INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
https://doi.org/10.21278/idc.2018.0381

NEW INTEGRATIVE APPROACH TO EXISTING DESIGN FOR ASSEMBLY (DFA) METHODOLOGIES: APPLICATION ON ELEVATOR COMPONENTS

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Abstract

This paper presents an integrative approach to the design for assembly (DfA) methodologies, adapting these to the particularities of the elevation industry. A friendly design tool in form of software has been developed implementing the proposed approach and methodology. A study case for an elevator counterweight design has been presented to show and test the advantages of the new approach and developed tool. Improvements of approximately 7.9 percentage points in the assembly effort of the elevator counterweight have been obtained following the proposed approach.

Keywords: design for x (DfX), design methodology, design tools, elevator counterweight, DfA

1. Introduction

The assembly process definition is an important step in the development of industrial products and commonly requires complex analysis to do it efficiently. An appropriate interrelation with well-focused synergies between designers, manufacturers and assemblers of products must exist to guarantee the correct assembly of the final product. Optimizing the assembly process of a product is a key aspect in modern industry, especially to minimize costs in production processes. There is currently a tendency to address assembly problems from the early phases of design due to the advantages that provides from the point of view of costs in the development of the product. To this end, appropriate design methodologies have been developed especially focused to consider key aspects of the assembly from the design phase. This methodologies have then been extended as DfX methods to the concept of "design for excellence" (Pahl and Beitz, 1996). These DfX methodologies have been developed and improved in the last years since Boothroyd and Dewhurst developed the first of the DfX methodologies in the 80s: Design for Assembly or DfA (Boothroyd, 1987).

The research on DfX areas, mainly design for manufacturing (DfM) and assembly (DfA) as a whole (DfMA), has shown a strong influence on the conditions of subsequent operation and the phases of manufacturing and product life (Huang, 2010). However, these general trends could undergo changes or variations when they are analyzed for different particular sectors. Hence, today there is no efficient methodology for each particular sector, such as the elevator industry, so it is interesting to develop general methodologies that take into account these particularities and facilitate the application and optimize the benefits (Fu et al., 2016). It can be observed in the elevation sector that, although some design techniques are mastered, there is no a structured and rigorous design process due to the great customization required in production. In the elevation industry the design process from the creation of new concepts to the development depends exclusively on the experience of the designer and additionally, group work techniques are used for the evaluation and selection between different design concepts. However, this sector is increasingly interested in innovative design techniques based on design for excellence such as the DfA. Through these techniques, a completely objective and quantitative evaluation of the different design approaches is sought: assembly and manufacturing, guiding the designer through clear and predefined steps in order to reach the optimal solution. Currently, these methodologies are used extensively in other sectors, with special relevance in those dedicated to mass production but it is still necessary to adapt them to the lean productions that have more and more weight in the industry such as the elevation sector.

The design for assembly (DfA) methodologies have been improved during the last decades to adapt them to the different applications in the industry (Boothroyd, 1996; Dochibhatla et al., 2017). However, today there are still three main reference methodologies: "Hitachi Assemblability Evaluation Method", "Boothroyd Dewhurst System" and "Lucas DFA Methodology". The most applied are the first two: Hitachi AEM and Boothroyd-Dewhurst DfMA (even if it also includes aspects of Manufacturing, it is considered a DfA methodology). Another extended methodology has been presented recently in the state of the art, Lucas / Hull DfA, similar to Boothroyd-Dewhurst (Dochibhatla et al., 2017). These methodologies are the most used ones, with different adaptations studied to specific cases but maintaining the same procedures.

In general, all these methodologies focus mainly on facilitating assembly, minimizing the number of parts or their variability and allow taking into account other issues such as: accessibility, handling and the need for fitting with tools (Favi et al., 2016). Another fundamental objective of these methodologies is to minimize the number of assembly operations and thus the assembly time / costs. Some examples of tools with DfA methodologies used in case studies can be found in the literature (Molloy et al., 1998; Owensby and Summers, 2014; Recalt et al., 2014).

Few examples of application of DfA methodologies to the design of elevators have been found in the reviewed literature (Imrak et al., 2006; Imrak and Kocaman, 2012), but the effectiveness of these methodologies on a case study with large components is not evident.

From previous researches (Dochibhatla et al., 2017) is known that different methods can work in tandem with each other to provide insight into: "how many functional parts are there in a product?" and "how long it will take for it to assemble?". In particular, for elevators design the Boothroyd based methodologies are most efficient to identify the critical parts regarding to the assembly process, while Lucas based methods are a better to evaluate components. However, there still are limitations due to the typology of the parts and the joints typically used in the elevator sector where large size components and bolted joints are primarily used. As mentioned in literature (Rodriguez-toro, 2004) current DFA methods have difficulties dealing with this aspect.

The main purpose of this work is to develop an approach that integrates the best aspects of each DfA methodology, adapting them to be applied to the assembly of elevator components. In Section 2, the new DfA methodology approach is proposed unifying the most relevant methodologies and also a design tool is developed with this new approach. In Section 3 a study case of the design of an elevator counterweight using the proposed DfA integrated approach is carried out. A discussion of the main results has been performed and some final conclusions have been given.

2. Combined DfA approach for elevator components

2.1. Hypothesis and proposed methodology

The proposed approach is to be integrated in a traditional design process and combines several aspects and parameters from two different DfA methodologies: Boorthroyd & Dewhurst DFMA and Lucas/Hull DFA, which are focused on reducing the number of parts and variability. The Hitachi AEM has not been used since it is based on a "one part, one motion" approach, which might not be applicable for large and heavy components such as the ones that integrate an elevator counterweight. The chosen methodologies, Boothroyd & Dewhurst (henceforth B&D) and Lucas/Hull, use similar approaches to reduce the number of parts and increase the efficiency of the design. However, while B&D is more focused on the evaluation of the components themselves, the Lucas/Hull method focuses more on the assembly sequence (Kocabiçak, 1999). Additionally, new considerations have been added to complement the

B&D and Lucas/Hull methodologies concerning to the identification of critical parts and the evaluation of joints in the context of large size components.

Regarding to the identification of critical parts, Boothroyd and Dewhurst proposed three questions which must be answered when designing a component (Boothroyd, 1987):

- Does it have a relative movement?
- Does it have a different material?
- Is it necessary to remove for maintenance?

According to the B&D DFMA methodology, if any of the proposed questions is answered positively, the component is considered essential or critical and should not be eliminated. However, a critical part might be modified in order to integrate a non-critical part. On the other hand, if the answer for the three questions is negative, the part should be eliminated from the assembly, since it is not essential for the correct functioning.

The B&D DFMA methodology is usually applied on small and mass produced products. However, large and heavy components like the ones on an elevator might be misidentified as non-essential by the proposed questions, so that three more questions have been included for the new approach in order to reduce the probability of misidentifying components:

- Is it the base part where the rest are assembled?
- Does it need to be separated from other parts in order to work?
- Is it necessary for the correct functioning of the assembly?

These six questions should be answered by the designer as a first step of the new DfA design process in order to identify the critical parts of the assembly. Then, each part, independently from the result of the criticality analysis, is to be evaluated by the Lucas/Hull DfA method. The evaluation by means of the B&D DFMA method is not used since it is based on the fact that the theoretical minimum time to assemble a part should be 3 seconds. Following the same criteria used to decide that the Hitachi method might not be valid for large and heavy parts, the authors decided to continue the evaluation with the Lucas/Hull method.

The second step is to evaluate the individual parts by the Lucas/Hull method, a penalty-based method that focuses on three important aspects of a product design and measures them by three indices called Efficiency Index, Handling Index and Fitting Index (Lucas Engineering Systems Ltd, 1993). The ratio between the previously obtained critical and non-critical parts is essential for this part of the evaluation. The Handling analysis scores the components depending on size, weight, handling difficulties and orientation. The Fitting analysis, on the other hand, scores the components depending on placing and fastening, alignment, access or insertion difficulties. Every part is given a score for different aspects concerning each analysis. The penalty scores for each aspect are presented on the Lucas/Hull tables (Kamrani and Nasr, 2010).

Regarding to the evaluation of joints in the assembly, variations have been included from the tables found on the literature, such as having different scores for screws that are directly tightened to the threaded part and the connections that require tightening both the screw and its nut. The number of fasteners is also taken into account for the evaluation.

Once the indices are calculated for each part, three ratios are calculated for the whole assembly. These ratios depend on individual part evaluations and the number of critical parts obtained from the B&D DFMA critical part evaluation. According to the Lucas/Hull method, handling and fitting ratios should have a maximum value of 2.5 and the design efficiency should be over 60% in order to successfully pass the evaluation.

$$\text{handling ratio} = \frac{\sum \text{handling index}}{\text{critical parts}} \tag{1}$$

$$\text{fitting ratio} = \frac{\sum \text{fitting index}}{\text{critical parts}} \tag{2}$$

$$\text{design efficiency} = \frac{\sum \text{total number of parts}}{\text{critical parts}} \tag{3}$$

The results of these ratios give the designer an overall view of the proposed design and the impact of each part on the whole assembly. It also offers information about which aspect of the assembly or part should be modified or is more critical. These design recommendations are given to the user by the evaluation tool that has been developed, where the designer can evaluate an assembly, follow the given design recommendations and redesign the assembly in order to receive a new report for the optimized design. The iterative process can be seen in the Figure 1.

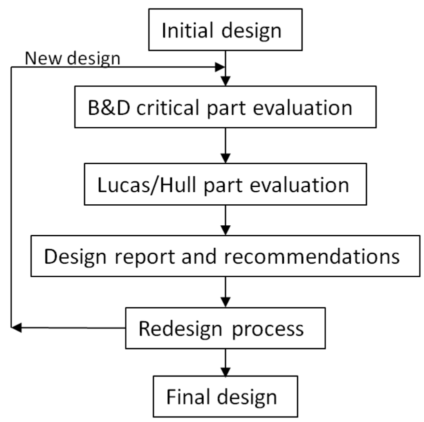


Figure 1. DfA evaluation diagram for the proposed approach

As a result of this iterative process, an efficient assembly is obtained, where the handling and fitting ratios and the design efficiency should be in the range proposed by Lucas/Hull. In addition, the B&D questions included in the tool complement the indicators and provide an overview of the assembly that suggests recommendations for design improvement.

2.2. Developed tool

A design tool through a graphical user interface has been developed. This tool allows to the designer to carry out an evaluation for different design concepts, and identifies the parts or assemblies that should be improved in relation with the assembly. A view of the developed tool appearance is shown in Figure 2.

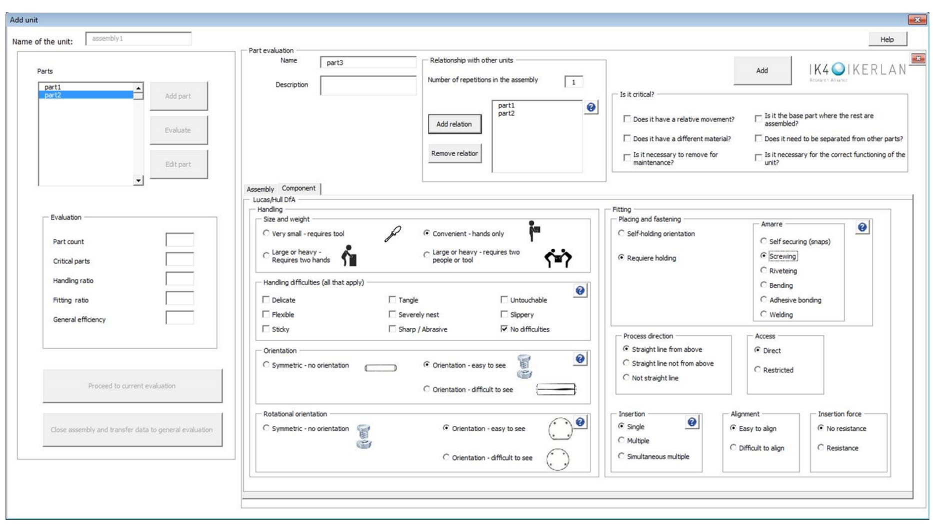


Figure 2. Designed tool with the implementation of the developed methodology

The developed tool allows introducing parts and assemblies in an orderly manner, associating each one with appropriate indicators that are automatically introduced by control questions. Using appropriate analysis algorithms, the tool identifies the critical parts / assemblies and the levels of interaction with others. The proposed approach, integrating DfA methodologies has been implemented in the tool. To

satisfy that need, software was created taking into account the aspects mentioned above, to better assist the engineers during design phase proposing recommendations that improve the assembly process.
Once the information of the components has been introduced into the tool and the calculations of the mathematical model have been completed, the results obtained are presented to the user in the form of a graphical interface and tables. The user can see a graph of the results of the model and the tables with the different ratios obtained. A version of the results datasheet is also available if the user wishes to process the results in a different manner. The models used in the tool were implemented following a simple set of rules and work using a black box implementation (only the input and output formats are known), and the programs of the models use a set of standardized input-output rules. This design format allows new improvement packages, which follow the implementation format, to be incorporated into the project with minimal effort.

3. Study case: Elevator counterweight

An exploratory study case has been carried out using the developed tool. In this case, the objective of improving the elevator counterweight design to reduce its assembly times has been proposed. The counterweight is an essential part for the operation of the elevator, minimizing energy consumption and, in turn, the dimensions of the machine, view Figure 3a. The basic function of a counterweight is to balance the load to facilitate the work of the motor and not to force it too much when moving a load. The counterweight is also driven by guides and all its components are mounted on a main chassis that is topped with the subassembly of the suspension system, as suggested in Figure 3b. In addition an eyebolt is part of the counterweight and is the subassembly used when handling the component in the factory and for its installation in the hoist.

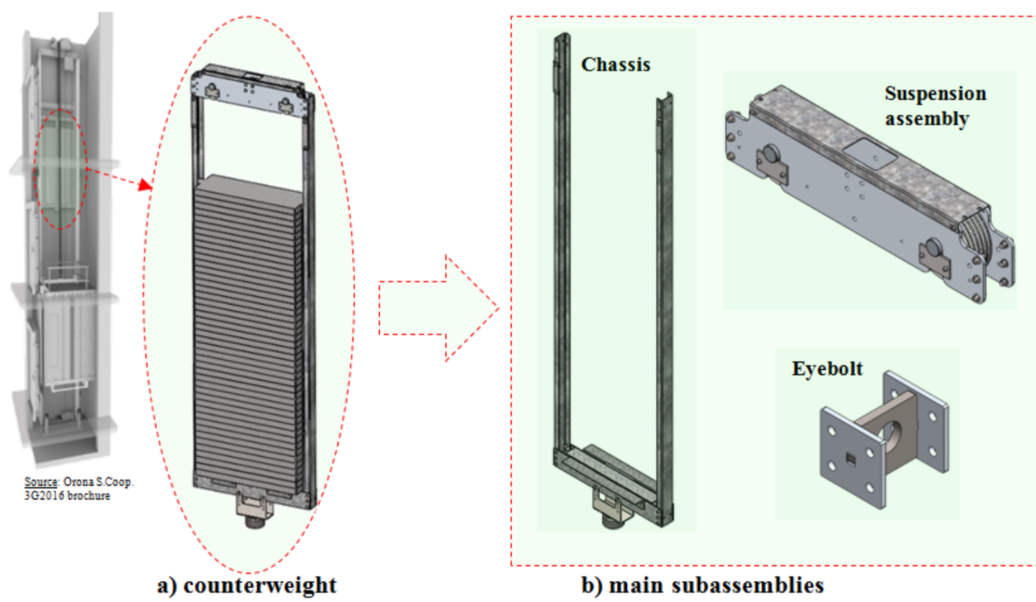


Figure 3. General view of a) a lift counterweight and b) main subassemblies in which the counterweight is divided

A first evaluation of the assembly of a counterweight according to its current design has been carried out using the developed tool. The parts of the counterweight studied and introduced into the tool are summarized in Table 1.
It is worth mentioning that part 13 called "Weight" has been introduced and analyzed as a single component although it is constituted by a set of small weights. This process of assembling small weights is not analyzed because the assembly is done at the place of installation and not during the assembly process of the counterweight taken place in the manufacturing plant.
After introducing the different parts of the counterweight in the tool and executing the post-processing, the evaluation summarized in Table 2 is obtained.

Table 1. Components of the counterweight (current design)

Part Nº	Component Name	quantity
1	Counterweight Pillar	2
2	Lower Closing	1
3	Lower Beam	2
4	Weight Support	2
5	Buffer	1
6	Weight Closing	2
7	Cover	1
8	Eyebolt	1
9	Upper Beam	2
10	Pulley	2
11	Pulley Shaft	2
12	Shaft retainer	4
13	Weight	20-40

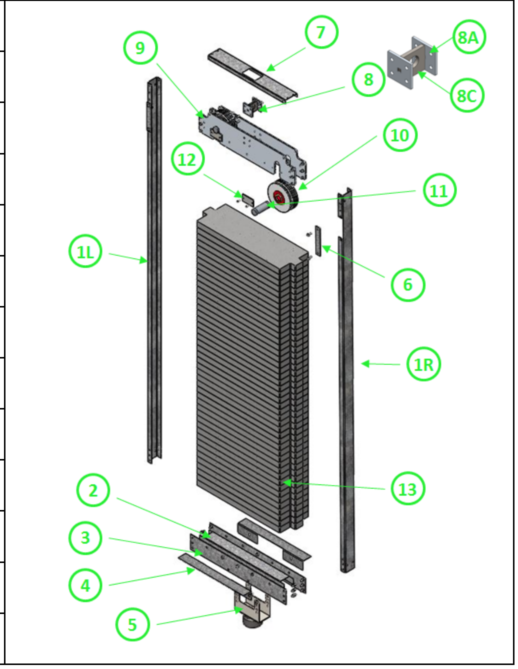


Table 2. Evaluation of the counterweight components (current design)

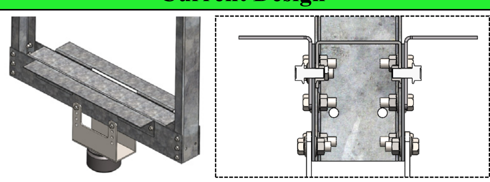
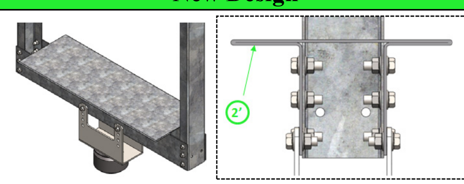
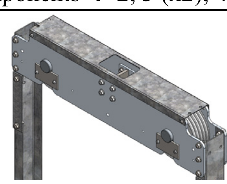
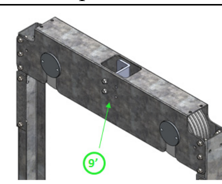
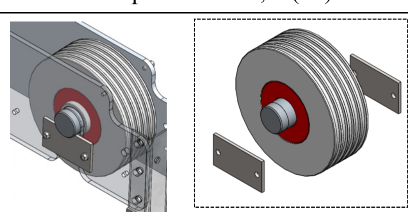
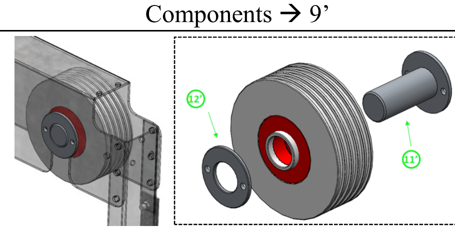
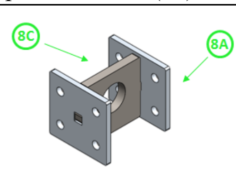
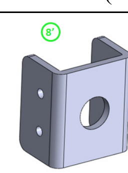
UNITS		EVALUATION				
Assembly	Component	Critical	Handling Ratio	Fitting Ratio	Repetitions	Recommendation
Chassis	**-**					**Design efficiency (%): 42,9**
	1L	Y	1,8	7,5	1	Check weight, size and symmetry. Check fasteners and insertion.
	1R	Y	1,8	7,5	1	Check weight, size and symmetry. Check fasteners and insertion.
	2	N	1,6	8,7	1	Consider redesign – Difficult to fit.
	3	N	1	7,5	2	Consider redesign – Difficult to fit.
	4	N	1,3	8,7	2	Consider redesign – Difficult to fit.
	5	Y	1,1	6	1	
	6	N	1	7,5	2	Consider redesign – Difficult to fit.
Suspension assembly	**-**					**Design efficiency (%): 33,3**
	7	N	1,2	7,5	1	Consider redesign – Difficult to fit.
	9	Y	1,2	8,7	2	Check fasteners and insertion.
	10	Y	1,1	3,8	2	
	11	N	1,2	2,5	2	
	12	N	1,2	7,3	4	Consider redesign – Difficult to fit.
Eyebolt	8					**Design efficiency (%): 0**
	8C	N	1	10,7	1	Consider redesign. Difficult to handle and manufacture.
	8A	N	1	10,7	2	Consider redesign. Difficult to handle and manufacture.

From Table 2 some previous recommendations are directly obtained. For example, parts 2-4, 6, 12, 8C must be considered to redesign. Other indications of redesign clues can be obtained from the obtained ratios. The main index ratio obtained for the three subassemblies that make up the counterweight are:

1. Chassis:
   - Handling ratio →4
   - Fitting ratio → 16,73
2. Suspension assembly:
   - Handling ratio →3,7
   - Fitting ratio → 19,23
3. Eyebolt:
   - Handling ratio →1,5
   - Fitting ratio → 18,4

The analysis carried out also took into account the number of screw connections used in the assembly of the counterweight and hence the relatively high fitting ratio obtained. However, the standards in the elevation industry do not allow too many modifications about the type of joints and the quantities of them. For this reason, in the analysis carried out, the screw connections have been maintained as fixed values.
According to the recommendations provided by the tool, four design modifications have been made. In Table 3 summarizes the main design modifications implemented.

Table 3. Concepts of proposed design improvements

Current Design	New Design
 Components → 2, 3 (x2), 4 (x2)	 Components →2'
 Components → 7, 9 (x2)	 Components → 9'
 Components → 11 (x2), 12 (x4)	 Components → 11' (x2), 12' (x2)
 Components → 8C, 8A (x2)	 Components → 8'

The first modification (in the chassis): consists of integrating the current components 2, 3 (2 units) and 4 (2 units) into a single component renamed as component 2'. With this redesign it is possible to reduce the number of components and the number of assembly operations related with the joining of this parts with each other. Furthermore, the new component (2') eliminates the need for adjusting the height of components 2 and 4 to achieve a level surface for the weights.

The second modification (in the suspension): consists of integrating the components 7 and 9 (2 units) into a single component renamed as component 9'. With this redesign it is possible to reduce the number of components and the number of assembly operations related with the joining of this parts with each other.

The third modification (in the suspension): consists of redesigning the pulley shaft (9) and the two shafts retainers (12), integrating them in a new shaft (11') and in only one shaft retainer (12'). With this redesign it is possible to reduce the number of components, one retainer less per shaft and assembling becomes easier, as all of the components become easy to align and self-sustaining while fastening them. Symmetry issues in the shaft are also avoided.

The fourth modification (in the eyebolt): consists of redesigning the eyebolt, from a welded component incorporating three different parts to a single component made from a unique metal sheet. With this redesign welding is no longer needed, therefore reducing assembly time. Joining to component 9 has also been simplified, reducing the number of fasteners in half.

An evaluation of the new counterweight design has been carried out. Table 4 shows the main results obtained from the tool for the evaluation of the new design.

Table 4. Evaluation of the counterweight components (new design)

UNITS		EVALUATION				
Assembly	Component	Critical	Handling Ratio	Fitting Ratio	Repetitions	Recommendation
Chassis	-					**Design efficiency (%): 54,5**
	1L	Y	1,8	7,5	1	Check weight, size and symmetry.
	1R	Y	1,8	7,5	1	Check weight, size and symmetry.
	2'	N	1,2	7,5	1	Difficult to fit.
	6	N	1	7,5	2	Difficult to fit.
Suspension assembly	-					**Design efficiency (%): 37,5**
	9'	Y	1,7	7,5	1	Difficult to handle and fit.
	8	Y	1	2,3	1	
	10	Y	1,1	3,8	2	
	11'	N	1	8,7	2	Difficult to fit.
	12'	N	1	7,5	2	Difficult to fit.

For the new design, the number of components that compose the counterweight has been significantly reduced (from 24 to 13 components). The reduction in the number of components directly influences the number of assembly operations and the efficiency of the design. In addition, the handling and fitting ratios have been generally improved. The new ratios obtained for the two resulting subassemblies that make up the counterweight are:

1. Chassis:
   - Handling ratio → 3,1
   - Fitting ratio → 11,52
2. Suspension assembly:
   - Handling ratio → 3,3
   - Fitting ratio → 16,1

Note that the subassembly called "Eyebolt" has been integrated in the suspension assembly.

Figure 4 shows a comparative summary between the previous and the new design in terms of total assembly efficiency.

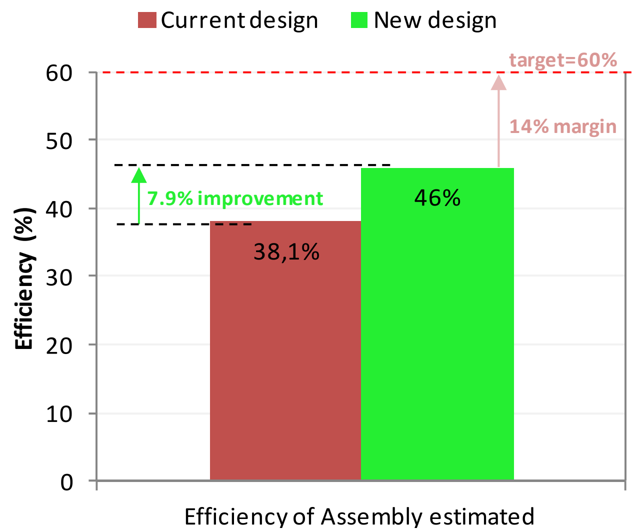


Figure 4. Comparison of the efficiency of the assembly between the previous and the new design

An improvement of the assembly process of the counterweight about 7.9 percentage points from the design has been obtained. There is still an improvement margin of approximately 14% up to the potential target of 60% assembly efficiency, but the necessary changes involve other joint types or other operations that complicate the manufacturability of the components. In this order an analysis based on design for manufacturing or regulatory changes may be required.

4. Results and discussion

An integrative approach of different methodologies (Boorthroyd & Dewhurst DFMA and Lucas / Hull DFA) has been implemented in a tool developed in the form of software. This tool allows adapting the most appropriate hypotheses of each methodology to the design of elevator components, providing designers with an evaluation and analysis tool. The tool is efficient to carry out redesigns that improve the assembly process of elevator components.

The new tool has been tested and validated through a study case focused on the design of an elevator counterweight. In this case of study, significant improvements have been obtained in the design of the counterweight to improve its assembly process. An improvement of approximately 7.9 percentage points in the estimated value of the assembly efficiency of an elevator counterweight has been achieved. In addition, it has been identified that despite the improvement made, there is still improvement margin in the assembly process of a counterweight. Even if high fitting ratios and recommendations, it needs to be appointed that assembly mechanisms in the elevation industry are based in bolts technology and no riveting or any other kind of fasteners are considered. However, improvements of 7.9% in the assembly of an elevator counterweight represent a significant impact on installation costs due to the high number of lifts that are assembled where a high percentage of the cost is due to the dedicated work hours.

As previously mentioned in this work, the assembly of the counterweight weights has not been taken into account. The installation of the weights has not been possible to be evaluated with the developed tool because the existing methodologies are not able to take into account the influence of the assembly processes on site and its close correlation with the logistic processes. Significant improvements of the design for assembly methodologies are necessary to consider the influence of the in site assembly that takes even more relevance for the assembly of the complete elevator or any other kind of heavy and large goods.

5. Conclusions

A new integrative approach to the use of the most relevant DfA methodologies has been proposed and implemented in a tool for design in the form of user-friendly software. The tool has been adapted to the particularities of the design of elevators but can be used in general for the design of assemblies of large pieces as long as they do not require assembly on site. This new approach uses a modified B&D strategy for critical part and assembly identification while applying the Lucas/Hull method for individual part evaluation and redesign. Modifications have been implemented in the Lucas/Hull evaluation coefficients to adapt them to large size components with predominant bolted joints.

Through a case study of the counterweight of an elevator, the tool has been tested and validated with the proposed new approach. Improvements in the assembly process of the counterweight of approximately 7.9 percentage points have been obtained through the proposed design modifications that were suggested by the tool. In order to consider relevant aspects of the assembly of the lift on site or installation, new design methodologies are required capable of considering aspects of assembly in combination with the particularities of the necessary logistics.

References

Boothroyd, G. (1987), "Design for assembly - The key to design for manufacture", *The International Journal of Advanced Manufacturing Technology*, Vol. 2 No. 3, pp. 3–11. https://doi.org/10.1007%2Fbf02601481

Boothroyd, G. (1996), "Design for Manufacture and Assembly: The Boothroyd-Dewhurst Experience", In: Huang, G.Q. (Ed.), *Design for X*, Springer, Dordrecht, pp. 19–40. https://doi.org/10.1007%2F978-94-011-3985-4_2

Dochibhatla, S.V.S., Bhattacharya, M. and Morkos, B. (2017), "Evaluating Assembly Design Efficiency : A Comparison Between Lucas and Boothroyd-Dewhurst Methods", *Proceedings of ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Cleveland, USA, August 6-9, 2017*, ASME, pp. V004T05A012. https://doi.org/10.1115/DETC2017-68126

Favi, C., Germani, M. and Mandolini, M. (2016), "Design for Manufacturing and Assembly vs. Design to Cost: Toward a Multi-objective Approach for Decision-making Strategies during Conceptual Design of Complex Products", *Procedia CIRP*, Vol. 50, pp. 275–280. http://doi.org/10.1016/j.procir.2016.04.190

Fu, K.K., Yang, M.C. and Wood, K.L. (2016), "Design Principles: Literature Review, Analysis, and Future Directions", *Journal of Mechanical Design*, Vol. 138 No. 10, pp. 101103. http://doi.org/10.1115/1.4034105

Huang, G.Q. (2010), *Design for "X" Concurrent engineering imperatives*, Springer, Dordrecht, http://doi.org/10.1007/978-94-011-3985-4

Imrak, C.E. and Kocaman, M. (2012), "Product design assembly application on double deck elevator systems", *Proceedings of TMT 2012 / the 16th International Research/ Expert Conference "Trends in the Development of Machinery and Associated Technology", Dubai, UAE, September 10-12, 2012,* pp. 539-542.

Imrak, C.E., Demir, U. and Livatyali, H. (2006), "Design of elevator car doors for assembly", *Proceedings of TMT 2006 / the 10th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology", Barcelona-Lloret de Mar, Spain, September 11-15, 2006*, pp. 721–724.

Kamrani, A.K. and Nasr, E.A. (2010), *Engineering Design and Rapid Prototyping*, Springer, Boston. https://doi.org/10.1007%2F978-0-387-95863-7

Kocabiçak, Ü. (1999), "Optimization of the mechanical component design using design for assembly techniques", *SAÜ Fen Bilimleri Enstitüsü Dergisis*, Vol 3. No 1, pp. 35–42.

Lucas Engineering Systems Ltd (1993), Design For Manufacture and Assembly Practitioners Manual Version 10, University Of Hull.

Molloy, O., Tilley, S. and Warman, E. (1998), *Design for Manufacturing and Assembly - Concepts, architectures and implementation*, Springer, Boston. https://doi.org/10.1007/978-1-4615-5785-2

Owensby, J.E. and Summers, J.D. (2014), "Assembly time estimation: assembly mate based structural complexity metric predictive modeling", *Journal of Computing and Information Science in Engineering*, Vol. 14 No. 1, pp. 011004. https://doi.org/10.1115/1.4025808

Pahl, G. and Beitz, W. (1996), "Design for Quality", In: Wallace, K. (Ed.), *Engineering Design*, Springer, London, pp. 455–465. https://doi.org/10.1007%2F978-1-4471-3581-4_9

Recalt, S., Bertschy, X., Tupin, L. and Conttassot, T. (2014), *DFMA: An Hybrid Design Gather DFM & DFA*. [online] ResearchGate. Available at: https://www.researchgate.net/profile/Thomas_Contassot/publication/261366198_DFMA_An_hybrid_design_gather_DFM__DFA/links/0a85e5341866babebe000000.pdf

Rodriguez-toro, C. (2004), Product Complexity Assessment for a Proactive-DFA Implementation (Simplicity + Simplicity ≅ Complexity), PhD thesis, Cranfield University.

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