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New design for assembly (DfA) methodology for large and heavy parts assembled on site

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Abstract

A literature review on the assembly design methodologies (DfA) oriented to the assembly of large and heavy parts, reveals the need to develop a DfA methodology. In addition, the lack of DfA evaluation methods for on-site assembly is also observed. The most widespread DfA methodologies are more oriented toward the improvement of factory assembly processes, where the assembly processes are well defined and standardised. Hence, this article presents a new methodology for the design of assemblies with large and heavy parts on site, called OSIA (On-Site Installation Analysis). OSIA methodology aims to provide data (indicators). On the one hand the theoretical basis of the OSIA methodology is based on three key concepts: i) analysis of assembly operations similar to the one used by the SMED methodology; ii) generic implementation process of DfA methodologies; and, iii) compilation of assembly operation times and estimation of standard times per operation. On the other hand, the steps in the implementation of the methodology are summarized in: i) database development with assembly operations and standard times; ii) assembly operations analysis; iii) calculation of assembly time; and iv) product optimization. In this way, OSIA methodology supports the designer in the specification phase, detailed design phase and in the redesign processes, providing the designer with indicators that make it possible to optimise the design of the parts and reduce the assembly operations of a product on site.

Keywords: Design for assembly; Design for assembly for large and heavy parts; Design for assembly on site; Design for installation

1. Introduction

The most widespread DfA methodologies (Boothroyd-Dewhurst (B&D) methodology [1], Lucas methodology [2], Hitachi AEM methodology [3], etc.) have been developed for the assessment of product assemblies in manufacturing environments. In these environments, assembly processes are well defined and standardised [4], assemblies are carried out in large series and assembly optimisation is assisted by new assembly technologies [5]. However, there are products that require on-site assembly (such as lifts, wind turbines, photovoltaic panels, bridges, etc.) where the standardisation of assembly processes is more difficult, as the spaces and conditions of the environment where assembly is carried out are changeable and the assemblies are unitary or small-medium series. In addition, there is a degree of uncertainty during assembly, as on-site assembly operations involve unanticipated misalignments or mismatches between parts, which are difficult to resolve using methods employed in a manufacturing environment [6], requiring unforeseen modification operations. The most widespread DfA methodologies have not been developed to implemented in these changing scenarios, even more so considering that products assembled on site are often made up of large and heavy parts, with sub-assemblies previously assembled in the factory [7]. These are parts weighing more than 20 kg and with dimensions greater than 1 m [8]. These sub-assemblies and parts require tooling or auxiliary elements for handling

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and assembly is often a complex process. The optimisation of product on-site assembly times and assembly times with products with large and heavy parts is a key factor for companies in reducing installation costs. For this reason, different authors have tried to tackle with this problem by the DfA approach [7-9].

2. State-of-the-art review

The state-of-the-art review in the studies that attempting to adapt DfA methodologies to large and heavy parts and on-site assemblies allows the identification of ten studies. In these studies, the DfA methodologies maintain the traditional "part" concept and approach, and they can be classified as follows: i) exploratory and application studies in the industrial field [8–13] and ii) studies of the construction field [4,7,14,15].

Thus, in the industrial field six studies have been identified. Boothroyd et al. [9] propose to complement the DfA methodology initially developed for implementation in large and heavy parts. In the study, they consider that the work area is a key factor to be taken into account when estimating assembly times. Wong et al. [10,11] determine that traditional DfA design methodologies are not implementable in the assembly of large and heavy parts. According to the authors, in this type of parts, the mass and inertia of the parts must be considered in order to obtain results that are closer to the reality. Wallace et al. [8] conclude in their study that there are many barriers for implementing DfA methodologies in products with large and heavy parts produced in short series. Therefore, the authors implement a DfA philosophy based on getting the right product at the first attempt. On the other hand, Wongwanich et al. [12] determine that the tooling used in the assembly of large and heavy parts is a key conditioning factor and for this reason, the difficulties in the tasks of handling, positioning, joining and fixing, vary depending on the tooling available. These authors carry out laboratory tests and make an in-depth analysis of the assembly difficulty index, the performance of humans during assembly and the limits of vertical forces. Cabello et al. [13] propose a DfA methodology for this type of products that must also be assembled at the final destination and based on the B&D [1] and Lucas [2] methodologies.

In the construction sector, four studies have been identified where the traditional DfA approach (part analysis oriented) is used to improve on-site assembly. In this way, Jürisoo et al. [4] developed a DfA methodology to implement it in the assembly of building structure connections. To do so, they use the most widespread DfA methodologies in the industrial sector. Gao et al. [14] review the principles of Design for Manufacturing and Assembly (DfMA) methodologies and explore possible adaptations for the construction sector. Remirez et al. [7] develop a design methodology for the installation of long-lasting and large-sized products on site based on the Lucas methodology [2]. Finally, Lu et al. [15], in their study, conclude that DfMA methodologies are presented as an opportunity to improve construction productivity.

Therefore, after this review it is concluded that the studies that have tried to develop a DfA methodology for on-site assembly are based on the most widespread DfA methodologies, and consequently, they do not consider: i) operations that arise during assembly such as drilling, measurements, part cuts, etc.; ii) movements made with parts and sub-assemblies during assembly due to environmental conditions; and iii) assemblies of sub-assemblies. On the other hand, the studies that have tried to adapt the most widespread DfA methodologies for large and heavy parts, have not succeeded in their implementation due to the large number of part characteristics they have to consider. For all these reasons, the need to develop a design methodology for the on-site assembly of products made of large, heavy parts and with sub-assemblies previously assembled in the factory has been identified.

Thus, the main objective of this article is to present a new design methodology called On-Site Installation Analysis (OSIA) to help designers optimise the on-site assembly of products with large and heavy parts. The OSIA methodology will fill the gap that traditional DfA methodologies have in optimising the on-site assembly of these types of parts.

The article is organized as follows. First, the OSIA methodology is presented, outlining its theoretical basis, the phases and steps of the methodology. The implementation of the OSIA methodology for the case of a lift is shown below. A discussion of the results obtained is then held and the limitations of the study are set out. Finally, conclusions are drawn and future lines are presented.

3. OSIA Methodology

The most widespread design for assembly methodologies (B&D, Lucas, Hitachi AEM) assist designers in making decisions during the design process [16]. These methodologies allow the designer to estimate the assembly time of the product parts at the factory, optimise the product assembly process and compare different products from the assembly point of view. To do this, designers must implement a generic three-step process inferred from the analysis of the most widespread methodologies.

- Step 1: parts analysis.
- Step 2: calculation of indicators and ratios.
- Step 3: Product optimization.

In the assembly of large and heavy parts on site, parts are combined with sub-assemblies previously assembled in the factory. During these assemblies, movements are made (both with the parts and with the subassemblies) that were not initially foreseen, but which are necessary due to the environmental conditions (characteristic of the available space, orography where the product is assembled, etc.). Another peculiarity of this type of assembly is that sometimes it is necessary to carry out operations to modify the part on site, due to maladjustments, adaptations, etc. Finally, it must be considered that sometimes the assemblies with large and heavy parts are products with small series or unique products. Therefore, the OSIA methodology aims to help designers in:

- Estimate the "assembly's operations" time on site.

- Optimise the product assembly process on site.
- Compare different products that are assembled on site.

To achieve these objectives, OSIA relies on the following three theoretical bases:

- SMED Methodology.
- Generic DfA process.
- Compilation of assembly operation times and estimation of standard times per operation.

3.1. Theoretical basis

This section describes in depth the three theoretical bases used in the methodology.

i) SMED Methodology

In the OSIA methodology as in the Hitachi-AEM methodology [3], the "part handling" analysis used in most of the more widespread DfA methodologies is discarded. While Hitachi-AEM focuses on “part movements and insertion” performed in a manufacturing environment (the principle of one motion for one part) [16], OSIA focuses on the "assembly operations" performed during the assembly of the product on site. The concept of assembly operation used in OSIA is similar to the concept of "operation" used in the SMED methodology [17]. The SMED methodology aims to reduce reference changeover times on machines in production environments, so as to increase machine availability. SMED is part of the Lean Manufacturing philosophy that seeks to improve and optimise production systems by eliminating waste [18]. In this philosophy, activities are classified into those that add value (VA), those that do not add value (NVA) and those that do not add value but are necessary.

In the OSIA methodology, as in the SMED methodology, a classification of operations is proposed. In this case, assembly operations are classified into Main Operations (MO) and Secondary Operations (SO).

MO are those operations that are performed during installation and that have a direct impact on the final product. In other words, they are operations that must be carried out in order to make the installation possible (screwing, connecting cables, etc.). These are VA operations.

SO are those operations that are carried out during installation and that have an indirect impact on the final product. Thus, they are complementary operations so that MO can be carried out correctly (transporting material, preparing cables, etc.). These are NVA operations but are necessary.

In similar way to SMED, in OSIA, SO must first be reduced and then optimised so that the time required for these operations is as short as possible. Secondly, the MO must be optimised so that their duration is also as short as possible.

ii) Generic DfA Process

The process of implementing OSIA methodology is based on the generic DfA process. As in the generic process, three steps are defined in OSIA methodology: (i) operations analysis; (ii) indicators calculation; and (iii) optimization of the product. During the first step, instead of performing an analysis of the parts as in a generic DfA process, an analysis of the assembly operations required to assemble the product is performed. In the second step the total assembly time (A_T) is calculated considering the times of the assembly operations. In the third step the product is optimised and the design efficiency (D_E) index is calculated. For the calculation of the D_E index, the number of MO and SO operations carried out during the assembly of the product is considered.

iii) Compilation of assembly operation times and estimation of standard times per operation

OSIA methodology for its development needs to have the reference times or the standard times for all the assembly operations. For the calculation of the standard times it is necessary to have a compilation of times of all the assembly operations. To facilitate the processing of all data, it is therefore recommended that a database is generated. OSIA methodology, therefore, requires the development of a database with its assembly operations for each product family. The following four steps must be followed to estimate the assembly operations standard times.

Step 1: Identify the assembly operations and collect the times of each operation.

The assembly operations identification and time measurement can be carried out directly on site or indirectly by viewing videos of the assembly on site. The onsite method is more suitable and precise since the monitoring is very detailed. Indirect measurement by means of videos requires very detailed recording.

Step 2: Group the assembly operations identified in step 1 by similar categories. For example: drilling, screwing, etc.

Step 3: Determine the standard time for each assembly operation.

In order to obtain a standard time for the assembly operations and include them in the OSIA database, it is convenient to have a sufficient number of data (times). To determine the sample size for each operation, it is recommended to use a 95% confidence level. The standard deviation and acceptable sampling error will depend on each type of operation. During the implementation of this step, a histogram is first performed for each assembly operation. In these histograms, the assembly operations are grouped into time intervals after applying the Sturgess [19] equation (1).

$$\text{Class interval width} = \text{Range of observations} / k \qquad (1)$$

where $k = 1 + 3,3 \times \log_{10} N$ and N = Number of data simples

Subsequently, by joining the midpoints of the bars in the histogram, a probability distribution curve is obtained. The type of curve and the parameters that define it are then identified. Finally, the parameter that best represents the reference time (mean, mode or median) is determined.

Step 4: Develop correction indices for operations with great dispersion of time.

For assembly operations that are not frequently repeated, it may be difficult to obtain a sample of data to adequately represent the distribution probability curve. Moreover, in some assembly operations, variables appear that cause a very high dispersion of times (part weight, part thickness, etc.) that do not allow a coherent distribution probability curve to be represented. Therefore, when the sample size is smaller than estimated and the variables affecting the assembly operation have a 50% difference in their order of magnitude, correction indices must be developed to estimate the standard time more accurately.

3.2. Phases and steps of the OSIA methodology

In the implementation of the OSIA methodology, designers must execute the following four phases: i) database development with assembly operations and standard times; ii) assembly operations analysis; iii) assembly time (A_T) indicator calculation; and iv) product optimization.

i) Phase 0: Database development

In this phase, the database for the product family to be analysed is developed. The database must be a dynamic element, which must be continuously fed with new assembly operations as they arise. To implement this phase, the four steps described in section 3.1 (iii) must be carried out.

ii) Phase 1: Assembly operations analysis

In this phase the designers must identify, analyse and note down the operations required to assemble the product on site.

iii) Phase 2: Assembly time (A_T) indicator calculation

The A_T indicator is an estimation of the total assembly time of a product on site. For its estimation, the standard times of the assembly operations noted in phase 1 must be added up (equation 2). The standard times of the assembly operations are obtained from the database developed in phase 0.

$$A_T = \sum_{i=1}^{n} OT_i \quad (2)$$

where n is the total number of assembly operations and OT_i is the standard time of each assembly operation.

iv) Phase 3: Product optimization

In this phase the product is optimised. The phase is executed through the following six steps:

Step 3.1: Classify and count the number of MO and SO.

Step 3.2: Calculate design efficiency (D_E). Design efficiency is defined by the formula in equation (3).

$$D_E = 100 \times (MO_T / (MO_T + SO_T)) \quad (3)$$

where MO_T are all the Main Operations and SO_T are all the Secondary Operations.

The D_E index is used to find out how much a product has improved after a redesign and/or to compare different product designs with each other.

Step 3.3: Identify which SO need to be improved. To this end, the designer should focus on two parameters: i) the most repeated SO; and ii) the SO that require the most time.

Step 3.4: Identify which MO need to be improved. To do this, the designer must focus on two parameters: i) the most repeated MO; and ii) the MO that require the most time.

Step 3.5: In this step design is optimised. Firstly, as in SMED, the designer tries to reduce SO. Then, designer must try to improve the SO and MO identified in steps 3.3 and 3.4. To do this, the designer can follow the three paths proposed in SMED: i) act on the design itself, making modifications [1,19-21]; ii) reduce the SO by acting on the movements of the workers and working in parallel; and iii) reduce the MO by acting on search times, movements and waiting times.

Step 3.6: Calculate the percentage of design efficiency improvement and the percentage of assembly time improvement. If the target values set by the designer are not reached, steps 3.3, 3.4 and 3.5 should be repeated.

4. Case study

The OSIA methodology has been partially implemented in the case study of the Orona 3G X-10 lift. Both phase 0 of the OSIA methodology and phases 1, 2 and 3 have been implemented on the same product.

4.1. Phase 0: Database development

As this is the first time that OSIA is implemented in this type of product, the database has been created in this phase. The following details how the four steps have been carried out.

Step 0.1: In the case study, the indirect method has been used to identify assembly operations and time measurement. Thus, after analysing the recordings of the assembly of the lift on site, 3,779 operations have been identified. In this case study, instead of selecting one sample per operation, all operations were measured as they were identified.

Step 0.2: The 3,779 operations have been grouped into twenty-six categories. Twelve have been classified as MO and fourteen as SO (Table 1).

Table 1. Main Operations (MO) and Secondary Operations (SO).

Main Operations (MO)		**Secondary Operations (SO)**	
- Cutting	- Screwing	- Transporting material	- Raise/lower platform
- Tightening	- Pour foam	- Collect the material	- Assemble/disassemble platform
- Positioning	- Place nut	- Unpacking material	- Mark dots/lines
- Drilling wall	- Hammering	- Preparing the wiring	- Unscrewing subassemblies
- Inserting	- Connecting cables	- Putting material into the pit	- Sorting bolts
- Fix parts		- Raising/lowering material with hoist	- Get to work
- Adjusting and levelling		-Temporarily lashing	- Cleaning up

Step 0.3: The standard or reference times for the twenty-six operations have been calculated. The histogram and probability distribution curve for the "screwing" assembly operation is shown in Fig. 1 as an example.

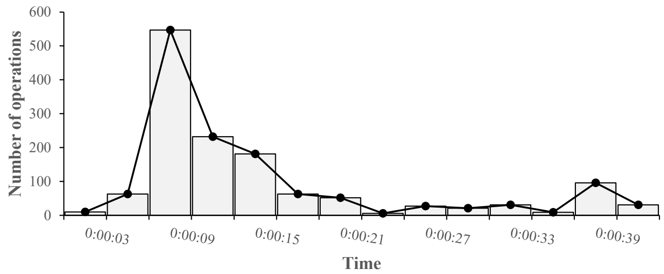

Fig. 1. “Screwing” probability distribution curve.

In the case of the "screwing" assembly operation (Fig. 1) the probability distribution curve resembles a log-normal distribution curve. The parameter chosen to determine the reference time for this operation was the median, since this parameter considers the right tail of the data without being too affected by its influence.

Step 0.4: This step has not been implemented in the case study. Nevertheless, it is necessary to develop correction indices for operations with a large time dispersion. For these operations it is necessary to identify the variables (thickness, weight etc.) that allow correction factors to be defined.

4.2. Phase 1: Assembly operations analysis

In this case of study, the analysis of the operations necessary for assembly has been carried out on the same product as that analysed in phase 0. Therefore, the number of operations necessary for the assembly of this product is 3,779.

4.3. Phase 2: Assembly time (A_T) indicator calculation

For the case study, an assembly time (A_T) of 62 hours has been estimated based on the standard times calculated in phase 0 (Table 2). Equation (2) has been used for the calculation.

Table 2. Examples of standard times per operation.

Adjusting and levelling…..1 min 10s	Screwing………………..12 s
Positioning …………..….50s	Hammering……………..11s
Drilling wall……………...18s	Temporarily lashing…...3 min 47s

4.4. Phase 3: Product optimization

Step 3.1: Of the 3,779 operations, 3,437 are MO and 342 SO. SO are 9% of the total operations but represent almost 28% of the total assembly time. Therefore, it is considered that there is room for improvement in SO.

Step 3.2: The design efficiency (D_E) of the lift in the case study is 91%.

Step 3.3: In order to identify the SO to improve the assembly, the two graphs in Fig. 2 are made. For this case study, five SO have been identified for improvement: temporarily lashing a part, mark dots/lines, transporting material, putting material into the pit and sorting bolts.

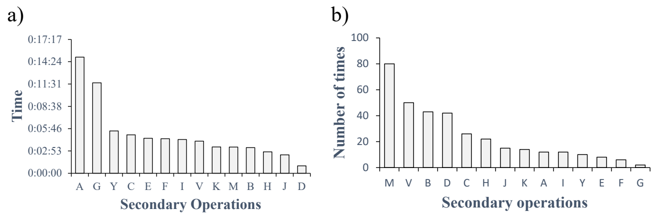

Fig. 2. (a) SO times; (b) Number of times the same SO is performed.

Step 3.4: In order to identify the MO to improve the assembly, the two graphs in Fig. 3 are made. For this case study, three MO have been identified for improvement: cutting, screwing and pour foam.

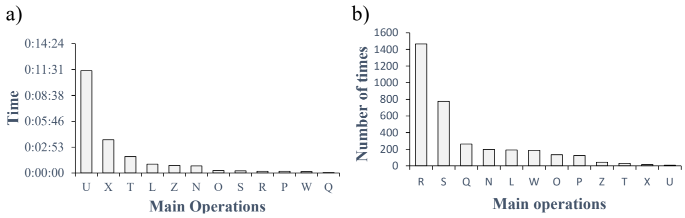

Fig. 3. (a) MO times; (b) Number of times the same MO is performed.

Step 3.5: In this case study, no improvements have been made on the five SO and the three MO identified.

Step 3.6: As the improvements in MO and SO identified have not been made, this step has not been implemented.

5. Discussion

The results obtained demonstrate that OSIA can be suitable to help the designer in improving product assembly on site: estimating assembly time, providing design efficiency and identifying key operations to improve. The implementation of OSIA in the case study has made it possible to obtain an assembly time estimate of 62 hours, which is a deviation of 11% from the real assembly time. The classification of assembly operations into MO and SO has been carried out by technicians who do not know the product in detail, so the prioritisation of assembly operations may not be the most appropriate. This problem could be overcome if the assembly operators themselves were to classify the assembly operations as they assemble the product; in the current industrial context, the characteristics of the 4.0 operator [22] would allow this to be carried out in a simple way.

5.1. Study’s limitations

In the case study the accuracy of the assembly time estimation can be improved by refining the database, by feeding it with more assembly operation times, as in some operations the sample used is small. The database has been developed through the analysis of a recording. In this case, the recording did not include all the operations of unloading and moving the material. The correction of these aspects may allow a better estimation of the assembly time. This aspect of the OSIA could be improved by incorporating an information-oriented and context-aware system [23]. This system would automate the collection of data from assembly operations and transfer the processed information to the OSIA database; in turn a recommendation system [24] could be included to collect operator feedback on assembly processes. Thus, systematically identifying operations that could be improved. In contrast to the more widespread DfA methodologies, where a single table is available for all products, in OSIA a specific database must be developed for each type of product, without being able to use the data from one database in another. This results in a higher time commitment for the designer. By means of the information-oriented and context-aware system, the generation of the databases would be automated and the designer's dedication to this task would be reduced. After the case study, it is inferred that the OSIA is not suitable for the optimisation of unitary products, as the development of a database for a single product that will not be reassembled again does not make sense. Therefore, OSIA is more appropriate to implemented with small or medium series.

6. Conclusions and future lines

This article addresses the limitations of DfA methodologies for large and heavy parts on site and presents a new methodology called OSIA that allows designers to optimise the assembly of products with these characteristics. To this end, OSIA considers the assembly operations as a key factor instead of considering the "parts" that make up the product as a key factor, as it is the case with the most widespread DfA methodologies. By identifying the operations with the greatest impact on product assembly, OSIA guides the designer to optimise them through design improvements. In this way, the assemblability of the product is improved. Through this approach, OSIA fills the gap left by DfA methodologies during the optimisation of the assembly of large and heavy parts on site. Future work with other case studies will allow the complete validation of OSIA and the development of a computer tool will allow to speed up its use.

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