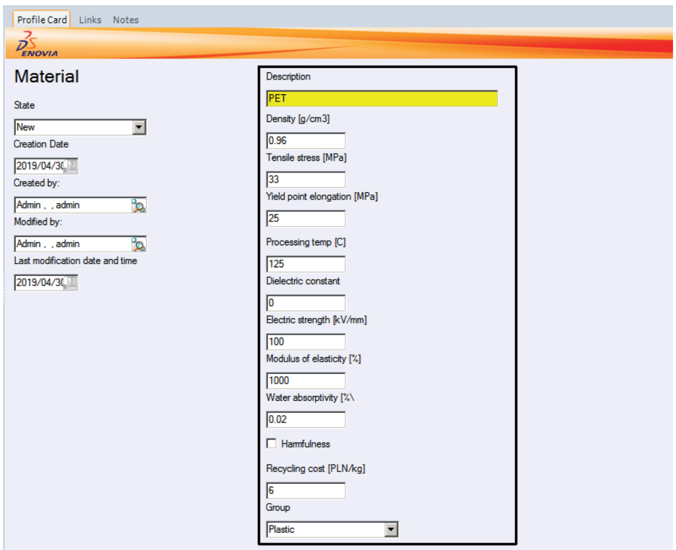

Fig. 4. Significant for recycling assessment material attributes implemented in PLM system used by agent during the analysis

Table 2
Components of the assessed product

Component	Materials
Base lid	PP
Base	PP
Heating element	X12CrMnNiN17–7-5
Button	PE
Connection between external and internal handle	PE
Handle cover	PE
External part of the handle	PP
Water container	PP
Hole plug	PP
Switch	PP
Top cover	PP
Bolt	St235
Rivet	X12CrMnNiN17–7-5

A total of 16 analyses were conducted, with different material, joint and disassembly configurations. The results of the project (RpM model and product categorization from the recycling point of view) are transferred into PLM system. It was possible due to appropriate customization of PLM by extending existing class of the objects describing project and material data (Fig. 4). An example result of the analysis for the selected configuration of materials is presented in Table 2.

In Table 2 the symbols represent: PE polyethylene; PP polypropylene; X12CrMnNiN17–7–5 austenitic stainless steel; St235 mild steel.

The research revealed that the CWR rate was 7 with WPR = 1, WRM = 3 and WRP = 3 (Fig. 5), the time of dis-

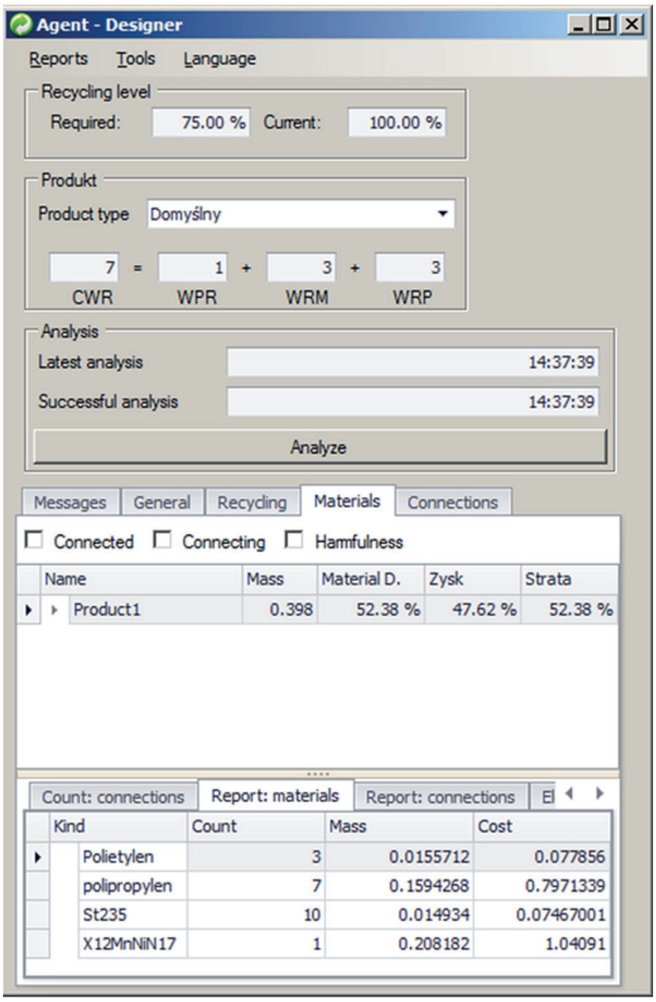

Fig. 5. Agent system during the analysis of product

assembly (TD) was estimated at 40 seconds, the number of different materials (LM) was 4, the number of different joints (LP) was 4, and the number of tools needed for the disassembly (LN) was 2. The recycling rate (WPR%) amounted to approximately 100%. Therefore, it can be concluded that the appliance is recyclable and meets the standards. Example of a final report from the agent system is shown in Fig. 6.

Recycling			
Required	75.00%	Achieved	100.00%

General information	
Recovery level	100.00%
Mass	0.398
Disassembly time	00:00:40
Recycling cost	1.03
Number of materials	4
Number of tools	2

Fig. 6. Final report of the analysis of electric kettle

7. Summary

In theory, PLM systems should support all stages of the product life cycle. In practice, however, the support is disproportionate: some stages receive sound support (e.g. geometric design support in 3D CAD systems), others are supported poorly or not at all. The latter include product's end-of-life, i.e. product retirement. The solution presented in this paper has been designed to ensure equal representation of all stages of product life cycle in a PLM system. 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 based on data acquired from various sources.

The presented solution takes into consideration a new approach to design, which includes 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 allows for easy expansion of the system. New functionalities can be added by programming new agents to cooperate 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 the evaluation of opportunities for its application in the area of disassembly, with the use of augmented reality.

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References

[1] J.W. Fischer, B. Lammel, D. Hosenfeld, D. Bawachkar, and B Brinkmeier,: "Do(PLM) Con: An Instrument for Systematic Design of Integrated PLM-Architectures", in *Smart Product Engineering. Lecture Notes in Production Engineering*, pp. 211–220, eds. M. Abramovici and R. Stark, Springer, Berlin, Heidelberg, 2013.

[2] E. Dostatni, J. Diakun, D. Grajewski, R. Wichniarek, and A. Karwasz, "Multi-agent system to support decision-making process in design for recycling", *Soft Computing* 20, 4347–4361 (2016).

[3] J. Libera and J. Labacka, "Eco-design – new approach to design", SKN Ekobiznesu przy Katedrze Ekologii Produktów. Poznań (2008) [in Polish].

[4] A. Lewandowska and Z. Foltynowicz, "Pro-environmental activities as source of innovations in company", in *9th Conference Companies development in aspect of pro-quality improvement and innovativeness*, Boszkowo (2006) [in Polish].

[5] E. Dostatni, J. Diakun, D. Grajewski, R. Wichniarek, and A. Karwasz, "Functionality assessment of ecodesign support system", *Management and Production Engineering Review*, 6(1), 10–15 (2015).

[6] S. Ferrendier, F. Mathieux, G. Rebitzer, M. Simon, and D. Froelich, "Environmentally improved product design-Case studies of the European electric and electronic industry", Report of European Network (2002).

[7] M. Stachura and A. Karwasz, "Eco-design in practice", *Zeszyty naukowe Politechniki Poznańskiej* 5, 53–63 (2007) [in Polish].

[8] E. Pająk, Production management, PWN, Warszawa, 2006 [in Polish].

[9] D. Yousnadj, G. Jouanne, N. Maranzana, F. Segonds, C. Bouchard, and A. Aoussat, "Integration of Environmental Assessment in a PLM Context: A Case Study in Luxury Industry", in *Product Lifecycle Management for a Global Market. PLM 2014. IFIP Advances in Information and Communication Technology*, vol 442, pp. 201–212, eds. S. Fukuda, A. Bernard, B. Gurumoorthy, and A. Bouras, Springer, Berlin, Heidelberg, 2014.

[10] M. Grieves, Product Lifecycle Management – Driving the Next Generation of Lean Thinking, McGraw-Hill, New York, 2006.

[11] A. Lenart, "Product lifecycle management and ERP systems", in *Computer-integrated management*, vol. II, pp. 115–123, eds R. Knosala, Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją, Opole, 2009, [in Polish].

[12] N. Madu and Ch. Kuei, ERP and Supply Chain Management, Chi Publisher, Fairfield, 2005.

[13] "The next levels of digital transformation in Germany: with Cloud-PLM toward improving innovation of product and efficiency", DC White Paper, (2017) [in German].

[14] P. Ghadimi, Ch. Wang, M.K. Lime, and C. Heavey, "Intelligent sustainable supplier selection using multi-agent technology: Theory and application for Industry 4.0 supply chains", *Comput. Ind. Eng.*, vol. 127, 588–600 (2019).

[15] S.A. Mostafa, M.S. Ahmad, M. Annamalai, A. Ahmad, and S.S. Gunasekaran, "A dynamically adjustable autonomic agent framework", in *Advances in Intelligent Systems and Computing*, vol. 206, pp. 631–642, eds Á. Rocha, A. Correia, T. Wilson, K. Stroetmann, Springer, Berlin, Heidelberg, 2013.

[16] P. Maes, "Modeling adaptive autonomous agents", *Artif. Life*, 1(1–2), 135–162 (1993).

[17] M. Wooldridge, An introduction to multi-agent systems, John Wiley & Sons, 2009.

[18] M.Pătraşcu and M. Drăgoicea, "Integrating agents and services for control and monitoring: managing emergencies in smart buildings", in *Service Orientation in Holonic and Multi-Agent Manufacturing and Robotics, Studies in Computational Intelligence*, vol. 544, pp. 209–224, eds. T. Borangiu, D. Trentesaux and A. Thomas, Springer, Cham, 2014.

[19] P. Qaderi-Baban, M.B. Menhaj, M.Ddosaranian-Moghadam, and A. Fakharian, "Intelligent multi-agent system for DC microgrid energy coordination control", *Bull. Pol. Ac.: Tech.* 67(4), 741–748 (2019).

[20] I. Rojek, "Technological process planning by the use of neural networks", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 31(1), 1–15 (2017).

[21] I. Rojek, "Neural Networks as Prediction Models for Water Intake in Water Supply System", in *Artificial Intelligence and Soft Computing – ICAISC 2008*, *Lecture Notes in Computer Science*, vol. 5097, pp. 1109–1119, eds L. Rutkowski, R. Tadeusiewicz, L.A. Zadeh and J.M. Zurada, Springer, Berlin, Heidelberg, 2008.

[22] I. Rojek, "Hybrid Neural Networks as Prediction Models", in *Artifical Intelligence and Soft Computing. ICAISC 2010, Lecture Notes in Computer Science*, vol. 6114, pp. 88–95, eds L. Rutkowski, R. Scherer, R.Tadeusiewicz, L.A.Zadeh, and J.M. Zurada, Springer, Berlin, Heidelberg, 2010.

[23] M. Zaborowski, "Data processing in self-controlling enterprise processes", *Bull. Pol. Ac.: Tech.* 67(1), 3–20 (2019).

[24] A. Byrski, R. Schaefer, M. Smołka, and C. Cotta, "Asymptotic guarantee of success for multi-agent memetic systems", *Bull. Pol. Ac.: Tech.* 61(1), 257–278 (2013).

[25] D.W. Qian, S.W. Tong, and C.D. Li, "Observer-based leader -following formation control of uncertain multiple agents by integraf sliding mode", *Bull. Pol. Ac.: Tech.* 65(1), 35–44 (2017).

[26] D. Choiński and M. Senik, "Distributed control systems integration and management with an ontology-based multi-agent system", *Bull. Pol. Ac.: Tech.* (66)5, 613–620 (2018).

[27] K. Magill and Y.J. Erden, "Autonomy and Desire in Machines and cognitive agent systems", *Cognitive Computation*, 4(3), 354–364, (2012).

[28] R.V. Florian, "Autonomous artificial intelligent agents". Center for Cognitive and Neural Studies (Coneural), Cluj-Napoca, Romania (2003).

[29] M. Wooldridge and N.R. Jennings, "Intelligent agents: Theory and practice". *The Knowledge Engineering Review*, 10(2), 115–152 (1995).

[30] H. Hexmoor, C. Castelfranchi, and R. Falcone, "A prospectus on agent autonomy", in *Agent Autonomy. Multiagent Systems, Artificial Societies and Simulated Organizations*, vol. 7, pp. 1–10, eds. H. Hexmoor, C. Castelfranchi, and R. Falcone, Springer, Boston, 2003.

[31] S. Falkenroth, "Intelligent Software Agents", Graduate Course Seminar, Linkoping University, 1998.

[32] S. Franklin and A. Graesser: "Is it an Agent, or just a Program?: A Taxonomy for Autonomous Agents", Springer-Verlag, Berlin, 1996.

[33] V. Galant and J. Tyburcy, "Intelligent software agent", *Prace Naukowe Akademii Ekonomicznej we Wrocławiu*, Wrocław, 2001.

[34] D. Grajewski, J. Diakun, R. Wichniarek, E. Dostatni, P. Buń, F. Górski, and A. Karwasz, "Improving the Skills and Knowledge of Future Designers in the Field of Ecodesign Using Virtual Reality Technologies", in *Proceedings of International Conference Virtual and Augmented Reality in Education*, pp. 348–358, Monterrey, Mexico, 2015.

[35] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), O.J. EU L197/38, 24.07.2012.

[36] „Act of 11 September 2015 on waste Electrical and Electronic Equipment" (2015).

[37] E. Dostatni, J. Diakun, R. Wichniarek, A. Karwasz, and D. Grajewski, "Product Variants Recycling Cost Estimation with the Use of Multi-agent Support System", *Advances in Manufacturing. Lecture Notes in Mechanical Engineering*, pp. 311–320, eds. A. Hamrol, O. Ciszak, S. Legutko, M. Jurczyk M., Springer, Cham, 2018.