LAMINATED OBJECT DESIGN: A DESIGN TECHNIQUE FOR RAPID PROTOTYPING AND MANUFACTURING

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Abstract. *The Laminated Object Design (LOD) is a rapid prototyping / manufacturing technique developed at the Federal University of Minas Gerais, Brazil, in the Welding and Robotics Lab (LRSS) to solve several problems related to the construction of special welding robots. The LOD is based on product design techniques, like the "Design for Manufacture and Assembly (DFMA)", the rapid prototyping method of "Laminated Object Modeling (LOM)", and good practices involved in LASER cutting of steel and welding, incorporating all that philosophy in the product design early on. The LOD starts with the optimization of the concept to minimize the part count (DFA) followed by the breaking down of every part in two dimensional shapes to be cut in metal plates of a single thickness (DFM taken to a extreme), making possible the construction of the concept from a single LASER cut metal sheet. Since every part shape concept was broken down into several small sub components, they must be welded together to make the desired part, and this is achieved by autogenous TIG welding. The precision and structural compliance is achieved through small male – female insert at every side of the sub component, making the assembly self aligning and holding the components in place prior to welding, without the need of jigs, vises or any kind of toll to ensure proper positioning. The economy achieved when building small welding robots for field welding was over 80% compared to a conventional prototyping with CNC milling. The technique allows the manufacture of all the components in one step, allowing that hundreds of different parts to be build in a couple of hours, from one metal sheet and only LASER cutting with one G Code. This provides a simplified logistics and an excellent turn over for the development of industrial equipment.*

Keywords: *Welding, Metal cutting, LASER, LOM, DFMA, LOD*

1. INTRODUCTION

The prototyping has always been a important step in the development process of a new product, especially difficult in time or budget constrained projects. The 3D CAD systems with the virtual prototype and the rapid prototyping techniques are good tools for the design process, helping to make important decisions, but the cost of these rapid prototyping machines still very high and these machines can work only with a very narrow selection of materials, most of the time only resins or thermoplastics, which may not be suitable for a working part. Nevertheless, these machines can build a complex component in a matter of hours, and designers can evaluate geometry features, especially in the consumer goods market, where the appearance data is more subjective and requires some hands on iteration.

The prototyping of complex machines is more difficult, although there is a lot of standardized parts and the shapes are not very complex, the numbers of parts necessary is often hundreds or thousands, and even a rapid prototyping technique that takes only a couple hours each part would take several weeks to build the whole machine, and for a high cost, specially with we are dealing with a medium or large machine. For these cases, the industry still build the whole machine in a conventional way, manually building each part. In 2004, a company came to the LRSS seeking partnership in the development of small welding robots. This was a time and budget constrained project that should be prototyped as quickly as possible, but the future industrialization wouldn't involve more than a dozen units. This means that not only the prototyping but also the manufacture of the parts should be efficient and extremely cost effective. The LRSS had been using through partners the LASER steel cutting technology through partners to manufacture small parts for building a diversity of projects, and used this technology to manufacture roughly 50% of the parts in the welding robot. One problem encountered with the use of the LASER cut parts was that some parts needed extensive cleaning, machining, drilling or assembly and welding with other parts, making everything very time consuming and giving mixed results. Since the company asked for the development of a second version, the manufacture process was further studied so the best practices could be incorporated as design rules (Bonsiepe, 1978; Boothroyd, 1996; Cross, 1996; Roozemburg, 1997). Product design techniques were also studied, like DFMA (design for manufacture and assembly) and LOM (Laminated Object Modeling), allowing a whole different approach to the development.

2. DESIGN FOR MANUFACTURE AND ASSEMBLY

The DFMA is a product design technique that allows the streamlining of the designing. It starts with the DFA (design for assembly) that aims in minimizing the part count through 3 simple rules, that states that 2 parts should be merged together except: They should be made of different materials, they move in respect to each other or they should be separate to allow maintenance or disassemble. Although simple, the results are extremely significant, sometimes reducing the part count up to 60%, like the example in Figure 1.

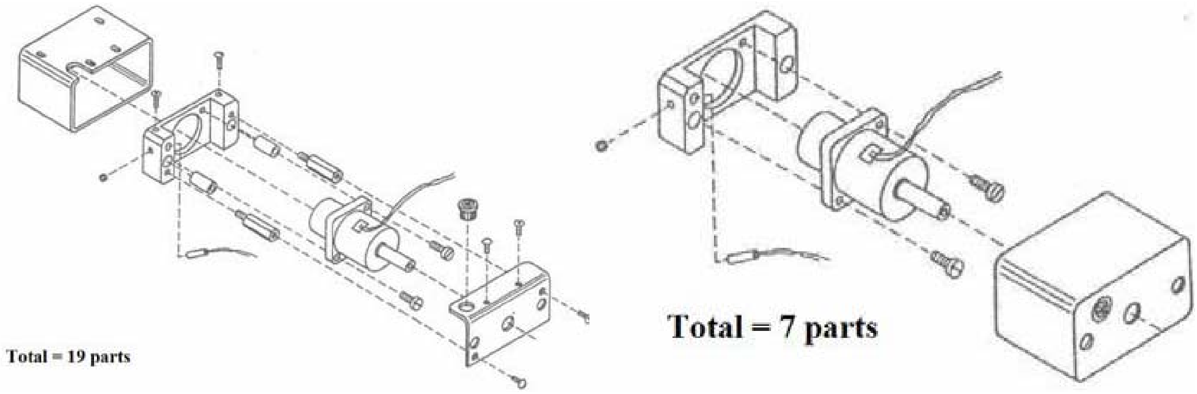

Figure 1. Motor Case before and after DFA: Minimizing part count without affecting quality or function (Cross, 1996).

After the DFA, the designer has to apply the DFM, or design to manufacture, that traditionally is used to minimize the diversity of materials and processes used to manufacture all the parts of the project, and a good example is the car industry, which tries to make a part made out of metal stamping whenever possible. This simplifies logistics and makes the material and process cheaper. The example in Figure 2 shows that the same part can be manufactured in many different ways; although without the same exact shape but able to perform the same function.

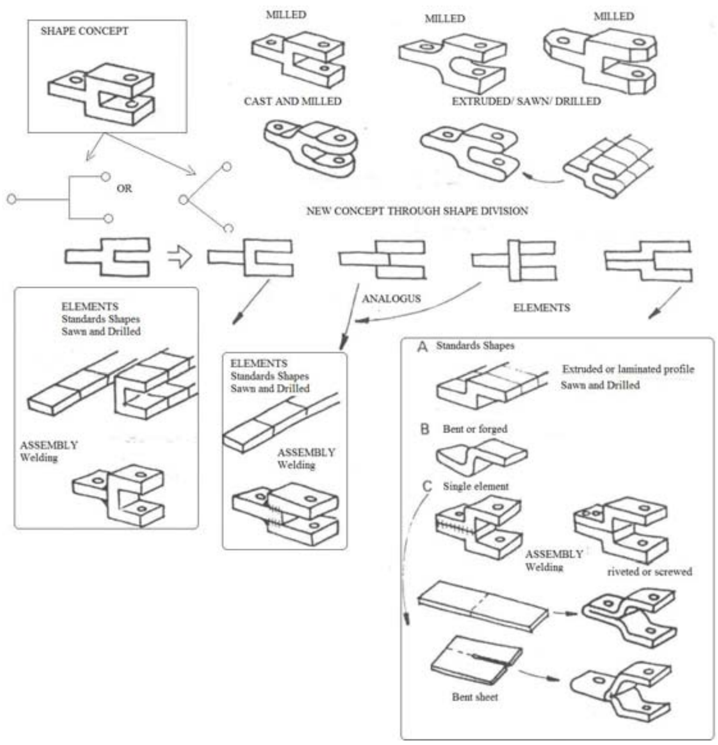

Figure 2. Design for Manufacture example: The shape concept can be manufactured by several different methods (Cross, 1996).

3. DESIGN FOR MANUFACTURE AND ASSEMBLY

The last technique that was used as inspiration was the Laminate Object Design (LOM), a trademark of Helisys, that is a rapid tooling or rapid prototyping technique that consists in taking a solid model and cutting it in slices, that will be eventually be LASER cut and joined together. The slices can be made of steel sheet or even paper, and although it can create complex shapes, it often leaves a staircase like surface, that has to be machined or filled with more material, as seen in Figure 3.

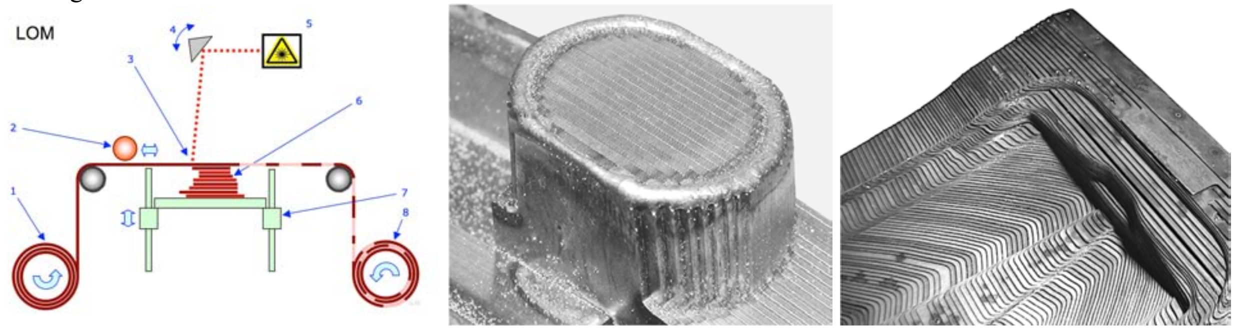

Figure 3. Cutting Process and LOM used for rapid tooling in die manufacturing.

4. NON- ORIENTED LAMINATE OBJECT MODELING

Although LOM is a well established prototyping technique, it does not provide a complete solution for building all the structural parts of a complex machine, and to achieve the desired results, a review of designing and building techniques was necessary. These 3 techniques together led the laboratory to develop the Non Oriented LOM where the concept shape of the machine is translated to steel plates, instead of building a design stacking sheets of material, as shown in Figure 4, an example of the construction of a hollow box with LOM and Non-Oriented LOM.

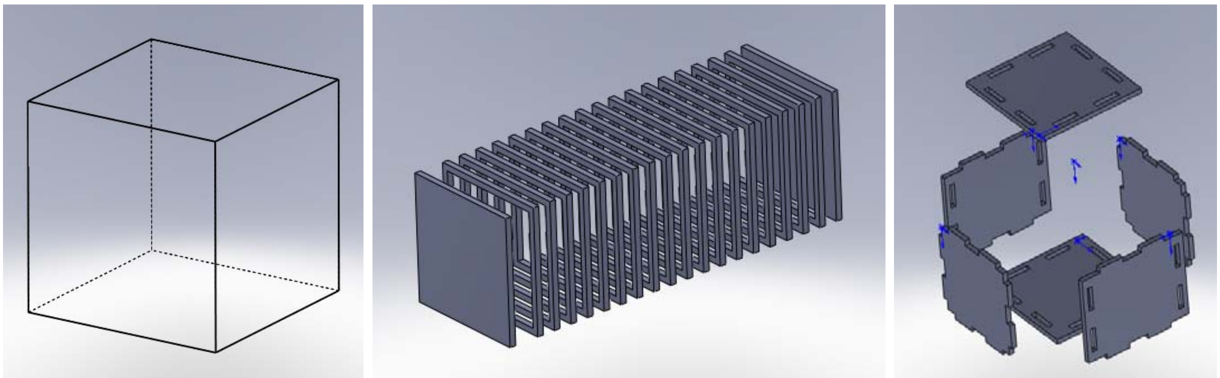

Figure 4. Concept shape of a hollow box and two different approaches for building.

5. METAL CUTTING AND WELDING

To build with this technique, first the part count have to be minimized by the DFA, and then every single part is subdivided in two dimensional shapes that can be cut from a single steel plate (DFM), and these sub components will be assembled through unique male-female slots which will position the sub components properly for the welding.

Although steel can be cut with Waterjet or Plasma, the best results will be achieved with LASER processing, all shown in figure 5, since it’s the process that can output the best quality for a good price for the steel gage most used (3, 5 and 6,35mm) with this technique at the Welding Lab. Every sub component is designed taking in account the LASER cutting design rules, in order to prevent any further processing of the part prior to assembly, with no need for cleaning, drilling, machining or other process.

Figure 5. Plasma, Waterjet and LASER cutting.

One of the major problems with LASER cutting is warping due to thermal stress, especially on long parts (over 100x the thickness). The warping can be more severe depending on the alignment of the part in respect of the plate and its lamination direction. So during the programming and nesting of the parts, similar parts should be cut in the same direction, to make even parts and minimize the problem. But this does not solve the problem, and for this is necessary a proper placement of the steel sheets, with every part with at least one plate in each axis, allowing the assembly to self correct any warping and welding thermal stress.

The welding of the structure cannot add additional stresses or warping, and it cannot modify the final shape of the structure, with a bead or the fusion of a corner. In order to achieve that, the structure should use mechanical inserts that holds the structure together while an autogenous TIG welding fuses the heads of those inserts in order to avoid disassembly. These inserts have to be placed away from borders in order to avoid fusion during the welding. This minimal impact approach not only is fast and economical, but provides satisfactory structural performance and does not alter the final shape of the part.

6. LAMINATE OBJECT DESIGN (LOD)

A design is based on three factors: Material, Process and Geometry. The material chosen is metal plates, and the process is LASER cutting. Now, to achieve optimal performance in the construction, the part have to be simplified and build according to a set of rules that are determined by the constraints of the process and the characteristics that are being pursued in the final part. There are two set of rules, one for part construction, which are mostly dependant on the process used, and other set of rules for assembly, which will compensate fabrication flaws, like warping, and provide a functional, structurally sound and easy to build part.

6.1. Part Design Rules for LOD

The choice of the metal cutting process and the material thickness (thk) will influence the design rules to be used. On Figure 6 it is shown different parameters that should be respected in order to achieve optimal results with this technique using LASER cutting and carbon steel sheet between 2 to 10mm, and it can be resumed as follows:

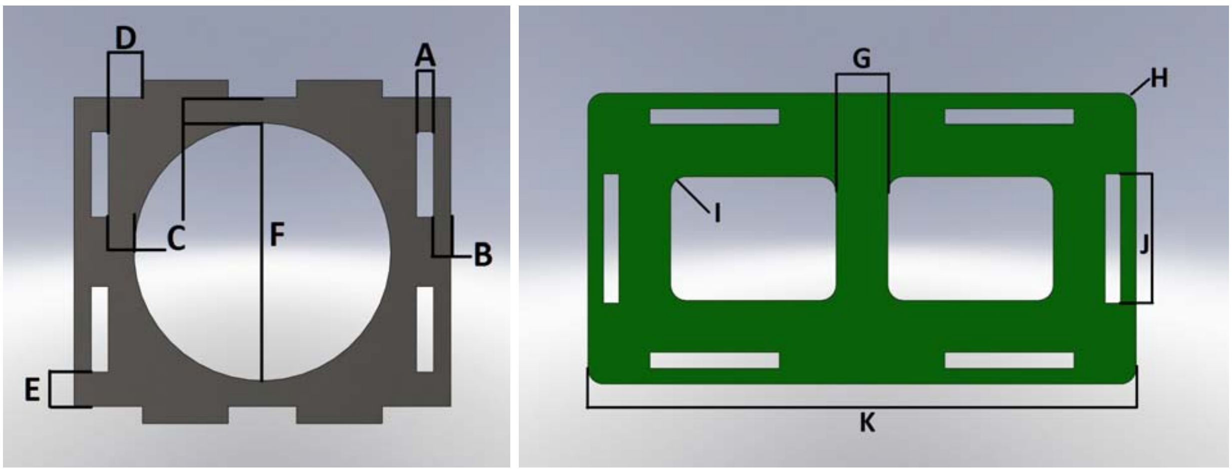

Figure 6. Design Rules for LOD with LASER cutting

- [A = thk] The inserts should be the exact thickness of the metal plate, in order to achieve a tight fit during assembly, making the part very strong even before the welding;
- [B > thk] Although external inserts can be used, only internal inserts provides a self-locking assembly. The external border width should be at least equal to the thickness;
- [C > 2thk] A hole inside the part may be needed for weight saving or to provide access to an internal component. It cannot be too thin because of the pressure applied during a tight fit assembly might deform the part;
- [D > thk] The insert on one side should not be in the same line of the insert on the order side, otherwise the assembly might end with two inserts in the same place (which would result in a fragile T shaped insert on the all female insert part)
- [E ± 2thk] The female insert have to be placed not too far away from the border otherwise will not provide a good locking effect, or too close to the border and it might create a fragility point;
- [F > thk] Holes, indentations or other small details have to be bigger than the plate thickness, although this limit depends only on the LASER machine used, and modern equipment can easily output features with half this size;
- [G > 2thk] Longer parts should divide the weight saving in order to minimize warping and to support the middle inserts during assembly (specially male inserts);
- [H = thk] The all female inserts part should have all the sides smoothed in order to avoid sharp edges. The radius should be equal to the thickness so it doesn't interfere with nearby female inserts or expose the corner of the mating part.
- [I > thk] The weight saving internal radius should be as big as possible in order to provide better structural resistance (but bigger radius provides smaller weight savings)
- [J > 2thk] The female insert should not be bigger than 60% of the side, and it can be divided in multiple inserts if needed.
- [K < 100thk] Long parts will always warp, and if cannot be avoided, use thinner plates, since a warped plate with more than 5mm can be very difficult to assemble.

6.2 Assembly Design Rules for LOD

The rules shown above provide a great guideline to build any part with LASER, that are basically a two dimensions part, but to create a three dimensions part that is structurally sound, easy to assemble and perform accordingly, it is necessary to design according to the following configurations.

The construction of mechanical components like gears, cams, pulleys and others with LASER is possible, as long they don't have very demanding performance targets. The superficial finish is a little rough and the mechanical properties may not be optimal, but considering that is one less part to machine or buy, it may be worthwhile. Others parts, like adapter plates, spacers, special washer and etc, can be easily built using the rules above, with a special attention to warping, so these components have to be designed as small as possible. On Figure 7, some of these one plate components can be seen, and the gear was successfully built and used in a 5mm steel plate (Z40, M1,5), although it had small teeth for a plate this thick.

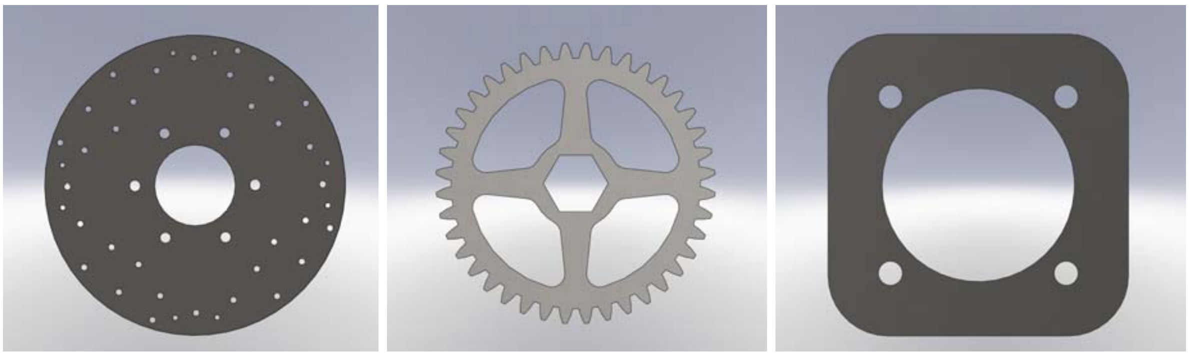

Figure 7. LOD example with 1 plates (Adapter, Gear and Spacer).

To make a three dimensional structural parts, at least four plates are needed, being at least one in each plane. Although it is possible to make parts with 2 or 3 plates, these parts will not be able to provide a self locking assembly and warp compensation, thus incapable of providing reliable results. In Figure 8 it is shown an example of a 4 plate structure, in which a pass through is needed in order to assemble the two parts together. This kind of feature should be avoided because it weakens the part, and configurations with 5 or more plates should be preferred.

Figure 8. LOD example with 4 plates (2 in X, 1 in Y, 1 in Z).

Configurations with five plates provide an open box architecture ideal to hold inside OEM parts while maintaining good structural properties and self locking and warp compensation. In the Figure 9 it is shown an example of a five plates configuration.

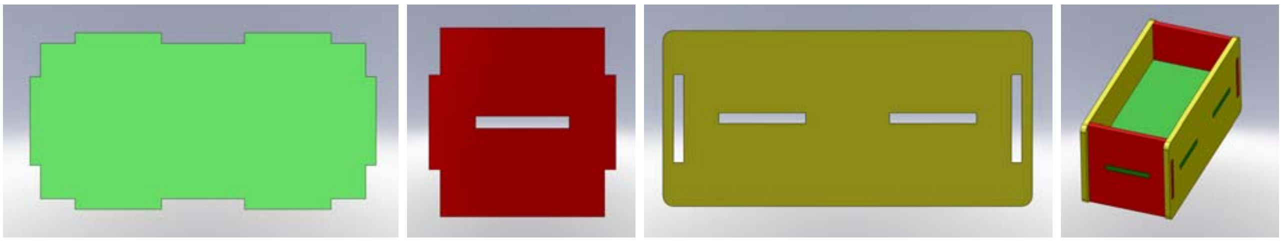

Figure 9. LOD example with 5 plates (1 in X, 2 in Y, 2 in Z).

The six plates configuration, shown in Figure 10, is the ideal for longer structures or lighter parts, since the closed assembly allows bigger weight savings. The problem with this configuration is accessibility to internal components or assembling OEM parts inside it, and in those cases a five plates configuration should be preferred.

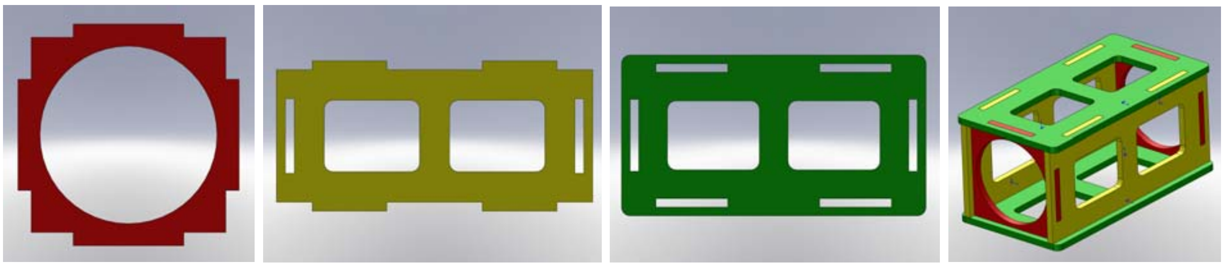

Figure 10. LOD example with 6 plates (2 in X, 2 in Y, 2 in Z).

For longer parts, like the one show in Figure 11, additional reinforcements should be added but ideally in only one axis so it does not impact negatively on the assembly. Reinforcements in more than one plane is possible but increases the assembly time significantly because it is much harder to negotiate several inserts in different direction at the same time

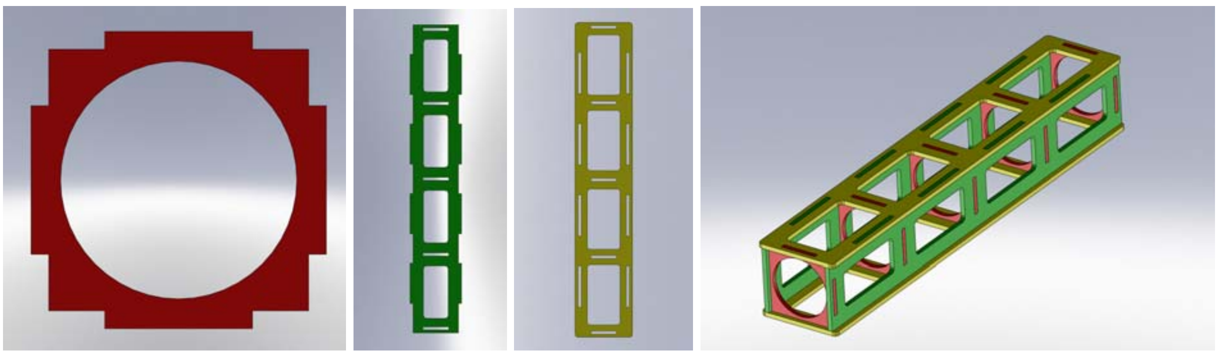

Figure 11. LOD example with n plates (n in X, 2 in Y, 2 in Z).

7. EXAMPLES

These examples are from projects developed in the Welding Lab since 2004 for partner companies. It is possible to see not only the evolution of the LOD but also the use of the DFMA and LOM techniques. In Figure 12, on the left, it is seen the first attempt to build a structure with LASER, and on the right the following structure that has been optimized to minimize part count and to be completely build from a single steel sheet (except the axis)

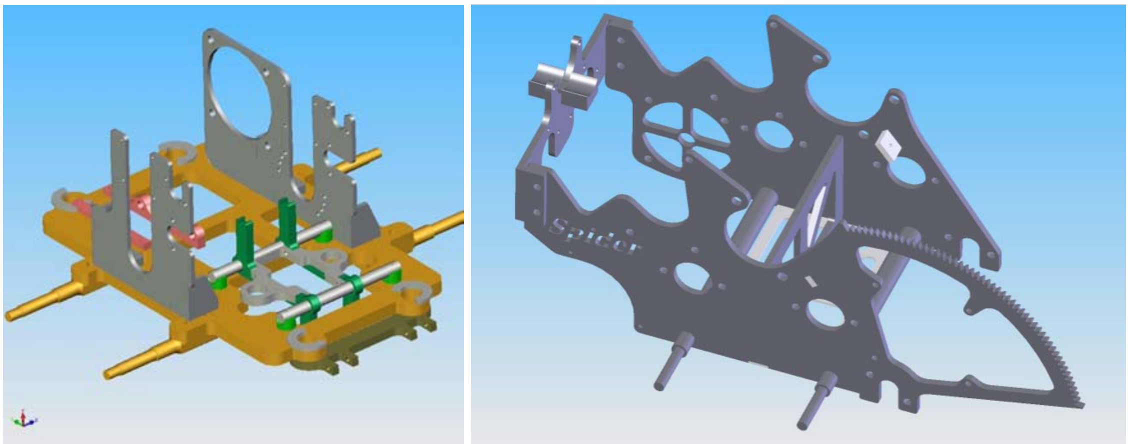

Figure 12. Comparison between the first and the second prototype structure: minimized part count and only one manufacture process and raw material

Other parts for this same welding robot could be built in a mix of the traditional LOM, but combining it with other parts to help the assemble to achieve self locking and better structural stability, as seen on Figure 13

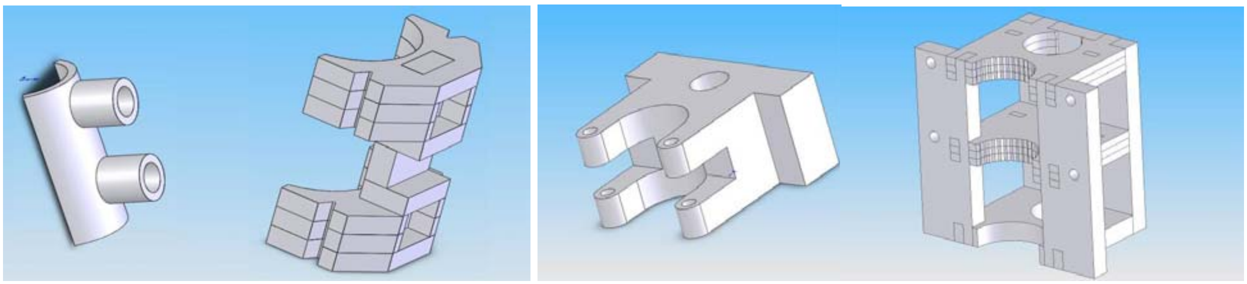

Figure 13. Two different tool holders and their LOD version

Another example of the LOD application is seen on Figure 14, the development of a pipeline ultrasound robot, where this technique allowed a complete development cycle from design to prototype in less than 30 days with very low costs.

Figure 14. Design, Manufacture and Assembly of the ultrasound Robot.

The Welding Laboratory also built a series of CNC machining with this technique, and in Figure 15 it is quite easy to see how the four structural parts on the system were developed and built according to the LOD design rules.

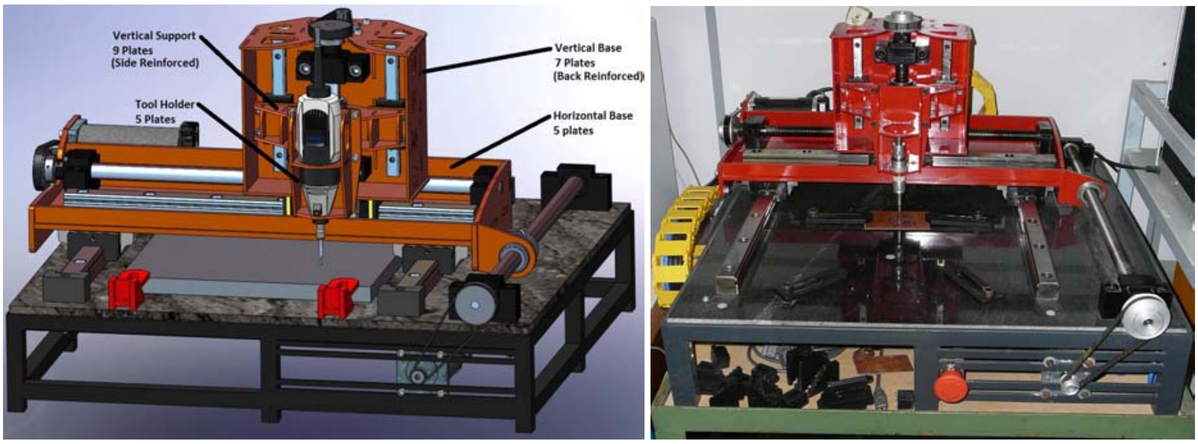

Figure 15. Design and result of a small CNC mill

8. RESULTS

These and many other structures were built on the past years, providing the Lab a powerful technique to rapidly build any machine structure needed. Although it cannot be directly compared with other kinds of manufacturing, since the design optimizes for LASER manufacturing, the costs can be compared with the most conventional process for manufacturing prototypes: the CNC machining. In table 1 is presented not only the necessary time to manufacture and assembly different projects, but also a cost comparison against the CNC milling of a similar structure.

Table 1. Estimated savings with the LOD technique on the examples shown.

	Manufacturing Cost of the Structure	Manufacturing Time (total/ LASER cutting)	Assembly Time (Fit and Welding)	Estimated Economy
Orbital System 1	U$1400,00	30 days / 120 minutes	50 hours	50%
Orbital System 2	U$390,00	7 days / 90 minutes	20 hours	71%
Ultrasound Robot	U$610,00	2 days / 110 minutes	8 hours	82%
Robotic Arm	U$500,00	6 days / 80 minutes	5 hours	Not Available
Welding Jig	U$780,00	10 days / 200 minutes	80 hours	72%
Mini CNC Mill 1	U$250,00	3 days / 30 minutes	4 hours	80%
Mini CNC Mill 2	U$200,00	3 days / 20 minutes	2 hours	90%

9. CONCLUSIONS

The LOD technique is a powerful development tool, based only on very simple and clear design rules that can be easily learned by any designer, leading to a faster development cycle, cheaper prototype and smaller time to market.

10. ACKNOWLEDGEMENTS

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