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CONVERGENT USE OF DFD-DFR PRINCIPLES AND OF ADVANCED INTEGRATED ENGINEERING SOLUTIONS FOR SUSTAINABLE PRODUCT DESIGN

BY

MARIUS MARIAN CUCOȘ*, VASILE MERTICARU, GHEORGHE NAGÎȚ and IONUȚ MĂDĂLIN PIȘTA

"Gheorghe Asachi" Technical University of Iași,
Faculty of Machine Manufacturing and Industrial Management

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Abstract. The presented research is oriented towards the convergent use of Design for Disassembly (DFD) and Design for Recycling (DFR) principles and of some advanced integrated engineering CAD/CAE/CAID/CAx solutions for enhancing the effectiveness and efficiency of design activities for Sustainable Product Development. At the beginning, a conceptual model for the research framework is proposed, where DFD and DFR principles are considered converging together with an integrated engineering solution in order to obtain a good modular product structure and a sustainable product design. As case study, an approach on the application of the above outlined principles for the development of a device adaptable on an electrical discharge machine has been considered as suggestive to be here presented. The presented case study refers also to the performance of using advanced capabilities of Solid Edge software as CAD solution which provide the parameterizing and optimization of the product model structure and also as valuable CAE instrument which provides geometrical/functional calculations for components (shafts, gears).

Keywords: integrated engineering; CAD/CAE; Design for Disassembly; Design for Recycling; Sustainable Product Development.

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*Corresponding author; *e-mail*: cucos.marius91@yahoo.com

1. Introduction. Research Problem Statement

Lately, manufacturers have begun to put as much emphasis on product quality, reuse through product maintenance and recycling of products.

To survive on the market, manufacturers had to come up with new ideas for improvement, to provide time and resources for the sustainable development of tools and principles for modern engineering design (Merticaru and Rîpanu, 2013).

Modern design philosophies are acting today, like the following:

– Design for Excellence - DfX

– Sustainable Product Development

– Integrated Engineering, CAD/CAE/PLM/CAx (Merticaru *et al*., 2014).

Sustainable Design is defined as being the philosophy of designing physical objects, the built environment and services to comply with the principles of social, economic, and ecological sustainability (McLennan, 2004).

Beyond the "elimination of negative environmental impact", sustainable design must create projects that are meaningful innovations that can shift behaviour. A dynamic balance between society - economy, intended to generate long-term relationships between user and object and finally to be respectful and mindful of the environmental and social differences (McLennan, 2004).

Design for Disassembly (DFD) and Recycling (DFR) is oriented to "eliminate negative environmental impact completely through skilful, sensitive design" (McLennan, 2004). The philosophy of DFD-DFR is about mastering the process of designing products so they can be cost-effective, and to be easy/quickly removed at the end of product's life, so the components can be recycled and/or reused with periodic maintenance (Crowther, 2005).

For sustainable disassembly and recycling, several general principles are usually considered within product design, like: structure simplicity, standardization, modularity, marking for identification, mistake proofing systems, recyclable or reusable components and materials etc. (Crowther, 2005).

Integrating engineering solutions for Computer-aided Design (CAD) and Computer-aided Engineering (CAE) have become a necessity in designing products, due to several reasons including the flexibility offered by CAD/CAE software, lower production cost by making better products and reducing time to launch the product on the market (Merticaru *et al*., 2008).

The present paper further on includes a theoretical research approach and some particular case study results referring to the convergent applying of DFD-DFR principles, instruments and methods together with some advanced Integrated Engineering solutions for Sustainable Product Design.

The research approach has been structured on the bases of systematically identifying, inventorying and analysing a set of functionalities and knowledge that focuses on successful product design activities using a desired set of characteristics.

2. Research Approach Description. Conceptual Research Framework

A conceptual model for defining the research framework has been firstly elaborated and is bellow proposed (Fig. 1).

Targeting the general objective of Sustainable Product Development, the core problem of translating Product Requirements into Product Specifications has been considered as starting point for the research approach conceptual model (Merticaru *et al*., 2014).

Based on the appropriately defined product requirements, the Product Structure Design can be purchased as a main stage in product design and there are several design philosophies, theories, methods and instruments to be used for solving that design step and for obtaining a sustainable product structure (Merticaru *et al*., 2017). Among them, Design for Excellence (DfX) have been considered within the mentioned conceptual model, where a set of design theories like Design for Manufacturing (DFM), Design for Assembly (DFA), Design for Environment (DFE), Design for Disassembly (DFD), Design for Recycling (DFR) etc. are included (Pișta *et al*., 2017). As long as DFD and DFR are particularly targeted to make the object of the research study, they are detailed within the model from Fig. 1, through some of their specific principles. Mainly, for DFD there have been considered the following aspects: simplified design; reduced number of parts; standard components (screws, nuts, bolts, etc.); use of Poka-yoke assembly/disassembly systems; fewer fasteners; avoid adhesive bonding. On the other hand, the following main aspects have been considered for DFR: recyclable materials; reusable components; component life span etc.

After a good product structure is identified, the next main stage in product design, respectively Product Engineering Design can be purchased and, for solving that step and for obtaining a sustainable set of Product Specifications, Integrated Engineering tools are to be used. Among them, CAD (Computer-aided Design), CAE (Computer-aided Engineering), CAM (Computer-aided Manufacturing), CAID (Computer-aided Industrial Design), PLM (Product Lifecycle Management), DXM (Data Exchange Management) etc. are nominated in the model. Further on, some well-known and widely used CAD/CAE solutions are exemplified and as long as Solid Edge (Siemens, 2017) represents the tool particularly used in the research approach, some of its main capabilities are nominated. Solid Edge Engineering Reference is also included in the model as valuable CAE instrument, together with some of its functionalities.

The use of DfX theories and of Integrated Engineering tools for solving the above mentioned design steps in translating Product Requirements into Product Specifications should converge towards supporting a Sustainable Product Development, as it is shown in the proposed model, under the general concept of Convergent Design.

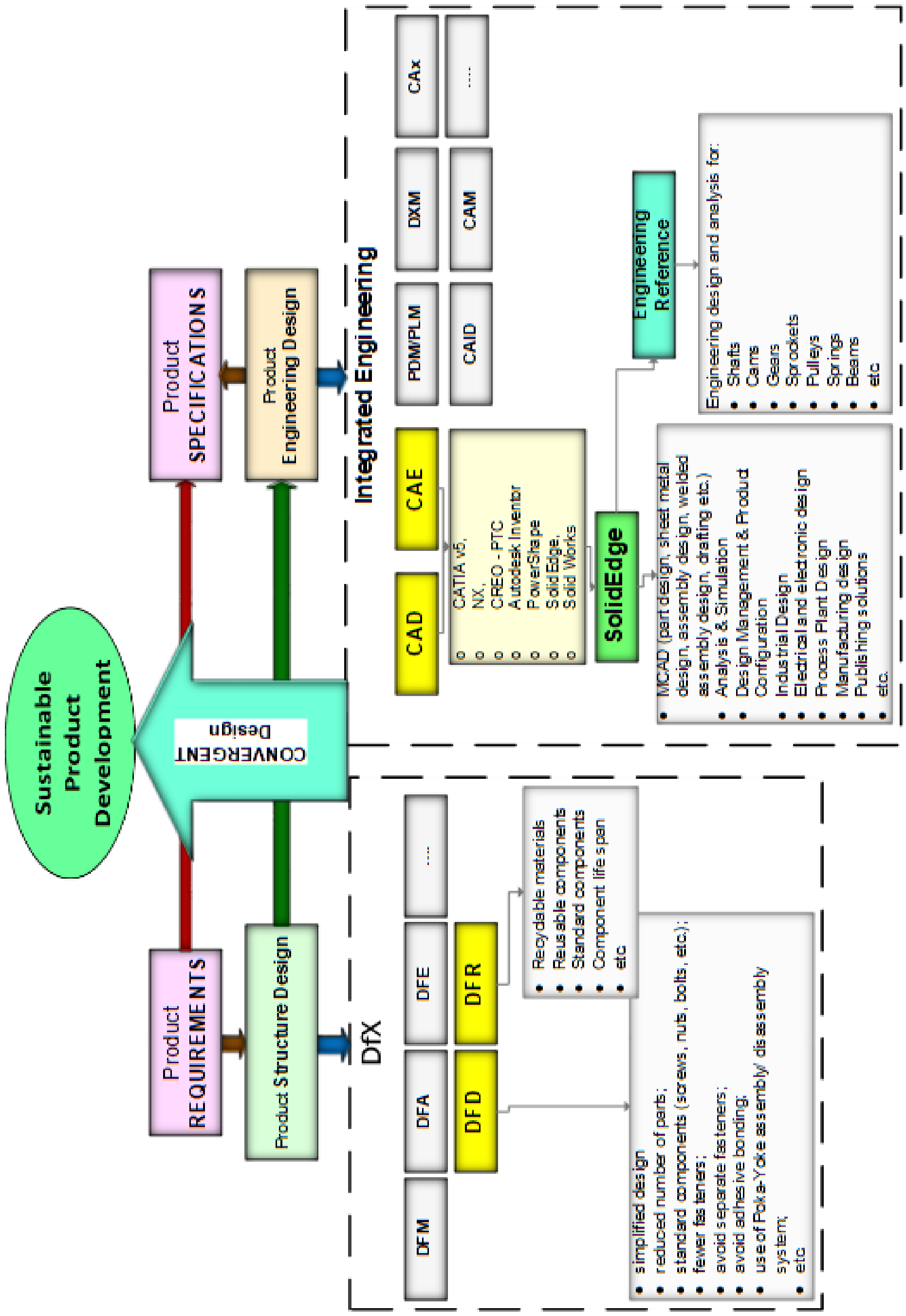


Fig. 1 – Conceptual model for the research approach.

3. Case Study – Approach, Results and Discussions.

As case study, an approach on the application of the above outlined principles of Design for Excellence (DFD, DFR) for the development of a sustainable product structure for a device adaptable on an electrical discharge machine has been considered as suggestive to be here presented.

The presented case study refers also to the performance of using advanced capabilities of Solid Edge software as CAD solution which provide the parameterizing and optimization of the product model structure and also as valuable CAE instrument which provides geometrical/functional calculations for components (shafts, gears).

The paper content further on includes a short description of the studied product, its detailed structure designed following the above mentioned principles and some aspects regarding the optimization of engineering design activities for some of the main components of the technological device using Solid Edge Engineering Reference tool. The exemplified automated calculation results obtained using Engineering Reference are presented in comparison with those corresponding to the design and engineering activities which had been previously developed in classical manual way, a lot of time consuming calculation and design tasks being involved in that old manner.

3.1. Product Description

The studied technological device, shown in Fig. 2, is adaptable on an electrical discharge machine tool, being able to generate cycloid profiles based on a double-planetary mechanism driving (Merticaru *et al*., 2017).

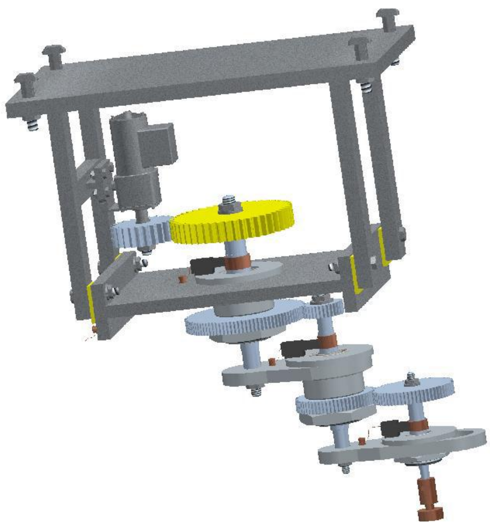


Fig. 2 – The studied technological device – Solid Edge model (Merticaru *et al*., 2017).

3.2. Application of DFD/DFR Principles in Product Structure Design

The DFD/DFR principles, as they have been above nominated, have been considered as having an important role in optimizing the parameterized structure of the technological device. By this way, a better product solution, lower production cost and reduced time to launch the product on the market has been provided. The component parts of the device (shafts, gears, bushings, parallel keys, etc.) have been designed to be easily re-usable and to be disassembled easily, with reduced damaging impact on the surrounding environment and implicitly on the efficiency and effectiveness of the product structure and functionality.

The DFD/DFR principles have also another important role in designing the product structure of the device, by tracking the traceability of the product from the initial moment to the end of the product lifecycle (recycling and reuse). The designed device adaptable on the electrical discharge machine has a complex modular structure that can generate a family of products, regardless of size, respecting the limit conditions. The device structure consists of several parts of resistance (frame, plates, etc.) and a series of functional elements (gears, shafts, bearings, etc.).

In Table 1 there is shown the list of components of the technological device as well as some additional material, weight, description and quantity information.

Table 1
Bill of Material for the Technologic Device

Nr.	Description	Quantity	Material	Weight, [kg]
1	Frame	1	S235	6.74
2	Gear motor	1		0.824
3	Screw M4x20	4	E295	0.0025
4	Nut M4	4	E295	0.0025
5	WasherN4	4	C55	0.001
6	Elastic Ring 8	4	C55	0.001
7	Gear m = 1, Z = 24	1	C45	0.213
8	Parallel key 3x3x10	1	E260	0.001
9	Electrical insulation	4	Polyamide	0.004
10	Bush	3	Graphite	0.006
11	Collector ring 1	1	Cu 99.5	0.004
12	Elastic Ring 45	2	C55	0.012
13	Gear m = 1, Z = 94	1	C45	0.423
14	Bushing 1	2	S275	0.467
15	Bearing 16002	4	100Cr6	0.025
16	Shaft 1	1	C45	0.203
17	Parallel key 3x3x8	4	E360	0.001

Table 1
Continuation

Nr.	Description	Quantity	Material	Weight, [kg]
18	Washer N8	7	C55	0.004
19	Nut M8	7	E295	0.003
20	Spacer Bushing 1	2	S275	0.034
21	Shaft 2	1	C45	0.145
22	Gear m = 1, Z = 62	1	C45	0.116
23	Washer N40	2	C55	0.008
24	Nut M40	2	E295	0.088
25	Elastic Ring 45	1	C55	0.001
26	Electrode tool	1	Cu 99.5	0.048
27	Port electrode Shaft	1	C45	0.050
29	Elastic Ring 8	1	C55	0.001
30	Bearing 608	2	100 Cr6	0.011
31	Nut M30	1	E295	0.029
32	Washer N30	1	C55	0.006
33	Port satellite Arm 2	1	S275	0.283
34	bushing 2	1	S275	0.139
35	Collector ring 1	1	Cu 99.5	0.005
36	Gear m = 1, Z = 63	1	C45	0.238
37	Port satellite Arm 2	1	E275	0.354
38	Collector ring 2	1	Cu 99.5	0.002
39	Gear m = 1, Z = 31	1	C45	0.053
40	Support Plate	1	E275	3.251
41	Parallel key 4x4x10	1	E360	0.001
42	Gear m = 1, Z = 47	1	Polyamide	0.098

3.3. Optimized Product Engineering Design Using Solid Edge Engineering Reference

Engineering Reference is an embedded functionality from Solid Edge (Musca, 2008) which provides design integrated tools to optimize product structures and to automatically generate calculations, graphs and 3D models.

Manual calculation (component resistance, geometric calculations, diagrams generation, etc.) have been replaced with automated calculation using Engineering Reference as a powerful calculation driven design tool for gears and shafts that are component parts of the studied technological device (Merticaru *et al*., 2015).

3.3.1. *Manual Calculation for Shafts and Gears from Technological Device*

The detailed calculation for the design and engineering activities were developed in classical manual way, a lot of time consuming calculation and design tasks being involved (Cucoș, 2014). In the classical calculation the results are not precise like the new automated method.

Some examples, for shafts and gears, are further on included.

Shaft I Classical Calculation

The predimensioning, geometric calculations and diagrams generation for the shaft I, are presented below.

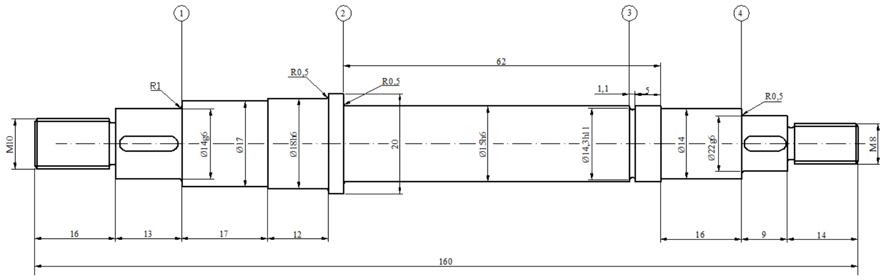


Fig. 3 – 2D Drawing for Shaft I.

Predimensioning for Shaft I

Material for Shaft I is a Steel Round Bar C45 (SR EN ISO 10083:2006).

This material is an unalloyed medium carbon steel, which is also a general carbon engineering steel. C45 is a medium strength steel with good machinability and excellent tensile properties and is generally supplied in the black hot rolled or occasionally in the normalised condition, with a typical tensile strength range 570 – 700 MPa and Brinell Hardness range 170 – 210 in either condition. C45 Round Bar Steel Chemical Composition Properties: 0.45-0.60% C, <0.40% Mn, 0.50-0.80% Si, <0.045 P, <0.40 Cr etc.

The preliminary diameter of the shaft is calculated with the relation:

$$d_p = \sqrt[3]{\frac{16 \cdot M_t}{\pi \cdot \tau_{at}}}, \tag{1}$$

where: τ_{at} – resistence to torsion; $\tau_{at} = 30\ \text{MPa}$; $M_t = 16473\ \text{N} \cdot \text{mm} \Rightarrow$ $d_p = 11.93\ \text{mm}$.

The diameters of the shaft sections are calculated with the relation:

$$d_p = \sqrt[3]{\frac{32 \cdot M_{iech}}{\pi \cdot \sigma_{ai_{III}}}}, \tag{2}$$

The diameters of the shaft I in the four considered sections are:

$d_1 = d_4 = 10.8$ mm; $d_2 = 14.5$ mm; $d_3 = 12.2$ mm;

Reactions in the supports

In vertical plane V:

$$V_1^{''} = \frac{125.2 \cdot 80 - 97 \cdot 25}{50} = 151.8 \text{ N} \tag{3}$$

$$V_2^{''} = F_{r_3} + V^{'} - V_1^{'} = 70.4 \text{ N} \tag{4}$$

In horizontal plane H:

$$H_1^{''} = \frac{344.1 \cdot 80 - 259 \cdot 25}{50} = 421 \text{ N} \tag{5}$$

$$H_2^{''} = F_{t_3} + H^{'} - H_1^{'} = 182 \text{ N} \tag{6}$$

Below is presented the effort diagram for shaft I.

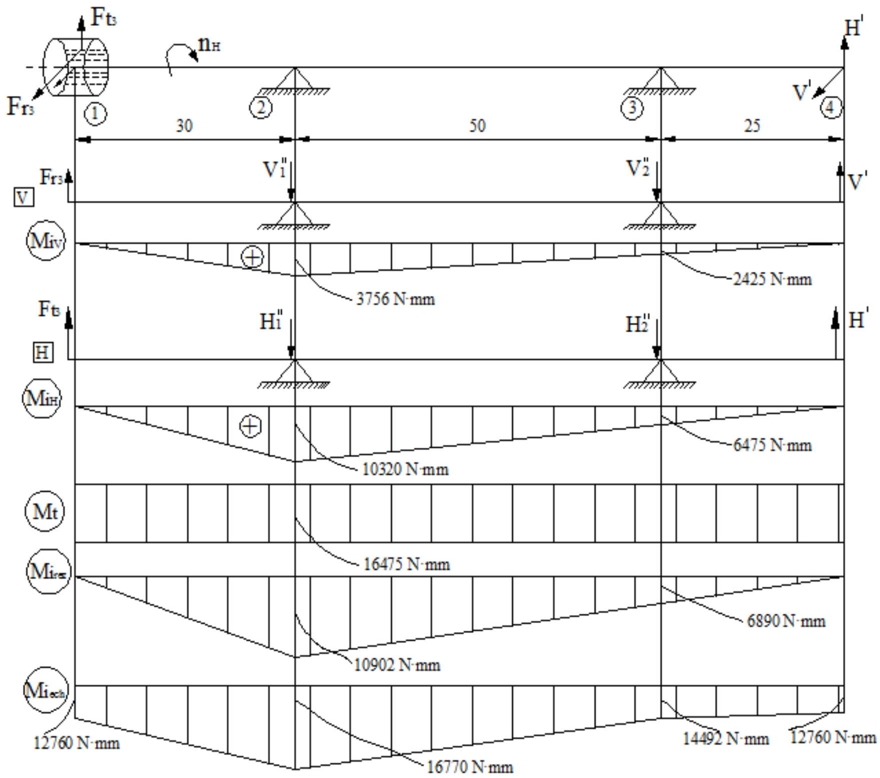


Fig. 4 – Effort diagrams for shaft I of the technological device.

Gear Z1/Z2 Classical Calculation - Predimensioning

Material for Gear is C45 SR EN ISO 10083:2006 improved with 185 Hardness Vickers (HV) and polyamide 6.6. Tensile strengths:

For C45

$-\sigma_{\mathrm{H\,lim}} = 560\,\mathrm{MPa}-$ tensile strength to contact

$-\sigma_{\mathrm{H\,lim}} = 560\,\mathrm{MPa}-$ limit strength at the bending

For polyamide 6.6

$-\sigma_{\mathrm{H\,lim}} = 560\,\mathrm{MPa}, -\sigma_{\mathrm{F\,lim}} = 120\,\mathrm{MPa}.$

In Table 2 are shown the calculation elements for the gear Z1/Z2.

Table 2
Calculation Elements

Description	Gears Z1/Z2
The gear ratio (i):	3
Tooth number report $u = \frac{Z_2}{Z_1}; (Z_1 < Z_2)$	3
Calculation power, *P*	$p = p_m \cdot \eta_A \cdot \eta_R \cdot \eta_A \cdot n_R = 33.74\,\mathrm{W}$
Speed	$n_2 = n_H\left(1 + \frac{Z_1}{Z_2}\right) = n_h = 80\,\mathrm{rot/min}$
Maximum torque at pinion shaft: $M_t = \frac{9550 \cdot P}{12}, \mathrm{N \cdot mm}$	4027 N·mm
Distance between axes (*a*):	*a* = 63 mm
Minimum Required Module $m \geq \frac{(u+1) \cdot M_I \cdot K_v \cdot K_\alpha \cdot K_{F\beta} \cdot y_F}{\psi_a \cdot a^2 (\sigma_{F\lim}/SF) \cdot K_{FN} \cdot y_s}, \mathrm{mm}$	$m \geq 0.37$ mm
Module minimum	*m* = 1 mm
Diameter of division	d_1 = 94 mm d_2 = 31 mm
Angle gear $\alpha_W = ar\cos \cdot \left(\frac{ad}{a} \cdot \cos\alpha_0\right)$	21.21°
Head diameter $d_{a1,2} = d_{1,2} + 2m\left(h^*_{0a1,2} + x_{1,2} - K^*_{h1,2}\right)$	d_{a1} = 96.5 mm d_{a2} = 33.5 mm
Foot diameter $d_{f1,2} = d_{1,2} - 2m\left(h^*_{fa1,2} - x_{1,2}\right)$	d_{f1} = 92 mm d_{f2} = 29 mm

Table 2
Continuation

Description	Gears Z1/Z2
Roll diameter $d_{W1,2} = d_{1,2} \cdot \cos {}^{\alpha_0}\!\big/_{\cos \alpha_w}$	d_{w1} = 94.75 mm d_{w2} = 31.25 mm
Width teeth $b = \psi_m \cdot m;\ \psi_m = 8 \div 10$	10 mm
Basic diameter $d_{b1,2} = d_{1,2} \cdot \cos \alpha_0$	d_{b1} = 88.33 mm d_{b1} = 29.13 mm

3.3.2. *CAD/CAE Study – Automated Calculation Engineering Reference*

Shafts and gears automate calculation and models generation are exemplified in the below figures.

Shaft I Automatic Calculation

Below is presented the way of shaft design, the tool being known as Solid Edge Shaft Designer, this is the new and powerful method to calculate material resistance, to realize geometric calculations and diagrams generation.

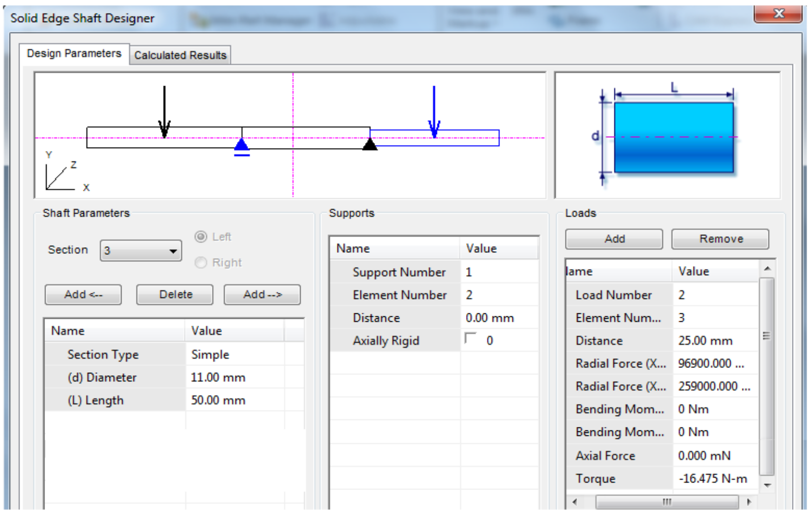


Fig. 5 – Solid Edge Shaft Designer tool.

The study is to check if shaft I resists in 4 sections as in Fig. 6. d_1 = 14 mm, d_2 =15 mm, d_3 =15 mm, d_4 =11 mm.

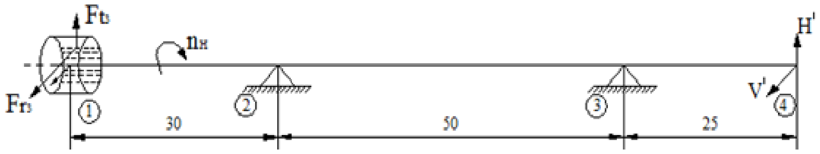


Fig. 6 – Diagrams section for the Shaft I.

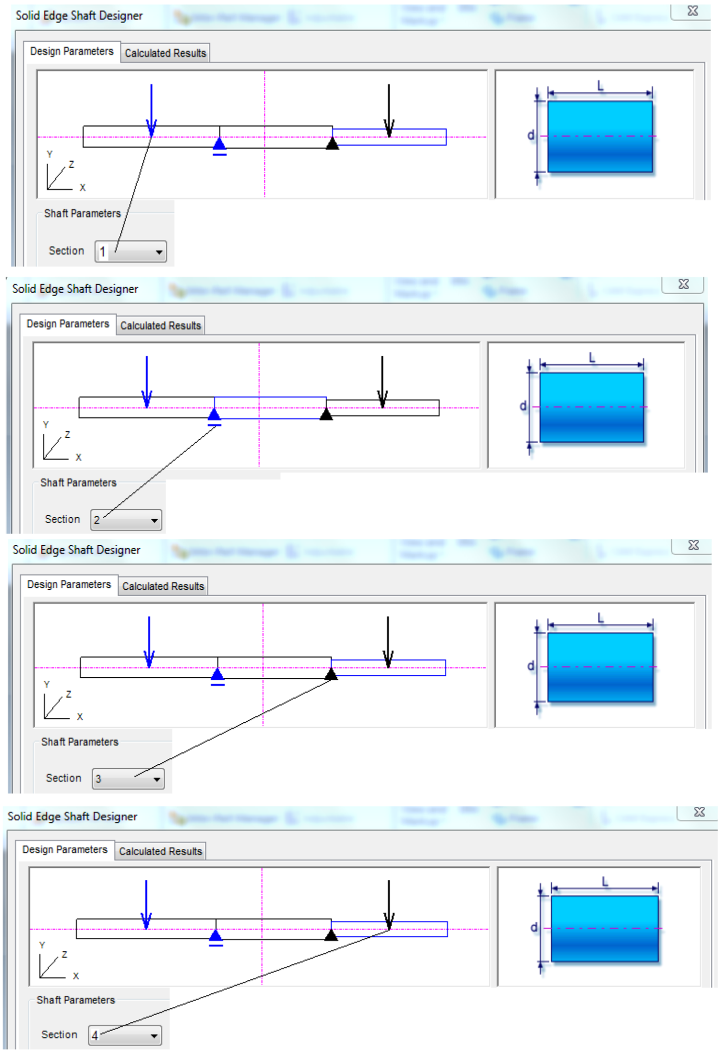


Fig. 7 – Section create in Solid Edge for shaft I.

Data entering starts with the material selection, respectively C45U steel having a 210000 MPa elastics modulus and a rigidity modulus of 81000 MPa.

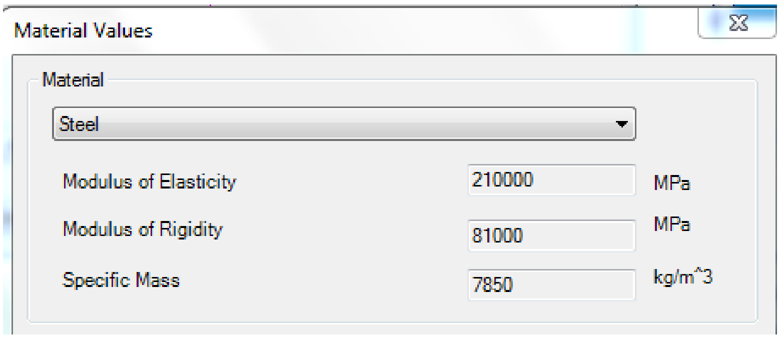


Fig. 8 – Material Values.

After introducing the initial data (diameter, length) for the 4 sections, the following diagram shows 2 actuating forces and 2 supports where the two bearings are mounted.

Force F1 acts on a diameter d1=14 mm with the following components: Radial force xy (radial force)=125000 mN, radial force xz=344100 mN, torque=16.475 Nm.

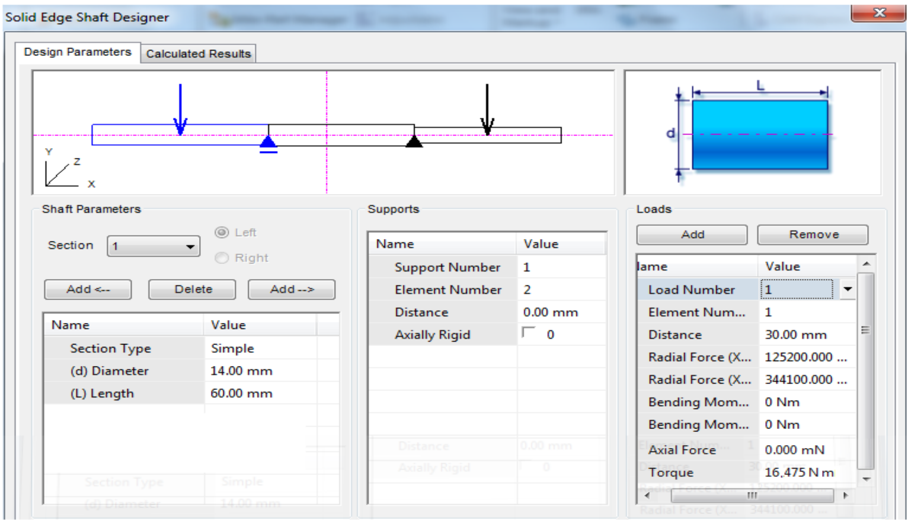


Fig. 9 – Diagram for force F1.

Force F2 acts on a diameter d1=11 mm with the following components: Radial force xy (radial force)=96900 mN, radial force xz=259000 mN, torque=-16.475 Nm.

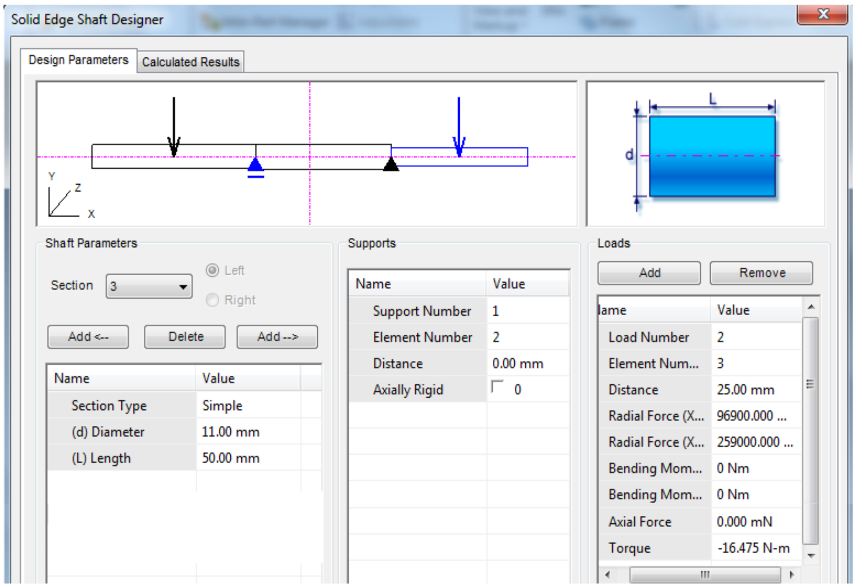


Fig. 10 – Diagram for force F2.

After entering data on diameter, length, radial forces, torques, the following characteristic diagrams are delivered:

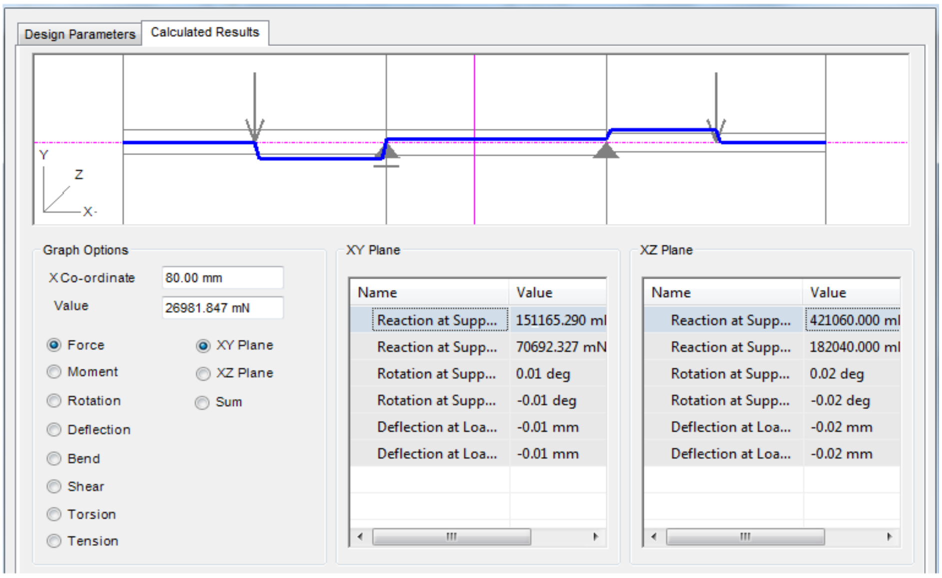


Fig. 11 – Automatic results for shaft I.

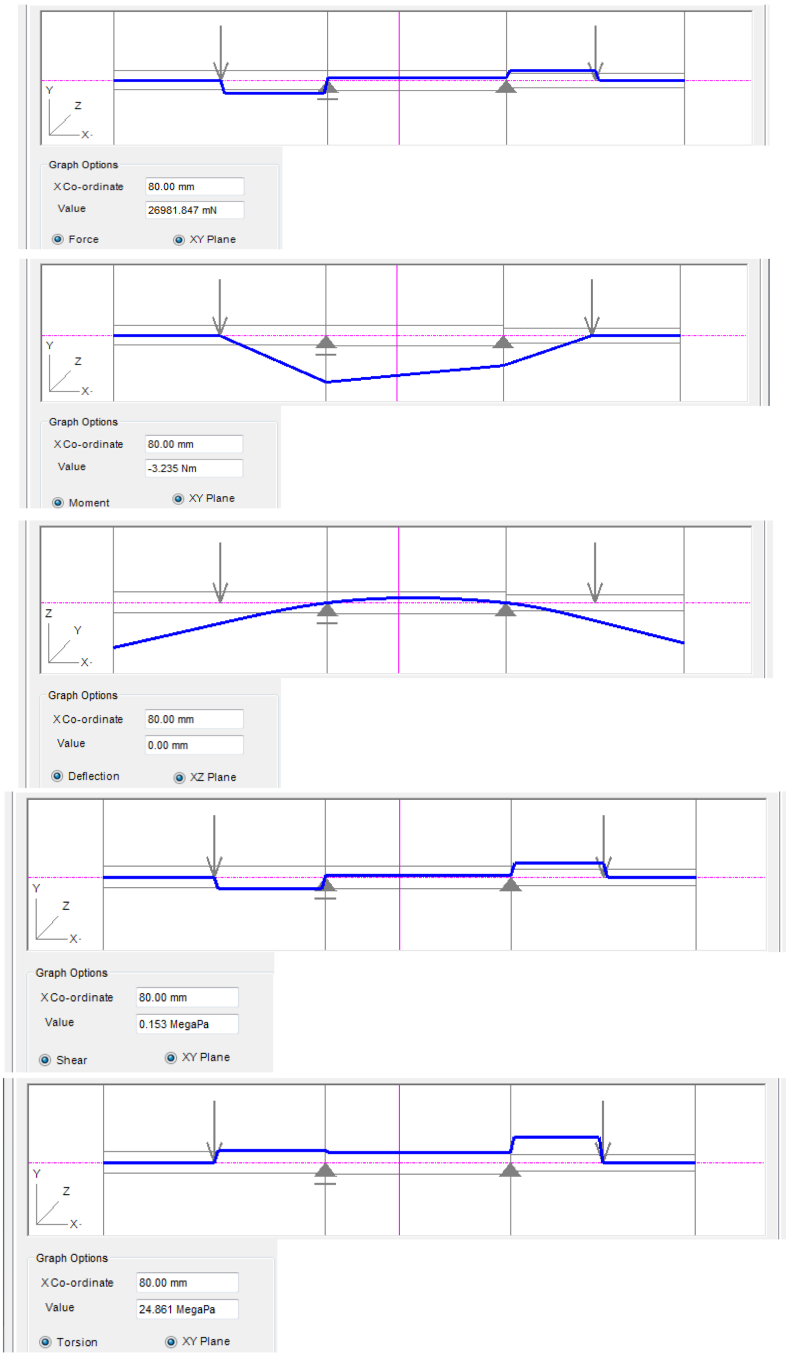


Fig. 12 – The charts resulting from the SE Shaft Designer, in the XY plane.

The following chart shows the following values of the actions in the two supports:

On XY plane

The reaction on the support 1= 151265.290 mN

The reaction on the support 2= 70692.327 mN

On XZ plane

The reaction on the support 1= 421060 mN

The reaction on the support 2= 182040 mN

In Fig. 12 and Fig. 13 there are presented the diagrams generated by the Engineering Reference module, namely: Force, Moment, Deflection, Shear, Tension, Bend, etc.

After entering the data in the Engineering Reference program, it automatically generates the rough 3D model for shaft I, without some detailed operations (threads, chamfers, holes, radiuses, etc.).

The model has to be further on developed accordingly to its positioning and functionality within the product assembly, as it is shown in Fig. 14.

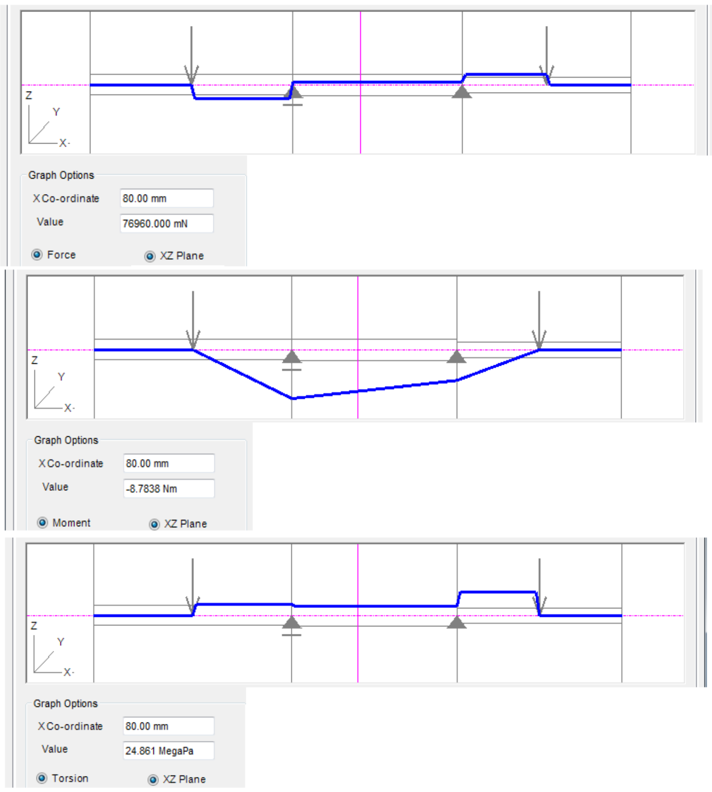


Fig. 13 – The charts resulting from the SE Shaft Designer, in the XZ plane.

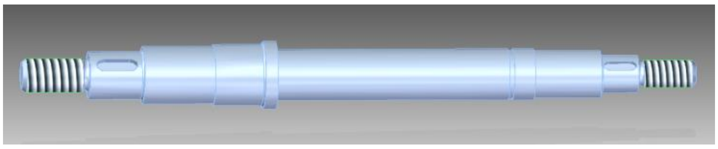


Fig. 14 – Models generation with SE Engineering Reference - Shaft I.

Gears Z1/Z2 Automated Calculation

As for the shaft I, calculations are made for gears using a special CAE facility called Solid Edge Gear Designer. This subprogram automatically has generated the 3D models for gear Z1/Z2, calculations and graphs for these parts.

Below there is included a description of the design steps for the gears Z1/Z2 using the Design Parameters tool from Solid Edge Gear Designer.

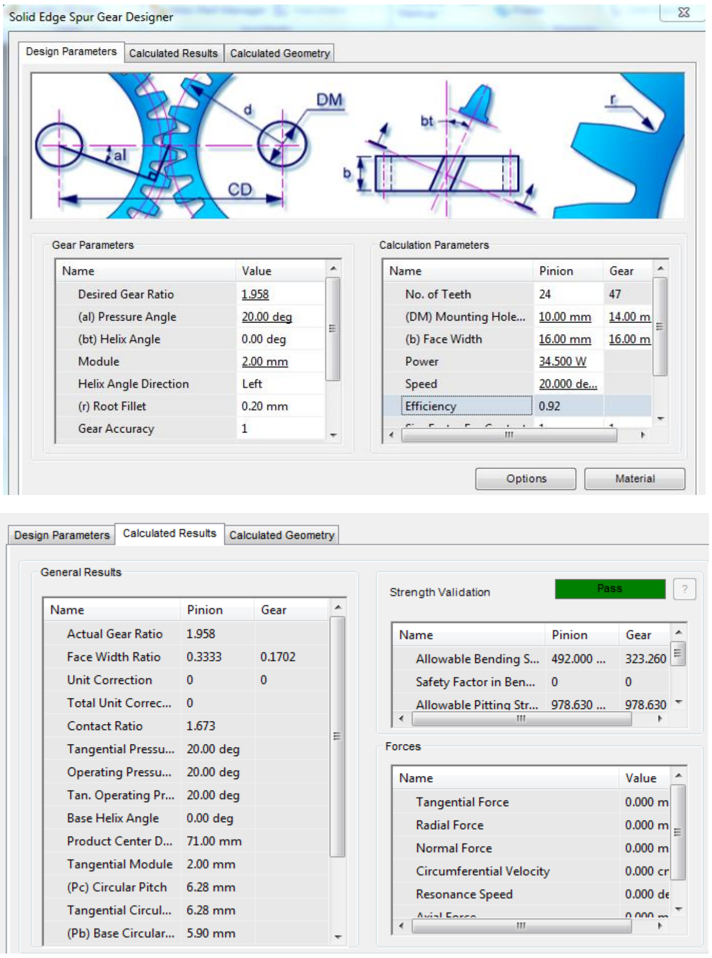
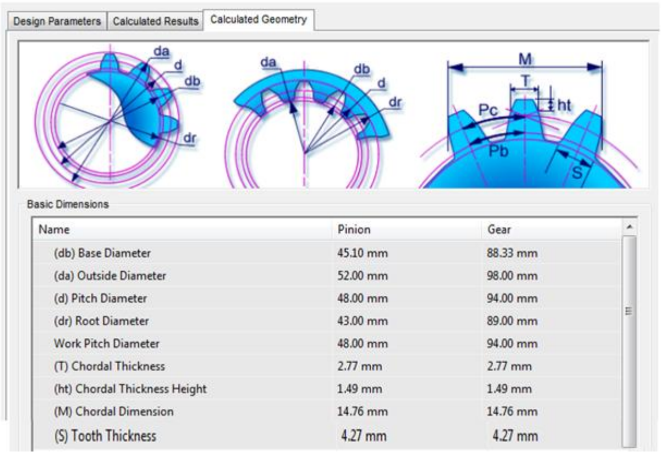


Fig. 15 – Solid Edge Gears Designer tool.

After data entering and calculations solving, a rectangle showing if the result has passed or not, appears on the right side.

Fig. 16 – Validation of the results.

If results are validated and are correctly entered, the program automatically calculates the geometry for the gears and generates the 3D models.



Name	Pinion	Gear
(db) Base Diameter	45.10 mm	88.33 mm
(da) Outside Diameter	52.00 mm	98.00 mm
(d) Pitch Diameter	48.00 mm	94.00 mm
(dr) Root Diameter	43.00 mm	89.00 mm
Work Pitch Diameter	48.00 mm	94.00 mm
(T) Chordal Thickness	2.77 mm	2.77 mm
(ht) Chordal Thickness Height	1.49 mm	1.49 mm
(M) Chordal Dimension	14.76 mm	14.76 mm
(S) Tooth Thickness	4.27 mm	4.27 mm

Fig. 17 – Geometric calculation.

After entering the data in the Engineering Reference, the program automatically generates the 3D model for gears Z1/Z2.

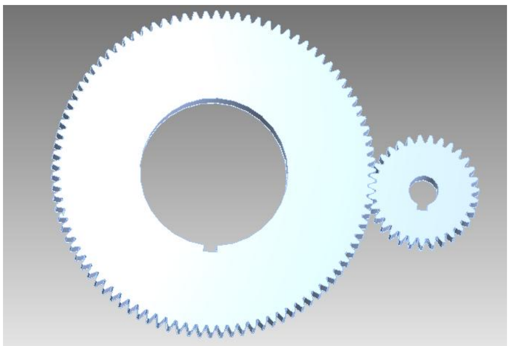


Fig. 18 – 3D models generation with SE Engineering - Gear ZI/Z2.

4. Conclusions

As a conclusion, we can firstly say that the theoretical approach and the case study from the paper, in which the use of principles Design for Disassembly and Design for Recycling converge with that of advanced Integrated Engineering solutions, together come to support the importance of integrating advanced CAD/CAE/PLM/CAx instruments for improving the Product Design & Development Sustainability.

As another conclusion, the new approach of the case study where modern CAD/CAE tools like Solid Edge (Solid Edge Shafts and Gears Designer) have been used within the product design for the technological device subjected to study provided optimization for products and more design productivity. This program has enhanced the flexibility of the product model and has increased the agility in technological changes implementation.

For the near future, a few research development directions on sustainable design are identified with the consideration of some new principles such as Holistic Design and Axiomatic Design Theory.

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UTILIZAREA CONVERGENTĂ A PRINCIPIILOR DFD-DFR ȘI A UNOR SOLUȚII AVANSATE DE INGINERIE INTEGRATĂ PENTRU PROIECTAREA SUSTENABILĂ A PRODUSELOR

(Rezumat)

Cercetarea prezentată este orientată spre utilizarea covergentă a principiilor din Proiectarea pentru Dezasamblare (DFD) și Proiectarea pentru Reciclare (DFR) și integrarea unor soluții avansate de inginerie CAD/CAE/CAID/CAx pentru sporirea eficacității și eficienței activităților de proiectare și pentru dezvoltarea sustenabilă de produs. La început, se propune un model conceptual pentru cadrul de cercetare, în care principiile DFD și DFR converg cu soluții de inginerie integrată pentru a obține o bună structură modulară a produselor și pentru a susține proiectarea produsului.

Ca studiu de caz, a fost considerată sugestivă pentru a fi prezentată aici o abordare asupra aplicării principiilor descrise mai sus în dezvoltarea unui dispozitiv tehnologic adaptabil pe o mașină de prelucrare prin electroeroziune.

Studiul de caz prezentat se referă și la performanța utilizării capabilităților avansate ale programului SolidEdge ca soluție CAD, care asigură parametrizarea și optimizarea structurii modelului 3D al produsului, dar și ca instrument CAE valoros, care permite realizarea de calcule de dimensionare și verificare pentru componente (arbori, angrenaje).