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THE DEVELOPMENT OF EXHAUST FAN HOUSING WITH CEILING MOUNTING FOR HIGH RISE BUILDINGS BY USING DFMA

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ABSTRACT
Design for manufacturing and assembly (DFMA) is widely applied in many industries to optimize the manufacturing and assembly process at the early stage of design, with the aides of the CAD model. Many researchers apply the DFMA to increase assembly efficiency, by decreasing the number of parts from a product, decreasing the manufacturing cost, and reducing assembly time. Therefore, this research applies DFMA to develop exhaust fan housing with ceiling mounting for high rise building type with the same purpose, and at the same time to justify that the method can overcome the problem of assembly time in a production line. Both designs from before and after the application of DFMA, are being compared by using finite element simulation and experimental. The simulation employs stress analysis, to predict the strength of those designs. While the experimental uses a manufacturing cost survey, real assembly time survey and failure test to show the advantages of DFMA design results. The research result shows that the DFMA method can decrease the manufacturing cost by 0.44%, and the assembly time by up to 2%, and able to withstand the entire mass of the ceiling mounting fan.
Keywords : *DFMA, FE Model, Exhaust Fan, Manufacturing Cost, Total Assembly*

1. Introduction

Product development in this Internet of Things era involves concurrent design and intelligent manufacturing. Design for Manufacturing and Assembly (DFMA) was introduced in the late 1980s and has been developed sustainably ever since (Barbosa & Carvalho, 2013; Campi et al., 2022; Formentini, Boix Rodríguez, et al., 2022). Few researchers compare the outcome design to the previous design (Vaz-Serra et al., 2021; Yuan et al., 2018), despite the fact that DFMA allows researchers to produce the optimal design with the goal of reducing manufacturing costs and assembly time (Formentini, Bouissiere, et al., 2022; Munanga et al., 2020; Sossou et al., 2018).

The application of DFMA requires the designer to provide specific times and additional efforts to gather integrated information related to the alternatives of manufacturing and assembly process, and market segment for their product, to present the optimum design (Naiju, 2021). The integrated information indicates DFMA application can reduce the trial and error activities during product testing, especially in the home appliance industry, as the industries often have modular products with hundreds and even thousands of components for one product (Ferreira et al., 2021). Subbaiah & Anthony are applied DFMA to develop the horn bike design by reducing the consumption of carbon filters, and DFMA able to decrease the manufacturing cost by up to 24.59% (Subbaiah & Antony, 2021). Ventilation modification in a high-rise building implemented the DFMA method to replace aged components, which involves big data, and the modification result is manufacturing cost suppression (Gbadamosi et al., 2020). The manufacturing cost reduction is also achieved by re-design the food processor by reducing components and replacing the threaded joint with the snap-fit joint (Harlalka et al., 2016). The development method to optimize the DFMA method is conducted through the application of the CAD model during the manufacturing process planning, and the development result shows features in a product can be an aid to predict the manufacturing cost (Favi et al., 2021). The reinforcement of plastic fan blades for a cooling tower is conducted by implementing the DFMA method, and the reinforcement result shows the plastic can replace the function of the previous material (Sharma et al., 2021). An alternator pulley in an automation industry is set as a case study to implement the combination between the DFMA method and sustainability analysis, afterward, the implementation result shows dimension geometrical modification able to ease the manufacturing and assembly process (Suresh et al., 2016). A portable Bluetooth speaker is set as another case study in implementing DFMA, to reduce components and replace material, and the implementation allows the suppression of selling price (Effendi et al., 2021). DFMA is applied to choose two designs of vehicle doors, and the application result shows the chosen design has a shorter assembly time and 15% higher assembly efficiency (Samad & George, 2022). Those applications show that DFMA has reached a combination with another method, organizing big data of manufacturing and assembly parameter, adaptable for various industries, and the after effect to the cost. However, those various applications do not yet describe in depth the effect of reducing the number of joints on manufacturing and assembly processes.

The ceiling-mounted exhaust fan in a high-rise building is designed to remove unwanted moisture and odors from a building or room and operates through the ventilation system. In the past decade, ceiling-mounted exhaust fans have seen advancements in vibration damper technology (Penlesky & Karst, 2008), housing and assembly method (Zakula et al., 2013), automatic suction and lighting system (A. H. Satoshi Kagawa et al., 2013), and housing coating material. This innovation altered the direction of exhaust fan design to reduce housing weight and increase product longevity. The material selection for the housing, the joining type selection for the assembly, and failure testing for the prototype are DFMA-implemented solutions for developing the exhaust fan's optimal design.

A product's complexity affects both its manufacturing cost and its assembly time. The applied machinery and its apparatus are determined by a combination of product complexity and material properties. whereas assembly efficiency is determined by a combination of product complexity, joint type, handling, and insertion time. A product with more than two assembly stations is complex because it requires parallel sequence planning (Liu et al., 2022) and station-by-station monitoring (Wang et al., 2015). Standardized and symmetrical designs for each product component are among the DFMA guidelines for achieving optimal design (Edwards, 2002). Therefore, this study employs the DFMA method to produce an optimal design and identify solutions to production line problems. So that the implementation of DFMA on a home appliance production line can be measured and the difference between before and after implementation can be evaluated.

2. Research Methods

This research applies the DFMA method (Boothroyd et al., 2010) to develop an exhaust fan housing with ceiling mounting and manufacture its prototype. To compare the before and after DFMA implementation, the design development employs manufacturing cost and total assembly time estimation. Figure 1 shows the previous and improved design of this exhaust fan housing. The exhaust fan housing is illustrated in Figure 1 as a product that relies on sheet metal fabrication and hand assembly. As shown in Figure 1(a)., the previous design required 10 screws to assemble the top cover and bottom cover. As shown in Figure 1(b)., the objective of this design development is to reduce the number of components without compromising the product's durability.

Using finite element analysis (FEA) and durability testing, the optimal design is compared to the previous design. As shown in Figure 2, the FE analysis uses a CAD model for static load analysis with a free-body diagram scheme. Figure 2 describes the exhaust fan housing as a beam with the distribution load on the upper part of the model.

(a) (b)

Fig 1. The exhaust fan housing design with ceiling mounting; (a) previous; (b) develop

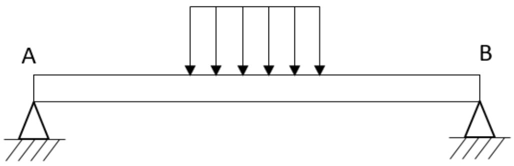


Fig. 2. The free-body diagram

(a). (b).

Fig. 3. The FE analysis; (a) static load position; (b) meshing arrangement

The distribution load is made up of the top plate, blade cover, motor, and blades as shown in Figure 3(a). The combined weight of all four constituents is 2,302.3 grams. The total mass is obtained by scaling each component. The FE analysis uses a meshing arrangement as shown in Figure 3(b). The durability test is the application test. The test is performed with a load of 22.5 N and a duration of eighty days.

The dies manufacturing cost

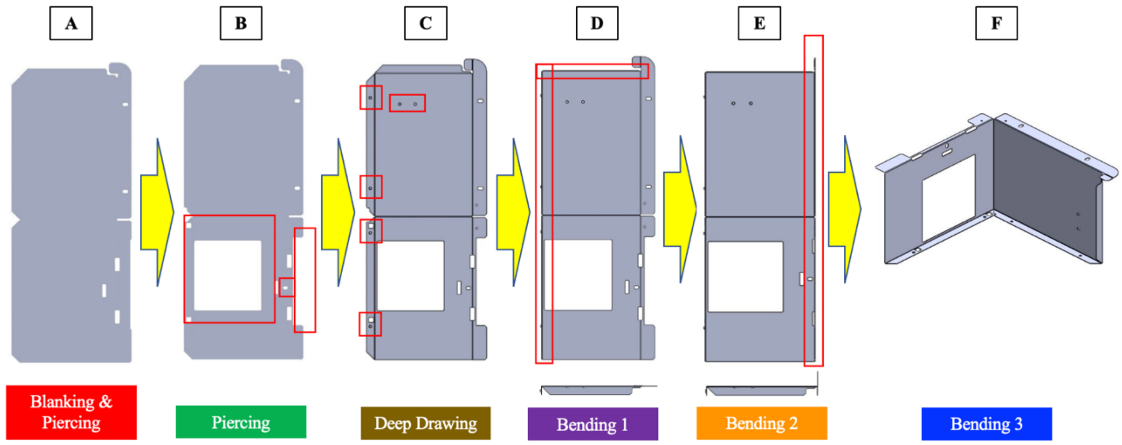


Fig. 4. The manufacturing sequences

Figure 4 is a summary of the manufacturing process sequence for the exhaust fan housing. Figure 4 shows a sequence that begins with blanking and ends with bending. Based on Figure 4, the first process is blanking and piercing. The blanking process produces sheets with a specified profile, while the piercing process produces several hole profiles. The second process produces a square cutting area in the middle of the sheet, a rectangle cutting area at the sides of the sheet, and one hole. The second process is carried out on the same sheet as the first. The third process is a deep drawing process to produce six holes in the housing. The fourth process is a bending process to produce a bending profile on several areas of the component. The fifth process is a bending process to produce a bending profile on top of the upper component. The sixth process is bending to produce V-profile bending. The sheet metal is made of SuperDyna Steel and is 0.5 mm thick.

Each manufacturer of sheet metal requires unique dies to create the designated holes and folded area. Therefore, each sequence has to calculate the total manufacturing die hours or known as manufacturing point (M_p)(Boothroyd et al., 2010), with the following formula:

$$M_p = f_p\left(f_{lw} f_d M_{po} + M_{ds}\right)$$

Equation (1) is a formula to calculate the manufacturing die hours for blanking and piercing process, where f_p is the die plate thickness, f_{lw} is the plan correction area, f_d is the die type factor, M_{po} is the basic manufacturing point, and M_{ds} is the die set of manufacturing point. M_{po} is calculated with:

$$M_{p0} = 28 + 1.03(X_P)$$

Where Xp is the profile complexity index to be sheared and is calculated with:

$$X_p = \frac{P}{(LW)^{1/2}}$$

Where P is length parameter to be sheared, L and W are length and width of the smallest rectangle that surrounds the punch.
M_{ds} is calculated with:

$$M_{ds} = 3 + 0.009\ (A_u)$$

Where Au is the useable area.
The plate thickness for the blanking and piercing process is calculated with:

$$h_p = 9 + 2.5\ log_e\left(\left(\frac{U}{U_{lc}}\right) Vh^2\right)$$

Where hp is the die plate thickness in mm, U is the ultimate tensile stress of the sheet metal to be sheared, U_{lc} is the ultimate tensile stress of annealed low-carbon steel, V is the required production volume in thousands, and h is raw sheet metal thickness in mm.
The total manufacturing die hours for piercing is calculated with:

$$M_p = 34 + 0.039LW + 0.6P_p + 3N_p$$

Where P_p is the circumference of all required holes, and N_p is the quantity of punch to be used.
For the deep drawing process, the total manufacturing point is calculated as follows:

$$M_p = M_{ds} + (f_{lw} * M_{p0})$$

where X_p is π because the deep drawing profiles has a circular profile, M_{p0} is calculated with Equation (2), and M_{ds} is calculated with Equation (4).
For all the bending process in Figure 4, the total manufacturing point is calculated by using the following:

$$M_p = 21 + 0.032LW + 0.68L_b + 0.58N_b$$

where M_p represents the manufacturing points, L_b represents the total length to be bent, and N_b represents the number of bends.

Afterward each of the total manufacturing point is multiplied by the tool-making rate per hour for a die set, so to obtain the total manufacturing cost. The tool-making rate per hour is set USD 40, which is summarized by (Geoffrey Boothroyd, Peter Dewhurst, 2010) from their survey result database.

The labor cost for die manufacturing

The labor cost for each process is calculated by multiplied the labor cost per hour with the total manufacturing time for each process. The labor cost is assumed to be USD 14.33 per hour for blanking and piercing process, while for piercing, deep drawing and bending is USD 14.60. The labor hours to produce die for each process is assumed to be 80 hours. The assumption is taken from the interviewed result by the researchers to a supplier.

The total dies cost

The total dies cost is a total between the total manufacturing point cost and the labor cost. Afterward the calculated total dies cost is compared with the real-time cost from the interviewed result.

The total assembly times

The total assembly time is calculated by considering in handling and insertion aspect between each components of the exhaust fan housing, with the following equation (Boothroyd et al., 2010):

$$Total\ time = n \times (wh \times wi)$$

where n is the total number of components, wh is the handling time, and wi is the insertion time. The assembly procedure for assembling the exhaust fan housing with the upper portion of the exhaust fan comprises the assembly of the upper cover and the assembly of the upper cover to the blade casing. Figure 5 shows the steps of aligning and fastening the upper cover, while Figure 6 shows the process of combining the upper cover and blade casing.

Afterward the total assembly time for the developed design is compared with the real assembly time of the previous design. The real-time for the previous design, is obtained from direct measurement in the production line. Manual assembly by manpower is applied to the previous and developed design of exhaust fan housing.

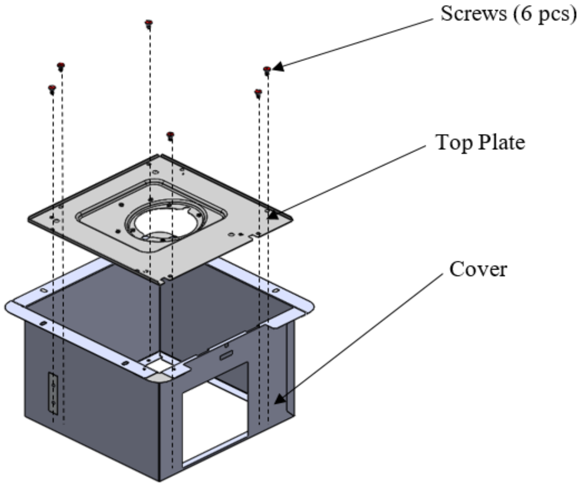


Fig. 5. Assembly scheme to form the upper cover

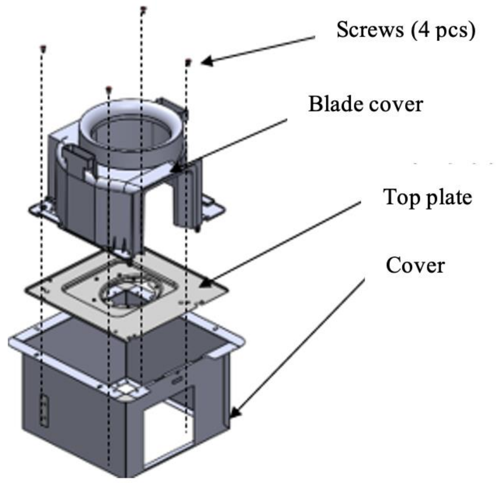


Fig. 6. Assembly scheme to merge top plate and blade cover

3. Results and Discussions

The dies manufacturing cost

Table 1 shows the setup and calculation result parameters for the total manufacturing point of each process in Figure 4. The calculation is conducted based on each step in the method section. Stage A represents dies-making hours for the blanking and piercing process with a useable area of 1699.4 cm^2 and is estimated to be manufacturing in 151.95 hours. Stage B represents die-making for the piercing process in five different areas and is estimated to be manufactured in 102.7 hours. Stage C represents die-making for the deep drawing process with a circular profile and is estimated to be manufactured in 50.29 hours. Stage D represents the bending process of the bottom part of the housing as shown in Figure 4 with the read marking, and the dies are estimated to be manufactured in 93.8 hours. Stage E represents the bending process of the upper part of the housing as shown in Figure 4 with the read marking, and the dies are estimated to be manufactured in 345.3 hours. Stage F represents the bending proses for the middle edge of the housing, and the dies are estimated to be manufactured in 156.6 hours.

The estimated manufacturing at stage E has the highest manufacturing hours in comparison to the other stages because the useable area to be bent is long, thin, and has a sharp edge. So, the bending process required guidance in the dies and alignment process during the positioning setup onto the machine. Stage C has the shortest manufacturing time because stage C only makes simple holes. The shortest manufacturing time shows that stage C has the lowest profile complexity index. The blanking and piecing process in stage A requires nine different features in the blanking die and the stripper plate, therefore the process must use the thick plate. The applied plate thickness for stage A is 25 mm. The piercing process in stage B requires a custom hole and rectangular feature for its blank, therefore the manufacturing point is high, because the process requires a custom die block, punch, retaining plate, stripper plate, and die backing plate. The bending process in stages D and F is classified as multiple bends type, based on the red marking area in Figure 4. The manufacturing point for stage F is higher than stage D because the total length of bend lines in stage F is 2.57-time the value in stage D.

Table 1 - The set-up parameter and die cost.

Stage A					**Stage B**	
Known parameter						
Parameter	A_u^*	h_p	f_p	f_d	LW^*	P_p^*	Np^*
Value	1699.4 cm^2	25 mm	0.75	1	310 cm^2	69.3 cm	5
Calculation result							
Parameter	M_{ds}	X_p	M_{p0}	M_p		M_p	
Value	18.3	5.35	33.51	151.95		102.7	
Stage C				**Stage D**			
Known parameter							
Parameter	X_p	M_{p0}	f_{lw}	LW^*	L_b^*	N_b^*	
Value	π	31.2	1.5	925.4 cm^2	60.9 cm	3	
Calculation result							
Parameter	M_{ds}	M_p	$M_{ds} + M_p$		M_p		
Value	3.04	47.25	50.29		93.8		
Stage E				**Stage F**			
Known parameter							
Parameter	LW^*	L_b^*	N_b^*	LW^*	L_b^*	N_b^*	
Value	925.4 cm^2	430.75 cm	3	925.4 cm^2	155 cm	1	
Calculation result							
Parameter		M_p			M_p		
Value		345.3			156.6		

*Data from SOLIDWORKS analysis

The cost to produce dies is detailed in Table 2. The highest production cost is stage E and the lowest is stage C. The total dies production cost is USD 36,026. The production cost is attained from the multiplication between the manufacturing point and the tool making rate per hour as per stated in section 2.1.

Table 2 - Manufacturing cost for the overall dies.

Stage	Process	Cost (USD)
A	Blanking & Piercing	6,078
B	Piercing	4,108
C	Deep Drawing	2,012
D	Bending 1	3,752
E	Bending 2	13,812
F	Bending 3	6,264
	Total Cost	36,026

Note: Currency on 26th July 2022 for 1 USD = 14.988 IDR

The labor cost for dies manufacturing

Table 3 provides a summary of the labor cost that occurred for six manufacturing process as shown in Figure 4. The labor cost for stage A is lower than the other stages, because the manufacturing process in stage A is an automatic ejection of the blanks and scrap from a raw sheet metal. So, the manpower for stage A didn't have to align the sheet, to monitor any restricted area, to conduct loading, and to conduct un-loading. Those jobs description reduce the time cycle and influence the labor rate per hour.

Table 3 - Labor Cost

Stage	Process	Cost per hours (USD)	Manufacture Times (hours)	Cost (USD)
A	Blanking & Piercing	14.33	80	1,147
B	Piercing	14.60	80	1,168
C	Deep Drawing	14.60	80	1,168
D	Bending 1	14.60	80	1,168
E	Bending 2	14.60	80	1,168
F	Bending 3	14.60	80	1,168
			Total Cost	6,987

Note: Currency on 26th July 2022 for 1 USD = 14.988 IDR

The total dies cost

The total dies cost for the developed design of exhaust fan housing (as shown in Figure 1(b)), is USD 43,013. That total dies cost is obtained from the sum between the total dies manufacturing cost and the total labor cost to manufacture dies, as stated in section 2.3. The total dies cost for the previous design as shown in Figure 1(a) is USD 43,201, based on the data from the interviewed result by the researchers. There is a difference of 0.44% between the design that was used before and the one that was developed. The difference is evidence that the DFM approach can accurately estimate and reduce production costs for the sheet metal process. Reducing the number of fastening in the developed design able to decrease the manufacturing cost.

Assembly time reduction

The assembly steps are consisted of two main steps. The steps are forming upper cover as shown in Figure 5, and merging upper cover, top plate and blade cover as shown in Figure 6. The assembly time for the previous design of the exhaust fan housing is shown in Table 4. The data in Table 4 is a result from real-time measurement in three production lines, which is operated by three different operators. Forming the upper cover step for the previous design requires 13 process as shown in Table 4. The estimated assembly time to form upper cover is conducted by using DFA index (Geoffrey Boothroyd, Peter Dewhurst, 2010)for both the previous and developed design. Table 5 shows the estimated result to form the upper cover. The estimation is calculated based on the CAD model approach. Table 6 shows the real-time measurement to merge upper cover, top plate, and blade cover. The procedure to merge the three components for the previous design, requires 10 process, as shown in Table 6. The estimated assembly time for those three components is shown in Table 7. This section compares the assembly time between the measurement data for the previous design, the estimated assembly time for the previous design, and the estimated assembly time for the developed design.

Fastening process during assembly in Table 4 consumes the longest assembly time in comparison to the other steps. The times to screw for the previous design are 16.19 seconds for the 1st screwing process and 9.25 seconds for the 2nd screwing process. Screwing application in the fastening process requires time to align, insert, and directly fasten each screw. The estimated assembly times in Table 5 for previous design are 15.78 seconds for the 1st screwing process and 10.4 seconds for the 2nd screwing process. The different between the real-measurement and the estimated result for previous design based on the screwing process, consecutively are 2.56% and 11.7%. The estimated assembly time in Table 5 for the developed design is 10.52 seconds for the 1st screwing process and 10.4 seconds for the 2nd screwing process. The different between the previous data in Table 4 and the developed data in Table 5 based on the screwing process, consecutively are 42.46 % and 11.7%. The differences indicate the developed design for the 1st screwing process is able to reduce the assembly time, yet for the 2nd screwing process gives the opposite result.

Table 4 - Assembly Time Required To Attach The Previous Upper Cover Design To The Top Plate

No	Assembly Step	Assembly Time (s)			Average	Time Requirement
		Operator 1	Operator 2	Operator 3		
1	Handling the cover	1.13	1.27	1.45	1.28	4%
2	Align and insertion jig to the cover	0.72	0.93	0.88	0.84	2%

3	Handling the top plate	0.50	0.89	0.74	0.71	2%
4	Align and insertion top plate to previous assembly	1.34	1.57	1.62	1.51	4%
5	Handling the screw	1.07	1.36	1.45	1.29	4%
6	Fastening the assembly by using the screw	14.92	16.23	17.42	16.19	44%
7	Release the assembled cover from the jig	0.41	0.75	0.54	0.57	2%
8	Handling the assembled cover as based	0.42	0.45	0.45	0.44	1%
9	Handling the motor	0.73	0.67	0.63	0.68	2%
10	Align and insertion the motor on to top plate	1.37	1.53	1.68	1.53	4%
11	Handling the screw	1.03	1.24	1.89	1.39	4%
12	Fastening the assembly by using the screw	8.91	9.82	9.02	9.25	25%
13	Handling the final assemble for the next process	0.71	0.88	0.94	0.84	2%
	Total	33.25	37.59	38.71	36.52	100%

Table 5 shows that the developed design has a 2% higher assembly efficiency compared to the previous design. The efficiency increases because the developed design reduces the number of fastening from six screw to four screw at the 1st fastening process. An assembly index close to one hundred percent for the developed design implies a highly efficient construction procedure. The 2nd fastening process for the previous design in Table 4 is 9.25 seconds to assemble the components, while the estimation in Table 5 is 10.4 seconds. The differences between measurement and estimation data is 11.7%. Obstruction in visibility during fastening process and the construction strength cause the estimator to choose high safety factor in estimating the assembly time. The 2nd fastening process for both the previous and developed design has the same values for the assembly times. The previous and developed design used the same procedure dan screw number in assembling the upper cover, top plate and blade cover as shown in Figure 6.

Table 5 - DFA Index Before And After DFMA Design To Assemble The Upper Cover And Top Plate.

No	Component Name	Before				After			
		Component Quantity (*n*)	Handling Time (*wh*)	Insertion Time (*wi*)	Total Time = *n x (wh x wi)*	Component Quantity (*n*)	Handling Time (*wh*)	Insertion Time (*wi*)	Total Time = *n x (wh x wi)*
1	Handling Cover (put to jig)	1	1.28	0.84	2.12	1	1.28	0.84	2.12
2	Top Plate	1	0.71	1.51	2.22	1	0.71	1.51	2.22
3	Screws (to top plate)	6	1.29	1.34	15.78	4	1.29	1.34	10.52
4	Cover (adjust position)	1	0.57	0.44	1.01	1	0.57	0.44	1.01
5	Motor	1	0.68	1.53	2.21	1	0.68	1.53	2.21
6	Screws (motor to cover)	4	1.39	1.21	10.4	4	1.39	1.21	10.4
7	Cover (to the next process)	1	0.84		0.84	1	0.84		0.84
Total		15	6,76	6.87	34.58	13	6.76	6.87	29.32
DFA Index (%)		96%				98%			

The steps consists of handling the upper part assembly, aligning the screws, fastening the screw, handling the casing cover, aligning and inserting the blade casing into the cover, aligning and inserting the screw, fastening the screw between the blade casing and the cover, handling the label of the serial code number, attaching the label to the blade casing, and then handling the final assembly for the next assembly process. The longest assembly times is 11.89 seconds and happen during the merging of top plate and blade case. The visibility obstruction, direct fasting, alignment process, and manual handling are the cause of that long duration in assembling. The shortest assembly times is 1.34 seconds and happen during the transferring process of the assembled product for finalization. The measurement result in Table 6 shows the alignment process requires cautious movement during assembly.

Table 6 - Assembly Time Required to Attach The Previous Upper Cover Design To The Blade Cover

No	Assembly Step	Assembly Time (s)			Average	Time Requirement
		Operator 1	Operator 2	Operator 3		
1	Handling the upper part assembly	1.09	1.26	1.70	1.35	4%
2	Handling and align the screws	2.04	2.34	3.16	2.51	7%
3	Fastening the screw	10.42	11.99	13.27	11.89	34%
4	Handling the casing cover	1.09	1.26	1.70	1.35	4%
5	Align and insertion of the blade casing to the cover	1.55	1.78	2.40	1.91	5%
6	Align and insertion of screw	1.37	1.58	2.13	1.70	5%
7	Fastening the screw between blade casing and the cover	8.24	9.48	8.75	8.82	25%
8	Handling the label of the serial code number	1.70	1.96	1.87	1.84	5%
9	Attached the label to the blade casing	1.79	2.05	2.77	2.20	6%
10	Handling the final assembly to the next process	1.26	1.45	1.32	1.34	4%
	Total	30.56	35.14	39.05	34.92	100%

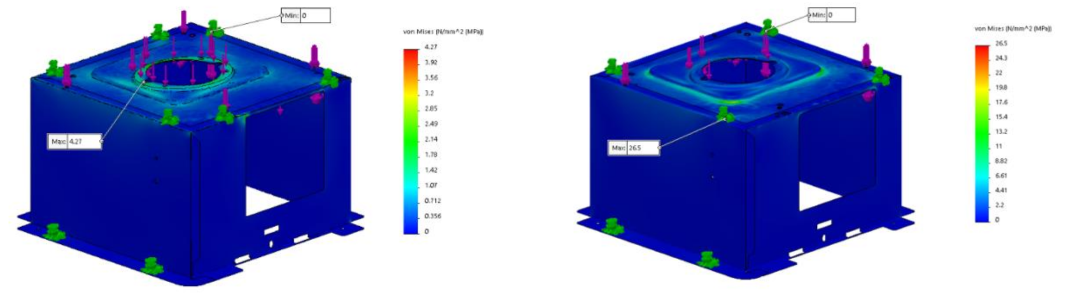
The average assembly times of the 1st fastening process for the previous design in Table 6 is higher than the estimation in Table 7. The discrepancy occurs because the estimation applied high safety factor in the calculation. The time estimation of the 2nd fastening process for the previous and developed design has the same value, because there are no components reduction in this process. The developed design has lower total assembly times in comparison to the previous design, with the differences of 21.05%. That suppression of time assembly takes place because of a reduction in the amount of time spent to screw. The differences influence the assembly efficiency, as the developed design has 2% increment than the previous design. The assembly efficiency of the developed design approximates 100%, is an indicator the assembly process for the exhaust fan housing already settled. The snap fit fastening can be an alternative to increase the assembly efficiency and to decrease the sheet metal manufacturing cost. The replacement from screw fastening to snap fit requires further study as it will affect the construction strength of a product.

Table 7 - DFA index before and after DFMA design to assemble upper cover, top plate, and blade cover.

No	Component Name	Before				After			
		Component Quantity (*n*)	Handling Time (*wh*)	Insertion Time (*wi*)	Total Time = *n x (wh x wi)*	Component Quantity (*n*)	Handling Time (*wh*)	Insertion Time (*wi*)	Total Time = *n x (wh x wi)*
1	Cover	1	1.35		1.35	1	1.35		1.35
2	Blade casing	1	1.08	1.26	2.34	1	1.08	1.26	2.34
3	Screws (to blade casing)	4	2.34	0.65	11.96	2	2.34	0.65	5.98
4	Blade casing cover	1	1.35	1.91	3.26	1	1.35	1.91	3.26
5	Screws (to blade casing cover)	4	1.7	0.79	9.96	4	1.7	0.79	9.96
6	Label	1	1.84	2.2	4.04	1	1.84	2.2	4.04
7	Cover	1	1.34		1.34	1	1.34		1.34
Total		13	11	6.81	34.25	11	11	6.81	28.27
DFA Index (%)		89%				91%			

Static Load Simulation

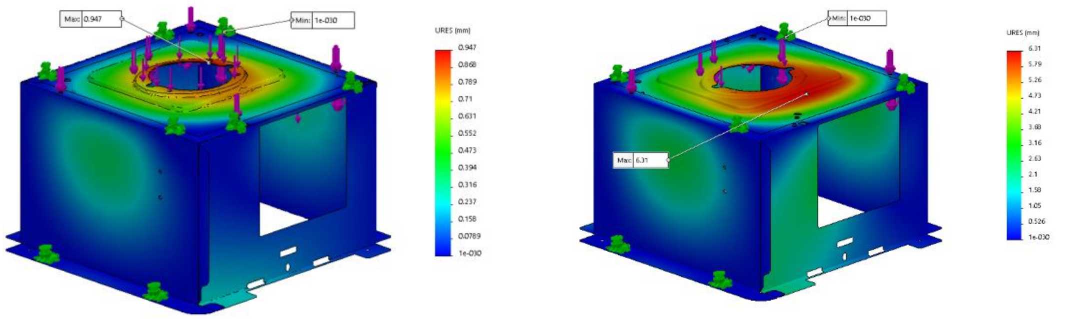
A static load analysis is required because the exhaust fan housing with ceiling mounting is subjected to a static load from the mass of the overall components to the connection between the housing and the ceiling. To predict the stress and displacement that occur because of the static load, therefore it is necessary to conduct a static load analysis. To make the prediction, the FE analysis model is run through the SOLIDWORKS software. On the upper cover, it is presumed that the load is a distributed load (shown in Figure 2).



(a). (b).

Fig. 7. Static load stress results; (a) the previous; (b) the developed designs.

Figure 7 shown the comparison result of the Von Mises stress between the older design of the upper cover and the more recent design that was developed. The previous design with more screws can uphold the load in a spot concentration manner, as shown in Figure 7(a). It has maximum stress on the area around the motor mounting hole (highlighted with green color), and it is safe because the maximum stress that occurred is less than the yield stress of the materials used for the upper cover, SuperDyma (Morimoto et al., 2002; Xu et al., 2022), and the top plate, SGCC (Sukarman et al., 2021). It can distribute the load, has maximum stress on the top plate and joints, and is safe because the maximum stress is less than the assigned yield stress material, which uses the same material as the previous design. This can be seen in Figure 7(b), which shows that. The newly developed design with fewer screws has a higher Von Mises stress occurrence than the older design with more screws, but it does a better job of evenly distributing the load throughout the structure. Therefore, the developed design is safe to be applied for long-term applications in terms of construction strength because the spring-back effect from the sheet metal can be suppressed if the load is distributed evenly (Dametew & Gebresenbet, 2017). This paves the way for the design to be used for applications that will last for a significant amount of time.



(a). (b).

Fig. 8. Static load displacement results; (a) the previous; (b) the developed designs.

Figure 8 shows the results of a comparison that was carried out between the previous design and the developed one's that was produced. Figure 8(a) shows the occurrence of displacement in the previous design with more screws, which included the following characteristics: displaying large displacement on the motor mounting (highlighted with red color), at joints (highlighted with green color), and on the upper cover wall (highlighted with green color); having distributed displacement behavior; and having the largest displacement, which is 0.947 mm. Figure 8(b) illustrates the occurrence of displacement at the design that was developed with fewer screws, displaying large displacement on the top plate (highlighted with red and green) and the joints (highlighted with green); having an uneven displacement behavior; and having the largest displacement, which is 6.31 mm. The design that was designed with fewer screws and an irregular pattern of the screws makes it necessary for periodic maintenance to be performed on a strict schedule or for an additional supporting structure to be added on top of the top plate for long-term applications.

Durability Test

The testing for the durability is carried out for a total of 80 days. The entire assembly of an exhaust fan is mounted to the ceiling and then put through its paces in a setting that is identical to the actual environment in which it will be used by the customer. The results of the durability tests performed on both the existing and newly developed designs for the upper cover indicate that the exhaust fan is still able to function normally and that the upper cover does not exhibit any signs of denting or cracking.

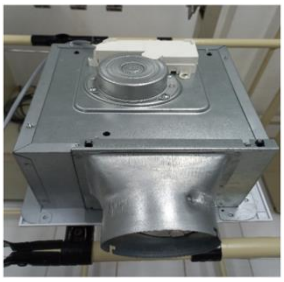


Fig. 9. The Exhaust Fan With The Developed Upper Cover Design After An 80-Day Durability Test

The condition of the exhaust fan after the newly developed upper cover design was implemented can be seen in Figure 9 The fact that the exhaust fan did not develop a dent or a crack after being subjected to a durability test for 80 days suggests that the reduction in the number of screws has only a slight impact on the fan's overall performance and its structural strength.

5. Conclusion

The application of DFMA to develop the upper cover design by lowering the number of screws on the exhaust fan with ceiling mounting results in a 0.46% decrease in die production costs, a 2% improvement in assembly efficiency, and able to up-hold the components loads. The improvement of exhaust fans by reducing the number of screws has a negligible effect on manufacturing costs and assembly times, so future work can concentrate on converting screw couplings to snap fit joints. Aside from that, the DFMA method has demonstrated the ability to forecast, monitor, and capture the impact of even the smallest design modification on the manufacturing and assembly processes.

The FE analysis with the static load and durability test of the upper cover with four screw joints may demonstrate the impact of the screw reduction effect on the construction and performance of the ceiling-mounted exhaust fan for high-rise structures. For a dynamic load implementation, the FE analysis and durability test can be developed.

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