Analyses and redesign of a technological device for automated assembly, using Design for Manufacturing and Assembly approach

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Abstract. This paper aims to present a theoretical approach and a case study within a research upon product and process design methods in terms of manufacturing and assembly – supported by DFMA (Design for Manufacturing and Assembly) techniques. Application of the integrated design capabilities provided by DFMA approach is illustrated with a case study on the development of a technological device for automated assembly of an industrial electrical plug inlet. The analysis and redesign using DFMA philosophy and advanced 3D design capabilities provided by CATIA V5 is an advanced engineering method for designing an innovative product in order to simplify the product, to quantify improvements and to reduce manufacturing and assembly costs. The new design of the studied product has been compared with the existing one from the aspect of parts quantity, handling time, assembly time and design efficiency. Finally, the study presents also some related conclusions together with further research directions.

1. Introduction. Problem statement

In the last decades, significant progress has been made in all stages of product design and development.

According to Boothroyd, designing is the first step in the manufacturing process and is the place where most of the important decisions that influence the final cost of a product are taken [1].

The interest of researchers around the world about this domain has continuously raised, many researches, studies and methodologies have been developed in recent years that has led to major technological results. An advanced design philosophy, which we consider useful to be applied even from the early design phases is Design for Manufacturing and Assembly (DFMA) developed by Boothroyd, Dewhurst, and Knight [2], which aims to minimize the overall cost of product manufacturing, through reducing the production cost, shortening the implementation time of the new product, and increasing the quality level. These are vital requirements that cannot be neglected by manufacturing companies which need to pay more and more attention to be competitive on a global dynamic market.

This paper is part of a wider research regarding the development of new or existing products, based on a conceptual model [3] which has been taking into consideration advanced design philosophies such as Axiomatic Design [4], Design for Excellence and Concurrent Engineering together with CAD/CAE tools. The further on presented case study and theoretical considerations represent a...
continuation of the research results achieved in previous works, related to optimizing an industrial
equipment for automated assembly [5].

2. Theoretical backgrounds. Research problem substantiation
Design for Manufacturing and Assembly (DFMA) consists of two main components which are Design
for Assembly (DFA) and Design for Manufacturing (DFM).

When the application of DFMA principles is considered, the first step is to analyze the product in
terms of assembly by applying the set of rules and principles provided by the DFA technique. Design
for Assembly (DFA) is a methodology that aims to simplify the product by focusing on parts count
reduction by eliminating unnecessary parts, by integrating them with other parts and by parts variants
reduction, thus improving product quality and minimizing the assembly problems [6].

The second step is applying DFM (Design for Manufacturing) guidelines, which have the role to
optimize the product configuration from the manufacturing perspective by focusing on two main
design aspects: first of them is selecting the adequate manufacturing processes chain for each
component followed by optimizing the geometry part design for the chosen processes chain [7].

In James Bralla’s view, the most significant benefits with design for manufacturing (DFM) comes
from design for assembly (DFA) because simplifying the product so that it has fewer parts, leads to an
easier and faster to fabricate assembly [8].

It has been proven that the best results achieved in product development come from parts count
reduction, because it eliminates unnecessary manufacturing and assembly costs. Designing with fewer
parts means fewer assembly operations and the facility required to make a product is also less, this
lead to fewer mistakes and more throughput. Another best improvement is given by reduction of parts
variants which enables to identify parts families and the use of standard components, the benefits
being a common assembly sequence and reduced tooling and storage costs [9].

These are key requirements that optimize a product in terms of manufacturability, the main
responsibility to achieve them dropping on the product-process designers, which have the main role to
find solutions to get the best design. Optimizing the part design to simplify manufacturing and
assembly process requires a vast knowledge of every available manufacturing and assembly process.

Fortunately, by using some advanced design philosophies such as DfX/DFA/DFM together with
CAD/CAM integrated solutions engineers can systematically study assemblies with the goal to
identify and correct downstream issues in the design stage, leading to the reduction of the cycle time
and the product development costs of the product. Applying in the same time DFA/DFM design
principles with CAD/CAM tools helps to optimize assembly tasks and manufacturing processes even
in the earliest stages of design when revisions are least expensive and easiest to make.

DFM Pro for SolidWorks provided by Geometric is an example of such advanced tool that has been
utilized in this larger research [5], for analyzing the considered device for automated assembly, in
order to achieve the best design for each part in terms of manufacturability. The achieved results have
been presented in previous work where issues of DFM were treated.

The theoretical approach is sustained by a case study bellow presented, which shows an example of
design analysis based on Design for Assembly (DFA) considerations upon assembly efficiency of the
components from an industrial device for automated assembly.

3. Case study
As case study, the research paper presents an approach on the application of the Design for Assembly
theory integrated together with Catia V5 [10] CAD software for increasing the effectiveness and
efficiency of analyses and design activities for a product assembly in connection with the necessity of
development of a technological device for automated assembly. The description of the device and the
working principle have been shown in previous works [4,5], hereby in this paper only the analysis of
the assembly efficiency of the product is summarized.
3.1 Design Assembly Efficiency - Methodology

Design for Assembly (DFA) methodology that is applied in this work to analyze the product is the Boothroyd DFMA method [2]. This method is characterized by the using of a measure of the DFA index or assembly efficiency of the proposed design. The main objectives of this research are to analyze the assembly efficiency of the initial design, and then based on the achieved results to redesign the assembled product. To validate the improvements that are made on the assembly, one needs to calculate the assembly index for redesigned product, which must be higher than for the current design.

This procedure helps designers to minimize the assembly time and cost and also manufacturing labor for the products. The two main factors that are taken into consideration when a product or subassembly is analyzed, are [2]:

• The number of parts in a product;
• The easiness of handling, insertion, and fastening of the parts.

Accordingly with this method, the process of manual assembly can be divided into two separate areas, manual handling and manual insertion. For each of them, a classification and encoding system gives a time standard system for designers to use in estimating manual assembly times.

The assembled product which is subjected to the analysis to illustrate how the DFA technique is applied in practice is shown in figure 1. This device is composed of many parts that are secured using especially screws and nuts. The assembly of this product first involves securing a series of parts together in subassemblies using screws and then securing the resulting assembly into the final product, again using screws.

First of all, the device is disassembled, and the current number of parts is written down in table 1. The main parameters which influence the assembly index, as total symmetry of the part, handling time, insertion time, total assembly time and assembly cost for each part are also written in the table.

Features of the part such as size, thickness, weight, flexibility, slipperiness, the necessity of using two hands, the necessity of using grasping tools, the necessity of optical magnification and necessity of mechanical assistance are taken into consideration to find the appropriate value of time needed for the manual handling of the part into an assembly [11].

Figure 1. Detailed view - 3D parameterized assembly model for the indexing mounting table [5].

Figure 2. Disassembled 3D view of the indexing mounting table (Catia V5 3D modelled parts). Main parts identification.
| Part No. | Part Name                          | Quantity | $\alpha$ | $\beta$ | $\alpha+\beta$ | Handling time (sec) | Insertion time (sec) | Total time (sec) | Assembly Cost (RM) | Theoretical Part Count |
|---------|------------------------------------|----------|----------|---------|--------------|--------------------|----------------------|-------------------|---------------------|------------------------|
| 1       | Base plate                         | 1        | 360      | 3       | 1.5          | 4.5                | 0.0375               | 1                 |                     |                        |
| 2       | Electrical motor                   | 1        | 360      | 360     | 720          | 3                  | 1.5                  | 4.5               | 0.0375               | 1                      |
| 3       | Worm gearbox                        | 1        | 360      | 360     | 720          | 3                  | 1.5                  | 4.5               | 0.0375               | 1                      |
| 4       | Hex Bolts M8x25                    | 8        | 360      | 0       | 360          | 1.5                | 5                    | 52                | 0.4333               | 4                      |
| 5       | Hex Nuts M8                        | 8        | 180      | 0       | 180          | 1.43               | 6                    | 59.44             | 0.4953               | 4                      |
| 6       | Flexible coupling                  | 1        | 360      | 540     | 1.8          | 5                  | 6.8                  | 0.0566            | 1                   |                        |
| 7       | Shaft                              | 1        | 360      | 360     | 720          | 2.73               | 5                    | 7.73              | 0.0644               | 1                      |
| 8       | Pinion                             | 1        | 180      | 360     | 540          | 2.57               | 7.5                  | 10.07             | 0.0839               | 1                      |
| 9       | Radial ball bearing                | 2        | 180      | 0       | 180          | 1.13               | 9                    | 20.26             | 0.1688               | 2                      |
| 10      | Cam shaft                          | 1        | 360      | 90      | 450          | 2.25               | 6.5                  | 8.75              | 0.0729               | 1                      |
| 11      | Groover washer                     | 1        | 180      | 0       | 180          | 1.13               | 1.5                 | 2.63              | 0.0219               | 0                      |
| 12      | Hex Nuts M16                       | 1        | 180      | 0       | 180          | 1.43               | 6                    | 7.43              | 0.0619               | 1                      |
| 13      | Bottom housing                     | 1        | 360      | 72      | 432          | 3                  | 1.5                  | 4.5               | 0.0375               | 1                      |
| 14      | Hex Bolts M8x25                    | 5        | 360      | 0       | 360          | 1.5                | 5                    | 32.5              | 0.2708               | 0                      |
| 15      | Gearwheel                          | 1        | 180      | 360     | 540          | 2.57               | 7.5                  | 10.07             | 0.0839               | 1                      |
| 16      | Parallel Keys                      | 4        | 180      | 90      | 270          | 1.43               | 7.5                  | 35.72             | 0.2976               | 4                      |
| 17      | Angular contact ball bearing       | 2        | 180      | 0       | 180          | 1.84               | 9                    | 21.68             | 0.1806               | 2                      |
| 18      | Tubular Shaft                      | 1        | 360      | 0       | 360          | 2.25               | 9                    | 11.25             | 0.0937               | 1                      |
| 19      | Upper housing                      | 1        | 360      | 360     | 720          | 3                  | 1.5                  | 4.5               | 0.0375               | 1                      |
| 20      | Hex Bolts M8x30                     | 5        | 360      | 0       | 360          | 1.5                | 5                    | 32.5              | 0.2708               | 5                      |
| 21      | Hex Nuts M8                         | 5        | 180      | 0       | 180          | 1.43               | 6                    | 37.15             | 0.3095               | 5                      |
| 22      | Thrust ball bearing                | 1        | 180      | 0       | 180          | 1.84               | 9                    | 10.84             | 0.0903               | 1                      |
| 23      | Bearing bushing                    | 1        | 360      | 72      | 432          | 1.5                | 6.5                  | 8                 | 0.0666               | 1                      |
| 24      | Support crown                      | 1        | 360      | 360     | 720          | 1.95               | 6.5                  | 8.45              | 0.0704               | 1                      |
| 25      | Rotary plate                       | 1        | 180      | 72      | 252          | 4.1                | 4                    | 8                 | 0.0675               | 1                      |
| 26      | Hex Bolts M6x25                     | 5        | 360      | 0       | 360          | 1.5                | 5                    | 32.5              | 0.2708               | 0                      |
| 27      | Prism                              | 5        | 180      | 360     | 540          | 1.8                | 1.5                  | 16.5              | 0.1375               | 5                      |
| 28      | Button head cap screw M6x30         | 10       | 360      | 0       | 360          | 1.5                | 5                    | 65                | 0.5416               | 5                      |
| 29      | Positioning Pin                    | 5        | 180      | 0       | 180          | 1.43               | 2                    | 17.15             | 0.1429               | 0                      |
| 30      | Cam                                | 1        | 360      | 360     | 720          | 1.95               | 9                    | 10.95             | 0.0912               | 1                      |
| 31      | Groover washer                     | 1        | 180      | 0       | 180          | 1.13               | 1.5                 | 2.63              | 0.0219               | 0                      |
| 32      | Hex Bolts M12x60                    | 1        | 360      | 0       | 360          | 1.5                | 5                    | 6.5               | 0.0541               | 0                      |
| 33      | Guiding element                    | 5        | 360      | 180     | 540          | 1.8                | 1.5                  | 16.5              | 0.1375               | 5                      |
| 34      | Button head cap screw M6x25         | 10       | 360      | 0       | 360          | 1.5                | 5                    | 65                | 0.5416               | 5                      |
| 35      | Follower rod                       | 5        | 360      | 180     | 540          | 1.8                | 1.5                  | 16.5              | 0.1375               | 5                      |
| 36      | Roller                             | 5        | 180      | 0       | 180          | 1.13               | 4                    | 25.65             | 0.2137               | 5                      |
| 37      | Button head cap screw M4            | 5        | 360      | 0       | 360          | 1.5                | 5                    | 32.5              | 0.2708               | 0                      |
| 38      | Flanged Nuts M4                     | 5        | 360      | 0       | 360          | 1.8                | 6                    | 39                | 0.325                | 0                      |
| 39      | Compression spring                  | 5        | 180      | 0       | 180          | 1.84               | 2                    | 19.2              | 0.16                 | 5                      |
| 40      | Tension spring                     | 5        | 180      | 360     | 540          | 2.57               | 2                    | 22.85             | 0.1904               | 5                      |
| 41      | Fixing jaw                          | 5        | 360      | 360     | 720          | 1.95               | 1.5                  | 17.25             | 0.1437               | 5                      |
| 42      | Washer                             | 20       | 180      | 0       | 180          | 1.69               | 1.5                  | 63.8              | 0.5316               | 0                      |
| 43      | Hex Bolts M10x40                    | 5        | 360      | 0       | 360          | 1.5                | 5                    | 32.5              | 0.2708               | 5                      |

**Total** 915.85 7.632 93
The manual insertion analysis refers to the accessibility of assembly location, ease of operation of an assembly tool, visibility of assembly location, ease of alignment and positioning during assembly and depth of insertion, when is selected the value of time required to perform this operation.

One of the main geometric design features that affects the time required to grasp and orient a part is its own symmetry, which refers to the necessity of rotation the part around its own axis, called alpha rotation and the rotation of the part around its axis of insertion, called beta rotation.

3.2 Design Assembly Efficiency - Results

In the last column of the table 1 is established the theoretical part count based on the importance of the parts in the assembly functioning. Each part is noted with 0 or 1: if the part is less important to the functioning of the product receives the number 0 and the part can be eliminated, if the part is important in the functioning of the product is noted with number 1, which means that these parts need to be kept or can be eliminated by redesigned or integrated with other parts, to keep or improve the functioning of the device.

The current analyzed device is composed of a number of 159 parts, from which 93 are considered as theoretical parts count. The basic assembly time estimated for theoretical parts is about 3 s. In this way, for the initial design it is necessary a time of 915.85 seconds to get the assembled product which gives us a DFA index of 30.4 %.

The DFA index is given by [2]:

\[ E_{ma} = \frac{N_{min} \cdot t_a}{t_{ma}} = \frac{93 \times 3}{915.85} = 30.4\% \]  

where \( N_{min} \) represents the number of theoretical parts, \( t_a \) is estimated time for assembling a theoretical part and \( t_{ma} \) is necessary time for assembling the analysed product.

3.3 Redesign for the indexing mounting table subassembly. Results and discussion

By applying DFA approaches, a few parts have been nominated for a complete removal, such as screws and nuts, and other parts have been redesigned and integrated with other parts, which has led to a large reduction in the number of parts. For the new design, DFA index value has risen to 26.8%, meaning that the assembly process is more efficient.

The subassemblies further on presented in the paper have been analyzed and redesigned by applying the DFA technique and using the advanced design capabilities provided by Catia V5, the detailed design activities and 3D modelling tasks, have been solved.

![Figure 3. DFA technique applied in redesigning of two main parts: tubular shaft and pressure plate.](image)
The subassembly of tubular shaft and pressure plate performs a circular movement, being a very important part for the function of the studied product and its removal is not allowed. Provided by the DFA technique, the three criteria [2] for separate parts have been applied for this subassembly: the tubular shaft does not move relative to the pressure plate, these parts do not have to be of different material and the tubular shaft clearly does not have to be separate from the pressure plate in order to allow the assembly of the pressure plate to the other subassembly of the product. None of these three criteria have been met and these parts have been redesigned and integrated one into another to achieve a single part. In this way, the total number of parts of the subassembly has been reduced from seven to four, also supported by a reduction in the number of screws needed for assembling with other parts. The new achieved part has brought a few advantages in terms of assembly, time and cost reduction.

Another subassembly that has been passed through radical redesigning, but also keeping its role, is cam subassembly. The cam is the central part of the product that requires special attention in the manufacturing and assembly process.

![Figure 4. DFA optimization - before and after redesigning.](image)

In the initial design, the cam was assembled through five pins with the support plate. Assembling and functioning analysis by applying the same three criteria as in the previous case, gave us suggestions for redesigning, which led to simplifying the subassembly, achieving an improved design for the cam with a single hole, and reducing the number of parts from seven to one. The new cam is locked by a screw, its round hole allows for continuous adjustment of the cam position instead of the square hole that is difficult to manufacture and allows a step adjustment.

4. Conclusions
In this paper, an application of DFMA philosophy and especially design for assembly (DFA) approach used to analyze and redesign an industrial equipment for automated assembly and the benefits of integration with some advanced 3D design tools like Catia V5 are presented. Through this study, DFMA presents a successful method of increasing design efficiency and reducing the number of parts, especially for the assembly process, which also has advantages for the manufacturing process. It is necessary to measure the impact of each component part in order to identify the overall performance of the existing product and to consider the possibility of changes or improvements of the current design.

Design for Assembly (DFA) method leads to a cheaper design because more efficient actions are taken to anticipate requirements for the beginning of the product development. In this way the assembly problems are reduced and the ideas to prepare the manufacturing chain are easy to take to achieve the best design.

The present case study succeeds in demonstrating the importance of implementing these guidelines in the design process, because we can minimize the number of parts that are not useful in the product, by elimination or integration, without affecting the function of the product or sometime improving it.

Studies will be continued upon the use of some other DfX philosophies and integrated engineering tools, within Product Design and Development improvement.
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