

# ECONOMIC VIABILITY OF LASER METAL DEPOSITION

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Abstract: Reports on large economic savings using Additive Manufacturing (AM) has been found in literature when exploiting the positive capabilities of AM. This paper evaluates the economic potential of, the AM method, laser metal deposition (LMD) in production of add-on features compared to conventional manufacturing methods. This is done by theoretical case studies, which explore factors critical to the cost of manufacturing a jet engine flange. LMD has the potential to be an economical viable alternative to conventional manufacturing methods when the manufactured component has a high buy-to-fly ratio, the component is small and complex, if the operator time can be kept to a minimum, and/or when the design freedom of LMD can be capitalized into lighter and more efficient components.

Keywords: Laser metal deposition, Additive manufacturing, Economic, Aerospace

## 1. INTRODUCTION

Additive Manufacturing (AM) is a collective name for layered manufacturing methods which has the capability of building direct 3D parts, preferably with the aid of a computer aided drawing software. Since AM builds component layer by layer it has the capability of building intricate 3D shapes that are hard to achieve with any other conventional manufacturing method e.g. hollow structures, lattice structures and other complex freeform geometries (Antony, 2012). During the last decade the interest of AM has markedly increased which is shown by the increased amount of research papers published during this period, Fig. 1.

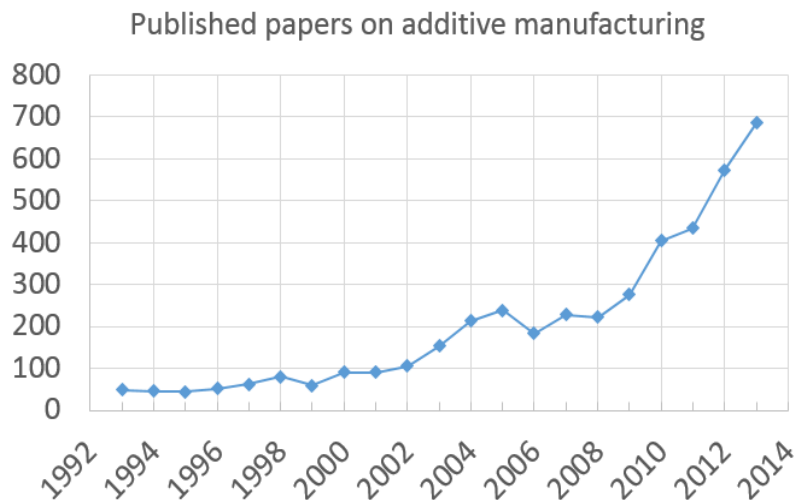


Fig. 1. Development of published paper during the period 1993-2013. Data from Scopus (Scopus, 2014).

AM has shown great potential in reducing material waste through near net shape production although this come at the cost of a low deposition rate. This results in a comparatively low production rate compared to most conventional production methods (Antonysamy, 2012). AM has gained most attention as a manufacturing method for add on features (Debicari, Moor et al., 2011), repair of damaged components (Graf, Gumenyuk et al., 2012), manufacturing of small and complex parts with small production series e.g. special tools (Karapatis, Griethuysen et al., 1998), prototypes (Antonysamy, 2012), medical implants and prosthetics (KTN, 2012) and aerospace components (Atzeni and Salmi, 2012). For the suitable part, AM has shown great feasibility through shorten lead time, less material waste, lowered energy consumption and increased design freedom leading to lighter, more efficient as well as more integrated products (Hedges and Calder, 2006; Antonysamy, 2012; Department of Energy, 2012; Liu, Huang et al., 2013; NASA, 2013).

A clear example where the implementation of AM has contributed to large cost savings is in the auto racing industry. The manufacturing time of a suspension mounting bracket for a Formula One (F1) car were cut by half with additional savings due to less material waste. Another example in the F1 industry is the manufacturing of a gearbox spider which had a material waste of 98% using conventional subtractive manufacturing methods. By manufacturing the gearbox spider using AM the material waste was considerably reduced and the manufacturing time was reduced from 10 to 2 hours (Hedges and Calder, 2006).

NASA recently reported successfully testing a new 3D printed rocket injector. Optimization was achieved through the increased design freedom which allowed a reduced number of parts for the injector to only two whereas an earlier tested injector had 115 parts! A decreased number of parts leads to a lower assembly cost which has the potential of large cost savings (NASA, 2013).

In the aerospace industry it has been reported that the cut in waste material can reach as high as ~90% for certain parts with an approximate buy-to-fly ratio (ratio between the weight of the material used to manufacture the part and the actual weight of the finished part) of 1.5–5:1. Meanwhile the conventional production methods used today, in worst case, have a buy-to-fly ratio of approximately 10-20:1 (Antonysamy, 2012; Department of Energy, 2012). The total energy needed to produce a component can also be reduced due to the capability of reducing the total amount of production steps, less material usage, produce lighter products, and allowance for re-manufacturing and repair of end-of-life products. This amounts to a total of 75-98% in potential saving in energy consumption (Department of Energy, 2012).

Another example where the flexibility of AM is of great use in the aerospace industry is by flexible manufacturing. Each airplane is composed of millions of parts and all critical parts must function properly in order for the airplane to be allowed to fly. If a critical component fails, the plane becomes land bound (in the best scenario) and starts costing money for the company. To be able to keep the land bound time to a minimum an inventory of all necessary parts could be kept although this would mean keeping enormous storage facilities and large costs just for the eventuality of a single part failing. Furthermore, each different plane has its own list of parts which need to be kept in case of a failure. Another alternative is to manufacture the part on demand which, with conventional manufacturing methods, would mean to manufacture the tools and or die for the specific part that fails leading to large costs for the part. Another alternative is to facilitate an AM machine with an inventory of feedstock material, an operator and a CAD system which can store millions of parts digitally and produce them on demand within days. This could potentially lead to large cost savings due to less inventory cost, shorter lead time and less production cost (Liu, Huang et al., 2013).

In this paper, theoretical case studies of laser metal deposition with wire (LMD-w) and laser metal deposition with powder (LMD-p), respectively, will be performed to compare with conventional manufacturing methods. The aim is to explore the feasibility of adding features to semi-finished parts using laser metal deposition (LMD) and compare it to a conventional manufacturing alternative. Emphasis is put on exploring the influence of material cost, building rate, and operator time on the cost of an LMD manufactured part.

## 2. LMD

LMD is an AM method which utilizes a high power laser in order to create a melt pool on a metal surface into which the feedstock material is supplied. The laser and feedstock delivery system are attached to a robot or gantry system which is able to follow intricate deposition paths with high precision. Components are built by depositing adjacent beads layer by layer until the geometry is completed. LMD is here divided into two groups where one is using powder as feedstock (LMD-p) material and the other is using wire (LMD-w).

LMD-p utilizes a powder nozzle in order to supply the powder into the melt pool, which is created by the laser. The powder is delivered to the nozzle by a powder feeding system where the powder is carried by an inert gas, usually Argon. Additionally, a shielding gas is applied in order to protect the melt pool from oxidation and other environmental disturbances. In Fig. 2 (a.) below an illustration of the LMD-p process is shown.

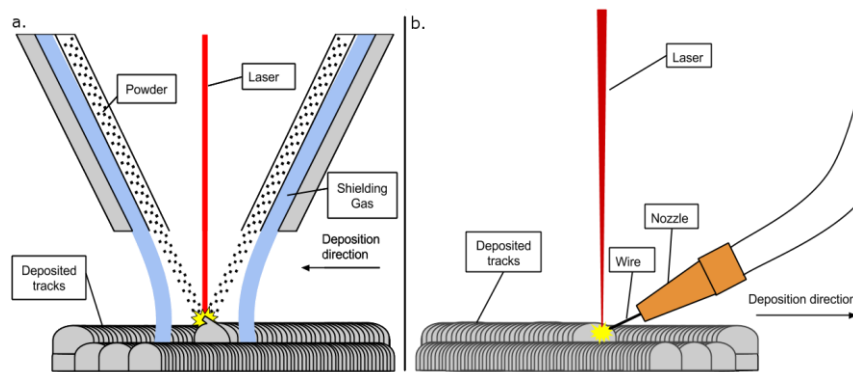


Fig. 2. (a.) In LMD-p, the powder is supplied into the melt pool created by the laser in order to deposit material onto a metal surface. (b.) In LMD-w, the laser creates a melt pool into which the wire is fed.

LMD-p has a low heat input which allows for deposition on thin sheets with minimal deformation. Furthermore, LMD-p's low heat input allows for repair of crack sensitive parts, e.g. turbine blades, that is hard to repair with other conventional repair methods (Bi and Gasser, 2011). In repair of these blades, the structural orientation of the grains can be partly controlled in order to maintain the epitaxial structure in the repair metal (Gäumann, Bezençon et al., 2001). Contrary to LMD-p which blows powder into the melt pool, LMD-w utilizes a wire feeding system similar to that of a welding system. LMD-p has a low deposition rate compared to LMD-w which makes LMD-w a more feasible alternative for manufacturing of larger components although LMD-w has an inherent weakness in that it gives a directional dependency which constricts the deposition path (Syed and Li, 2005). The LMD-w deposition process is illustrated in Fig. 2 (b.).

### 3. CASE STUDY

In this case study LMD-p and LMD-w will be compared to conventional manufacturing methods. The case study is strictly theoretical and stipulated dimensions will be used in the examples. A flange that is used to connect jet engine modules will be used as an example (Sandberg, 2005).

In the case study the following assumptions will be made

- The needed equipment and machines is already installed and ready to use and the cost of milling machines, robots, powder feeder, laser source, and other machines will not be accounted for in the calculation of part cost. However, tool wear will be included in the cost analysis as will all consumable material.
- It will be assumed that it is a new component design that will be manufactured where no tools, moulds or dies exist at present.
- For add on features it will be assumed that the deformation is in an acceptable range for both LMD methods.
- In the evaluation of the cost of material it is assumed that all scrap material is recovered from the milling and drilling operation.
- Any re-design of geometries in order to capitalize the potential of LMD will be assumed to be in compliance with specifications for the part and will serve as proof of concept.
- The drilling operation is assumed to be identical between the LMD and the conventional manufacturing method. The cost for drilling the holes will therefore be excluded in the cost evaluation of the flange.
- The deposition of the flange is assumed to be built directly on the module which means that no assembly welding operation is needed for LMD.
- Ring roll forging gives residual stresses in the finished rings which are released during the turning operation of the flange. Solution heat treatments may therefore be necessary in order to minimize deformation. It will be assumed that the conventional method may need up to two solution heat treatments during the turning operation followed by one solution heat treatment plus aging heat treatment after the assembly. LMD will be assumed to only need one solution heat treatment and one aging heat treatment due to the low heat input of the operation.
- The cost of processing the component in the workshop will be summed up in an hourly cost. This cost will include tool wear, operator cost, heat treatment cost, overhead cost and all other cost which is expected when processing the part.

### 3.1. Cost evaluation flange

A jet engine is constructed of different modules. Some of the modules which aren't critically loaded are welded together while other that are load bearing needs to be reinforced. This is typically done with flanges that are welded onto the module. These flanges are designed to carry load, seal the engine from leakage and to allow for disassembly of the engine (Sandberg, 2005), see Fig. 3.

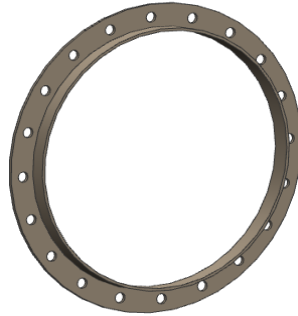


Fig. 3. Jet engine flange.

The conventional way to manufacture this sealing flange is by ring rolling and machining. For the conventional method the cost will be evaluated in three different areas which are *cost of a forged ring*, *scrap total earnings*, and *workshop total cost*. For LMD there is less workshop time since the deposition of the flange is assumed to be directly on the module there is no need for weld assembly. LMD is evaluated in three areas, which are *material cost*, *LMD process cost* and *workshop total cost*. The cost of a single produced part will be evaluated using the criterion in Table 1 and Table 2 for the conventional manufacturing method and LMD, respectively.

## 4. RESULT AND DISCUSSION

For a simple duct flange the buy-to-fly ratio, which is the ratio of the weight of the total amount of material used to build the component to the weight of the finished component, is approximately 6:1 (Allen, 2006). In Table 1 below three different scenarios are specified for the conventional method.

The finished flange is assumed to range between 1 kg to 30 kg which for the conventional method means a forged ring weight in the range of 6 kg to 180 kg, with the assumed buy-to-fly ratio. The cost of forged Alloy 718 is assumed to be approximately 400SEK/kg. The subtracted material from the machining processes is re-sold to the current scrap price of Alloy 718 which according to, (Metalprices.com, 2014) is approximately 80 SEK/kg. The three scenarios are as following:

- The first scenario assumes a low workshop time where one solution heat treatment is sufficient with a subsequent aging treatment. The turning operation is assumed to have a material removal rate (MMR) of 25000 mm<sup>3</sup>/h leading to a turning time in the range of approximately 0.4 h to 13 h. The welding time is assumed to be 1 h.
- The second scenario assumes a medium workshop time where two solution heat treatments are needed with a subsequent aging heat treatment. The MMR in the turning operation is 20000 mm<sup>3</sup>/h, which results in a turning time in the range of approximately 0.5 h to 16 h. The welding time is assumed to be 2 h.
- The third scenario is assumed to need three solution heat treatments with a subsequent aging heat treatment. The MMR is 15000 mm<sup>3</sup>/h which results in a turning time in the range of approximately 0.7 h to 21 h. The welding time is assumed to be 3 h.

Additionally, three scenarios for the LMD method are evaluated, see Table 2. The hourly cost of the operator is 1000 SEK/h and the feedstock material price is 1200 SEK/kg. 4 h solution treatment and 20 h aging heat treatment is assumed sufficient for the LMD method. The material waste with the LMD method is assumed to be 10% with a building rate of 0,24kg/h, resulting in a building time in the range of approximately 4.6 h - 139.9 h. The turning time is estimated to be 2 h for the components produced with the LMD method. The three scenarios for the LMD method are:

- First scenario assumes that an operator is present 10% of the manufacturing time of the flange.
- Second scenario assumes that an operator is present 30% of the time.

- Third scenario assumes that an operator is present 50% of the time.

A graph comparing the different scenarios is shown in Fig. 4. The equations used to plot the graph is found in Table 1 and Table 2.

Table 1. Three cost scenarios of manufacturing a flange with conventional method.

<i>Conventional Method</i>	Unit	Notation	Low work time	Mid work time	High work time
Rolled ring weight	kg	<i>RRW</i>	6-180	6-180	6-180
Price of forged material	SEK/kg	<i>RCW</i>	400	400	400
<i>Cost of a forged ring</i>	SEK	$FRC = RRW * RCW$	2400-72000	2400-72000	2400-72000
Weight scrap metal	kg	<i>WS</i>	5-150	5-150	5-150
Scrap re-sell price	SEK/kg	<i>SRP</i>	80	80	80
<i>Scrap total earnings</i>	SEK	$STE = WS * SRP$	400-12000	400-12000	400-12000
Turning time	h	<i>TT</i>	~0,4-13	~0.5-16	~0.7-21
Heat treatment time	h	<i>HTT</i>	4+20 = 24	2*4+20=28	3*4+20=32
Welding time	h	<i>WT</i>	1	2	3
Workshop cost per hour	SEK/h	<i>WC</i>	1200	1200	1200
<i>Workshop total cost</i>	SEK	$WTC = (TT + HTT + WT) * WC$	30480-45600	34200-55200	42840-67200
<i>Total cost per part</i>	SEK	$CTC = FRC + WTC - STE$	32480-105600	36200-115200	44840-127200

Table 2. Three cost scenarios of manufacturing a flange with LMD method.

<i>LMD Method</i>	Unit	Notation	LMD 10% OP-TIME	LMD 30% OP-TIME	LMD 50% OP-TIME
Price of material	SEK/kg	<i>PM</i>	1200	1200	1200
Weight of finished part	kg	<i>WP</i>	1-30	1-30	1-30
Material efficiency	%	<i>MEF</i>	0,9	0,9	0,9
<i>Material cost</i>	SEK	$MTC = PM * WP / MEF$	1333-40000	1333-40000	1333-40000
Feedstock feeding rate	kg/h	<i>PFR</i>	0,24	0,24	0,24
Processing time	h	$DT = WP / (PFR * MEF)$	~4,6-138,9	~4,6-138,9	~4,6-138,9
Hourly cost of operator	SEK/h	<i>DC</i>	1000	1000	1000
LMD operator work load	%	<i>DWL</i>	10%	30%	50%
<i>Operator cost LMD</i>	SEK	$DOT = DC * DWL * DT$	460-13890	1380-41670	2300-69450
<i>LMD cost</i>	SEK	$MDC = MTC + DOT$	2	2	2
Turning time	h	<i>TT</i>	24	24	24
Heat treatment time	h	<i>HTT</i>	26	26	26
Workshop cost per hour	SEK/h	<i>WC</i>	1200	1200	1200
<i>Workshop total cost</i>	SEK	$WTC = (TT + HTT) * WC$	31200	31200	31200
<i>Total cost per part</i>	SEK	$DTC = MTC + MDC + WTC$	32993-85090	33913-112870	34833-140650

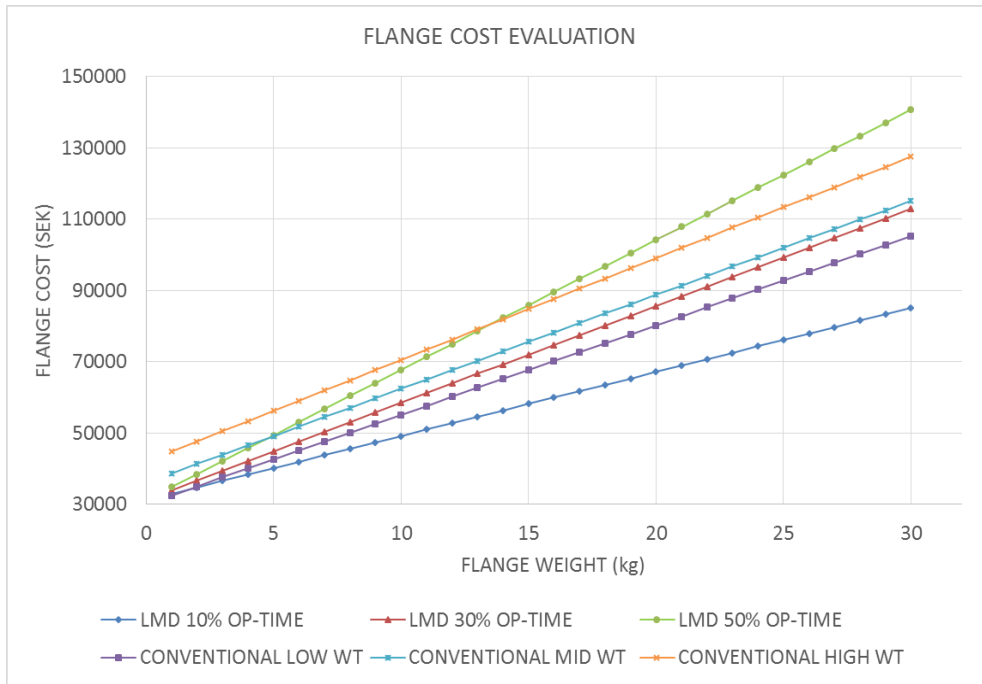


Fig. 4. A graph comparing three laser metal deposition scenarios with three conventional manufacturing scenarios.

In Figure 4 it is clearly shown that it is detrimental for the feasibility of LMD to be as automated as possible since the influence of the operator cost is substantial. LMD with 10% operator time of total manufacturing time is here the most feasible method followed by the conventional method with the lowest workshop time. For smaller parts 1 kg to 5 kg all of the LMD scenarios is fairly feasible but with the increased weight the manufacturing time quickly increases resulting in substantial cost increase, especially for the LMD methods utilizing 30% and 50% operator time.

Effect of deposition rate. LMD-w has a higher deposition rate than LMD-p. However, as discussed earlier, LMD-w has a higher heat input and not as high directional freedom. This makes it a poor choice if the component is to be deposited on a sensitive substrate or if the complexity of the component creates a too intricate path for the method to follow. Additionally, the cost for wire compared to powder is essentially the same, although the powder may be marginally more expensive than the wire. In Fig. 5 the effect of deposition rate on the cost of the flange is shown. The same scenarios as described in Table 2 are used in this evaluation with the exception that the weight of the flange is assumed to be 15 kg while the deposition rate is in the range of 1 g/min to 30 g/min.

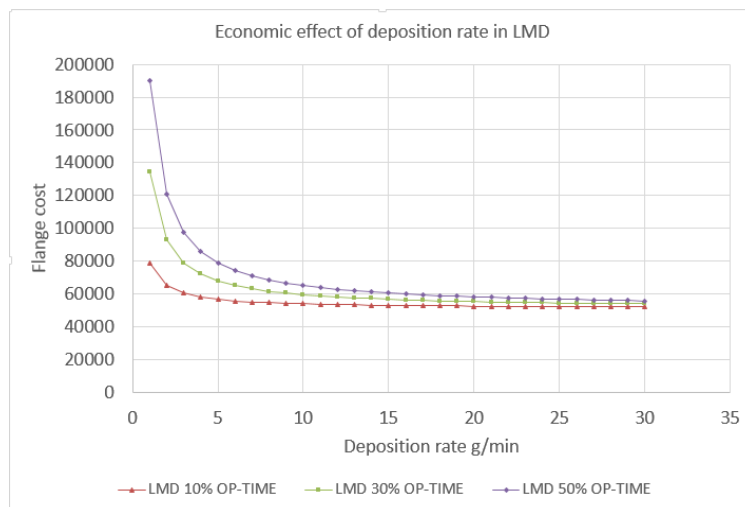


Fig. 5. Effect of deposition rate on flange cost.

At low deposition rates, 1 g/min to 10 g/min, the influence of the deposition rate is significant, especially if the operator time is high. At higher deposition rates, 10 g/min to 30 g/min the effect is much less significant which can be attributed to that the building time is reduced by 250 h when the deposition rate is increased from 1 g/min to 10 g/min while only being reduced 18.5 h between 10 g/min to 30 g/min. From this it can be concluded that if LMD-w is a viable option it is more economical than LMD-p. However, this depends on the level of automation in the different methods. For instance if LMD-w is to be used but an operator needs to be present 50% of the manufacturing time while an operator only need to be present 10% for the LMD-p method, it is likely that the LMD-p method is more economical than the LMD-w method.

Material cost sensitivity of conventional vs LMD methods. The material cost is an important factor to the final cost of the component. If the material cost increases the total cost of the flange quickly increases. To evaluate how sensitive the different methods are to cost fluctuations it is assumed that the material cost of the forged ring is increased from 300 SEK/kg to 600SEK/kg and the re-sell price for the scrap is increased from 80SEK/kg to 160SEK/kg. Furthermore, the material cost of the LMD feedstock is increased from 800SEK/kg to 1600SEK/kg. All other factors are kept constant. The result is shown in Fig. 6.

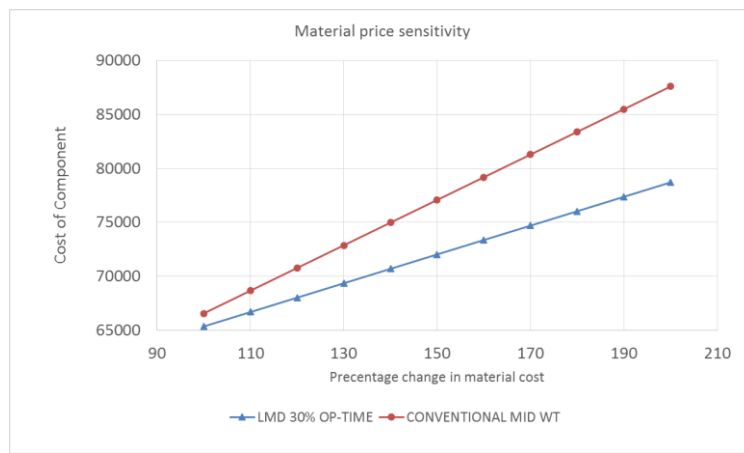


Fig. 6. Material cost sensitivity of LMD compared to conventional manufacturing method.

The conventional method is proven to be more sensitive to material price fluctuation and have a steeper curve than the LMD method. This can be attributed to the large amount of material needed in the conventional method to be able to produce the final component.

Capitalization of the LMD method. Redesigning of the flange to capitalize the potential of LMD can lead to cost reductions through less material usage and lowered manufacturing time while at the same time producing lighter and more tailored products. An example of re-design of the flange to capitalize the manufacturing potentials of LMD is shown in Fig. 7. By depositing less material between the mounting holes a reduction in weight by approximately 30% is possible. This in turn results in a reduction of material cost and building time by approximately 30%, respectively. A similar redesign done with conventional manufacturing methods would mean more machining time, which in turn would result in a more expensive component. Again, this redesign only serves as proof of concept and no claim to the suitability of this redesign is made by the authors of this paper.



Fig. 7. Example of the re-design capabilities of LMD with reduced time, weight and material.

## 5. CONCLUSION

LMD has the potential to be an economical viable manufacturing method in the right conditions. The most significant factors contributing to the feasibility of the LMD methods are:

- The buy-to-fly ratio of the component. One of LMD's largest weaknesses is the high material price for high quality powder which results in that much of the gain of producing near net shape products is lost due to the high material cost of the powder. A component with a high buy-to-fly ratio is therefore potentially more suitable for the LMD method.
- The low deposition rate, which results in long manufacturing times for larger components. This makes LMD most suitable for smaller components.
- The operator time needed. A large fraction of the component cost will be contributed to the cost of an operator supervising the manufacturing of the component. The more automated the process is the less influence the manufacturing time will be on the final cost of the component.

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