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DETERMINATION OF DISASSEMBLY INTERFERENCE MATRIX AND IMPROVED NONDESTRUCTIVE DISASSEMBLY SEQUENCES FOR THE PRODUCT

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Abstract: *This paper presents improved method for determination of disassembly interference matrix and improved nondestructive disassembly sequences during the product evaluation stage. The main objective of the improved method for nondestructive disassembly is increasing of recycling, recovery or reuse of the components. The determination of disassembly interference matrix is based on information obtained from 3d CAD model of product and developed software package. The goal of this research is to support and help product designer to create product with improved performance in order to nondestructive disassembly and predict, evaluate and define nondestructive disassembly sequences with low costs for disassembly, minimizing of reorentation of tools in the design stage when the 3d CAD model of product is avaliable. Verification of the improved method for determination of disassembly interference matrix and improved nondestructive disassembly sequenses is presented through an illustrative example.*

Key words: *Disassembly interference matrix, nondestructive disassembly sequences, product.*

Određivanje matrice smetnji demontaži i poboljšanih nedestruktivnih demontažnih sekvencija proizvoda. *Ovaj rad predstavlja poboljšanu metodu za određivanje interferencione matrice rastavljanja i poboljšane sekvence nerazornog rastavljanja tokom faze evaluacije proizvoda. Glavni cilj poboljšane metode za nerazorno rastavljanje je povećanje recikliranja, upotreba ili ponovne upotrebe komponenata. Određivanje matrice smetnji rastavljanja zasniva se na informacijama dobijenim iz 3D CAD modela proizvoda i razvijenog softverskog paketa. Cilj ovog istraživanja je podržati i pomoći dizajneru proizvoda da stvori proizvod sa poboljšanim performansama u cilju nerazornog rastavljanja i predviđanja, procene i definisanja nerazornih sekvenci demontaže uz niske troškove demontaže, minimiziranje ponovnog usvajanja alata u fazi projektovanja kada je 3D CAD model proizvoda dostupan. Verifikacija poboljšane metode za određivanje matrice smetnji rastavljanju i poboljšanih sekvenci nerazornog rastavljanja predstavljena je kroz ilustrativni primer.*

Ključne reči: *Demontaža interferencijalne matrice, nerazorna sekvence rastavljanja, proizvod.*

1. INTRODUCTION

Nondestructive disassembly is the process of removing the connectivity of components in the product and separate components in order to improved process of recycling, recovery or reuse. At the end of their useful life, products become waste [1]. The waste from end-of-life products can be defined as unnecessary goods or residues that do not have value for the owner [2]. During the last few decades, the rapid development of automobiles, electric and electronic equipment, resulted in creation of billions tones of waste. For instance, “around 3 billion tonnes of waste are generated in the EU each year - over 6 tonnes for every European citizen [3].” Current legal regulations clearly indicate that technical products should be designed considering the recovery of the product at its end-of-life stage. In Europe, designers have to follow European directives for environment protection and are obliged to incorporate these directives into the product design in order to preserve the environment or minimize the impact of pollution.

Design for Disassembly – DfD is a design tool for optimization of product structure and other design parameters in order to simplify and improve the disassembly of components for service, replacement or reuse [4]. DfD improves the disassembly of components by selecting proper fasteners, grouping the materials for recycling, and optimizing the product architecture and characteristics of the components in the product assembly to limit the costs of disassembly. The benefits of the design for disassembly are resulting in: increasing the percentage of reuse of components and material recycling; reduction of their adverse impact on the environment; easier servicing and maintenance of products, and greater total return from the end-of-life products.

2. RELATED WORK

Product disassembly is required both during the product life cycle and after the end of the product useful life. The disassembly process can be destructive and non-destructive. Destructive disassembly represents a process where the stream of end-of-life products is shredded in small fragments which are later separated according to their material composition using special separation techniques [5]. Non-destructive disassembly process is applied during the exploitation of the product and at product end-of-life. During the product exploitation, maintenance, service or replacement of some non-functional components is needed. For end-of-

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life products, the nondestructive disassembly process is needed for: the recovering of functional components; the removal of hazardous materials from the product that can have negative influence on the recycling process and can pollute the environment; the extraction of precious materials from the product; remanufacturing, etc [6]. In general the disassembly process requires two main processes which are the disjoining process and removal of the components from the product structure [7].

Many authors have developed different methods for determining of the improved disassembly sequence and for planning of the disassembly process. Lambert and Gupta in series of papers [8-10] propose a linear programming method for determination of optimal disassembly sequences for end-of-life products. The method of linear programming contributes to the optimization of the disassembly process. F. Cappelli et al. [11] presents a theoretical basis for creation of computer-aided design tool for optimization of the disassembly sequences of mechanical systems for improving maintenance and recycling activities. In the first step, the physical constraints that oppose the movement of mechanical elements are investigated, starting from the three-dimensional computer-aided design representation and an AND/OR graph of mechanical disassembly are generated. The second step is the representation of binary trees that allow automatic exploration of the set of all possible disassembly sequences. F. Giudice et al. in the papers [12,13] proposed a structured methodology for analysis and reconfiguration of disassembly depth distribution of components in the product assembly with aim for obtaining a generalised improvement in disassemblability in relation with requirements for servicing.

Computer-aided design (CAD) today is an inseparable part of the design process. In the paper [14] is presented an integrated approach of disassembly constraint generation, based on object-oriented prototype which is designed and developed. With this approach is obtained CAD model information necessary for designers for implementation of information in further application for disassembly planning. Huang et al. presents [15] disassembly matrix in a binary system for solving of disassembly processes of product. By using a Boolean operation or arithmetic operator with depth-first-search method is developed algorithm for generating of possible disassembly sequences together with directions of components removing. Disadvantage of proposed algorithm is the inability to obtain parallel disassembly sequences. This algorithm can be used only for obtaining of sequential disassembly sequences.

3. DETERMINATION OF DISASSEMBLY INTERFERENCE MATRIX

3.1 Product representation

The product assembly consists of a number of discrete components, such as, parts, fasteners, etc. Components can be grouped in subassemblies. A subassembly is a connected set of components and fasteners. If components are physically linked, such link is called a connection.

Connections restrict the freedom of motion of the components involved. In many cases, specialized components such as fasteners are used for connections. Fasteners can be discrete components such as screws, which are obtained with developed CAD macro module for reading from the CAD assembly model or non-discrete virtual objects such as snap fits, press fits, etc, which are defined manually in the developed software module between connection of components. The set of components can be given by the following expression:

$$C = \{C_1, C_2, ..., C_n\} \qquad (1)$$

The set of fasteners can be given by the following expression:

$$F = \{F_1, F_2, ..., F_m\} \qquad (2)$$

where n is the number of components in the product assembly and m is the number of fasteners in the product. The assembly is composed of all components and fasteners and can be represented mathematically with the expression $A = C_1 C_2 ... C_n F_1 F_2 ... F_m$.

In order to demonstrate the proposed 3D CAD integrated method for improving of the design for nondestructive disassembly process, the shaft with gears assembly shown in the Figure 1 is used as an example.

3.2 Contact matrix

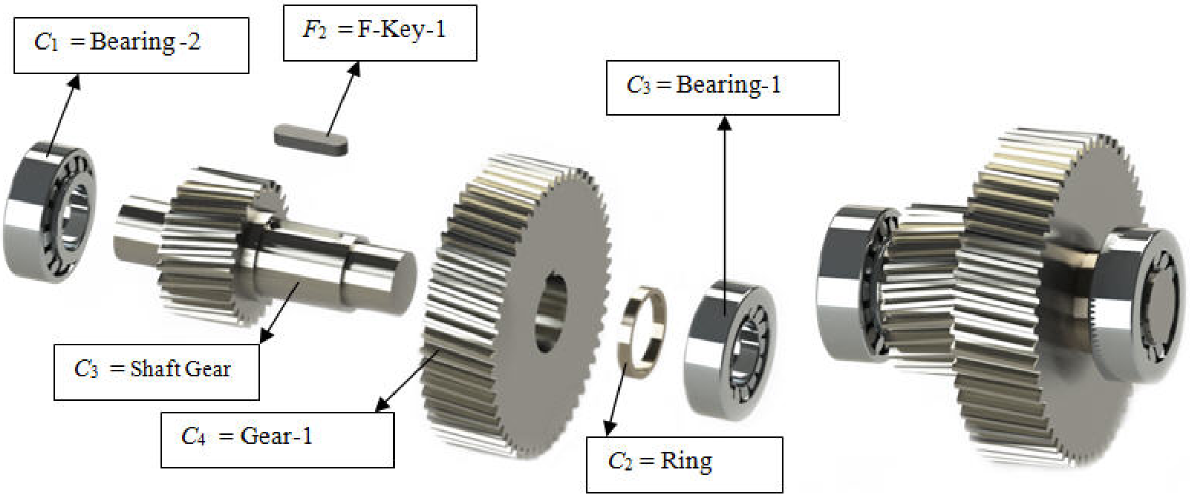
The relationships between components and fasteners in an assembly are required in order to determine all subassemblies in the assembly. For this reason, a contact matrix and contact diagram between components and fasteners and components and components are defined. The contact diagram represents a visualization tool for analysis of the subassemblies in the product assembly. If the component is in contact with some fastener in the assembly the element $F_j C_i$ in contact matrix will be equal of 1, in otherwise 0. If the component is in contact with other component in the assembly the element C_{ij} in contact matrix will be equal of 1, or otherwise 0. The contact matrix between components can be represented with the follow equation [16]:

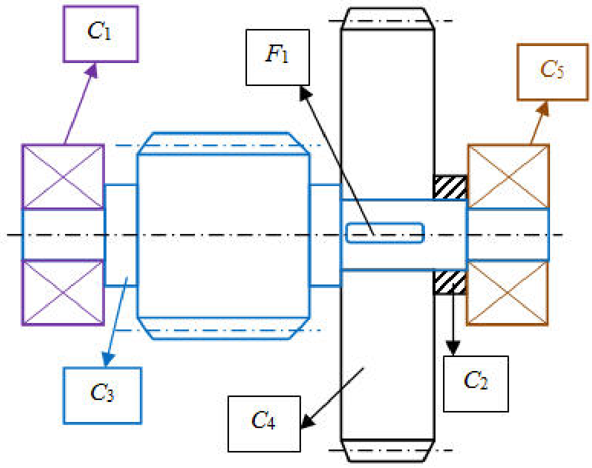
$$CC = \left[C_{ij}\right]_{i=1,2,...,n}^{j=1,2,...,n} \qquad (3)$$

The contact matrix between components and fasteners can be represented with the following equation [16]:

$$FC = \left[F_j C_i\right]_{i=1,2,...,n}^{j=1,2,...,m} \qquad (4)$$

In the Figure 2a) is represented contact matrix and diagram between components, and 2b) contact matrix and diagram between components and fasteners for example which is shown in the Figure 1.





Virtual fasteners	Between components	
F_2	C_1	C_3
F_3	C_2	C_3
F_4	C_3	C_5

Fig. 1. Exploded view, assembly and cross-section view of subassembly shaft with gears.

$$FC = \begin{array}{c|cccc} & F_1 & F_2 & F_3 & F_4 \\ \hline C_1 & 0 & 1 & 0 & 0 \\ C_2 & 0 & 0 & 1 & 0 \\ C_3 & 1 & 1 & 1 & 1 \\ C_4 & 1 & 0 & 0 & 0 \\ C_5 & 0 & 0 & 0 & 1 \end{array}$$

a)

$$CC = \begin{array}{c|ccccc} & C_1 & C_2 & C_3 & C_4 & C_5 \\ \hline C_1 & 0 & 0 & 1 & 0 & 0 \\ C_2 & 0 & 0 & 1 & 1 & 1 \\ C_3 & 1 & 1 & 0 & 1 & 1 \\ C_4 & 0 & 1 & 1 & 0 & 0 \\ C_5 & 0 & 1 & 1 & 0 & 0 \end{array}$$

b)

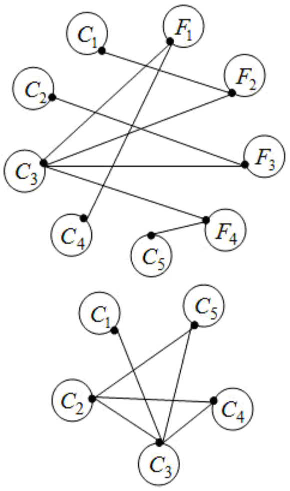


Fig. 2. Contact matrix and diagram for a) contacts between components, and b) contacts between components and fasteners in the product assembly.

3.3 Subassemblies

The total number of subassemblies generated for the example assembly is 14.

SA = { $C_1C_2C_3C_4F_1F_2F_3$, $C_1C_3C_4C_5F_1F_2F_4$, $C_2C_3C_4C_5F_1F_3F_4$, $C_1C_2C_3C_5F_2F_3F_4$, $C_1C_3C_4F_1F_2$, $C_2C_3C_4F_1F_3$, $C_3C_4C_5F_1F_4$, $C_1C_2C_3F_2F_3$, $C_1C_3C_5F_2F_4$, $C_2C_3C_5F_3F_4$, $C_3C_5F_4$, $C_2C_3F_3$, $C_1C_3F_2$, $C_3C_4F_1$}.

3.4 Disassembly operation

The total number of disassembly operations for this example is 38. The disassembly operations are shown in Figure 3.

```
0;C1,C2,C3,C4,C5,F1,F2,F3,F4;
1;C1,C2,C3,C4,F1,F2,F3;C5,F4
2;C1,C3,C4,C5,F1,F2,F4;C2,F3
3;C2,C3,C4,C5,F1,F3,F4;C1,F2
4;C1,C2,C3,C5,F2,F3,F4;C4,F1
5;C1,C3,C4,F1,F2;C2,C5,F3,F4
6;C2,C3,C5,F3,F4;C1,C4,F1,F2
7;C2,C3,C4,F1,F3;C1,C5,F2,F4
8;C1,C3,C5,F2,F4;C2,C4,F1,F3
9;C3,C4,C5,F1,F4;C1,C2,F2,F3
10;C1,C2,C3,F2,F3;C4,C5,F1,F4
11;C1,C3,C4,F1,F2;C2,F3
12;C2,C3,C4,F1,F3;C1,F2
13;C1,C2,C3,F2,F3;C4,F1
14;C1,C3,C4,F1,F2;C5,F4
15;C3,C4,C5,F1,F4;C1,F2
16;C1,C3,C5,F2,F4;C4,F1
17;C2,C3,C4,F1,F3;C5,F4
18;C3,C4,C5,F1,F4;C2,F3
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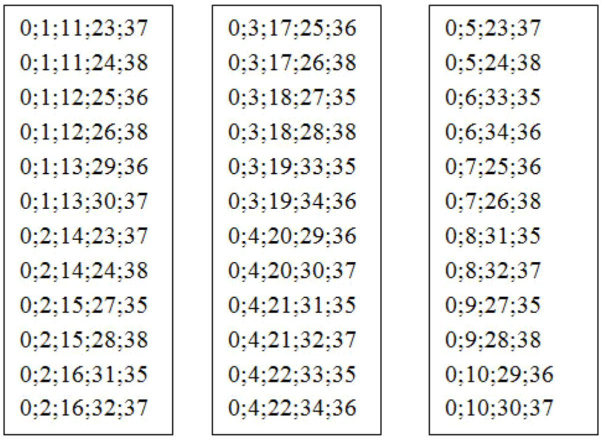
```
19;C2,C3,C5,F3,F4;C4,F1
20;C1,C2,C3,F2,F3;C5,F4
21;C1,C3,C5,F2,F4;C2,F3
22;C2,C3,C5,F3,F4;C1,F2
23;C1,C3,F2;C4,F1
24;C3,C4,F1;C1,F2
25;C2,C3,F3;C4,F1
26;C3,C4,F1;C2,F3
27;C3,C5,F4;C4,F1
28;C3,C4,F1;C5,F4
29;C2,C3,F3;C1,F2
30;C1,C3,F2;C2,F3
31;C3,C5,F4;C1,F2
32;C1,C3,F2;C5,F4
33;C3,C5,F4;C2,F3
34;C2,C3,F3;C5,F4
35;;C3,C5,F4
36;;C2,C3,F3
37;;C1,C3,F2
38;;C3,C4,F1
```

Fig. 3. List of disassembly operations

3.5 Nondestructive disassembly sequences

The total number of nondestructive disassembly sequences is shown in Figure 4.



```
0;1;11;23;37
0;1;11;24;38
0;1;12;25;36
0;1;12;26;38
0;1;13;29;36
0;1;13;30;37
0;2;14;23;37
0;2;14;24;38
0;2;15;27;35
0;2;15;28;38
0;2;16;31;35
0;2;16;32;37
```

```
0;3;17;25;36
0;3;17;26;38
0;3;18;27;35
0;3;18;28;38
0;3;19;33;35
0;3;19;34;36
0;4;20;29;36
0;4;20;30;37
0;4;21;31;35
0;4;21;32;37
0;4;22;33;35
0;4;22;34;36
```

```
0;5;23;37
0;5;24;38
0;6;33;35
0;6;34;36
0;7;25;36
0;7;26;38
0;8;31;35
0;8;32;37
0;9;27;35
0;9;28;38
0;10;29;36
0;10;30;37
```

Fig. 4. List of the total number of nondestructive disassembly operations

3.6 Disassembly interference matrix

Disassembly interference matrix is obtained from 3D CAD assembly model of product based on the directions of ±x, ±y and ±z axis, respectively. The matrix is with dimension n+m x n+m which depends on the number of components n and fasteners m in the product. The elements in the matrix are binary pairs of numbers $x_i y_i z_i$ where i = 1,…,n+m. If interference exists between components or fasteners C_i or F_i and C_j or F_j, where j = 1, …, n+m and i < j, in direction of the +x-axis, then the element $x_{i,j}$ in the matrix (5) is equal to 1. In the opposite, the element $x_{i,j}$ in the matrix (5) is 0. If i=j the element $x_{i,j}$ is equal to 0, because no component or fastener can have interference with itself [17].

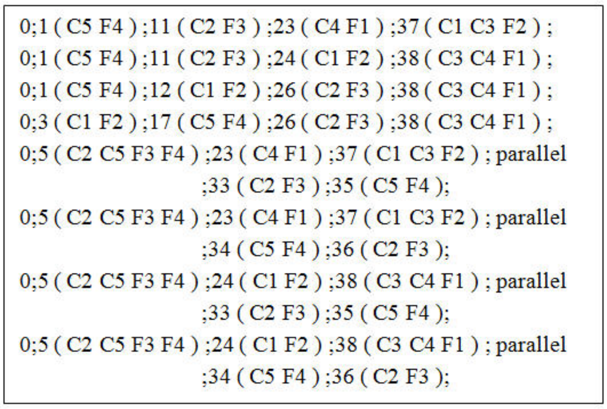
With the disassembly interference matrix, the priority for detachment of components and fasteners in directions of ±x, ±y and ±z axis is defined. The disassembly priority is required in the process of the generation of disassembly sequences with a goal to keep only the feasible disassembly operations. The disassembly interference matrix for the product assembly example is given with equation (5).

$$I_{\pm xyz} = \begin{array}{c|ccccccccc|} & C_2 & C_1 & C_4 & F_1 & C_3 & C_5 & F_2 & F_3 & F_4 \\ \hline C_2 & 000000 & 001000 & 001000 & 001000 & 111110 & 000001 & 000000 & 000000 & 000000 \\ C_1 & 000001 & 000000 & 000001 & 000001 & 110111 & 000001 & 000000 & 000000 & 000000 \\ C_4 & 000001 & 001000 & 000000 & 110110 & 111110 & 000001 & 000000 & 000000 & 000000 \\ F_1 & 000001 & 001000 & 110110 & 000000 & 111101 & 000001 & 000000 & 000000 & 000000 \\ C_3 & 110111 & 111110 & 110111 & 101111 & 000000 & 110111 & 000000 & 000000 & 000000 \\ C_5 & 001000 & 001000 & 001000 & 001000 & 111110 & 000000 & 000000 & 000000 & 000000 \\ F_2 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 \\ F_3 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 \\ F_4 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000000 \\ \hline \end{array} \quad (5)$$

4. DETERMINATION OF IMPROVED NONDESTRUCTIVE DISASSEMBLY SEQUENCES

After determining the priority of detaching of components and fasteners in the product and after definition of the lists for all disassembly direction, all disassembly sequences are checked and impossible disassembly operations are deleted.

The generated possible disassembly sequences are shown in Figure 5. The total number of disassembly sequences is this case is 8.



```
0;1 ( C5 F4 ) ;11 ( C2 F3 ) ;23 ( C4 F1 ) ;37 ( C1 C3 F2 ) ;
0;1 ( C5 F4 ) ;11 ( C2 F3 ) ;24 ( C1 F2 ) ;38 ( C3 C4 F1 ) ;
0;1 ( C5 F4 ) ;12 ( C1 F2 ) ;26 ( C2 F3 ) ;38 ( C3 C4 F1 ) ;
0;3 ( C1 F2 ) ;17 ( C5 F4 ) ;26 ( C2 F3 ) ;38 ( C3 C4 F1 ) ;
0;5 ( C2 C5 F3 F4 ) ;23 ( C4 F1 ) ;37 ( C1 C3 F2 ) ; parallel
                      ;33 ( C2 F3 ) ;35 ( C5 F4 );
0;5 ( C2 C5 F3 F4 ) ;23 ( C4 F1 ) ;37 ( C1 C3 F2 ) ; parallel
                      ;34 ( C5 F4 ) ;36 ( C2 F3 );
0;5 ( C2 C5 F3 F4 ) ;24 ( C1 F2 ) ;38 ( C3 C4 F1 ) ; parallel
                      ;33 ( C2 F3 ) ;35 ( C5 F4 );
0;5 ( C2 C5 F3 F4 ) ;24 ( C1 F2 ) ;38 ( C3 C4 F1 ) ; parallel
                      ;34 ( C5 F4 ) ;36 ( C2 F3 );
```

Fig. 5. The list from all possible disassembly sequences

5. CONCLUSION

The goal of the paper is to provide an improved method for DfD analysis of the product in the early phase of the product development, through generation of the improved disassembly sequence, fastener analysis and product structure examination. Such method should help the designers during of virtual design phase in order to satisfy the European waste directives, and to improve further the suitability of the new products from the aspect of disassembly and recycling.

3D CAD integrated methodology for product design for nondestructive disassembly process for determination of the improved disassembly sequence is presented. The proposed methodology is applied in solving a realistic problem in the product design phase. With the developed method and software, all possible subassemblies and disassembly operations for the product can be determined, based on the priority for detachment in different disassembly directions. Also, the improved disassembly sequence can be estimated based on the disassembly times, revenue and costs of disassembly. The input of geometric data in the system is performed automatically by analysis of the CAD model of the product.

The developed method and integrated software package will assist designers in creating better technical products that will be improved for nondestructive disassembly. However, as the efficiency of the disassembly sequence is strongly governed by the relationship between the cost of the envisioned disassembly operations and the respectively generated potential revenues, the excellence of the designer in selecting the most desirable fasteners in terms of nondestructive disassembly of the final product remains to be of crucial importance.

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