NEW DESIGN FOR INSTALLATION (DFI) METHODOLOGY FOR LARGE SIZE AND LONG LIFE CYCLE PRODUCTS: APPLICATION TO AN ELEVATOR

Retolaza, Iban (1);
Zulaika, Izaro (2);
Remirez, Adrian (1);
Cabello, Mario Javier (1);
Campos, Mikel Alberto (1);
Ramos, Ainara (1)

1: IKERLAN Technology Research Centre;
2: ORONA Elevation Innovation Center

ABSTRACT

This paper presents a new design methodology for improving the installation of large size and long life cycle goods that need to be assembled in the field. The approach integrates a modified design for assembly (DfA) methodology. A new approach is proposed for integrating different DfA methodologies and tested in a real case study of a machine room-less (MRL) elevator. A tool for analyzing and quantifying the proposed solutions is developed. Improvements of approximately 20 pp are achieved during the elevator installation and on-site assembly process, which could mean a potential reduction in assembly time of 11 h or 6%. Additional extensions and guidelines are recommended to improve the methodology and the tool.

Keywords: Design for X (DfX), Design methodology, Research methodologies and methods, Design for installation, MRL elevator

Contact:
Retolaza, Iban
IKERLAN Technology Research Centre
Mechanical systems design
Spain
iretolaza@ikerlan.es

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1 INTRODUCTION

The main purpose of this work is to develop a new methodology based on existing DfA methodologies, adapt the approach to the installation of large size (Ls) goods and test it in a real case study.

Installation factors for certain types of products determine the final cost and correct performance and therefore need to be considered when designing a system. Wind turbines, photovoltaic power stations, elevators, truss structures, and products in the construction industry are examples of these kinds of products. All these products need to be assembled in place, have long life cycles (more than 25 years) and have parts or subparts that are large (Wegelius-Lehtonen, 1995; Azambuja and Formoso, 2003; Aas et al., 2008; Woyte and Goy, 2017). Although installation resources are costly (cranes, lorries, workforce…), the design and the decisions made during the design phase determine the installation cost.

The costs associated with assembly in the field (including transportation, handling and installation tools, personnel) are a significant percentage of the total cost of the project (Vis and Ursavas, 2016; Schuknecht et al., 2018; Steyn and Heerden, 2015; Price and Mahaley, 2013; Mignacca et al., 2018; Fournier, 2017; Ou et al., 2018; Tomek, 2017). In short, roughly, assembling time reductions between 20% and 50% and cost reductions between 10 and 20 could be achieved.

Few references about Design for Installation (DfI) are found in the literature and less facing future problems through design changes.

Even if the assembly process and the installation of a product are strongly connected, there is no design methodology that can couple the two processes. Assembly processes have been widely studied for years, and appropriate design methodologies have been developed that focus on key aspects of assembly during the design phase. The methodologies have been extended as DfX methods to include the concept of "design for excellence" (Pahl and Beitz, 1996). DfX methodologies have been developed and improved in recent years since Boothroyd and Dewhurst developed the first DfX methodologies in the 80s: Design for Assembly or DfA (Boothroyd, 1987). Furthermore, research has shown that DfX, mainly design for manufacturing (DfM) and assembly (DfA) as a whole (DfMA), has a strong influence on manufacturing, assembly and product life (Huang, 2010). In general, all of the methodologies focus primarily on facilitating assembly, minimizing the number of parts or variabilities and allow for the consideration of other issues, such as accessibility, handling and the need for fitting with tools (Favi et al., 2016).

Reducing the number of parts, it is not always the best strategy. The final goal is always to reduce the global cost of the product. In general, and more with Ls products that need to be assembled in the field, it means also to reduce on-field assembling time. In this way, another fundamental objective is to minimize the number of assembly operations and thus assembly time and costs. Some examples of tools with DfA methodologies used in case studies can be found in the literature (Bhurat et al., 1998; Owensby and Summers, 2014; Recalt et al., 2014). However, these methodologies are not implemented for products where on-site assembly becomes installation and other issues need to be taken into account, such as in-place resources, handling of large or heavy parts, or weather issues.

Even more, applying the traditional DfX methodologies for these kinds of goods, which are not usually mass produced and are highly customized, becomes even more challenging (Wallace and Sackett, 1996; Lassl and Lofgren, 2006). There is currently no efficient methodology that addresses the unique nature of this type of products. Thus, it is interesting to develop general methodologies that takes the nature of the product into account and facilitate the application and optimization of the benefits (Fu et al., 2016).

A machine room-less elevator has been chosen to validate the effectiveness of the new approach. Few examples that apply DfA methodologies to the design of elevators, a product that due to its characteristics could be designed using installation parameters, have been found in the reviewed literature (Imrak et al., 2006). In addition, the studies are focused on the assembly of particular components and not the elevator installation as a whole.

2 NEW APPROACH: DESIGN FOR INSTALLATION BASED ON DESIGN FOR ASSEMBLY METHODOLOGIES

The new design for installation methodology stems from the need to adapt the existing DfA to the installation of property type Ls-Ll (Large Size – Long Life). The proposed DfI approach is intentionally kept simple and based on DfA methodologies resulting in a generic methodology of simple application in the design phase, in which the contribution of the designer is a key. The approach can be summarized using the chart shown in Figure 1.

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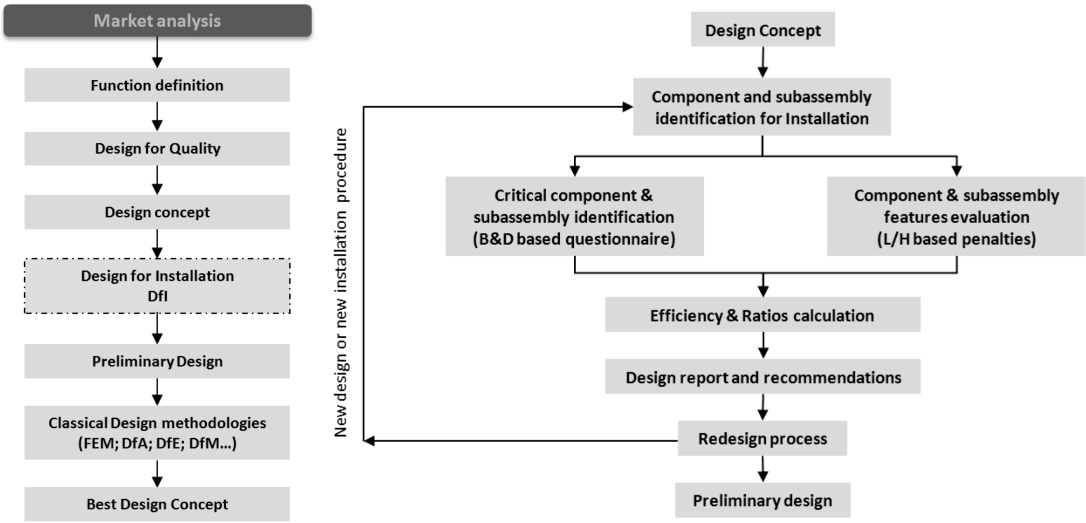

Figure 1. Ikerlan's product design process & proposed DfI approach

The new methodology combines and adapts two different DfA methodologies: Boorthroyd & Dewhurst DfMA and Lucas/Hull DfA, both that major successful (major Trackrecord) have had since the creation of the DfX and being also the most used, their benefits are beyond doubt.

They are focused on reducing the number of parts and variability. Both use similar approaches to reduce the number of parts and increase the efficiency of the design. However, the B&D method is more focused on the assembly sequence, while the Lucas/Hull method is more focused on the evaluation of the components themselves (Kocabiçak, 1999).

The B&D DfMA is usually applied on small and mass produced products and analyses operations during the assembly process while the Lucas/Hull method is a penalty-based method that focuses on three important aspects of product design and measures them with three indexes: the Efficiency Index, the Handling Index and the Fitting Index (Lucas Engineering Systems Ltd 1993). Another unique aspect of the B&D DfMA methodology is the use of three questions to identify critical components.

New penalty factors have been proposed using the Lucas/Hull DfA methodology as a base. Penalties for subassemblies were also considered, not only for components, and also some new penalties for component fastening such as adhesive bonding, welding or interference fitting were added.

For each component, the overall efficiency, handling ratio and fitting ratio are calculated depending on the different associated design features and penalty factors that are related, not only to the assembly processes as in with the Lucas/Hull method, but to installation issues. Furthermore, penalty factors have been fitted, not only to parts assembled in place, but to bigger subsets of parts that are usually manufactured in a factory, moved to the installation site and assembled on-site. The Lucas/Hull standard formulation is used for the calculations, such that

$$Handling\ ratio = \frac{\sum Handling\ index}{Critical\ parts} \tag{1}$$

$$Composing\ ratio = \frac{\sum Composing\ index}{Critical\ parts} \tag{2}$$

$$Commissioning\ ratio = \frac{\sum Commisioning\ index}{Critical\ parts} \tag{3}$$

$$Design\ efficiency = \frac{Critical\ parts}{\sum Total\ number\ of\ parts} \tag{4}$$

where parts can be components or bigger subassemblies/subsets of parts since both small assemblies and installation of bigger structures have to be analysed. As seen in equations (1), (2) and (3), critical part identification is necessary so that the ratios can be calculated using the methodology. For this purpose, B&D DfMA is implemented using control questions. However, the proposed questions need to be different since the installation requirements are also independent from the assembly questions.

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B&D DfMA questions:

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

Are replaced by:

- Is it fixed to an in-place foundation?
- Is it necessary to remove for maintenance?
- Is it necessary to remove for upgrading?
- Is special transportation required?
- Are special machines needed for handling/installation?
- Does it need to be fine-tuned in place?

Simultaneously, critical factors for handling, assembly and installation are identified and penalty factors are specified. Originally 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. The penalty scores for each aspect are presented in the Lucas/Hull tables (Kamrani and Nasr, 2010). The penalty factors have been adapted from those in the original Lucas/Hull methodology because they affect in a different way in a factory assembly or in a field installation and new features have been analysed. Table 1 shows some examples of the new factors that depend on the nature of the subassembly.
The means of transportation and installation or assembly in the field would be critical. Some of the main barriers could be (Micheli et al., 2019):

- Lack of lifting and transport equipment at the construction/production site
- Module size and weight limitations in transport
- Site layout constraints
- High transportation fees and tariffs

Other factors such as the weather, diseases, strikes... could be crucial but are not correctable from the design. The management of this kind of uncertainties is out of the scope of this work.
Some factors related to logistics and assembly tools are taken into account in a shallow way with penalty factors but not in detail. These means of logistics and installation and the corresponding penalty factors could be updated by the designer in each project, having more relevant knowledge and data.

Table 1. DfI penalty factors for subassemblies

	Evaluation	Type	L/H DfA penalty	DfI penalty	
A	Size and weight	Convenient - hands only	-	1	Handling
		Large or heavy – Requires two hands	-	1.5	
		Large or heavy - requires two people	-	3	
		Large or heavy - requires pulleys, ropes or similar hand tools	-	5	
		Large or heavy - requires pallet truck, small crane or similar power tools	-	10	
		Large or heavy - requires special tools	-	20	
B	Transportation	Special transportation required (size, weight, hazardous materials…)	-	20	
C	Placing and fastening	Screwing +	-	+4	Composing
		+ nut	-	+2	
		+ washer	-	+1	
		Riveting	-	+4	
		Bending	-	+1	
		Adhesive bonding	-	+5	
		Welding	-	+6	
		Interference fitting +	-	+2	

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		+ Tool	-	+5	
D	Fine Tuning	Hand made	-	1	Commissioning
		Special tools	-	2	

Once the Design Efficiency and Handling and Fitting Ratios as well as the proposed Commissioning Ratio are calculated for each component or subassembly, the three ratios are calculated for the whole installation. According to the Lucas/Hull method, handling and fitting ratios should have maximum values of 2.5 and the design efficiency should be over 60% to successfully pass the evaluation. However, the ratios are defined for DfA analyses and do not perform well when the goal is to evaluate the installation processes. For this reason the next targets are defined:

- Design efficiency > 50%
- Handling ratio < 4
- Composing Ratio < 30
- Commissioning Ratio < 1

The objective ratios have been defined based on different case studies analysed in Ikerlan and should be redefined depending on the results achieved using the new DfI methodology in real environments.

The ratios offer information about which aspects of the installation, component or subassemblies should be modified or are more critical. As a result, a designer can evaluate different concepts in an easy and fast way from the installation point of view and can analyse several concepts early in the design phase.

The methodology can be used iteratively so that a given installation can be analysed more than once. Improvements can be made in each step so that finally an efficient design for installation is obtained where the handling and fitting ratios and the design efficiency should be in the range proposed.

3 CASE STUDY: MACHINE ROOM-LESS (MRL) ELEVATOR

3.1 Existing installation process

There are several assembly/installation methods for residential (not high-rise) passenger elevators. A generic method has been chosen for this paper since each original equipment manufacturer has its own and confidential procedure. The main components of an elevator are shown in 2.

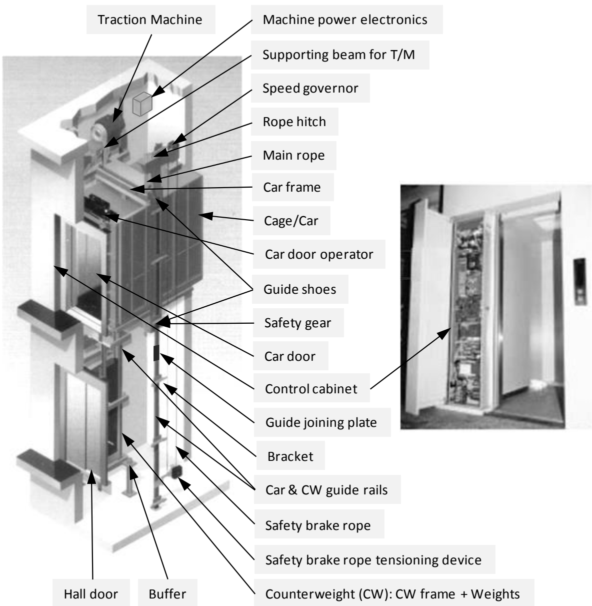

Figure 2. Passenger MRL elevator description (Modified from Vintec elevators; http://vintecelevators.com/machine-room-less-elevators/)

The installation method has been modified from the Orona S. Coop. OEM installation manual (confidential). It takes approximately 26 effective work days for a single 10 landing elevator (see the schedule in Figure 3).

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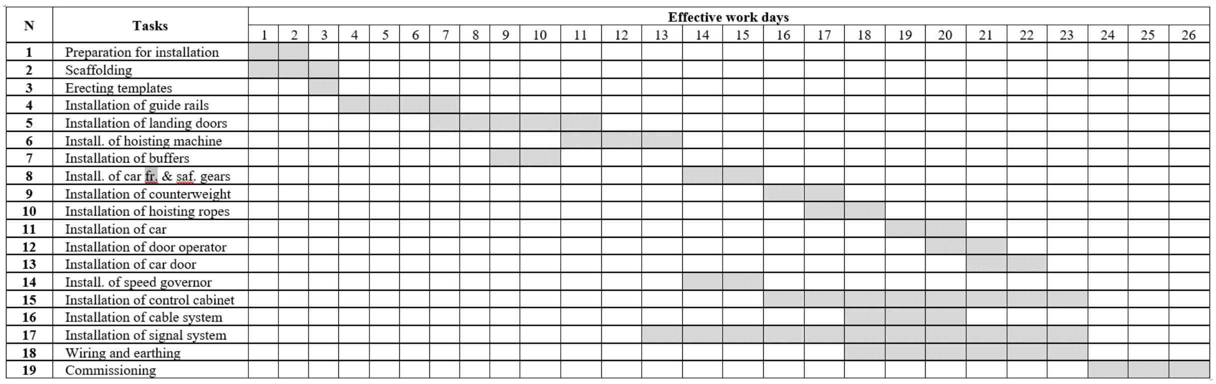

Figure 3. Elevator installation schedule

Tasks 11 to 13 have been excluded in this study since small components are involved in the car and the related car door and do not have the characteristics of the studied components. Task 18 is also not studied since the wiring procedures are completely different than those with related mechanical tasks. Figure 4 shows the main tools needed for the installation of an elevator.

Handling tools	Levelling / Aligning tools	Hand / Fitting tools	Power tools	Cutting tools	Testing / Inspection tools	Miscellaneous
Chain block Slings & shackles Suction cups F clamps	Plumb bobs: 10～15 kg Magnetic plumb Levelling rod Steel rulers, Angle rulers Steel measure tape: 3 m Marker, pencil	Spanners (Socket & Monkey) Hexagon socket wrench, Box wrench Screwdrivers, Cross screwdrivers Screw dies & Screw die rack Hammers (Ball pein and wood) Flat chisel	Angular finishing grinder Drills & Electric drill Electric soldering iron	Pliers, Hand shears Wire stripper & cutter Hacksaw frame	Multimeter, Clip-on ammeter Tachometer Decibel meter	Ladder Portable work light Flashlight

Figure 4. Main tools used for elevator installation (Modified from Orona-S.Coop. 2018)

3.2 DfI evaluation

The main parts and assemblies of an MRL elevator have been introduced one by one into the DfI evaluation tool and few results are shown in Table 3 as an example.

Table 3. DfI evaluation of an MRL elevator

Name	Critical	Handling index	Composing index	Commissioning index	Evaluation	Rep
Car guide rail	YES	2	4,9	0	Check number of repetitions	8
Bracket (guide fixings)	YES	1	45,7	1	Check number of repetitions Check fitting features	28
Car Guide joining plate	NO	1,1	60,4	0	Check number of repetitions Check fitting features Consider merging with other components	6
Buffer	YES	1,5	32,9	1	Check fitting features	2
Traction machine (T/M)	NO	2,3	32,9	0	Check fitting features Consider merging with other components	1
Speed governor	NO	1,8	17,7	0	Consider merging with other components	1
Weight	NO	1,5	2,7	0	Check number of repetitions Consider merging with other components	72
Vertical car frame (+ safety gear + g. shoes)	YES	5,1	63	0	Check handling Check fitting features	1

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Car (+ car door + car door oper.)	YES	5,1	139	0	Check handling Check fitting features	1
Main rope	YES	2,8	8,5	0	-	5

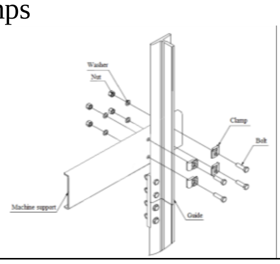
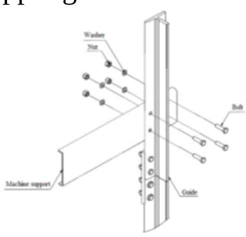
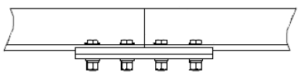
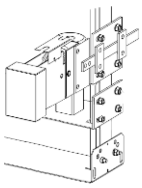
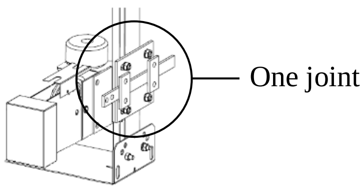
- Number of components: 152
- Number of critical components: 58
- Design efficiency: 38.16%
- Handling ratio: 4.06
- Composing ratio: 59.46
- Commissioning ratio: 0.78

The methodology takes the designer to identify and evaluate critical design factors.
According to the evaluation, composing or fitting features are the most complex aspects associated with the product installation. The designer should make suggestions in order to make the installation easier and improve the efficiency by changing fastening methods, merging components and reducing the number of repetitions for the most impactful aspects of the installation performance.

3.3 Proposed improvements

The recommendations proposed by the implementation of the methodology have been used to inspire changes in the design of an MRL elevator. Some improvements are shown in Table 4 as an example.

Table 4. Proposed changes

Part or assembly	Proposed changes to the design		
	Num.	Current design	New design
Supporting beam for T/M and upper guides	1	Machine support fixed with clamps 	Machine support fixed with screws, holes in upper guide 
Guides and joining plates	2	Guide assembly with joining plates using screws, washers and nuts 	a) Use joining plates with punching nuts, so when assembling guides and joining plates, only the screw is threaded into the punching nut (avoid assembly effort at installation)
Guide, buffer, cabin frame and safety brake rope tensioning device	3	Tensioning device is extra part 	Tensioning device is linked to the buffer on one side 
	4	Guide, buffer, cabin frame and tensor are assembled on-site	Guide, buffer, cabin frame and tensor are preassembled in the factory
Weights (counterweight)	5	72 single weights 25 kg	8 weights 200 kg with crane-handling + 8 weights 25 kg for adjustment

The proposed changes are evaluated again using the proposed metrics (examples in Table 5).

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Table 5. DfI evaluation of the new design

Name	Critical	Handling index	Composing index	Commissioning index	Evaluation	Rep
Car guide rail	YES	2	4,9	0	-	5
Bracket (guide fixings)	YES	1	45,7	1	Check number of repetitions Check fitting features	28
Car Guide joining plate	NO	1,1	35,9	0	Check fitting features Consider merging with other components	6
Buffer	YES	1,5	32,9	1	-	1
Traction machine (T/M)	NO	2,3	32,9	0	Consider merging with other components	1
Speed governor	NO	1,8	17,7	0	Consider merging with other components	1
Small weight	NO	2	2,7	0	Consider merging with other components	8
Heavy weight	NO	3,5	2,7	0	Check handling – Excessive weight Consider merging with other components	8
Foldable car frame (+ safety gear + g. shoes)	YES	15,1	63	0	Check handling Check fitting features	1
Car (+ car door + car door oper.)	YES	5,1	139	0	Check handling Check fitting features	1
Main rope	YES	2,8	8,5	0	-	5

- Number of components: 94 (-58)
- Number of critical components: 55 (-3)
- Design efficiency: 58.51% (+20,35 pp)
- Handling ratio: 3.83 (-0,23)
- Composing ratio: 51.82 (-7,64)
- Commissioning ratio: 0.8 (+0,02)

In labour hours, a total reduction of 10.8 h has been identified, which means that the changes could potentially reduce the total installation time by almost two days to a total of 24 days (6% reduction).

4 DISCUSSION OF THE RESULTS

A new design for installation (DfI) methodology for Ls-Ll cycle products has been proposed and validated through a case study focused on the design of a machine room-less elevator.
A design for assembly based approach has been suggested due to the similarities between assembly and installation. A L&H penalty-based analysis has been chosen for that purpose. The approach was combined with the B&D approach for critical part identification. These methodologies were originally derived for in-factory production of small products, thus, the need to adapt them to the unique aspects associated with Ls-Ll cycle products is evident and new evaluation criteria have been proposed. The main differences are the new questions developed to identify critical parts and the incorporation of two new ratios, composing and commissioning, that replace the original fixing index.
The design targets have also been reformulated to adapt them to the features of Ls-Ll products. The main difference is associated with the composing ratio. Fixing means are not the same for mass produced products and Ls goods assembled in the field, therefore the target for the composing ratio is increased.
The overall results look promising since a 6% reduction of assembly time has been achieved and the design efficiency has been increased 20.3 pp up to 58.5%. A ratio of only 0.71 non-critical components per critical

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component has been achieved. This suggests that there are not many ways to reduce the total amount of components and efforts should be focused on improving the composing ratio.

Table 6. Results summary

	Target	Original design	Proposed design
Design efficiency	> 50%	38,16%	58,51%
Handling ratio	< 4	4,06	3,83
Composing ratio	< 30	59,46	51,82
Commissioning ratio	< 1	0,78	0,8

If the achieved results are compared to the initial targets, it can be seen that the main challenge is to reduce the composing ratio. However, a deeper analysis shows that biggest areas for improvement are in the Hall Door and in the Counterweight frame components.

Achieving composing ratios below 30 can be quite challenging since, as previously mentioned, construction standards are based on welded, screwed or riveted fixings that are adversely impacting composing ratios. If these fittings are compared to clamps or other types of fast fixing used in mass production, a reason for high ratios is found. However, any reduction in this ratio is considered positive.

The upgrade proposals should focus on the study of logistical factors, such as transportation, packaging, preparation, material handling in the work zone, or nonconformities, etc. which should be analysed and implemented in a new logistic ratio that would be added to the proposed ratios.

5 CONCLUSIONS

A new design for installation methodology has been used to analyse and redesign machine room-less elevator components and reduce the installation time by 6%. Furthermore, the method enables identification of the most critical components in terms of handling, composing and commissioning so traditional DfA methodologies can be applied and address particular weaknesses.

For a deeper analysis and better design results, penalties related to maintenance and refurbishment should be added in form of critical part questions, as well as larger studies should be done on penalties related to logistics. The authors propose that transportation, packaging and work zone preparation could be considered in a new logistic ratio that could be truly helpful for products that, because of their characteristics, are manufactured far from the installation places or have high logistic costs.

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