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A 4M approach for a comprehensive analysis and improvement of manual assembly lines

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Abstract

Design for Assembly (DfA) is a well-known technique that supports in the reduction of manufacturing costs. Traditional DfA methods are generally focused on the product design lacking of a holistic view. The proposed 4M approach takes into account all the most important aspects involved in the manual assembly: Method, Machine, Man and Material. The final goal is to provide a means for the concurrent improvement of the product design, the workstation ergonomics, and the assembly tasks. Results obtained with the electric spindle motor case study confirmed the usefulness of the approach in optimizing the manual assembly.

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Keywords: Design for assembly, 4M approach, Material, Method, Machine, Man

1. Introduction

Different Design-for-X (DfX) methods have been developed in recent years to support the design process and the product engineering stages. Methods and tools for efficient Design-for-Assembly (DfA) are well-known techniques, widely used throughout many industries. DfA supports in the reduction of product manufacturing costs and it

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potentially leads to other relevant greater benefits. DfA techniques have been developed since the early 1980's and among them the most popular one is certainly the Boothroyd and Dewhurst (B&D) method, widely accepted and used in industrial contexts [1]. The B&D method allows measuring the complexity of assemblies and deriving quantitative results. However, in most cases, such method only focuses on the optimization of the product design, missing to provide a holistic view of the assembly line, workstations, assembly tasks, etc.

In this context, this paper proposes a holistic approach to overcome the abovementioned weak points and to optimize the assemblability of complex mechanical products, by taking into account all the aspects involved in the manual assembly. The proposed 4M DfA approach is based on the observation (recording) and analysis of each task of an existing manual assembly line. The four "M" considered within the approach are:

- *Material* – Assembly issues related to the product and components design;
- *Method* – Assembly issues related to the assembly procedure;
- *Machine* – Assembly issues related to the workstation layout;
- *Man* – Assembly issues related to the workers.

The main novelty of the proposed approach is the clear identification and classification of manual assembly issues by means of a systematic approach able to split these issues in four specific categories (*Material, Method, Machine, and Man*). In this way, the re-design process is assisted and designers are guided during the decision-making process for the optimization of assembly time and cost. The final goal is the concurrent improvement of the product design, the workstation and equipment ergonomics, as well as the assembly tasks.

The paper is structured as follows: Section §2 analyses the state of the art on the existing DfA methods; Section §3 details the 4M approach; Section §4 presents a case study (electric spindle motor assembly line) and highlights the results obtained with the approach application; finally, Section §5 summarizes conclusions and future work.

2. State of the art about DfA methods

DfA is a methodology which gives the designer a thought process and guidance so that the product can be developed in a way which favors the assembly process [2]. DfA has been implemented in numerous operative tools in order to simplify product design and to support designers during the decision-making process [3]. The aim of DfA methods is to maximize the use of the same components and to identify design solutions for reducing the most critical tasks in terms of assembly time and cost [4]. DfA leads to relevant benefits if used during the first phases of conceptual design, since it can improve the manufacturing process and has a deep influence on product cost [5] [6].

The first proposed DFA methods were the Hitachi method [7][8], the Lucas method [9][10] and the Boothroyd and Dewhurst method [1]. The Hitachi method (called also AREM – Assembly Reliability Evaluation Method), developed by Hitachi Corporation, aims to detect the different kinds of faults which may be generated when many parts are assembled together [7]. This method considers both costs and quality by means of two principal indicators: (i) an assemblability evaluation score ratio (E), which assesses design quality by determining the difficulty of operations, and (ii) an assembly cost ratio (K), which gives elements of assembly costs [8].

The Lucas method is based on a "point scale" which gives a relative measure of the assembly difficulty. This method is based on three separate and sequential analyses: functional, feeding, and fitting. Three indices which determine the designer's choice are calculated for each analysis [9]. Each assembly parameter is estimated by the method application. The last step of the Lucas method is finalized to calculate the manufacturing cost of each component. Such cost can influence the choice of material and the process used to realize the part [10].

Boothroyd and Dewhurst have formulated a quantitative DfA methodology, which is the most widespread in industrial practice. The method is grounded on the analysis of the product assemblability through the calculation of a numerical index. Different design solutions can be compared by evaluating the impacts related to the elimination or integration of parts in an assembly and the time to execute the assembly operations. The manual assembly design efficiency index (Em) is obtained dividing the ideal time for assembly (Tm) and the real time to make the task (Ta). The ideal time can be correlated to the ideal number of parts (Nm) by considering 3 seconds for their assembly [1].

The abovementioned DfA methods have two main limitations: (i) they mainly focus on the component/product design, and (ii) they do not consider the assembly as a whole, since some important aspects of the manual assembly phase are not considered in the analysis (e.g. assembly line, workstation, ergonomics, etc.) [6].

Different methods to approach manual assembly issues have been developed grounded on the concept of product assembly complexity, defined as the degree of difficulties to manage the components during the assembly process. These approaches are strongly related to the geometrical and physical attributes of components, such as the handling and insertion attributes, and consider the arrangement of components in the product assembly [11]. The way to predict and estimate the manual assembly complexity has been investigated by using different criteria with the aim to aid designers in preventing errors during the assembly phase and creating good basic assembly and manufacturing conditions [12]. Based on the concept of complex assembly, recent research studies propose the integration of DfA concepts with manufacturing and cost features using multi-objective optimization methods [13]. Based on these premises, Favi et al. developed a structured method with the aim to have a holistic view of the assembly and manufacturing problems during the preliminary conceptual phase of the product development process [14]. Multi-criteria mathematical models can be adopted to solve the trade-off among cost, manufacturing issues and assemblability based on the company's targets and requirements [15].

Another perspective is the definition of the assembly workplace/line, which involves layout organization, equipment, line balancing, productivity, personnel training, workstation ergonomics, etc. Usually, the assembly workplace/line design is an independent task that follows the product development process [16][17]. Assembly line balancing is generally part of the lean manufacturing concept and it encompasses different methods, classified in previous studies[18]. Such reviews highlight that manufacturing companies require holistic approaches for the optimization of assembly lines, including material flow, line saturation, type of operations, qualification of operators, etc. [19]. In addition, ergonomics aspects have been investigated to link productivity, product quality, and human factors [20]. Productivity is an important aspect to face for the implementation of ergonomic interventions in product assembly [21]. Concurrently to productivity, another positive impact of the ergonomic interventions is the increment of the overall performance of the product assembly, which means the minimization of manual errors during assembly tasks, as well as the reduction of assembly time and cost [22].

In conclusion, the literature review highlights a lack in DfA methods for the concurrent re-design of products and assembly workplaces, able to take into account all the potential issues related to the manual assembly activities (materials, operators, equipment, tools, layout, sequence, tasks, etc.).

3. The 4M approach

In order to solve the abovementioned issues related to the existing DfA methods, an holistic approach is needed to support the improvement of both the product design and the related assembly line. The main phases of the proposed 4M approach are depicted in Fig. 1. Details of each phase are explained in the next sub-sections.

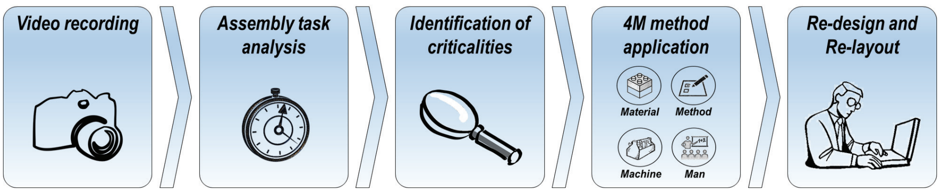


Fig. 1: 4M design approach

<u>Video recording</u>

Video recording is the first phase of the 4M approach and it consists in the recording of the manual assembly tasks. The video recording should be performed at least three times for each manual assembly task, to reduce the influence of casual events, and should involve at least two operators, to cover the highest possible number of issues.

It is clear that this step can be performed only when a workplace or an assembly line is existing and a product re-design is necessary. In case of new products and/or new projects, this phase can be performed starting from a simulation of the assembly tasks, realized by using a product prototype specifically developed for this purpose. Physical prototypes can be available during the product development process for mechanical and structural tests, fluid dynamics simulations, etc., thus they can be also used for assembly simulations.

The focus of the video recording should be on the hands of the operator, with the foresight to follow him/her movements inside the factory environment, when he/she has to leave his/her workstation for a specific task. This permits to easily distinguish the *handling* and the *insertion* operations. The operator movements is particularly interesting to identify (i) the value added activities, (ii) the no value added activities and, (iii) the waste of time.

<u>*Assembly task analysis*</u>

After the video recording, the video analysis is the second step of the proposed approach. This phase is generally the most time consuming and it mainly implies the video elaboration. The goal is to classify every single assembly task and to assign an assembly time (extrapolated from the recorded video) to each task. For this analysis, a specific matrix template have been developed (Fig. 2).

Task No.	Class	Task description	Consumables	Tools&Equipment	*Starting time*	*Finishing time*	Effective time [sec]	Rhythm	Task time [sec]

Fig. 2: Assembly task matrix template

Here below the items of the matrix (columns) are detailed:

- the *Task No.* is the number that univocally identifies a specific assembly task;
- the *Class* identifies a class of assembly tasks which can be grouped together. A list of possible classes is reported in Table 1. The tasks characterized with "*O*" are Value Added (VA) activities, the tasks characterized with "*A*", "*C*", "*P*", "*S*" are No Value Added (NVA) activities and the tasks characterized with "*X*" are Waste (W) of time;

Table 1. Class types and description.

Class	**Class description**	**Type**
A	Personnel movements inside the factory (picking, displacement, etc.)	N-VA
C	Test and dimensional control (check tolerances, roughness, etc.)	N-VA
O	Manual assembly operations	VA
P	Cleaning operations (packaging removal, part degreasing, workplace cleaning, etc.)	N-VA
S	Set-up operations (positioning and repositioning, etc.)	N-VA
X	Waste operations (smoking, talking, etc.)	W

- the *Task description* summarizes with a brief explanation the activity performed;
- the *Consumables* refer to additional components used during the task (e.g., glue, screws, grease, etc.) ;
- the *Tools & Equipment* is used to report if some tools or equipment are used during the task;
- the *Starting time* identifies the initial time of the assembly task retrieved from the recorded video;
- the *Finishing time* identifies the final time of the assembly task retrieved from the recorded video;
- the *Effective time* is used to report the task effective duration (calculated as the difference between the *Finishing time* and the *Starting time*) ;
- the *Rhythm* is a corrective factor needed to consider the operator efficiency and to remove any personal behavior that could affect the assembly task. Indeed, different operators can perform the same task in different time and a standardization is necessary to remove the personal behavior and inefficiencies observed during the analysis. This factor is particularly important for the *handling* and *insertion* phases. The standard *Rhythm* value is set to 1 (maximum efficiency value independent from the operator behaviors). In case of operator inefficiencies observed during the video analysis, the analyst should increase the *Rhythm* value. In such cases the *Effective time* is divided by this corrective factor to obtain the corrected time for the task performance (called *Task time*).

Identification of criticalities

Once completed the assembly task matrix, it is possible to identify the criticalities in the current assembly plan. The criticalities assessment is a function of a defined *assembly time threshold* which can be set by the analyst (designer and/or engineer). Usually, the *assembly time threshold* is set to 3 [sec] on the basis of the B&D DfA approach [1]. In other cases, the threshold value can be incremented to take into account specific conditions inside the assembly plant (e.g., not optimized layout, lack of conveyors or automation, etc.) or the specificity of the product to assemble (e.g. component dimensions, component weight, etc.). Such analysis can be easily performed filtering the retrieved *Effective time* for each assembly task.

It is worth to notice that an assembly task is defined as a single operation whether handling than insertion. Several assembly tasks can take part of an assembly operation. Based on this definition, it makes sense to consider the assembly time for each assembly task as the parameter for the identification of criticalities. The geometry of components, the characteristics of the assembly connections (type, size length, etc.) are accounted within the time measured for each specific assembly task.

This analysis can consider all the tasks or only those ones that have an *Effective time* much greater than the *assembly time threshold* (i.e. ten times higher than the *assembly time threshold*). The outcome of this step is a list of assembly tasks that have a time higher than the prefixed threshold. Those assembly tasks can be further analyzed to identify the reason behind the time increment and to categorize each specific issue, by assigning the relative "M".

4M method application

Once identified the criticalities, it is possible to proceed with the application of the 4M approach to subsequently fix them with specific corrective actions. The meaning of the four "M" is described here below:

- *Material* – Assembly issues related to the product and components design, including the number of components, the geometrical entities, the assembly systems, etc.
- *Method* – Assembly issues related to the assembly procedure, including unclear instructions, errors, etc.
- *Machine* – Assembly issues related to the workstation layout, including tools arrangement, available equipment and consumables, etc.
- *Man* – Assembly issues related to the workers, including task errors, not adequate training, ergonomics aspects, etc.

The final goal of this step is to group the assembly issues in different classes in order to propose a structured "map" to be used for the subsequent product re-design and workstation re-layout. The previous identified criticalities are reported in the 4M table (see Table 2 in the case study). For each criticality, a brief description of the issue and one or more corrective actions which can be taken to solve the issue are assigned.

The adoption of the most suitable and robust corrective action is demanding to the engineering skills based on different assembly features (e.g. costs, impacts on the workspace layout).

Re-design and re-layout

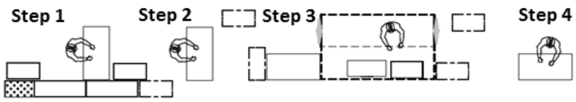
The re-design phase is the last step of the proposed approach. Based on the 4M table the corrective actions are implemented. It is worth to notice that for the *Material* and *Method* classes the B&D DFA approach [1] can be used to make a product re-design, by using an existing and well-structured method. For the other classes (*Machine* and *Man*) the corrective actions are mainly oriented to a workstation re-layout and/or to provide the right knowledge and skills to the assembly operators. In this second case, the actions can be taken following structured approaches (i.e. lean manufacturing) and/or specific measures conceived by the product designer.

4. Application of 4M approach to the assembly line of electric spindle motor

A complex assembly product (electric spindle motor) used in CNC (Computer Numerical Control) machine tools has been selected to validate the 4M approach. Electric spindle motor belongs to the mechatronic product family and it can be considered as complex assembly systems, characterized by numerous components which require several manual assembly tasks including the final test. Fig. 3 shows the analyzed product and the related virtual model.

Fig. 3: Electric spindle motor (picture and CAD model exploded view)

At first, the product and relative assembly line have been analyzed following the proposed 4M approach, in order to highlight the most relevant issues. The analysis has been carried out by the design & engineering department of the involved firm. The assembly line is composed of four steps and each one has a dedicated workplace, as depicted in the upper part of Fig. 4. After a video recording of the current assembly operations, the assembly task matrix have been filled in and the criticalities have been univocally identified (lower part of Fig. 4).



		1° step	2° step	3° step	4° step
Total number of tasks		1271	1184	663	756
Average rhythm		1	1	1.06	1.17
Class [sec]	*A*	37.73	27.98	11.66	22.85
	C	26.55	53.65	312.46	109.16
	P	33.65	29.73	10.75	20.16
	S	20.16	102,36	72.30	99.40
	X	204.16	191.00	179.58	205.46
	O	161.18	129.95	28.93	126.47
Effective time [sec]		483.43	534.67	615.68	583.50
Total tasks time [sec]		483.43	534.67	580.83	498.72

AV	N-AV	W
O	A C P S	X

Fig. 4: Assembly line representation and assembly task matrix summary

Based on the assembly task matrix previously defined (lower part of Fig. 4), an *assembly time threshold* has been set to identify the critical tasks. Fig. 5 reports the assembly time for the first 33 tasks of the Step 2. In this case, setting a time threshold of 5 [sec] means to account in the re-design activities approx. 40% of the current assembly tasks and thus the same amount of parts/components used in the electric spindle motor.

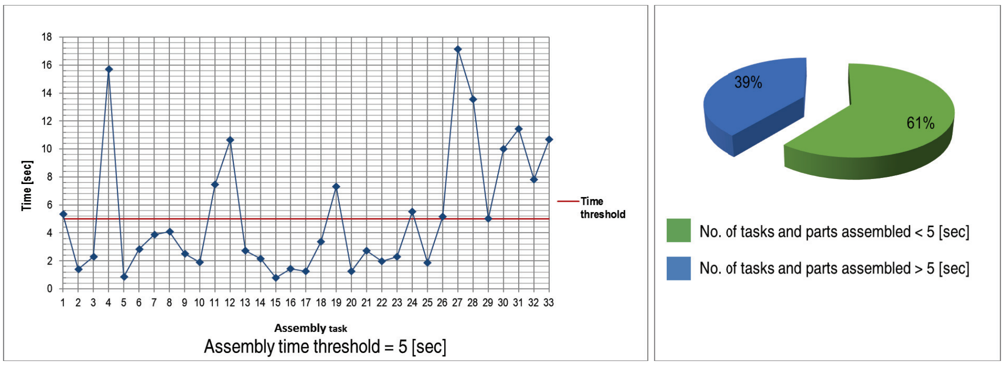


Fig. 5: Analysis of the criticalities for the *Step 2* (first 33 tasks) and setting of the *assembly time threshold (5 [sec]*

Analyzing the graph in Fig. 5, it is clear that the most critical operation is related to the *task 27*. Here below (Fig. 6), the criticality observed in correspondence of the *task 27* of the *Step 2* (grinding of the spacer due to not correct tolerances in the original design) is reported as example. The assessment phase has been performed by the design & engineering team under the supervision of the researchers.

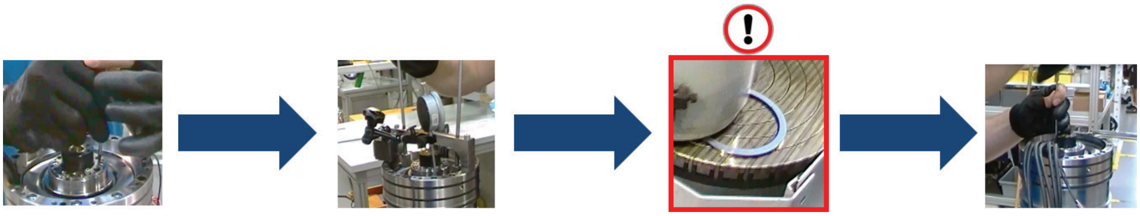


Fig. 6: Criticality assessment example of the task 27 of the Step 2

Different corrective actions have been implemented to mitigate the criticalities related to product design (Material), assembly procedures (Method), workstation layout (Machine) and workers (Man). In particular, the corrective actions related to the *Man* and the *Machine* issues have been developed mainly involving the plant manager in collaboration with the researchers. On the other hands, the *Method* and *Material* corrective actions have been developed involving the product design team, the product engineer and the researchers as well. As example, an extract of the 4M table related to the *Step 2* is reported in the following Table 2.

Table 2. Extract of the 4M table for the Step 2.

Task No.	Typology	Problem	Corrective action	Typology
12	Man	The operator asks how to use the equipment for the bearings assembly	- To make a dedicated training session for the operators	Man
14	Machine	The operator must move on the workstation 3 to pick up the glue (Loctite)	- To provide all the workstation with glue	Machine
19	Method	The operator wastes time to wear and to remove the gloves	- To impose to operators to wear gloves for the entire shift work	Man
27	Material	The operator must grind the spacer till the correct height	- To make a design review of the spacer (including height tolerances)	Material
			- To make a design review of the spacer (using DfA B&D approach)	Material
…	…	…	…	…

Results obtained with the new product configuration have been finally compared with the performance of the original design configuration. Important improvements have been highlighted in terms of relevant parameters of the assembly process, such as assembly time, number of needed assembly operations, takt time of the assembly line and overall manufacturing costs. The bar graphs reported in Fig. 7 highlight the assembly time savings related to each corrective action class for each step of the assembly line.

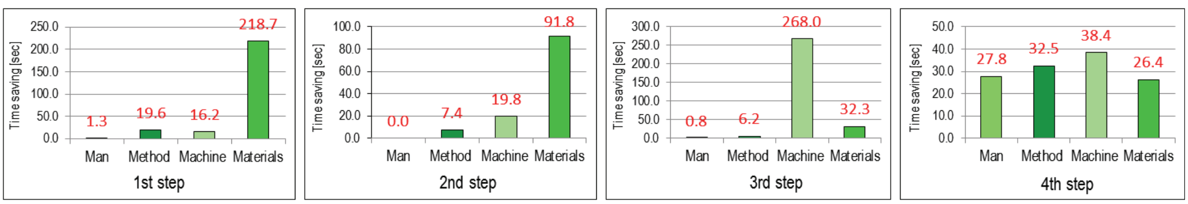


Fig. 7: Breakdown of the assembly time saving due to the corrective actions undertaken in the different assembly steps.

5. Conclusions

This paper presents a comprehensive DfA approach, called 4M, which aims to support the optimization of the assemblability of complex products. The 4M approach is based on five steps that allow analyzing and improving both the product design and the assembly line: (i) video recording, to capture the assembly tasks, (ii) assembly task analysis, to investigate in detail each operation, (iii) identification of criticalities, to derive the most critical tasks, (iv) 4M method application, to group the assembly issues according to the four different classes, and (v) re-design and re-layout, to implement corrective actions. The main novelty in comparison with traditional DfA techniques is related to the possibility to concurrently improve issues related to the product design and geometry (Method), the workstation layout and ergonomics (Machine), the workers (Man), and the tools and equipment (Material).

The proposed case study, focused on the improvement of an assembly line of electric spindle motors, demonstrates that the application of the 4M approach leads to relevant improvements. In particular, different criticalities have been identified (e.g. incorrect tolerances in the original design) and subsequently solved through corrective actions (e.g. training to workers, product redesign) to finally obtain relevant assembly time savings.

Future work will mainly focus on the investigation of software system for the semi-automatic acquisition and elaboration of videos, with the aim to decrease the time required for the development of the assembly task analyses, which is most impactful step of this approach.

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