Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 84 (2019) 673–679

www.elsevier.com/locate/procedia

29th CIRP Design 2019 (CIRP Design 2019)

DFA-SPDP, a new DFA method to improve the assembly during all the product development phases

Iñigo Ezpeleta[a]*, Daniel Justel[a], Unai Bereau[a], Julen Zubelzu[a]

[a]*Mondragon Unibertsitatea, Faculty of Engineering, Mechanical and Industrial Production, Loramendi 4, Mondragon 20500 Guipuzkoa, Spain*

* Corresponding author. Tel.: +34-664-299-221; fax: +34-943-791-536. *E-mail address:* iezpeleta@mondragon.edu

---

Abstract

Design for Assembly (DFA) methodologies help the designer to take into account the assembly process during the development phases of a product (specifications, conceptual design and detailed design), thus improving the assembly process of the product. After a bibliographic review, it is verified that the most extended DFA methodologies are: Boothroyd-Dewhurst method, Lucas method, Hitachi AEM method and Modified Westinghouse method. All these methodologies help to achieve improvements in some of the development phases, but none of them assist the designer in all the phases of the process.

This article presents a DFA methodology that considers the assembly process of a product during all the phases of its development (DFA-SPDP). For this purpose, DFA-SPDP method is created from the four most widespread methodologies. This methodology brings together the main quantitative parameters of the four methodologies in a single method. As a conclusion, applying DFA-SPDP method, the designer is supported throughout the process of developing a product, with information equivalent to that resulting from the application of the four methodologies.

Keywords: DFA; Product development; Design optimization; Conceptual design; Assembly

---

1. Introduction

Nowadays, companies are facing the challenge of designing, manufacturing, assembling and launching new products that meet the needs of consumers in the shortest possible time. It is of vital importance for this purpose to reduce costs and time to market as much as possible. Therefore, it is necessary to make an efficient conceptual design of the products to avoid further corrections and losses of time during the detailed design and industrialization of products.

Among different existing tools, design for assembly methodologies (DFA) are tools available for designers to achieve this goal, which try to improve the assemblability of products [1]. DFA methodologies are aimed to support designers reducing product assembly times by simplifying design [2]. These methodologies assist designers in making decisions during the design process, providing them with different quantitative indicators: design efficiency, assemblability ratio, handling ratio, etc. After a DFA methodologies bibliographic review [3,4,5], it is concluded that: (i) there are many DFA methodologies, but the most widespread are: Boothroyd-Dewhurst (B&D) methodology [6], Lucas methodology [7], Hitachi-AEM methodology [8] and Modified Westinghouse methodology [9]; (ii) there is no DFA methodology that assists designers throughout the design process (design specifications, conceptual design, detailed design).

Some researches such as Dochibhatla *et al.* [10] have tried to overcome this lack proposing the joint implementation of two methodologies, Lucas and B&D. The first, in the conceptual design phase and the second in the detailed design phase, but causing an increase in implementation time for

2212-8271 © 2019 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the CIRP Design Conference 2019.
10.1016/j.procir.2019.04.273

designers. Thus, the main objective of this article is to present a new DFA-SPDP methodology that considers the process of assembling a product throughout the design process from the four most widespread methodologies. For this purpose, firstly, a theoretical analysis of the B&D, Lucas, Hitachi-AEM and Modified Westinghouse methods is carried out in order to detect the characteristics and indicators used by each methodology. Then the DFA-SPDP methodology is presented in detail and applied in the real case of a stapler. Subsequently, the results of the new methodology and the four methodologies analysed previously are compared. Finally, conclusions are drawn.

2. Analysis of DFA methodologies

2.1. B&D Methodology

The B&D methodology began to be developed by Geoffrey Boothroyd at the University of Massachusetts in the 1970s. However, it was not until the 1980s that the B&D methodology was completely developed. The application of this methodology tries to improve the assemblability of the product based on two principles: reducing assembly operations by reducing the number of parts and facilitating the execution of assembly operations [7].

The methodology can be implemented manually [11] or by software. In manual implementation, an evaluation sheet is filled in.

The implementation of this methodology gives four interesting indicators: product assembly time (T_M), product assembly cost (C_M), minimum number of components (N_M) and design efficiency (E_M). The steps to follow during its manual implementation are as it follows [2]:

- List the parts of the product according to the assembly sequence and indicate the quantity of each (N).
- Perform the handle analysis for each part. For this, the handling code is determined, to which a handling time (T_H) corresponds.
- Perform the insertion analysis for each part. For this, the insert code is determined, to which an insert time (T_H) corresponds.
- Calculate the total assembly time of each part ($T_A = T_H + T_I$) and the total assembly time of the product ($T_M = \sum T_A$).
- Calculate the total assembly cost for each part (C_A) and the product assembly cost (C_M).
- Determine the minimum number of parts (N_M). To do so, classify parts as essential and non-essential.
- Calculate design efficiency (E_M).
- Evaluate the results. If design efficiency (E_M) is lower than desired, it is recommended to redesign the product. For this purpose, eliminate parts, join several parts or replace one part with another that performs more than one function.

For the correct implementation of the methodology, it is necessary that the analysed product is fully dimensionally detailed [10]. During the conceptual design phase, which is when the most important design decisions are made, these data are not present and therefore this methodology cannot be implemented [12].

2.2. Hitachi AEM methodology

Hitachi AEM methodology was developed in 1976 by Miyakawa and Ohashi [13,14]. Afterwards, the methodology evolved into the New AEM methodology. The methodology is based on the principle of one motion for one part [15]. During the manual implementation of this methodology, a form is filled out in the same order as the assembly sequence. For this, it is necessary to make a clear assembly sequence using the symbols and letters defined in the methodology [2]. With the application of this methodology five interesting indicators are obtained: assembly time (*AT*), assemblability (*E*), assembly cost ratio (*K*), design efficiency based on parts (*PCDE*) and the simplicity factor (*SF*). The steps to follow during manual implementation are as it follows [7]:

- List the parts according to the assembly sequence and indicate the quantity of each.
- Draw the assembly sequence with the symbols and letters defined in the methodology. Each symbol has a value that refers to the time required. The unit of time used is T_{down}.
- Calculate the product assembly time (*AT*).
- Calculate the assemblability (*E*). This index shows the difficulty of assembly. The ideal mounting value is 100. A value less than 80 is considered non acceptable.
- Calculate the design efficacy (*PCDE*). For this purpose, it is necessary to determine the number of parts candidates for elimination (*CFE*).
- Calculate the simplicity factor (*SF*). The target value of this index is 100. If the value is less than 60, a redesign of the product is recommended.
- Calculate the assembly cost ratio (*K*). A value less than 0.7 is acceptable.

For the implementation of the methodology, it is not necessary for the design to be completely dimensionally defined, but the more detailed it is, the better the obtained results are [16].

2.3. Lucas methodology

Lucas methodology was developed by Lucas Corporation in collaboration with Swift of Hull University (England) in the 1980s [17]. Lucas methodology is based on a scale point [5], which gives a relative measure of the difficulty of the assembly. For this, penalty factors associated with possible design problems are assigned. It can be implemented manually using penalty tables or with its software. In case of manual implementation, a form called the assembly flow chart [2] must be completed. After the implementation of this methodology, three interesting indicators are get: design efficiency, handling (feeding) ratio and fitting ratio [7]. The steps to follow during its manual implementation are the following ones[16]:

- Perform a functional analysis and calculate design efficiency. For this, classify parts as essential (A) or non-essential (B). A target value of 60% is suggested for design efficiency. To improve efficiency value, reduce non-essential parts (B) or increase essential parts (A) [18].
- Carry out the analysis of the difficulty of handling parts. To perform this, the handling ratio is calculated. The suggested value is 2.5. If this value is exceeded, a redesign must be carried out to improve it.
- Carry out a fitting analysis. This analysis shows the difficulty of operations or processes with the parts. To do this, first represent the assembly sequence tree using different shaped symbols for different assembly operations defined in the methodology. Subsequently, calculate the fitting ratio. The suggested value is 2.5. If this value is exceeded, a redesign must be carried out to improve it.

In order to implement the methodology, it is not necessary to define completely the product dimensionally. Therefore, the methodology can be used in the initial phases of the design [10].

2.4. Modified Westinghouse methodology

The Design for assembly calculator methodology, widely known as Westinghouse, is a DFA methodology developed by Sturges [19] in the early 1990s for the Westinghouse Electric Corporation. Based on this methodology, GE Aircraft Engines produced a simpler version called Modified Westinghouse [20]. Based on the latter, Hinckley [9] included a product complexity factor, which indicates the excess time required for the assembly.

The methodology can be implemented manually completing a form or using a software. In the case of manual implementation, an evaluation sheet is completed and four interesting indicators are obtained: total assembly time (*TAT*), complexity factor (*C*), assembly ratio (*AR*) and parts efficiency (*PE*).

The steps in its implementation are the following [9]:

- Draw the assembly sequence with five different types of arrows and the letter F defined in the methodology.
- Carry out the handling analysis of each part assigning penalties defined in the tables of the methodology.
- Carry out the insertion analysis of each part assigning penalties defined in the tables of the methodology.
- Calculate product assembly time (*TAT*).
- Determine the number of essential parts (*NP*).
- Determine the level of design optimization by calculating the assembly rating (*AR*).
- Calculate the complexity factor (*C*) of the product. It shows the complexity of the product to be assembled.
- Calculate the part efficiency (*PE*).

For the implementation of the methodology, it is not necessary, but it is advisable to define the product dimensionally.

2.5. Comparison of the four methodologies

In order to compare the phases in which each methodology helps the designer in the design process, a comparison is made in Table 1. In this table, in the specifications phase, the methodologies, which during their implementation recommend minimum or maximum values of their indicators have been included, although they do not explicitly mention their use in this phase. In the conceptual design phase, only Lucas methodology has been considered since it can be implemented when not all the dimensional details of a product are available. On the other hand, Hitachi AEM and Modified Westinghouse methodologies are not considered because they have limitations in this phase. Finally, in the detail design phase all methodologies except for Lucas have been included. From Table 1 is concluded that no methodology supports the entire design process.

Table 1. Phases of application of the four methodologies

Design process	B&D	Hitachi	Lucas	Westinghouse
Specifications	X	X	X	
Conceptual design			X	
Detailed design	X	X		X

Table 2 summarizes the most important aspects or parameters used by the four methodologies to assess the assemblability of a product. In addition, it is indicated the way in which each methodology develops this aspect or parameter.

Table 2. Assemblability evaluation parameters.

Aspects / parameters	B&D	Hitachi	Lucas	Westinghouse
Sequence	-	Tree	Tree	Tree
Design efficiency	E_M	*PCDE*	Efic.	*PE*
Handling	T_H	-	Ratio	Time
Insertion	T_I	-	Ratio	Time
Assembly time	T_M	*AT*		*TAT*
Assembly cost	C_M	*K*		
Assemblability	-	*E*		*AR*
Assembly complexity	-	*SF*		*C*

3. DFA-SPDP methodology

DFA-SPDP methodology (Fig. 1) considers the assembly process of a product during all the phases of the design process, integrating all the parameters of Table 2. In addition, it tries to simplify the implementation process and consequently to reduce the time needed for its application. To this end, DFA-SPDP methodology is built taking the Modified Westinghouse methodology [9] as the backbone and adding particular aspects of Lucas [16] and B&D [6].

Hitachi AEM methodology is not integrated because it considers a particular unit of time, which complicates its integration with the other three methodologies, although its theoretical considerations are taken into account.

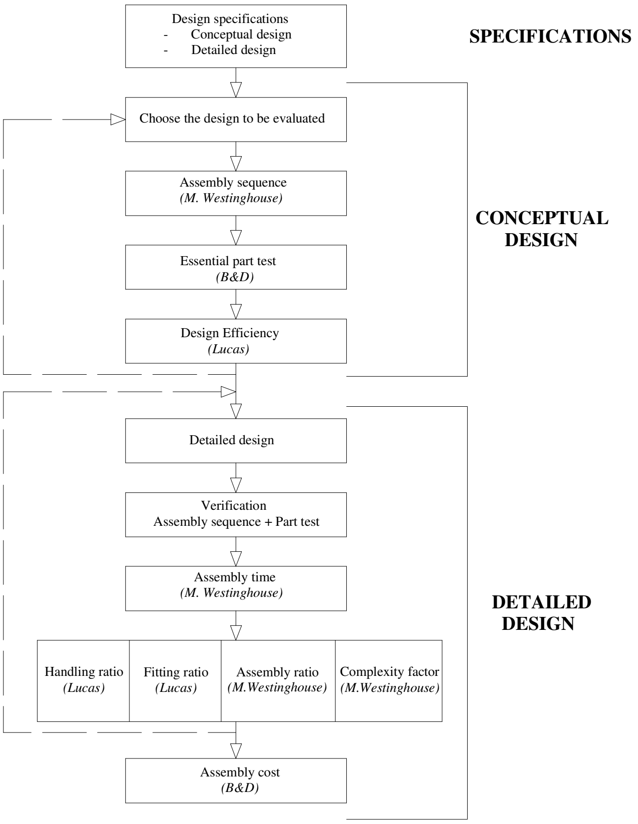


Fig. 1. DFA-SPDP Methodology

DFA-SPDP methodology, as the product design process, has three phases: specification phase, conceptual design phase and detailed design phase. In the last two phases, an evaluation form must be completed (Fig. 5).

3.1. Phase 1: Specifications

In this phase, seven assembly specifications (Table 3) are proposed to be included in the product requirements document (PRD).

Table 3. Assembly specifications.

SPECIFICATIONS		
Phase	**Specifications**	**Value**
Conceptual design	Design Efficiency (D_E)	>60%
Detailed design	Handling Ratio (H_R)	<2.5
	Insertion Ratio (I_R)	<2.5
	Assembly time (TAT)	…seconds
	Complexity Factor (C_F)	…seconds
	Assemblability Ratio (A_R)	50%÷100%
	Total assembly Cost (C_T)	…€

3.2. Phase 2: Conceptual design

In this phase, the conceptual design is analysed from the assembly perspective.

To meet it, the following steps are proposed:

- List the parts in the assembly sequence, specifying the quantity of equal parts.
- Draw the assembly sequence tree with the symbols used in the Modified Westinghouse methodology. The sequence tree is a tool that in a visual way enable to show which the assembly order is and clarifies the components that can be assembly in parallel.
- Classify the parts as essential (A) or non-essential (B) on the basis of the part test in Fig. 2. For this purpose, the questions of the B&D methodology are used. The other three methodologies use similar questions, but they differ from B&D when they classify the parts.

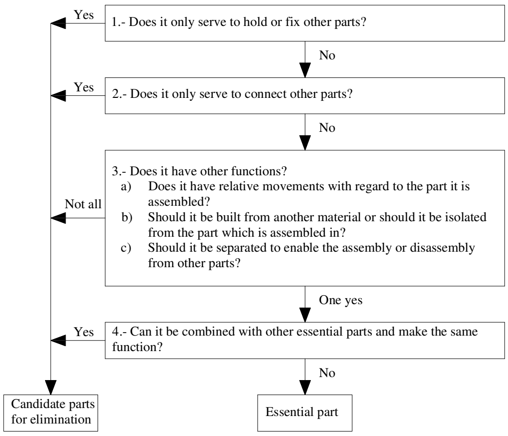


Fig. 2. Part test

- Calculate the design efficiency (D_E). Use equation (1) from Lucas methodology.

$$D_E = 100 \cdot \frac{\sum A}{\sum A + \sum B} \tag{1}$$

Where A is an essential part and B is a non-essential part.

The design efficiency (D_E) indicates the possibility of improvement that the initial design has. If the design efficiency (D_E) value is lower than the one defined in phase 1, a redesign is carried out. In the redesign, non-essential parts are reduced by combining several parts or functions. This phase is not completed until the objective defined in phase 1 is reached.

3.3. Phase 3: Detailed design

Starting from the detailed design of the product, the assembly is analysed with the following these steps:

- Check that the assembly sequence and part test have not changed respect to phase 2.

- Calculate the handling time (T_H) of each part based on the tables of the Modified Westinghouse methodology [9].
- Calculate the insertion time (T_I) of each part based on the tables of the Modified Westinghouse methodology [9].
- Calculate the total assembly time (*TAT*) using equation (2).

$$TAT = \sum T_H + \sum T_I \tag{2}$$

Where T_H is the handling time and T_I is the insertion time.

- Calculate the handling ratio (H_R). The ratio is calculated using equation (3) (used in Lucas methodology). The variable (*NUP*) is the non repeated quantity of essential parts (A). The ratio indicates the handling difficulty.

$$H_R = \frac{\sum T_H}{NUP} \tag{3}$$

Where T_H is the handling time.

- Calculate the insertion ratio (I_R). The ratio is calculated using equation (4) (used in Lucas methodology). The ratio indicates the insertion difficulty of the parts.

$$I_R = \frac{\sum T_I}{NUP} \tag{4}$$

Where T_I is the insertion time and *NUP* is the non-repeated quantity of essential parts (A).

- Calculate the quality of the design using the assemblability ratio (A_R). The ratio is calculated using equation (5) (used in Modified Westinghouse methodology).

$$A_R = 100 \cdot \frac{2.35 \cdot \sum \mathrm{A}}{TAT} \tag{5}$$

Where A is an essential part and *TAT* is the total assembly time.

- Calculate the product assemblability complexity factor (C_F). The factor is calculated using equation (6) (used in Modified Westinghouse methodology) and indicates how longer it takes compared to the ideal design to assemble the product. The lower the (C_F) value, the easier the product will be to assemble.

$$C_F = TAT - 2.35 \cdot (\sum \mathrm{A} + \sum \mathrm{B}) \tag{6}$$

Where *TAT* is the total assembly time, A is an essential part and B is a non-essential part.

If the ratios do not meet the specifications of phase 1, a redesign of the product is done to meet the desired specifications. The assembly costs are then calculated using equations (7) and (8).

- Calculate each part assembly cost (C_C), equation (7).

$$C_C = \text{Hourly rate} \cdot \ (T_H + T_I) \tag{7}$$

Where T_H is the handling time and T_I is the insertion time.

- Calculate total assembly cost (C_T)

$$C_T = \sum C_C \tag{8}$$

Where C_C is a part assembly cost.

4. Application of DFA-SPDP methodology

To verify that the results obtained with the DFA-SPDP methodology are valid, the case study of the stapler (Kangaro Mini-10 Stapler) by Dochibhatla *et al.* [10] is used.

4.1. Phase 1: Specifications

Table 4 shows the specifications defined for the stapler. In this case, some specifications such: time, cost and complexity factor are not defined.

Table 4. Stapler design specifications.

STAPLER DESIGN DESPECIFICATIONS	VALUE
Design Efficiency (D_E)	60%
Handling Ratio (H_R)	< 2.5
Insertion Ratio (I_R)	< 2.5
Assembly Ratio (A_R)	70%

4.2. Phase 2: Conceptual design

In this phase, as the stapler is an existing product in the market, it will be considered that the conceptual design could be one similar to the one shown in Fig. 3 (a). Thus, the list of parts in the assembly order is that of Fig. 5 and the tree of the assembly sequence is shown in Fig. 3 (b).

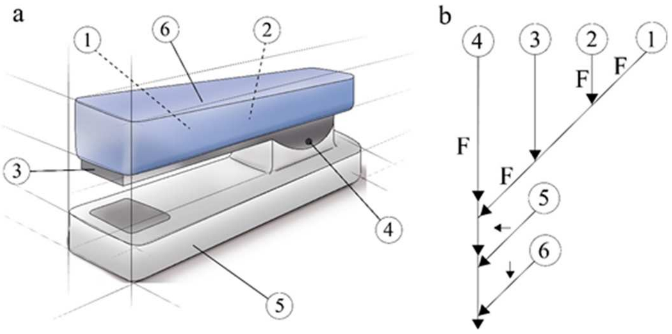


Fig. 3. (a) Conceptual design, (b) sequence tree

Then the part test (Fig. 2) is carried out, in total there are seven essential parts and none non-essential parts (Fig. 5). At the end of this phase, the design efficiency is calculated (D_E), which in this case is 100% and complies with the specification.

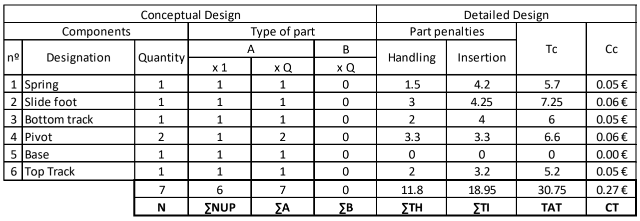
4.3. Phase 3: Detailed design

In this phase, the detailed design of the product is carried out. In this case, the existing design of the stapler in Fig. 4 is evaluated.

Fig. 4. Kangaro Mini-10 Stapler

In order to evaluate the assembly we follow the next steps:

- Check that the assembly sequence and essential parts have not changed.
- Fill in the form in Fig. 5 noting down the values (T_H) and (T_I) of each part.
- Calculate total assembly time (*TAT*), 30.75 seconds (Fig. 5).



Conceptual Design						Detailed Design			
Components			Type of part			Part penalties		Tc	Cc
nº	Designation	Quantity	A		B	Handling	Insertion		
			x 1	x Q	x Q				
1	Spring	1	1	1	0	1.5	4.2	5.7	0.05 €
2	Slide foot	1	1	1	0	3	4.25	7.25	0.06 €
3	Bottom track	1	1	1	0	2	4	6	0.05 €
4	Pivot	2	1	2	0	3.3	3.3	6.6	0.06 €
5	Base	1	1	1	0	0	0	0	0.00 €
6	Top Track	1	1	1	0	2	3.2	5.2	0.05 €
		7	6	7	0	11.8	18.95	30.75	0.27 €
		N	**∑NUP**	**∑A**	**∑B**	**∑TH**	**∑TI**	**TAT**	**CT**

Fig. 5. DFA-SPDP evaluation form

- Finally, calculate the ratios (H_R, I_R, A_R) and the complexity factor (C_F), Table 5.

Table 5. Ratio results.

Stapler Specifications	Value	Results
Handling Ratio (H_R)	< 2.5	1.97
Insertion Ratio (I_R)	< 2.5	3.16
Assemblability Ratio (A_R)	70%	54%
Complexity Factor (C_F)	-	14.3

Assemblability ratio (A_R) value indicates that the stapler assembly is acceptable but that it is at 16% of the target set in the specification. The handling of the parts does not present any difficulty since the insertion ratio (H_R) is less than the maximum of 2.5. The insertion can be improved since insert ratio is (I_R) above the maximum value of 2.5. The complexity factor (C_F) was not considered in the phase 1 specifications, but it is acceptable since it is 14 seconds higher than the ideal assembly (zero value). Facing this situation, redesigning the product should be considered with the aim of improving the insertion and thus the overall assemblability of the product.

In the case study, it is considered that the design of the product is optimized; therefore, the assembly cost is calculated. The cost of assembly is calculated at an hourly rate of 31.82 € [21], which result in a total cost (C_T) of 0.27 €.

4.4. Implementation time of the DFA-SPDP vs. implementation time of the analysed DFAs

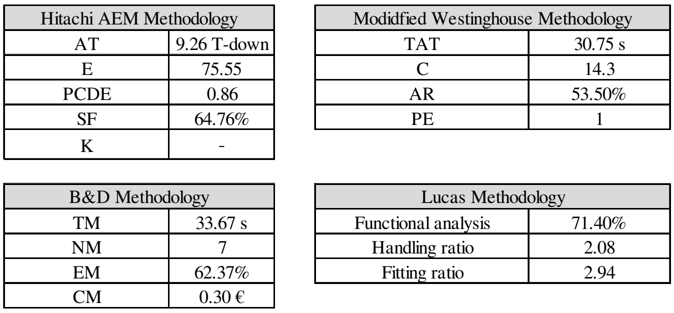
The time needed to apply the DFA-SPDP methodology has been measured and compared with the time needed to apply each of the four methodologies considered in this article. To this end, an engineer with knowledge of the five methodologies applied them individually in the case study and another person timed it (Table 6).

Table 6. DFAs implementation time.

	B&D	Hitachi	Lucas	Westinghouse	SPDP
Time used	16min 08s	11min 04s	21min 10s	18min 11s	20min 03s

The results of the study carried out by Dochibhatla *et al.* [10] match with the results obtained from the individual application of the B&D and Lucas methods (Fig. 6). For this reason, we consider times to be valid.

Compared to the three methodologies which it is based on, the DFA-SPDP methodology is not the most time-consuming for implementation because it uses the simplest parts of these methodologies.



Hitachi AEM Methodology	
AT	9.26 T-down
E	75.55
PCDE	0.86
SF	64.76%
K	-

Modidfied Westinghouse Methodology	
TAT	30.75 s
C	14.3
AR	53.50%
PE	1

B&D Methodology	
TM	33.67 s
NM	7
EM	62.37%
CM	0.30 €

Lucas Methodology	
Functional analysis	71.40%
Handling ratio	2.08
Fitting ratio	2.94

Fig. 6. Results of indicators of the four methodologies

Table 6 shows the implementation time for each methodology. The implementation time of the DFA-SPDP methodology is longer than B&D and Modified Westinghouse but provides more indicators than each of them analysed individually. Compared to the Lucas methodology, the implementation time is shorter and also provides a greater number of indicators.

5. Conclusions

This article presents a new DFA methodology that assists designers in making decisions throughout the design process of a new product. The DFA-SPDP methodology is developed from other four methodologies: B&D, Hitachi AEM, Lucas and Modified Westinghouse. Through this new integrative methodology, seven indicators are obtained that help to optimize the assembly process throughout the design process. The required implementation time is longer than three of the methodologies (B&D, Hitachi AEM, Modified Westinghouse) but includes more assembly indicators than each of them individually. The methodology has been implemented on a stapler and has demonstrated its usefulness. The results demonstrate its potential, as a methodology, to support designers. Future work with other case studies will allow the complete validation of this new methodology and the development of a computer tool to speed up its use.

Acknowledgements

The authors thank Mondragon Unibertsitatea engineering faculty, IHOBE (Public Society for Environmental Management of the Basque Government) and Orona S.Coop. for funding this work.

References

[1] M.-C. Chiu and G. E. Okudan, “Evolution of Design for X Tools Applicable to Design Stages: A Literature Review,” in *Volume 6: 15th Design for Manufacturing and the Lifecycle Conference; 7th Symposium on International Design and Design Education*, 2010, pp. 171–182.

[2] P. G. Leaney and G. Wittenberg, “Design for assembling: The Evaluation Methods of Hitachi, Boothroyd and Lucas,” *Assem. Autom.*, vol. 12, no. 2, pp. 8–17, 1992.

[3] P. J. Sackett and A. E. K. Holbrook, “DFA as a primary process decreases design deficiencies,” *Assembly Automation*, vol. 8, no. 3. MCB UP Ltd, pp. 137–140, 10-Mar-1988.

[4] M. Esterman Jr. and K. Kamath, “Design for assembly line performance: The link between DFA metrics and assembly line performance metrics,” in *Proceedings of the ASME Design Engineering Technical Conference*, 2010, vol. 6, pp. 73–84.

[5] A. Desai and A. Mital, “Facilitating Design for Assembly Through the Adoption of a Comprehensive Design Methodology,” *Ind. Eng.*, vol. 17, no. 2, pp. 92–102, 2010.

[6] G. Boothroyd, P. Dewhurst, W. A. Knight, P. Dewhurst, and W. A. Knight, *Product Design for Manufacture and Assembly*, 2nd ed. New York: Marcel Dekker, 2002.

[7] G. Q. Huang, *Design for X: concurrent engineering imperatives*. Chapman and Hall, 1996.

[8] T. Ohashi, M. Iwata, S. Arimoto, and S. Miyakawa, “Extended Assemblability Evaluation Method (AEM). Extended Quantitative Assembly Producibility Evaluation for Assembled Parts and Products.,” *JSME Int. J. Ser. C*, vol. 45, no. 2, pp. 567–574, 2002.

[9] C. M. Hinckley, *Make no mistake : an outcome-based approach to mistake-proofing*. Portland: Productivity Press, 2001.

[10] S. V. S. Dochibhatla, M. Bhattacharya, and B. Morkos, “Evaluating Assembly Design Efficiency: A Comparison Between Lucas and Boothroyd-Dewhurst Methods,” in *Volume 4: 22nd Design for Manufacturing and the Life Cycle Conference; 11th International Conference on Micro- and Nanosystems*, 2017, p. V004T05A012-8.

[11] G. Boothroyd, P. Dewhurst, and W. Knight, *Product Design for Manufacturing and Assembly*, Marcel Dek. New York: Marcel Dekker Inc.: New York, 1994.

[12] C. Favi, M. Germani, and M. Mandolini, “Design for Manufacturing and Assembly vs. Design to Cost: Toward a Multi-objective Approach for Decision-making Strategies During Conceptual Design of Complex Products,” in *Procedia CIRP*, 2016, vol. 50, pp. 275–280.

[13] S. Miyakawa and T. Ohashi, “The Hitachi Assemblability Evaluation Method (AEM),” in *Proceedings of 1st Int. Conf. on Product Design for Assembly, 1986*, 1986.

[14] S. Miyakawa, “The Hitachi assemblability evaluation method (AEM) and its applications,” *Journees Microtech.*, vol. 88, pp. 99–114, 1988.

[15] T.-C. Kuo, S. H. Huang, and H.-C. Zhang, “Design for manufacture and design for ‘X’: concepts, applications, and perspectives,” *Comput. Ind. Eng.*, vol. 41, no. 3, pp. 241–260, Dec. 2001.

[16] J. Chal and A. H. Redford, *Design for assembly: principles and practice*, vol. 240. 1994.

[17] K. Swift, “Expert system aids design for assembly,” *Assem. Autom*, vol. 9, no. 3, pp. 132–136, 1989.

[18] J. Volotinen and M. Lohtander, “The re-design of the ventilation unit with DFMA aspects: case study in Finnish industry,” in *Procedia Manufacturing*, 2018, vol. 25, pp. 557–564.

[19] R. H. Sturges, “A quantification of manual dexterity: the design for an assembly calculator,” *Robot. Comput. Integr. Manuf.*, vol. 6, no. 3, pp. 237–252, Jan. 1989.

[20] K. A. Beiter, B. Cheldelin, and K. Ishii, “Assembly Quality Method: A Tool In Aid Of Product Strategy, Design, and Process Improvements,” in *Proceedings of DETC 2000, ASME Design Engineering Technical Conferences,* 2000, pp. 1–9.

[21] “Encuesta Trimestral de Coste Laboral,” *INE (Instituto Nacional de Estadística)*, 2019. [Online]. Available: http://www.ine.es/jaxiT3/Datos.htm?t=6062. [Accessed: 05-Feb-2019].