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Analysis of Selected IT Tools Supporting Eco-Design in the 3D CAD Environment

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ABSTRACT The concept of eco-design is an area of interest of many manufacturers. Its implementation provides a framework that allows companies to adapt to the requirements of sustainable development related to the design and manufacturing of environmentally-friendly products. Implementation of eco-design in the industry requires dedicated information technologies. Many types of software tools are offered which support eco-design, and the choice of the one which suits the user best is not easy. The paper describes an analysis of three selected IT tools dedicated to the environmental assessment of products, integrated with the 3D CAD environment. The analysis has been carried out on the basis of specially developed reference models of sets (assemblies) imitating small household appliances. The models have been designed to support the creation of various configurations of connections between elements (parts of the assembly). The study experiments consist in changing the configurations and observing how the changes affect the environmental parameters of the modelled structure. The results have been used to describe the scope of support offered by each of the tools under analysis and their suitability for the environmental assessment of products.

INDEX TERMS Eco-design, recycling, product design, 3D CAD systems.

I. INTRODUCTION

Application of the principles of sustainable manufacturing means that the product is expected to be economically viable – from the point of view of both the consumer and the manufacturer. It should generate minimum possible impact on the environment throughout its lifecycle, and be safe for the manufacturer's employees, customers, and the society. Sustainable products are designed to be eco-friendly, optimised in terms of material and energy consumption, and durable [1]. This is related to the concept of the circular economy, which assumes a closed loop of processes, where waste from some processes is used as raw materials in other processes. This means that the material efficiency and design for dissassembly should be analyzed at an early stage of product development [2]. The most important activities of the manufacturers in the area of sustainable production include boosting efficient use of resources, application of alternative power sources, revisiting of the entire supply and manufacturing network life cycle [3] and ensuring full recyclability of the product. This will allow to achieve the policy objectives in line with the EU CEAP (EU Circular Economy Action Plan), which are: reduction of the negative impact of the product on the environment, reduction of waste and extension of the life cycle, as well as increasing the company's competitiveness. There should be a harmonization of the requirements for products and standardization of information provided about products regarding the impact on the environment [4]. Considering the above, the process of product design aimed at achieving the maximum environmental friendliness, also referred to as eco-design, is growing in importance.

Individuals involved in product development are required to have extensive knowledge which needs optimisation in a number of aspects. Considering the entire product lifecycle, the design stage is a focal process leading to the development of the product in its final form. Computer Aided Design (CAD) software supports designers in creating new products and key decision-making processes. In the recent years, the CAD software developers have noted the need for inclusion of environmental factors into early stages of product lifecycle. The number of available specialised eco-design tools, supporting effective decision-making processes, has been on the rise. Most of them were reviewed by [5]. These innovative solutions facilitate a complex assessment of

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products taking into consideration the environmental impact, and suggest alterations which can be made to improve environmental rating of the designed object. One of the great advantages of the 3D CAD environment is the freedom which the designer has to implement modifications, as the feature of product modelling makes it possible to select individual product parameters at a very early stage of the design process. In this way, the number of errors which occur at subsequent stages, as well as the costs which would have to be incurred for the development of updated physical prototypes or modification of an initiated manufacturing process, can be significantly reduced. The range of software solutions available is wide. Some of them feature additional tools or modules which support the environmental assessment of products as early as at the modelling stage. With such modules integrated into the software, the decision-making processes gets significantly streamlined, time required for the eco analysis of the product reduced, and the final version of the product optimised.

The authors attempt to analyse and compare functionalities of selected software tools, integrated into the 3D CAD system, which support product eco-design and recyclability assessment. The analysis has been conducted on specially developed reference models of sets (assemblies) imitating household appliances. The sets have been designed in a way allowing for the creation of various configurations of elements (sub-sets) – a factor of great importance for the conducted analyses.

The first part of the article provides an extensive analysis of the literature, and then presents the design of the experiments. The second part describes the steps of the eco-design experimental activities carried out in all three IT tools, which were then analyzed.

II. LITERATURE REVIEW

Eco-design defines a new way of product development, where environmental aspects have a status equal to that of functionality, durability, cost, time to market, physical appearance, ergonomics, and quality [6]–[8]. Luiz *et al.* [9] noted that eco-design related research intensified in the 1990s, in connection with the introduction of the lifecycle assessment and development of analyses of the environmental impact [10], [11].

The development of environmentally friendly products became an important topic of environmental research [12]. Since 2000, eco-design has been defined as a research area and organisational practice [13]–[15]. Approaching eco-design as a strategic design activity, designers take into consideration not only functionality of the designed product, but also its entire lifecycle, from the concept through to the disposal, with the aim to reduce energy consumption, eliminate the use of harmful substances, and minimise the use of materials. It is equally important to extend the product lifecycle by ensuring that it be repairable, made of recyclable materials, have a structure which facilitates disassembly (provided through appropriately selected assembly methods ensuring quick and easy disassembly of components) and be made of recycling-compatible materials [16].

Modular design facilitates the achievement of recyclability [17]. In products with a modular structure, faulty modules can be easily repaired or replaced with new ones without the need to decommission the entire product. What is more, a product with a modular structure can be easily improved by adding a new module with additional functionality; thus, the entire system can be expanded [18]. This is one of the ways to introduce solutions which have been thoroughly tested for environmental friendliness and functionality. Another way to optimize eco-design activities is to use Product Service Systems (PSS), which are based on various design research methodology frameworks [19]. In the future, products will be equipped with self-repair systems which will make them more reliable and extend their service life [20].

Integration of environmental aspects into product design is time-consuming and requires certain knowledge [21], [22]. Designers find it more and more difficult to handle the environmental aspects on their own [23] whereas the team dynamics and competences required for decision-making in the process of eco-design performed by a multidisciplinary design team are still unexplored [24]. Therefore, supporting tools are required to develop the concept of a new environmentally friendly product [5], [13] and technologies [25]. Tools supporting eco-design are referred to by Chou [26] as techniques applied to assess the product's environmental impact and streamline the product process design (PPD), and classified as:

- guidelines, standards, norms,
- checklists,
- comparative tools (e.g., lifecycle design strategies (LiDS), eco-compass),
- analytical methods (e.g., eco-indicators, environmental consequence analyses, environmental impact analyses, lifecycle analyses (LCA), material, energy and toxicity matrix (MET).

IT tools supporting eco-design are broken down into two groups [27]. One of them are databases storing information useful for designers. Most of them require cumbersome implementation of product structure, other do not take into consideration the structure of the designed product and are merely a set of general tips on eco-design. The other group is formed by analytical tools integrated into CAD systems. One of their advantages is that they use data from 3D CAD models for the environmental assessment or analysis of the designed product. Some CAD/LCA integration methods have been proposed by [28], who developed an algorithm for data transfer between the Solid Edge system and the LCA SimaPro Tool, and [29], who proposed data integration with the use of a database containing parameters which define the environmental impact of the designed product.

There are references in the literature to a number of prototype tools aimed to retrieve data from a 3D CAD model in order to assess the environmental impact of the product. One of them is Demonstrator, developed by [30], which combines the CATIA system with the EIME (SLCA) software. Another one is EcoFit, proposed by [31], which is an overlay designed for the 3DSmax system, connecting it with EcoIndicator99. EcoCAD, proposed by [32], uses data included in the product structure created in a CAD system for the eco analysis of the product. Another solution [33], on the other hand, makes it possible to integrate the LCA and the lifecycle cost analysis with the product lifecycle management (PLM) software. Leibrecht [34] developed EcologiCAD – a tool which supports assessment of the environmental impact of a product being still a virtual prototype [35].

Another possible solution are additional modules in commercial 3D CAD systems. One of them is Eco Materials Adviser for Inventor 2020 from Autodesk Labs, designed for use with the Autodesk Inventor software. This tool supports the decision-making process concerning selection of environmentally friendly materials, and thus helps to reduce the environmental impact of products without compromising their performance parameters [36]. Another example of an IT tool supporting eco-design is the SolidWorks Sustainability application, being part of the SolidWorks solutions which support design, simulation, sustainable development, technical communications, and data management [37]. SolidWorks Sustainability is a practical tool for the implementation of the sustainable development strategy at the stage of product design. The application uses models of processes and databases for the lifecycle assessment, also used in the GaBi software [38].

The tools briefly discussed above show that CAD developers have noted the need for taking into consideration the environmental aspects of a product at an early stage of product design. However, the applications are merely modules working with a particular 3D CAD software tool. All the apps have one thing in common – they do not provide a clear answer as to which of the solutions under analysis has the least environmental impact. They support comparison of various models and give prompts as to which of the alternatives should be selected given the predefined criteria. However, once the criteria are changed, it can turn out that another solution is even better.

The product environmental assessment is a complex multicriteria process, whilst eco-design supporting tools make it possible to compare various product variants and make an informed decision. Organizations striving for the implementation of eco-design face the challenge of choosing suitable software, which is not easy. The outcome of a study conducted by the authors can facilitate it.

III. METHODOLOGY

Three selected IT tools, integrated into the 3D CAD environment, have been analysed for support of the environmental assessment of a designed product. The analysis consisted in checking functionality of the solutions and subjectively evaluating their usefulness at the stage of new product design. The key steps of the experiments are shown in Figure 1.

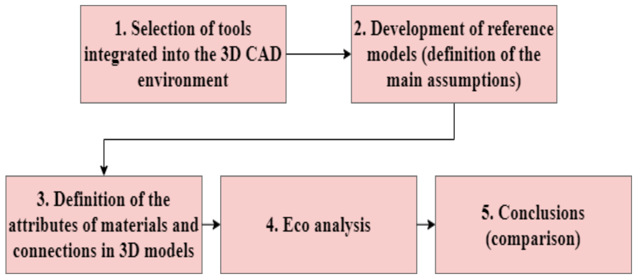

FIGURE 1. Steps followed in the study.

In step one, three tools integrated into a 3D CAD environment, designed for the eco analysis of a designed product, were selected:

- the Eco Materials Adviser module of the Autodesk Inventor Professional 2018,
- the SolidWorks Sustainability module of SolidWorks 2020,
- an original application, developed by a team of scientists at the Poznan University of Technology on the basis of the agent technology, integrated into the CATIA v5 system from Dassault Systèmes.

The advantage of the selected solutions over other tools supporting the eco analysis is that the geometric structure of the designed models (the list of parts and connections between them) does not need to be implemented or processed in separate systems designed for the eco analysis and assessment.

In step two, reference models for two assemblies were developed, which could then be used to create any configuration of structures and materials. Due to a limited functionality of the free version of Inventor (Eco Materials Adviser supports the analysis of only the first twenty parts of a structure tree), the models can imitate only small household appliances composed of not more than twenty structural elements. The geometry of the models and their bills of materials (BOM) are shown in Figure 2. The BOM numbering is consistent with Tables 1 (for the reference model of set no. 1) and 6 (for the reference model of set no. 2).

The reference model of set no. 1 was used as a common base for the examination of the IT solutions. The model was analysed according to the following scheme:

A. ECO ANALYSIS OF THE BASE ASSEMBLY

The analysis consisted in the identification of materials and connections of the assembly. A list of parts for the base assembly of the reference model of set no. 1 as well as numbers of parts and materials they are made of (broken down by the IT systems) is included in Table 1.

A list of connections in the base assembly is included in Table 2.

Next, two variants of the set presented above were developed. In variant 1, the types of materials were modified, whilst in variant 2 different types of connections were applied.

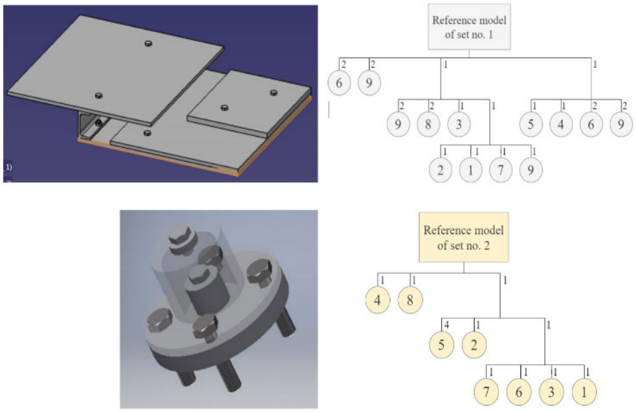

FIGURE 2. Geometry and BOM for reference models of set no. 1 (top) and 2 (bottom).

TABLE 1. List of parts in the base assembly of the reference model (set no. 1).

Part no.	Part name	Number of items	Material (Eco Materials Adviser)	Material (SolidWorks Sustainability)	Material (agent app)
1	Part1(metal sheet 500x500x10)	1	Low-alloy steel	Non-alloy steel	Low-alloy steel
2	Part10(metal sheet 400x500x10)	1	Low-alloy steel	Non-alloy steel	Low-alloy steel
3	Part5(metal sheet 250x300x15)	1	Low-alloy steel	Non-alloy steel	Low-alloy steel
4	Part6(metal sheet 500x450x10)	1	Low-alloy steel	Non-alloy steel	Low-alloy steel
5	U bar 76x38x7x500	1	Low-alloy steel	Non-alloy steel	Low-alloy steel
6	Bolt DIN 933 M10x30	4	Low-alloy steel	Non-alloy steel	Common grade steel
7	Bolt DIN 933 M10x35	1	Low-alloy steel	Non-alloy steel	Common grade steel
8	Bolt DIN 933 M10x50	2	Low-alloy steel	Non-alloy steel	Common grade steel
9	Nut DIN 934 M10	7	Low-alloy steel	Non-alloy steel	Common grade steel

TABLE 2. List of connections in the base assembly of the reference model (set no. 1).

Part no.	Part name	Connection no.	Connected with [(part no.) part name]	Type of connection	Connecting elements [number x (part no.) part name]
1	Part1(metal sheet 500x500x10)	1	(5) U bar 76x38x7x500	Dismountable	2 x (6) Bolt M10x30 2 x (9) Nut M10
		2	(2) Metal sheet 400x500x10	Dismountable	(7) Bolt M10x35 (9) Nut M10
		3	(3) Metal sheet 250x300x15 (2) Metal sheet 400x500x10	Dismountable	2 x (8) Bolt M10x50 2 x (9) Nut M10
2	Part10(metal sheet 400x500x10)	2	(1) Metal sheet 500x500x10	Dismountable	(7) Bolt M10x35 (9) Nut M10
		3	(3) Metal sheet 250x300x15 (1) Metal sheet 500x500x10	Dismountable	2 x (8) Bolt M10x50 2 x (9) Nut M10
3	Part5(metal sheet 250x300x15)	3	(1) Metal sheet 500x500x10 (2) Metal sheet 400x500x10	Dismountable	2 x (8) Bolt M10x50 2 x (9) Nut M10
4	Part6(metal sheet 500x450x10)	4	(5) U bar 76x38x7x500	Dismountable	2 x (6) Bolt M10x30 2 x (9) Nut M10
5	U bar 76x38x7x500	1	(1) Metal sheet 500x500x10	Dismountable	2 x (6) Bolt M10x30 2 x (9) Nut M10
		4	(4) Metal sheet 500x450x10	Dismountable	2 x (6) Bolt M10x30 2 x (9) Nut M10

TABLE 3. Changes of materials with reference to the base assembly – variant 1.

Part no.	Part name	Material	Number of items
3	Part5(metal sheet 250x300x15)	PC	1
4	Part6(metal sheet 500x450x10)	POM	1

B. ECO ANALYSIS OF VARIANT 1

A list of parts and materials used in variant 1 (modified with reference to the base assembly) is included in Table 3.

C. ECO ANALYSIS OF VARIANT 2

The modifications in variant 2 (with reference to variant 1) of the reference model of set no. 1 are shown in Tables 4 and 5.

In the next step, three eco analyses of the reference model of set no. 1 were conducted, taking into consideration the variants discussed above. The analyses were aimed to examine the software tool by comparing the responses provided by each of the tool when introducing modifications to the product structure and materials.

Next, the eco analysis of the reference model of set no. 2 was conducted. The analysis was adjusted to the software tool used, depending on the responses provided by the system in step one, so that it was a value added to the complete analysis of a given software tool. The assembly data are shown in Tables 6 (materials) and 7 (structure).

The performance of works as described above provided an opportunity to carry out a comprehensive analysis of functionalities as well as limitations to the software tools (applies to basic versions of commercial software tools).

IV. RESULTS

A. ECO MATERIALS ADVISER

Eco Materials Adviser is a module added to the basic version of Autodesk Inventor. It supports the eco analysis of an assembly at the product level, as modelled in the 3D CAD environment. In order to carry out the analysis, it was necessary to assign materials and processes to particular parts of the assembly. All parts of the initial assembly of the reference model of set no. 1 (also referred to as the base assembly) were assigned low-alloy steel material and forging/rolling process.

TABLE 4. Change of connection to non-dismountable.

Part no.	Part name	Connection no.	Connected with [(part no.) part name]	Type of connection	Connecting elements [number x (part no.) part name]
4	Part6(metal sheet 500x450 x10)	4	(5) U bar 76x38x7x500	Non-dismountable	-

TABLE 5. Connecting elements – updated (reduced by two nuts and two bolts).

Part no.	Part name	Number of items	Material (Eco Materials Adviser)	Material (SolidWorks Sustainability)	Material (agent app)
6	Bolt DIN 933 M10x30	2	Low-alloy steel	Non-alloy steel	Common grade steel
9	Nut DIN 934 M10	5	Low-alloy steel	Non-alloy steel	Common grade steel

TABLE 6. List of parts in the reference model (set no. 2).

Part no.	Part name	Number of items	Material (Eco Materials Adviser)	Material (SolidWorks Sustainability)	Material (agent app)
1	Part 1 (base)	1	Acrylic glass (PMMA)	Acrylic glass (PMMA)	Acrylic glass (PMMA)
2	Part 2 (housing)	1	Polycarbonate (PC)	Polycarbonate (PC)	Polycarbonate (PC)
3	Part 3 (interior)	1	Polyethylene (PE)	Polyethylene (PE)	Polyethylene (PE)
4	Part 4 (top)	1	Rubber	Rubber	Rubber
5	Bolt ISO 4014 M10x45	4	Low-alloy steel	Non-alloy steel	Common grade steel
6	Bolt ISO 4014 M8x40	1	Low-alloy steel	Non-alloy steel	Common grade steel
7	Nut ISO 4032 M6	1	Low-alloy steel	Non-alloy steel	Common grade steel
8	Bolt ISO 4014 M8x12	1	Low-alloy steel	Non-alloy steel	Common grade steel

The software module searches the Granta Eco Database for appropriate materials by names of materials or their properties. If any information on a particular part of the assembly is missing (e.g., the part is not assigned a material or process), the software returns an error message. With all the data entered, the tool analyses the assembly for its environmental impact. The implemented computation methods make it possible to obtain information on the manufacturing process, such as:

- quantitative indicators (expressed in values): energy consumption [MJ], carbon footprint [kg], water consumption [l], cost of raw materials and materials [currency, as preselected],
- binary indicators: compliance with the RoHS Directive, food compatibility,
- end-of-life strategy for individual parts of the product.

The eco analysis of the base assembly of the reference model of set no. 1, carried out using Eco Materials Adviser, is shown in Figure 3.

TABLE 7. List of connections in the reference model (set no. 2).

Part no.	Part name	Connection no.	Connected with [(part no.) part name]	Type of connection	Connecting elements [number x (part no.) part name]
1	Part 1 (base)	1	(2) Part 2 (housing)	Dismountable	4 x (5) Bolt M10x45
		2	(3) Part 3 (interior)	Dismountable	(6) Bolt M8x40 (7) Nut M6
2	Part 2 (housing)	1	(1) Part 1 (base)	Dismountable	4 x (5) Bolt M10x45
		3	(4) Part 4 (top)	Dismountable	(8) Bolt M8x12
3	Part 3 (interior)	2	(1) Part 1 (base)	Dismountable	(6) Bolt M8x40 (7) Nut M6
4	Part 4 (top)	3	(2) Part 2 (housing)	Dismountable	(8) Bolt M8x12

A detailed analysis is also possible; e.g., each of the values can be broken down by lifecycle stages, or the assembly parts can be arranged in a hierarchy from those of the greatest share in a given indicator. The cost of materials and raw materials is provided in the currency preselected in the module settings. The Restriction of Hazardous Substances (RoHS) indicator shows compliance with the RoHS Directive, whilst the food compatibility indicator shows whether the product can be approved for use in direct contact with food. Both these indicators are comprehensive, i.e., apply to the entire product.

Each of the materials in the database has a default end-of-life scenario assigned. It is not possible to determine an end-of-life scenario for the entire product on the basis of its components. Additionally, an assembly report has been developed, which is downloadable in the.pdf format. The report is an aggregate summary of detailed information on the assembly and the calculated environmental indicators. A more detailed analysis of the report provides the user with information that the basic version of Autodesk Inventor does not support the analysis of product in transport or use, and the eco analysis applies to the first twenty parts of the structure tree only. This limitation to the software was the main factor determining the structure of the developed reference models of both assemblies.

The base assembly was a starting point for further eco analysis. The module enables the user to set baselines, i.e., store the current values of particular indicators and set them as benchmarks for comparison of modified versions of the assembly (with different configuration of materials and structure).

The second version of the reference model of set no. 1 under analysis was variant 1, modified according to Table 3. The modification applied to materials of two parts only – the low-alloy steel was changed to plastics (PC and POM); the modification resulted in incompatibility of materials. As mentioned before, the benchmarks were the values of indicators for the reference model of set no. 1. The modification resulted in an increase or decrease of certain indicators, as well as a change in the proportion of the end-of-life scenario. The changes can be intuitively noted in the charts, where deviations from the rated values (marked

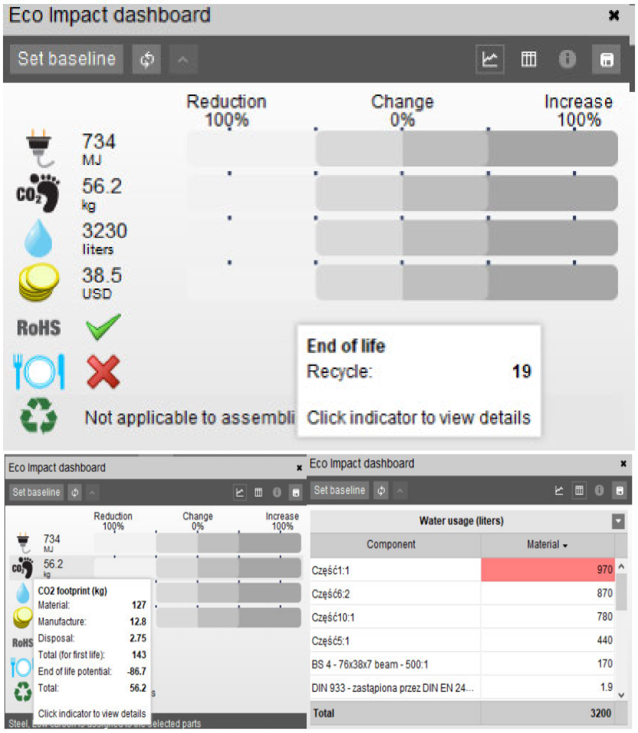

FIGURE 3. Eco analysis of the base assembly of the reference model of set no. 1 using Eco materials adviser.

with a vertical line in the centre of the chart) are marked as coloured bars (red – increased (undesired) or green – decreased (desired)) (Fig. 4). The data on indicators represented in numerical values are stored as total values as well as values of increase/decrease of the indicator at each stage of the product lifecycle. The system provides various options of generated reports, e.g., a detailed report on the analysed element, or – if a comparative analysis of two versions of the assembly is carried out – a comparative report showing a list of differences between the two analysed versions.

The third version of the reference model of set no. 1 under analysis was variant 2, which was a modified version of variant 1. The modification consisted in a change of dismountable connections into non-dismountable, i.e., welded connections between incompatible materials. The experiment was aimed to verify the system's response to the introduction of changes which led to a more difficult disassembly of the product and a more complicated end-of-life strategy. The number of connecting parts was reduced – two nuts and two bolts were replaced with welded connections (two fillet welds 10 × 10 [mm]) of metal sheet with a U bar (Fig. 5). The indicator values for variant 2 of the reference model of set no. 1 were compared to those for variant 1.

Once the modification was implemented, it was noted that the software did not register the change of the connection type. Compared to the previous version of the assembly (variant 1), 15 rather than 19 parts were included in the analysis (the difference corresponds to the four connecting elements removed), which was also indirectly noticeable in the slight

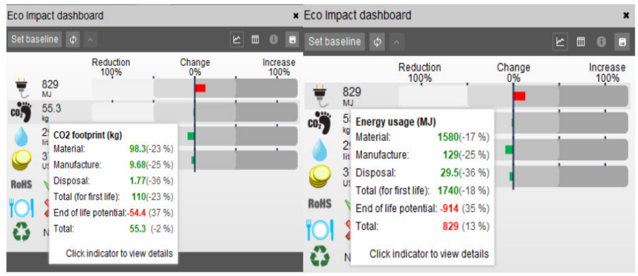

FIGURE 4. Visualised differences between indicators for two versions of assembly 1 reference model.

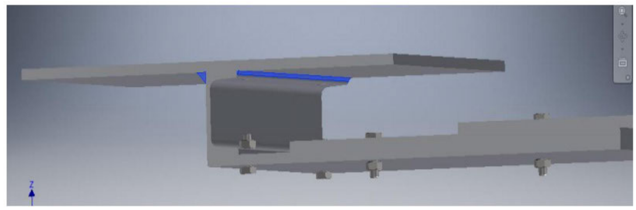

FIGURE 5. Welded connection of the top sheet metal (made of POM) with the U bar (made of low-alloy steel).

decline of the quantitative indicators. The detailed assembly report also lacked any feedback on the implemented structural modification.

In step 2, the eco analysis of the reference model of set no. 2 was conducted. The model had materials assigned according to Table 6, and connections assigned according to Table 7. The materials had also been assigned manufacturing processes (PMMA – moulding, low-alloy steel – forging/rolling, other – extrusion). The assembly was analysed and baselines were set for particular indicators. In the alternative version, materials were modified based on a suggestion provided by the agent application during an analysis of an assembly of the same composition of materials (the analyses were parallel). Therefore, according to Table 6, material of Part 2 (housing) was changed from PC to rubber. In spite of significantly lower values of most of the indicators (down by more than 10%), the water consumption rate went up by as much as 2,500%.

B. SOLIDWORKS SUSTAINABILITY

SolidWorks Sustainability is a software tool integrated into the SolidWorks environment, which supports real-time assessment of environmental impact of a product designed in a 3D space. Prior to the analysis, each part of the assembly needs to be assigned a material it is made of. There is a possibility of excluding certain elements of the assembly from the analysis. The product also needs to be assigned basic information concerning its lifecycle, related to:

- the manufacturing process: the region, how long the product is expected to last, and (optionally) the energy required to carry out the manufacturing process;
- the service life: the region, the energy required for the service life (optionally);
- the transport: type;

- the end-of-life strategy: the percentage breakdown of the end-of-life process.

In order to examine the reference model of set no. 1, the information presented in Figure 6 below was used as a basis for eco analyses of three variants of the reference model.

With the input data in place, a recyclability analysis was conducted. The tool provides a quantitative analysis of the product's environmental impact, measured by four indicators and visualised on a pie graph, as well as a computation of the financial impact of the material. SolidWorks Sustainability analyses:

- carbon footprint [kg CO2],
- energy consumption [MJ],
- air acidification potential [kg SO2],
- water eutrophication potential [kg PO4].

When hovering the cursor over the pie chart of a particular indicator, a breakdown appears into lifecycle stages and their quantitative share in the indicator. With a click on the indicator, results are visualised on a bar chart, broken down by lifecycle stages. The tool also supports the generation of general reports with additional information about the product, presented in the form of clear charts or lists, such as, e.g., a hierarchy of the environmental impact of particular parts of the product, broken down into indicators represented by numerical values and visualised as bars for a more intuitive comparison of the values.

The base assembly of the reference model of set no. 1 was agreed to be the baseline (black bars next to the indicators of the environmental impact), which means that values of particular indicators for the base assembly would serve as reference for comparison of variant 1 of the same reference model. Changes to the model were introduced according to the scheme discussed in the Methodology section, i.e., materials were changed (Table 3) to test the function of comparison of alternatives with unchanged initial assumptions. The values of indicators for variant 1 under analysis are shown as additional bars of respective colours, where red represents a value worse than the baseline, and green represents a (desirable) decrease in the indicator value, i.e., its improvement (Fig. 7). Similarly to the analysis of a single assembly, with a click on the area of a particular parameter one can obtain additional information, here – about the different values of the indicator for two alternative versions of the product, broken down by lifecycle stages. The general report includes an additional analysis referred as a comparison of environmental impact, with a list of numerical values of environmental indicators.

Next, variant 2 of the reference model of set no. 1 was analysed. Variant 2 was modified according to Table 4, i.e., a welded connection was introduced between incompatible materials, and four connecting elements were removed (Table 5). The initial assumptions remained unchanged. The change of type of connection from a dismountable to a non-dismountable one went unnoticed by the system (no changes to the indicators either on the chart or in the report) and had no impact on the quantitative analysis. Even though two bolts and two nuts were removed from the assembly, the system failed to mark a change in the value of the indicators in percentage or numerical terms (the change was 0%). It may be due to a slight decrease in the value of the indicators, caused by small sizes of the parts which were removed, which the system ignored given the rounding setting applied.

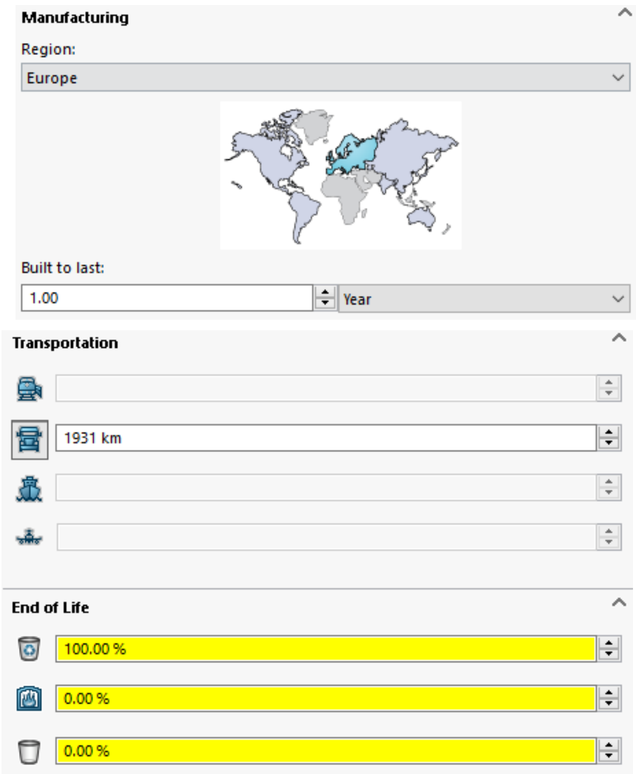

FIGURE 6. Basic information implemented in SolidWorks Sustainability-supported analysis of assembly 1 reference model.

At stage 2, the eco analysis of the reference model of set no. 2 was carried out. Initially, materials were assigned according to Table 6 and some basic information about the assembly was entered. However, the value of energy required to put the assembly together and consumed during the service life was missing. The eco analysis of the assembly was carried out in order to set the baselines. An alternative version of the same assembly was different from the base assembly only in terms of the values of energy – the values of 7BTU [British thermal unit] (required to put the assembly together) and 10kWh (energy consumption required for the usage/year). It can be seen in Fig. 8 below that values of all the indicators deteriorated significantly (by several hundred percent), compared to the assembly in which the energy consumption parameter was not taken into consideration. The results show how important it is to include the parameter of energy consumption in the eco analysis.

C. AGENT APPLICATION SUPPORTING DESIGN FOR RECYCLING

The agent application based on the product recyclability model (PRM) is a software tool developed by a team of

FIGURE 7. Comparison of alternative versions (of the base assembly and variant 1) of the reference model of set no. 1 in solidworks sustainability.

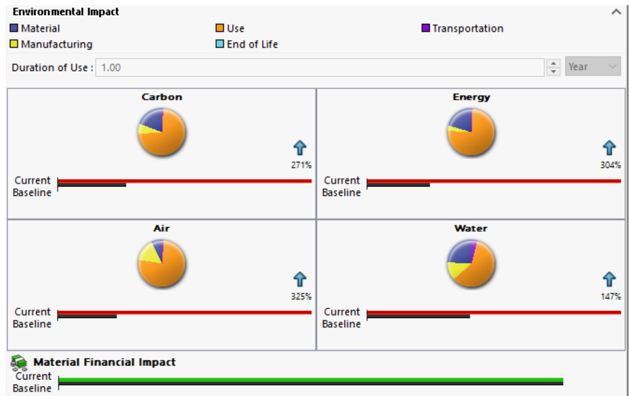

FIGURE 8. Results returned by solidworks sustainability.

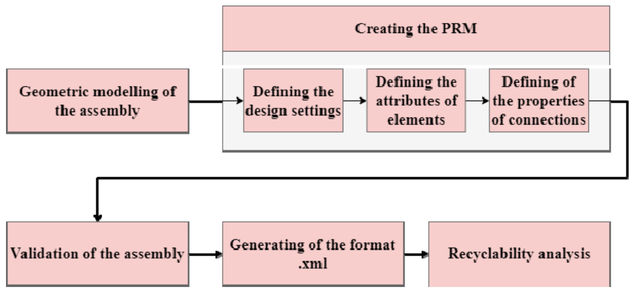

FIGURE 9. Recyclability analysis procedure in the agent application integrated into the CATIA system.

scientists of the Poznan University of Technology [7], dedicated to the assessment of recyclability of designed products in a 3D CAD environment (here – in the CATIA system from Dassault Systèmes). The analysis procedure is shown in Figure 9.

The recyclability analysis was also carried out for the reference model of set no. 1. First, the properties of the base assembly of the model were entered (according to Tables 1 and 2), such as its elements (not necessarily interrelated) and the required general information, such as the material base in a specially created file, type of product and path to the agent system swap file.

Next, all the preparation activities were performed to develop the product recyclability model (PRM). Each of the elements needed editing (Edit Element Type), i.e., assignment of the group (whether it is a connecting element or an element to be connected) and material it is made of. The materials were assigned according to Table 1. Nuts and bolts were assigned the group ''connecting element'', whilst other elements were assigned the group ''connected element''.

In the next step, a list of connections in the assembly was developed, according to Table 2. Each of the connections was described with the following data:

- type (dismountable/non-dismountable),
- type (bolted, welded, etc.),
- duration of the dismounting procedure,
- the cost of man hour,
- tools required for dismounting,
- the connecting and connected elements.

The connecting and connected elements mentioned above were entered based on the elements existing in the system environment (and grouped according to the group assigned to each element in the Edit Element Type option) – a fact which is made possible owing to the integration of the PRM module into the 3D CAD environment. The window for describing connections is shown in Figure 10.

Once the above PRM data had been entered, the assembly was validated to verify whether all the connecting and connected elements had been assigned to one of the connections. Next, a swap file was generated in the.xml format. Only then the actual recyclability analysis of the assembly began. The software, operating on the basis of the agent technology, running in the background, analysed the base assembly on the basis of the PRM and determined the recyclability level of the designed product, comparing it with the required recyclability level based on the initial declaration, as well as the total recyclability indicator (TRI), which is a numerical value. The lower the TRI of the assembly, the more environmentally friendly the assembly (optimisation = minimisation of the TRI). The recyclability level of the base assembly of the reference model of set no. 1 equalled 100%, while its TRI was 3.0.

The next step was the analysis of variant 1 of the reference model of set no. 1. No comparison was made between the alternative versions, since the agent app does not provide this functionality. Instead, the system analysed various versions of the assembly. The modifications introduced into the assembly (materials, as shown in Table 3) were not reflected in any

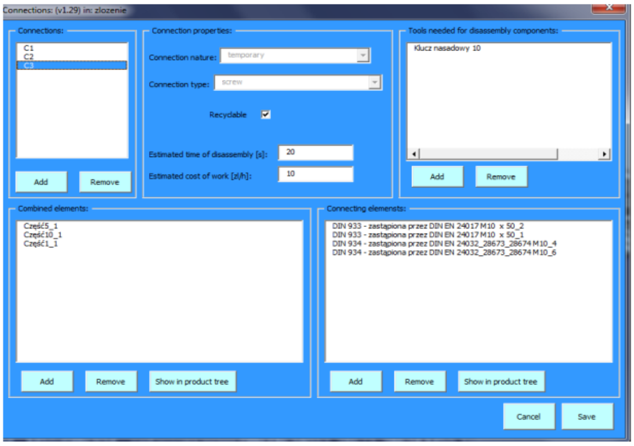

FIGURE 10. Dialogue window for describing connections.

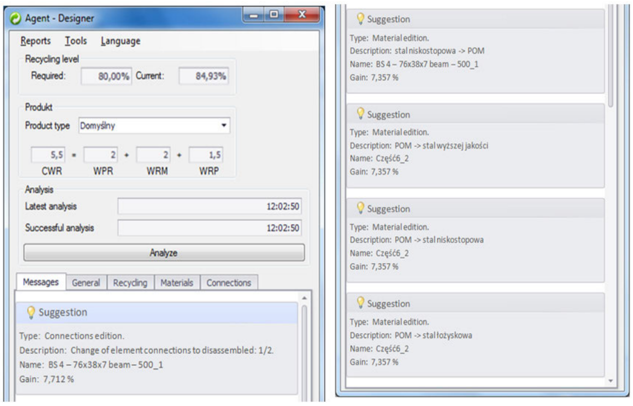

FIGURE 11. Suggestions generated by the agent app on the basis of the designed PRM based on the database of materials.

way in the results of the analysis – both the recyclability level indicator and the TRI remained unchanged. The reason behind it is that in spite of the different materials used in the assembly, the dismounting and recycling were not made more difficult, since none of the connections changed its type and they could still be easily dismounted.

Variant 2 of the reference model of set no. 1 made it possible to identify an additional functionality of the agent app. The structural change introduced (the change of the type of connection – to a welded, non-dismountable one, between incompatible materials) was registered by the software tool and interpreted as an obstacle to the decommissioning of the product, what resulted in a decrease in the recyclability level to nearly 85% and an increase of the TRI to 5.5. Although the required minimum recyclability level (80%) was achieved, the agent app suggested enhancements which could be made to improve the above indicators (Fig. 11).

Two of the suggestions above were implemented (change of material for part no. 5 to PCV and change of the type of connection no. 4 from non-dismountable to dismountable, what increased the recyclability level to 98.5% and decreased the TRI to 4.5.

The reference model of set no. 2 was analysed in three variants. Variant 1 was designed according to Tables 6 and 7. The structure ensured 100% of recyclability, confirmed by the result generated by the software tool. In variant 2, a non-dismountable connection was introduced between the top and the housing (connection no. 3 according to Table 7), made of incompatible materials (top – rubber, bottom – PC), what reduced recyclability to nearly 75%. In variant 3, one of the suggestions by the agent system was introduced. The material of the housing (part no. 4, according to table 6) was changed from PC to rubber, to ensure compatibility of elements connected with a non-dismountable connection. It improved recyclability to 100%. The suggestion was also used for modification of the same assembly in Eco Materials Adviser (carried out in parallel).

V. DISCUSSION

Carrying out two-stage analysis focused on a given IT tool made it possible to fully recognize its capabilities. Some limitations in each of them have also been identified. Therefore, the evaluation strategy of these tools consisted in demonstrating the key functions which, according to the authors, should support obtaining more complete information about the environmental performance of the designed product.

Assuming that the user may want to search for information needed to perform the ratio analysis (e.g. water consumption, energy consumption), but also to analyze the compatibility of the materials used, the focus was on defining the Key Performance Indicators (KPIs) of these tools. For this purpose, a summary has been prepared (Table 8). The analysis of the indicators contained in the table may provide significant support in the selection of a tool for specific eco-design works.

Eco Materials Adviser and SolidWorks Sustainability support qualitative analyses of selected environmental impact indicators and their presentation in a breakdown by lifecycle stages. It can be stated, therefore, that these tools are useful in management (decision-making) processes, but not so in eco-design of products. They actively support comparison of alternative versions of assemblies (where different materials are used), however, do not provide an analysis of connections between elements of which an assembly is made, as none of the software tools noted a change of connection from a dismountable to a non-dismountable one.

It can be then concluded that integration of a module supporting the environmental analysis of products and a 3D model implemented in the system environment is carried out through reading the dimensions of individual model elements and using them for the computation of values of particular indicators. A useful function offered by both systems is a ready-made database. Eco Materials Adviser offers the option of assigning a manufacturing process to each of part of the designed product, which translates into the values of environmental indicators.

SolidWorks Sustainability, on the other hand, supports calculation of the indicators taking into consideration the region of manufacturing, region of use, energy consumption and type of transport. The analytic functionality of Eco Materials

TABLE 8. Key performance indicators of analyzed IT tools.

KPIs	Eco Materials Adviser (Inventor Professional 2018 basic version)	Agent system integrated with CATIA system	SolidWorks Sustainability (basic version)
Uploaded database / library of materials with their properties	Yes	No (need to prepare your own database)	Yes
Analysis of connections between elements	No	Yes	No
Suggesting optimal solutions (change of connection type / material ...)	No	Yes	No
Comparing alternative solutions	Yes	No	Yes
Ratio analysis	- water consumption - Energy consumption	- overall recycling rate (index compiled by the authors)	- water consumption - Energy consumption
Generating a summary report on the analysis	Yes	Yes	Yes
Product end of life scenario	Yes (but not accidental)	No	No
Compliance with the product's RoHS directive	Yes	No	No
Calculation of the cost of purchasing materials	Yes	No	Yes
Determining the characteristics of the product	- material assignment - assignment of the manufacturin g process	- selection of small / medium / large household appliances - determining the level of recycling required	- region of production, region of use, type of transport and distance travelled [km], determination of the percentage of the end-of-life distribution of the product (recycling / incineration / landfill)

Adviser in its basic version is limited, as it does not cover the stages of service life or transport. Moreover, it supports an analysis of only the first twenty parts of the structure tree of the assembly.

The agent app is a universal tool which can be integrated into any 3D CAD system, with the core of the integration being the product recyclability model. The application also supports the designer in the field of material engineering. Using a predefined database of materials, it draws on the data on their compatibility to create suggestions and tips supporting the decision-making and the design processes. The development of an appropriate PRM (product recyclability model) is time-consuming, as it requires that information about connections be entered manually, whilst integration into the 3D CAD system is carried out through the reading of the list of parts from the system environment. The parts need not be interrelated, because full information about the assembly and its connections is included in the user-developed PRM.

Based on this, the agent app analyses types of connections and checks the design for non-dismountable connections made of incompatible materials which compromise the recyclability rating of the product. Suggestions and tips are generated based on material compatibility matrices and suggestions which have been previously followed, as those are stored in the agent system memory.

To sum up, the three IT tools analysed in this paper do not have many comparable features, hence the presented analysis is rather descriptive than strictly comparative. The analysis of Table 8 presented above also allows the conclusion that in the row where the result "yes" appears in SolidWorks or Inventor, the answer in CATIA is "no" and vice versa (the first four rows of Table 8).

It can therefore be concluded that these are mutually complementary tools that, if used simultaneously (or to some extent are integrated), will reflect the full picture of the environmental performance of a product designed in a 3D CAD environment.

The agent app integrated into the 3D CAD system (through the feature of automated change tracking in an.xml file) is an innovative design supporting tool with a focus on the end-of-life of product and its recyclability. Its major advantage over commercial solutions are smart suggestions and tips generated based on the information on materials and connections between assembly elements.

The solutions support the designer in a field they are not required to be experts in (material engineering), thus bringing more universality to the job of a designer. It can be stated on the basis of the analysis of the reference model of set no. 2 that obtaining full information about the designed product is only possible upon integration of various design support tools.

A modification of materials, which increased the product recyclability rating (on the basis of an analysis in the agent app) hiked up the water consumption (on the basis of an analysis in Eco Materials Adviser), whereas none of the systems offered the option to enter the parameter of water consumption during service life, which greatly affected the indicators of the environmental impact (on the basis of an analysis in SolidWorks Sustainability).

The comparison shows that a decision to introduce modifications to the model is the resultant of many factors. In the end, it is a decision to be made by the designer, and – to be the best at the moment – should be made in cooperation with other experts who know the process and the enterprise strategy.

VI. CONCLUSION

In the face of a deepening environmental crisis, changes in the manufacturing are gaining momentum. Therefore, a rapid growth of eco-design supporting tools offering extensive analytical functionalities can be anticipated in near future.

According to the authors, the necessary information about the designed product and the answers received from this type of IT tools should be formalized. A framework should be created, which should include such aspects as:

- assignment of material and manufacturing process to each part,
- analysis of the joints used in the product and checking the material compatibility between the parts that are inseparably connected,
- suggesting changes to improve recycling and dismantling (suggestions supported by similar properties), as well as analysis (in real time) of the impact of the introduced change on quantitative measures, i.e. water consumption, energy consumption, cost, etc.,
- declaration of waste generated during production,
- transport analysis at every stage of the life cycle,
- determining the proportion of the end of life of the product,
- suggesting the possibility of preparing a physical prototype (e.g. using 3D printing technology) in order to verify a change in the nature or type of connection.

The further direction of the authors' work will be the integration of the developed agent system with the Inventor system to obtain the analysis results from both systems in real time. Previous work and research on the agent system were carried out in integration with the CATIA system (software integration was easier to perform from the technical side). The conducted research was used to assess the purposefulness of the use of the agent system and to demonstrate the correctness of its operation.

In addition, it was decided to further develop the application towards more in-depth analysis so that the suggestions generated by the agent system were supported not only by the mutual compatibility of inseparably joined materials, but also by the interchangeability of their properties (e.g. strength), which may be of key importance for the structure of the product. This requires the implementation of appropriate algorithms for analysis in terms of many factors.

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