Cost reduction of a diesel engine using the DFMA method

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Abstract: This work presents a study of manufacture and assembly costs reduction in a diesel engine model manufactured in an industry situated in Curitiba that intends to make this engine economically feasible. The study presents a brief literature review about product development and technological resources to support product design, emphasizing a review about the DFMA (Design for Manufacturing and Assembly) method. The paper presents a detailed description of how delimited the most critical subsystem of the engine was, considering the cost and the application of DFMA guidelines for the delimited subsystem. The results show an impact in the cost reduction of the subsystem chosen of 1.8% and in the entire engine of 0.7%.
Keywords: design for manufacturing and assembly, product design, product development

1. Introduction

The competition and the globalization had taken the companies to introduce its products in the market faster, with smaller cost and better quality, demanding a reorganization of its product development processes (ANDREASEN et al., 1988; BOOTHROYD & DEWHURST, 1990; BLACKBURN, 1991; BOOTHROYD, 1994; BARNETT & CLARK, 1998).

Due to these factors, many companies have searched the benefits proceeding from the new product development support resources and, mainly, from those that contribute with the design stage (ESTORILIO, 2003).

According to NUMA classification (Nucleus of Advanced Manufacture of USP, in São Carlos/SP/BR, 2005), these technological resources may be classified in three distinct categories referring to: tools (software), methodologies (which involve conceptual aspects), and methods.

The methods involve restricted knowledge about a specific subject and they are structured in steps, aiming to reach an objective. A method can be related to a methodology, concept or philosophy. Some examples are listed below:

- **QFD** (quality function deployment) (AKAO, 1990) - used to deploy the customers requirements in the first product technical features;
- **FMEA** (failure mode and effect analysis) (PALADY, 2002) - used to anticipate and to prevent product failures at the design stage; and
- **DFX** (design for X) (YANG & EL-HAIK, 2003) – used to assist the designers to rethink the design. The aim is to simplify and to facilitate the manufacture, the assembly, the maintenance, and other procedures.

As said by PEREIRA & MANKE (2001), these methods contribute to establish the knowledge foundation in the product design and they have been associated to concepts like Simultaneous Engineering, Six Sigma, and other concepts.

According to BACK & OGLIARI (2000), the decisions taken in the product design stage not only have a significant effect in the production costs, but also in the products manufacturability. Therefore, wrong decisions during the design might compromise, in greater or minor degree, the cost and time of development as well as the product integrity in others phases of its life cycle.

SAVOIE et al. (1990) say that manufacture costs are compromised during the design because its definitions tend to affect the tools manufacture used in the production, responsible for the greater part of the outlay.

Among the support methods of product design that assist to consider the manufacture and assembly during the design stage, from DFX category, there is the Design for Manufacturing and Assembly (DFMA).

This method is used as support to improve the product concept or an already existing project, resulting in a better design. After all, the focus of the DFMA is to contribute to generate a design considering the company manufacture capacity, also aiming at facilitating the assembly of the final product.

Design for Manufacturing (DFM) means design lots of components that will shape the product after the assembly considering an easy manufacture. Design for Assembly (DFA) means design for easy assembly. The manufacture process means to manufacture a product component and assembly refers to the addition of parts to construct a final product (BOOTHROYD, 1994).

Aiming at testing DFMA method in a practical case of product design, this paper presents a study of manufacture and assembly costs reduction in a diesel engine design of a company located in Curitiba that intends to make this engine economically feasible.

This company is a large multinational, which deactivated an engine series due to the high operation costs, low interchange ability, and the non-attendance of the environment requirements and the evolution of diesel engine market.

Aiming to meet the market requests, a new engine series was designed, however, in the implementation phase, this series did not attend the costs requirement, evidencing the necessity of a design revision to prevent the production cancellation.

To accomplish this work of project improvement, the methods DFM and DFA were adopted as support, applying their guidelines in the highest cost engine of the series.

With the results of the analyses, project alterations are suggested and incorporated to the original project, having a new product documentation emitted, which is compared to the original project documentation with the objective of quantifying the respective gains in cost.

2. Research methodology

Considering that the research's objective is to reduce diesel engine costs through the design improvement, the following methodology is applied: initially, it is realized a design review of the critical series of diesel engine aiming to identify the costlier engine, called in this work of "engine X".

The method used as support for the design review of the engine X is the DFMA because it allows a review from the aspects that impact in the manufacture and assembly costs.

This method often produces a considerable reduction in the component inventory, resulting in products more trustworthy, simpler, and cheaper to assembly and to produce. The reduction of parts number has a significant effect on the costs reduction, highlighting the several unnecessary items and other wastefulness (HUANG, 1996).

The method supplies a quantitative measurement of the **design efficiency**, allowing a comparison of the total time of the studied product assembly with the assembly time of an ideal product considering the improvements. The same procedure could be used to compare various different designs in terms of its efficiencies (BOOTHROYD & DEWHURST, 1990).

To apply the DFMA in the engine X, it is adopted the guidelines suggested by JONEJA (2005). They are the following:

1. to get the design details, engineering drawings, three dimensional models (3D), physical prototype or the own product;
2. to disassembly the ensemble observing the sequence and how each part is disassembled. To consider the sub-assemblies as spare parts, identifying each one of them;
3. to start the product re-assembly since the major part to the minor, writing the assembly time; and
4. to calculate the design efficiency through the following formula: $EP = 3 \times NP/TM$, being (EP: design efficiency, NP: parts number, and TM: assembly time).

After the assembly analysis, the manufacture of each component is analyzed, considering the DFMA guidelines described in the next sections of this work.

3. Diesel engine

Diesel engine or engine for ignition by compression is an engine that gets the ignition without an exterior intervention. The fuel ignition is gotten through the energy resulting from the compression phase. The increase of the temperature and pressure during the compression phase is enough to generate the fuel spontaneous ignition (RAYNAL, 2005).

According to the author, for a satisfactory diesel engine work, it is necessary a good control of the injected fuel and air into the combustion chamber, which occurs by the fuel injection system.

The diesel engine may be divided in two categories according to the combustion chamber design: diesel engine of direct injection and diesel engine of indirect injection. The engines of direct injection, which is the case of the engine X studied, have only one combustion chamber where the fuel is injected directly.

The main components of a diesel engine are:

- **cylinder block:** rigid structure that keeps the cylinders in an appropriate alignment;
- **injection pump:** responsible for the fuel pressurization at the moment of injection;
- **cylinders:** pipes where the pistons slide up and slide down inside;
- **cylinder head:** delimits with the piston the combustion chamber volume;
- **oil carter:** rigid structure situated at the inferior part of the engine which allows the lubrication system to feed the engine mobile elements;
- **piston:** it assures a tight blockade between the combustion chamber and the block. When the piston is submitted to the gases pressure, it transmits

the explosion force to the connecting rod through its shaft;
- **connecting rod:** transmits the force exerted by the piston when the mixture air-fuel burns;
- **crank shaft:** transforms the alternated movement of the pistons in rotating movement and transmits the engine power for the gearbox, which relays for the wheels;
- **flywheel:** maintain the uniformity of the rotation movement of the winches tree, assuring the constant speed of the crankshaft;
- **valves:** each cylinder has an admission valve where the mixture to be burnt enters and an expulsion valve to leave the burnt gases escape; and
- **camshaft:** responsible for opening and closing the valves.

The next item presents the engine X features and the development of the analysis realized with DFMA method.

4. DFMA application in the engine X

After the analysis of the engine design, it was identified that the production time is approximately 5 hours and 35 minutes, and the production capacity correspond to one engine in each 7 minutes.

The engine assembly process detail is not described in this paper due to excessive amount of information.

The manufacture, assembly, test, and packing processes of the engine were studied, resulting in the following sequence:

1. components received;
2. inspection of components received;
3. components available for the assembly line;
4. engine assembly in the main line;
5. dynamometer test in the engine during 31 minutes to verify: torque, power, noises, balancing lack, valves and leaking adjustment;
6. items assembly for engine transport such as covers and drain plugs threaded in the final of assembly line;
7. anti-corrosive fluid application in the engine; and
8. engine availability for transport to the customer.

5. Delimitation of the most critical subsystem

Analyzing the manufacture costs of the engine X, it is evidenced the applicability of the DFMA considering that components represent 66.23% of the total cost. Other costs are related to the transport, taxes, and other factors.

To identify the "relevant components" to be analyzed, these components are listed according to its cost, from the highest to the minor. It was delimited as "relevant components" the first ones of the list that, together, added 98.5% of the engine total cost.

Afterwards, the components of the engine X were associated to the following subsystems:

- structural and sealing (cylinder head, cylinder block, joints, etc.);
- rotating elements (crankshaft, gears, shock absorber pulley, flywheel, main bearing, connecting rods, crankshaft seals, water pump);
- injection (Injection pump, fuel injectors, high pressure pipes, etc.);
- air, lubricant, and refrigeration (gases recirculation valves, heat exchanger, collectors, water pump, etc.); and
- valves (command shaft, valves, seats, springs, rocker arms, rods) and cylinder (jackets, pistons, bolts, piston rings, coolers, etc.).

To make sure the components mentioned above are really necessary, three questions were asked for each one, recommended by BOOTHROYD (1994):

a) is it necessary a relative movement between the parts?
b) is it necessary the specification of different materials for physical and/or chemical reasons? and
c) must the component be dismountable to facilitate the maintenance?

The components that had affirmative answers show little flexibility for alterations, according to DFMA guidelines.

To organize these and other results, a Table was designed containing the following items: Amount of each component described; Component description; Subsystem to which component belongs; Component cost percentage in relation to the total cost of the components considered relevant in the engine, and the three questions (a, b and c) previously mentioned.

Analyzing this Table, it was determined that the subsystem to be studied would be the **Structural and Sealing**, considering its representation of 37.915% in the total cost of the "relevant components" of the engine. In addition, this subsystem reached 100% of negative answers to **question a**, 73% of negative answers to **question b**, and 53% of negative answers to **question c**, demonstrating, thus, flexibility for design alterations.

From the components of this subsystem, four of them were chosen for this study, considering the cost percentage in the 37.915%: the **Cylinders block** (19.99%), the **Cylinders head** (8.35%), the **Oil carter** (3.67%), and the **Gearbox** (1.55%). The other components showed percentages below 1.5 % from the 37.915%, not being considered in this study.

6. DFMA application for the cylinder block

The **Cylinder block** does not have casings, has an open refrigeration system, and it is structured for direct groove in the tractor gearbox (Figure 1).

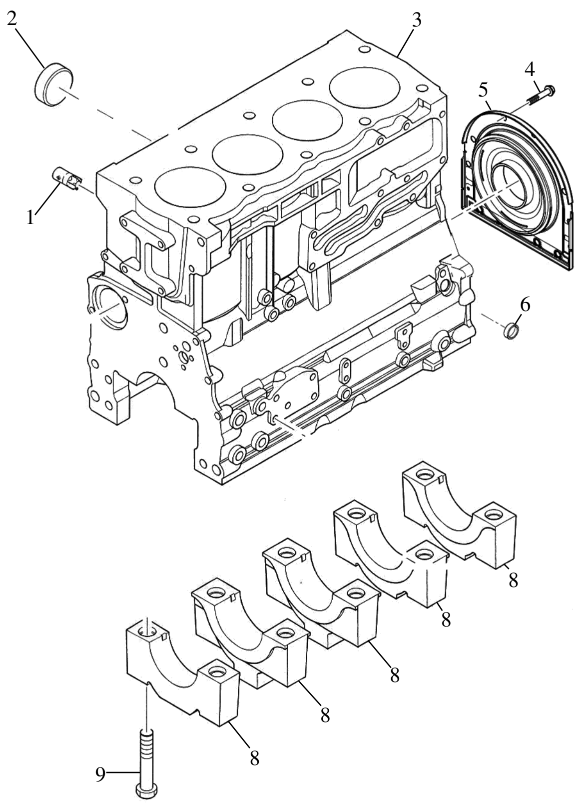


Figure 1. Isometric view of the cylinder block (Elaborated by the authors).

Firstly, the design efficiency is calculated through the following formula: EP = 3 x NP / TM, being (EP: design efficiency, NP: parts number, and TM: assembly time), detailed in Table 1.

Aiming to suggest the modifications, the study is developed based on the DFMA guidelines that are as follows:

- To project for a minor parts number;
- To develop modulate designs;
- To design multifunctional components;
- To design components of easy manufacture;
- To prevent or to reduce setting components (screws, rivets, bolts);
- To eliminate unnecessary adjusts and tolerances;
- To emphasize the standardization of components;
- To reduce the product parts number;
- To facilitate the manipulation and the assembly of the final parts; and
- To simplify the product structure, reducing the assembly costs and other factors of this nature.

Thus, the first analysis result is related to a feature of the cylinder block known as **bearing cover bores**, shown in Figure 2, which **could be eliminated**.

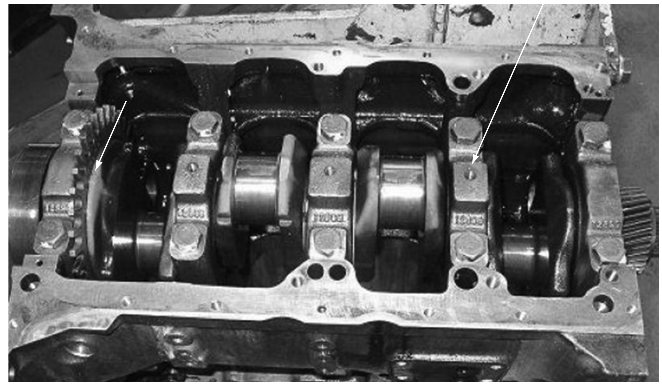


Figure 2. Bearing cover bores in the cylinder block (Elaborated by the authors).

Following the assembly process with the part supplier, it was possible to observe that these milling and non-pass bores are unnecessary for the assembly continuity. After all, they do not have direct contact with any part of the system and do not serve as reference to any other mounted part. After the Oil carter assembly, this part remains isolated

It was detected that the reason of the bores existence was due to the utilization of the cylinder block design from another engine series that used these bores to fix the oil fisherman. In the engine X, the oil fisherman is fixed in the balancing set, which is fixed in the block, becoming the three bores superfluous.

Due to this alteration, the cost reduction occurs as consequence of the economy of machine time, tool consuming, and inspection time of the three bores. Quantifying this reduction, it implies in 0.05% in the cylinder block cost and 0.03% in the cost of "Structural and sealing" subsystem.

Another analysis result was **to eliminate the block painting**. Part of the cylinder block manufacture process is the electrostatic painting after the casting process (see Figure 3). The objective of the painting is to protect the cylinder block against the corrosion during the transport from the supplier to the enterprise.

Before packing the lot produced by the supplier, the cylinder block receives an anticorrosive oil application. After that, they are wrapped in plastic films with corrosion inhibitors. This protection was necessary when the supplier was located in Europe, having a delivery time of one month. With the block nationalization, the transport time was reduced for two days, making this level of protection unnecessary.

Moreover, it was evidenced that during the engine assembly in the tractor, the engine and chassis set were entirely painted black, covering any previous painting of the engine, which made the painting of the cylinder block to become redundant.

Table 1. Cylinder block design efficiency calculated before the DFMA study (Elaborated by the authors).

C1	C2	C3	C4	C5	C6
Component	**Description**	**Number of times that the operation is consecutively executed**	**Assembly and insertion time by part (seconds)**	**Operation time (C3*C4)**	**Minimum number of parts estimated**
1	Drain plug of the oil feeding	1	20	20	1
2	Drain plug of the oil drain	1	20	20	1
3	Cylinder block	1	30	30	1
4	Screws of the back oil stamp	10	8	77	10
5	Back oil stamp	1	14	14	1
6	Drain plug of the speed sensor	1	20	20	0
7	Plaque of the serial number	1	60	60	0
8	Bearing covers	5	18	90	5
9	Screws of the bearing covers	10	5	50	10
				TM	**NP**
				381	29
Design efficiency				0.23	

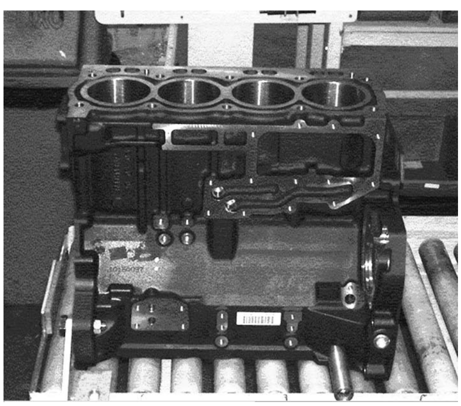


Figure 3. Cylinder block painting (Elaborated by the authors).

With this modification a cost reduction occurs in 0.26% in the cylinder block and 0.13% in the cost of "Structural and sealing" subsystem.

Another modification proposal was **to eliminate the puncture and spot facing of the seat of speed sensor**. The passing puncture of nominal diameter 17.1 mm, the M6 thread, and the spot facing shown in Figure 4 are necessary only in the models with injection through **electronic** fuel bomb. The engine studied present a **mechanical** injection system, making this feature unnecessary.

This modification results in a cost reduction of 0.18% in the cylinder block and 0.10% in the cost of "Structural and sealing" subsystem.

Following with the analysis, another modification proposed was **to eliminate the identification plate with the engine serial number**, used to register the product.

This operation consists to record an aluminium plate and to use two rivets to fix the plate in the block (Figure 5). If the writing is done directly in the cylinder block, the plate and the rivets become unnecessary.

In this case, the modification would impact in a cost reduction of 0.29% in the cylinder block and 0.15% in the cost of "Structural and sealing" subsystem.

Considering all modifications described for the "cylinder block", the calculations of design efficiency were remade, resulting in an improvement from 0.23 to 0.29. The subsystem cost was reduced in 0.41%, as shown in the Table 2.

7. DFMA application to the other components

Beyond the alterations suggested in the cylinder block, other modifications were also suggested and applied for other components previously mentioned; the headstock, the oil carter, and the gearbox. The study results and their costs impacts are shown, briefly, in the Tables 3, 4, and 5.

With the implementation of the modifications proposed for the cylinder headstock, it was not obtained design efficiency improvement related by assembly. The value was maintained in 0.49. It was identified, however, a cost reduction of "Structural and sealing" subsystem of 0.10%.

With the implementation of the modifications proposed for the Oil Carter, the design efficiency improved from 0.19 to 0.20 and the cost of "Structural and sealing" subsystem was reduced in 0.90%.

With the implementation of the modification proposed for the Gearbox, the design efficiency improved from 0.53

Table 2. Cylinder block design efficiency calculated after the DFMA study (Elaborated by the authors).

C1	C2	C3	C4	C5	C6
Component	**Description**	**Number of times that the operation is consecutively executed**	**Assembly and insertion time by part (seconds)**	**Operation time (C3*C4)**	**Minimum number of parts estimated**
1	Drain plug of the oil feeding	1	20	20	1
2	Drain plug of the oil drain	1	20	20	1
3	Cylinder block	1	30	30	1
4	Screws of the back oil stamp	10	8	77	10
5	Back oil stamp	1	14	14	1
6	Drain plug of the speed sensor				
7	Plaque of the serial number				
8	Bearing covers	5	18	90	5
9	Screws of the bearing covers	10	5	50	10
				TM	**NP**
				301	29
Design efficiency				**0.29**	

Table 3. Modifications suggested for the cylinder headstock (Elaborated by the authors).

Cylinder headstock (impact in 8.4% of 37.915%)		
Modifications suggested	**Justification**	**Cost impacts**
Elimination of the spot facing around the seat of injector peaks.	The assembly of the injector peak and the locking are made through the clamp mechanism that pushes the injector peak inside the combustion chamber, sealing the thermal bushing. Neither the injector peak nor the clamp touches the faced area, making it unnecessary.	Cost reduction of 0.18% of the cylinder headstock and 0.04% of the cost of "Structural and sealing" subsystem.
Elimination of the headstock electrostatic painting.	With the transport time reduction from one month to two days, this level of protection became unnecessary.	Cost reduction of 0.26% of the cylinder headstock and 0.06% of the cost of "Structural and sealing" subsystem.

Table 4. Modifications suggested for the oil carter (Elaborated by the authors).

Oil carter (impact in 3.67% of 37.915%)		
Modifications suggested	**Justification**	**Cost impacts**
Elimination of Oil Carter joint.	This joint is composed of aluminium alloy with an interior lip in silica. This joint can be substituted for a liquid joint of silica.	Cost reduction of 84% of the joint and 0.57% of the cost of "Structural and sealing" subsystem.
Elimination of electrostatic painting.	With the transport time reduction from one month to two days, this level of protection became unnecessary.	Cost reduction of 0.26% of the Oil Carter and 0.03% of the cost of "Structural and sealing" subsystem.
Elimination of seal ring of oil drain plug.	These two components can be substituted for a plug with conical screw.	Cost reduction of 40% of the plug and 0.3% of the cost of "Structural and sealing" subsystem.

to 0.58 and the cost of "Structural and sealing" subsystem was reduced in 0.53%.

8. Solutions synthesis

The synthesis of the features analyzed, its costs, the improvements proposed, and the cost reductions are demonstrated in the Table 6.

The design efficiency was evidenced in three of four studied components and the subsystem cost reduction was reached in all of them. This relation can be seen below:

- block of cylinders: increased efficiency from 0.23 to 0.29 with subsystem cost reduction of 0.41%;
- headstock of cylinder: subsystem cost reduction of 0.10%;

Table 5. Modifications proposed for the Gearbox (Elaborated by the authors).

Gearbox (impact in 1.55% of 37.915%)		
Modifications suggested	**Justification**	**Cost impacts**
The exclusion of the frontal cover joint utilized to seal the frontal cover and the gearbox.	This joint is composed by aluminium alloy with an interior lip in silica. This joint can be substituted for a liquid joint of silica.	Cost reduction of 0.79% of the joint and 0.53% of the cost of "Structural and sealing" subsystem.

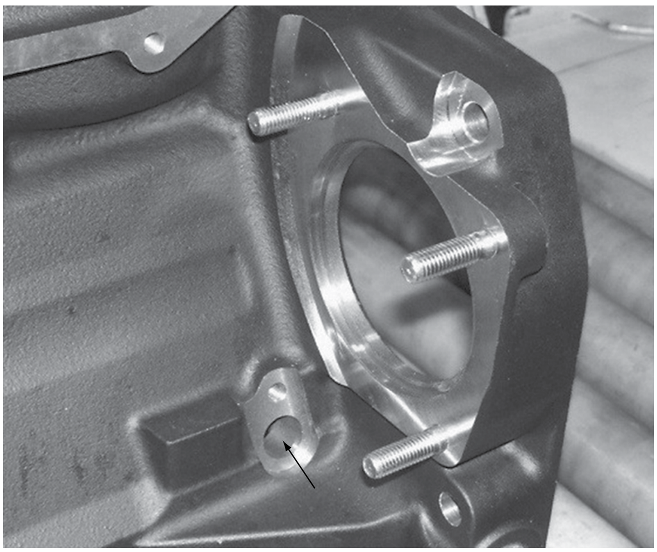


Figure 4. Puncture and spot facing of the speed sensor (Elaborated by the authors).

Figure 5. Engine identification plate (Elaborated by the authors).

- oil crankcase: increased efficiency from 0.19 to 0.20, with subsystem cost reduction of 0.90%; and
- box of gear: increased efficiency from 0.53 to 0.58, with subsystem cost reduction of 0.53%.

The total cost reductions of the "Structural and sealing" subsystem and the engine cost reduction are the following ones:

- total cost reduction in the subsystem: 1.94%; and
- total cost reduction in the entire engine: 0.71%

9. Conclusion

This study presented a DFMA method application in a diesel engine to reduce the manufacture and assembly costs, aiming to make this engine economically feasible.

For the application of DFMA method, the study showed the most critical subsystem identification based on the cost impact in the entire engine and, of this subsystem, the delimitation of the most representative components.

It was identified that "Structural and sealing" subsystem represent 37.915% of the main engine components, taking the cost into account.

Considering the components are part of this subsystem, four of them were chosen to be studied due to the cost percentage of 37.915%: the cylinders block (19.99%), the headstock (8.35%), the oil crankcase (3.67%), and the gearbox (1.55%). The other components showed percentages below 1.5% from 37.915%, not being considered in this study.

As a general result, only 0.71% of cost reduction was gotten in the engine studied, meaning 1.14% in the subsystem considered, which still makes the engine manufacture unfeasible.

However, other potential improvements that were identified could be carried out in future works using the DFMA method. These alterations could result in bigger cost impacts.

Among the potential improvements, they are the following: to reduce tolerances of the casting block, to remove the guides and seat of valves that are pressed and to substitute them for machining and posterior thermal treatment, and to reduce finishing specifications in surfaces where silica could be applied.

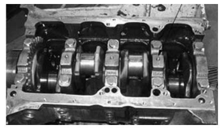
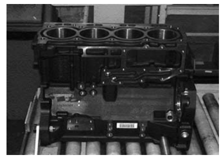
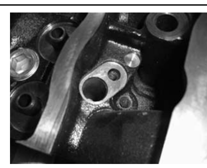
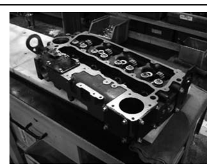
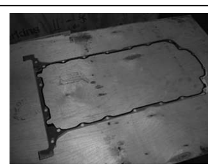
In this way, it is not recommended that the analyst narrows his focus only in components of bigger economic impact. After all, the other components could present major possibilities of alterations, resulting in better-cost impacts. Consequently, the best is to explore all possibilities in the entire product to try to obtain the highest costs reductions possible.

With this study, however, it was possible to realize how important the knowledge about manufacture and assembly process is, beyond the design experience, it is important to apply the DFMA with a team.

10. Acknowledgements

We would like to thank the company that made the accomplishment of this study possible and Teacher Fernanda Cervi Rolkouski for the support with the translation from Portuguese to English.

Table 6. Features analyzed, its costs, the improvements proposed, and cost reductions (Elaborated by the authors).

Component	Feature description	Original feature	Modification	Component cost reduction (%)	Subsystem cost reduction (%)
Cylinder Block	Cylinder puncture		To eliminate the puncture	0.05	0.03
	Block painting		To eliminate the painting	0.26	0.13
	Puncture and spot facing		To eliminate puncture and spot facing	0.18	0.10
	Identification Plate		To eliminate plate and rivet	0.29	0.15
Headstock	Puncture and spot facing		To eliminate puncture and spot facing	0.18	0.04
	Headstock painting		To eliminate the painting	0.26	0.06
Oil carter	Oil carter Joint		To change for liquid joint	84.00	0.57
	Oil carter painting		To eliminate the painting	0.26	0.03
	Oil drain plug		To eliminate the oil drain plug	40.00	0.30
Gear cover	Joint of gear cover		To change for liquid joint	79.00	0.53

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