Aluminium versus steel in low-volume production of structural applications

Comparing aluminium and steel in structural applications for low-volume production based on mechanical properties and economic aspects

Andreas Thoresen
Department of Design
Norwegian University of Science and Technology

ABSTRACT

Based on a case where a mechanical workshop plans to establish a low-volume production of ATV trailers, the pros and cons of using aluminium in the load-bearing parts of the structure are explored and compared to the traditional use of steel. The goal of the paper is to provide a recommendation for selection of materials and production methods for the case, considering mechanical properties of the materials and the limitations of low-volume production, which normally requires cost-effective materials and simple manufacturing techniques and processes. The paper shows that with use of aluminium in favor of steel in structural applications, significant weight savings can be made. This change of material requires increased dimensions of standard components, or use of custom developed components. Aluminium also shows other advantages over steel in both production and use, but essentially the selection of aluminium as a material requires a compromise between weight and price, as aluminium appears to be more expensive. The recommendation to the mechanical workshop is to consider this compromise before a final material and production method is selected.

KEYWORDS: Low-volume production, aluminium versus steel, structural applications, material properties

1. INTRODUCTION

In 2016 the author of this article carried out a design and development project with a local company. The client, a mechanical workshop in Lierne, Nord-Trøndelag, plans to start low-volume production of combination trailers for snowmobiles and ATVs in 2018. The project included definition of product requirements and conceptual design based on the clients demands and analysis of existing products. The results indicate that to be competitive on the market there are rigid requirements related to the products strength-to-weight ratio and the production costs. The focus of this initial project was on the load bearing structure (the frame). It was found that more knowledge on alternative materials and production methods was needed which initiated this study.

Products built on steel structures dominate the market for snowmobile and ATV trailers. The use of aluminium is not common despite that concept studies has shown that substituting existing steel structures with aluminium structures can provide up to 50% weight reduction. [1] With typically around 40% of the fuel consumption being directly related to weight (inertial and rolling losses) and a further 40% (power-train losses) being secondarily related, it follows that substantial fuel efficiency improvements can be achieved if the vehicle weight can be significantly reduced. [2]

The load bearing structure must be compatible with a static and dynamic load of minimum 600 kg. Low-volume production involves production of a relatively low number of units annually, and sets in this case primarily requirements for cost-effective materials as well as cost-effective and simple manufacturing techniques and processes.

The paper seeks to find the most optimal construction material for the bearing structure of the trailer based on mechanical properties and the economic aspect. The first part looks at low-volume production and what this implies. The second part compares aluminium and steel based on the materials mechanical properties, production and economics. Finally, the findings are discussed and a recommendation for material selection based on the case is given.

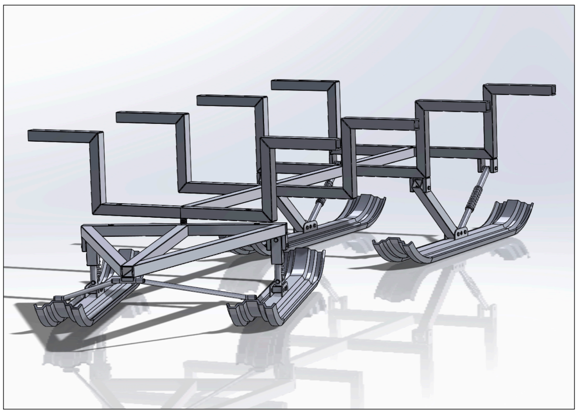


Figure 1: Example frame in steel, snowmobile setup

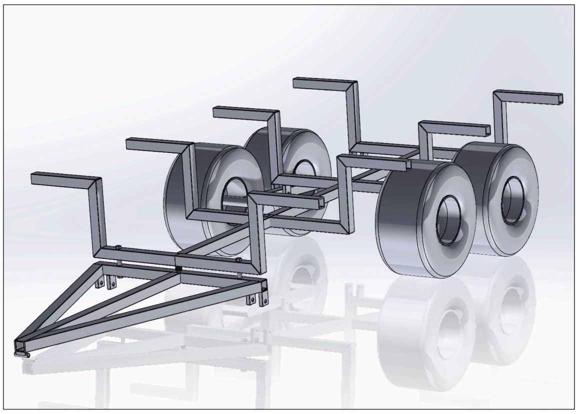


Figure 2: Example frame in steel, ATV setup

1.1 Methods

This paper reviews literature from various research domains, mainly textbooks and material handbooks. In areas where there is no available literature, consultations with Sapa, a Norwegian-owned aluminium company that develops and manufactures aluminium profiles, NTNU Aluminium Product Innovation Center (Napic) and Norsk Stål has been used.

2. LOW-VOLUME PRODUCTION

Jina et al. (1997) define low-volume production as a production rate of 20-500 units per year. [3] Some consider it as production where the nonrecurring engineering costs become a large portion of the overall product cost. Others claim that low-volume production is characterized not by a production number, but rather by certain overarching, general characteristics. Low-volume production is typically characterized by few technical prototypes, manufacturing of complex or customized products, make-to-order production, uncertain and limited numbers of pre-series productions and the infeasibility of conventional production ramp-up. Other identification factors include modifying existing products, the use of existing products instead of developing entirely new products, and the use of existing production systems with slight modifications for new products. [4][5][6] According to Vallhagen et al. (2013), it is more common in low-volume production to focus on product functionality than its manufacturability compared to high-volume production industries. [7]

2.1 Challenges and limitations

According to Schneider, E. (2012), low-volume production always comes down to a balancing act among desired features, cost, and speed. As the costs of tooling and setup in low-volume production become more significant components of the project budget, cost effective methods require designers to make compromises on aesthetics and material properties. In low-volume production, commercial off-the-shelf parts (COTS), generic parts, are much cheaper than custom parts, but this means the design has to accommodate pre-made parts, something that set limitations to the aesthetics and creativity. When ordering off-the-shelf parts, it is also appropriate to use parts that come in standard sizes or have multiple sources, so they can be substituted without requiring a substantial product redesign. Managing client expectations can be difficult in low-volume production. They might not be aware of the challenges of low-volume production, and might want a device with features similar to high-end consumer products. Also vendors can provide challenges in low-volume manufacturing. In a world of mass production, more products equal more money. Vendors tend to be less responsive to small-quantity orders typical of low-volume manufacturing unless they are specifically set up for that scale of business. The designer himself must also be fully aware of the limits in low-volume production. Understanding the fabrication volume and selecting an appropriate manufacturing process early can optimize the design for the best form and function for the selected process. This is usually a far better choice than trying to push the limits of a manufacturing technology to achieve something that is not appropriate for the technology. By understanding the limitations of each process, an engineer can tailor the design to make great parts with low-volume techniques, for instance, by adding compliance features to reduce the need for tight tolerances, reinforcing the walls with ribs, or combining processes. [8]

For the client, low-volume production will as previously described primarily mean the importance of cost-effective and simple product- and production solutions considering the choice of material and features, but with an executive focus on the strength-to-weight ratio.

3. MATERIAL PROPERTIES

To form a basis for comparison of the metals, this review is mainly based on aluminium alloy 6063 and steel alloy S355. In areas where it is considered difficult to obtain properties of the specific alloy, approximations are used by properties of aluminium and steel in general. The 6063 alloy is in consultation with Harald Vestøl, Napic, and Svein Erik Brenna, Sapa, deemed appropriate for this purpose based on the mechanical properties and the financial aspect. S355 is a weldable structural steel and is, based on correspondence with two of the largest trailer providers in Norway, Gaupen-Henger A/S and Tysse Mekaniske Verksted, and Scandinavia's largest provider of trailers, Brenderup Group, exclusively the most common steel alloy used in comparable products.

3.1 Physical and mechanical properties

A materials strength is defined as the force per unit area at failure. [11] This is expressed through Young's modulus, which describes a materials resistance to elastic deformation as a function of the force *f*. The ultimate tensile strength (UTS) describes the highest amount of tension a material can handle before violation occurs. This failure can express a materials strength, but is not interesting because when dimensioning structures, it is always the structures original shape and cross section which forms the basis for the calculations. To protect this, the material must be within the elastic zone, below the yield point, which requires that the material returns to the original shape when the tension creases. [12][13] In this case "strength" refers to the 0.2% offset yield strength (YS) for metals. [14]

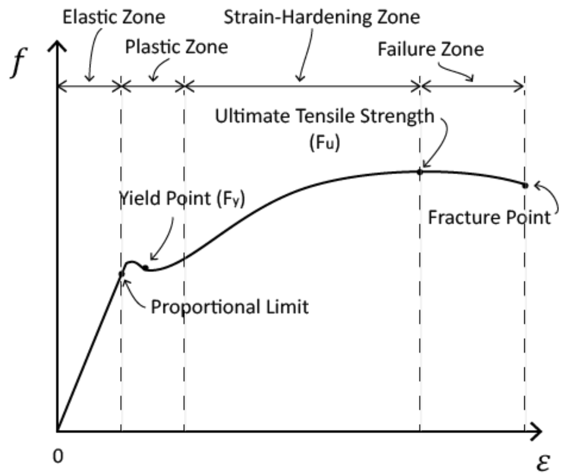


Figure 3: Young's modulus

The strength-to-weight ratio, also known as the specific strength, is defined as the materials strength divided by its density. [11] The table below shows the strength-to-weight ratio of the 6063-T6 aluminium alloy and the S355J2 structural steel alloy based on the yield strength.

	6063-T6	S355J2
Density (g/cm^3)	2,7	7,8
Strength (MPa)	215	315
Strength-to-weight ratio	≈ 79,6	≈ 40,4

Table 1: Strength-to-weight ratio

To illustrate the deflection difference between a steel and an aluminium structure, a simple strength simulation in the 3D-CAD design software SolidWorks is set up. A 1 meter long I-section (100 x 100 x 4 mm) is used as test beam. The test beam is stored in the left-hand end and has a downward-pointing force of 1000 N in the right-hand end. For the calculation aluminium alloy 6063-T6 and structural steel alloy S355J2 is used. Values are derived from SolidWorks' material database. Tension in the section is shown in the figure below. All the values are far below the YS for both materials.

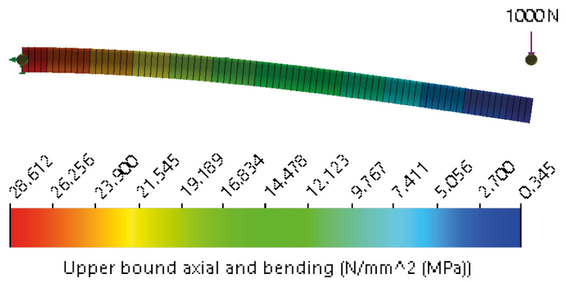


Figure 4: Tensions in the I-section

Tensions of this magnitude give the test beam a deflection. *Figure 5* and *6* show the deflection for the aluminium and structural steel alloy.

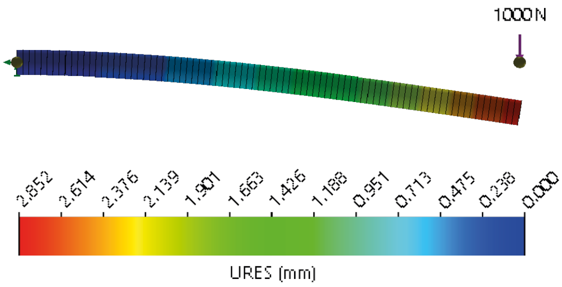


Figure 5: Deflection in 6063-T6

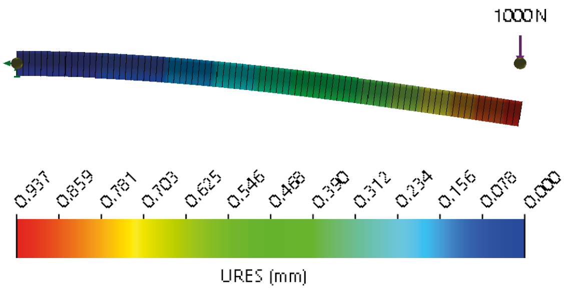


Figure 6: Deflection in S355J2

3.2 Weight reduction by design

In general, the modulus of elasticity *E* of aluminium is about one third of steel. [12] The 6063-T6 has an $E \approx 69000$ MPa, and the S355J2 has an $E \approx 210000$ MPa, – roughly three times higher. According to Sapa (2015) possible weight saving can be made by replacing a steel beam with an aluminium beam. Since aluminiums YS often is higher than one third of steel, the strength often is not fully exploited, and deflection calculations is adequate. A 1 meter long I-section is used as an example of possible weight saving if deflection and strength is the critical design factor.

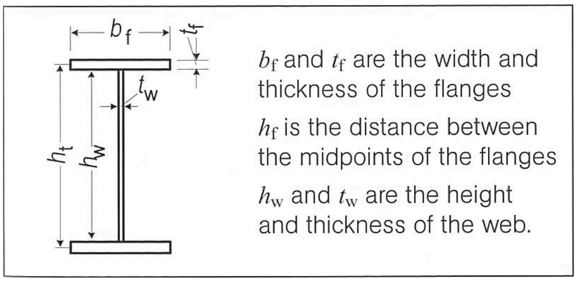
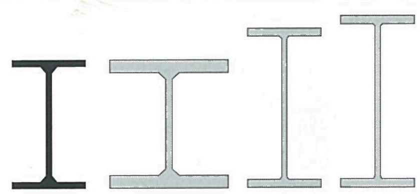


Figure 7: Terms for dimensions of I-section

If the deflection must remain the same, i.e. the stiffness *EI* must be the same. Because the modulus of elasticity of the aluminium alloy is one third of the steel alloy, the moment of inertia *I* for the aluminium beam must be three times as large. If the height of the beam is not increased, the flange area must be increased by a factor of three, and because the density of aluminium roughly is a third of steel this means that the aluminium beam will be roughly the same weight as the steel beam. If it is acceptable to increase the height of the beam, a considerable weight saving can be made by choosing aluminium. [9]



	IPE 240 Steel	Aluminium		
EI	8,17	8,17	8,17	8,17
h	240	240	300	330
b_f	120	240	200	200
t_f	9,8	18,3	12,9	10
t_w	6,2	12,0	6,0	6,0
Weight	30,7	30,3	18,4	15,8
Saving		**0%**	**40%**	**49%**

Figure 8: Weight comparison for same deflection and strength

3.3 Production

For steel structures, according to Norsk Stål the use of COTS is highly appropriate. Hollow sections of steel are mainly produced as welded sheets, or as seamless hollow profiles using the Mannesmann-method. [10] An interesting question is whether it will be profitable to use COTS in an aluminium structure. Extrusion is the process of pushing a billet through a die to reduce its cross section or to produce various solid or hollow cross sections. This process generally is carried out at elevated temperatures in order to reduce the extrusion force and improve the ductility of the material. [18] Solid profiles are produced using a flat, disc-shaped die, and hollow profiles are extruded through a two-part die. [9] According to Sapa these dies are relatively cheap to custom make to extrude own aluminium profiles. This will, according to themselves enable an optimization of the product weight, strength and functionality. In addition, providers can hypothetically save labor hours per unit produced by avoiding any modifications of COTS, something that must be substituted in extra costs relating to a custom extrusion. Temporarily Sapa has some quantity requirements, as the profiles are commonly extruded in lengths between 25 and 45 meters. Customer profiles can be delivered from a diameter of five millimeters and up to a diameter of 620 millimeters where the maximum weight is 65 kilograms per meter. From an economic point of view, Sapa recommends to choose a profile diameter in the midrange and rather combine multiple profiles. Low alloy steel may also be extruded, but this is a process which requires considerably more energy in form of heat and pressing force and is according to Norsk Stål not profitable.

Joining of metals can be done in several ways. As with steel, aluminium is also very suitable for fusion welding. Nowadays, gas arc welding methods, MIG and TIG in particular, dominate. [9] These welding methods are relatively cheap in themselves, and human-operated equipment has a relatively low investment cost. In addition, the necessary skills for fusion welding are affordable to acquire. Fusion welding can also be performed by welding robots, but has a significantly higher investment cost. When jointing metals with fusion welding a heat-affected zone (HAZ) will occur. The HAZ is located on either side of the weld, and tend to cause stresses that reduce the strength of the material due to changes in the materials microstructure. By using jointing methods that causes a HAZ, this must be considered in the calculations. [18]

Extrusion technology provides a variety of possibilities for joining aluminium profiles. [9] When purchasing profiles from Sapa, they offer to join them with friction stir welding (FSW) at the factory. In FSW one of the workpiece components remains stationary while the other is placed in a chuck or collet and rotated at a high constant speed. The two members to be joined are then brought into contact under an axial force. This leaves a strong and clean joint which has a narrower HAZ compared with traditional fusion welding. [18] According to Sapa the costs of FSW are relatively low. The elasticity of aluminium makes it also suitable for snap-fit joints. [10] The profiles are extruded with a male-/female solutions that are pressed together and form a permanent, locked joint. These allow, according to themselves, a far quicker assembly than for example screwed or welded joints. Besides the joints have no loss of strength and the jointed profiles can be considered as one piece of goods.

The machinability of a material can be defined as the ease with which it can be machined, and depends on the materials composition, properties, and microstructure. Machinability can be expressed as a percentage or a normalized value. The American Iron and Steel Institute (AISI) has determined AISI No. 1112 carbon steel a machinability rating of 100%. [18] With numbers received from The Engineering ToolBox, the machinability of construction steel is 78% and the machinability of aluminium is 360%. The higher machinability percent a material has, the easier it is to perform machine operations in the material. The machinability of a material induces tool wear which is a major consideration in all machining operations. Tool wear adversely affects tool life, the quality of the machined surface and its dimensional accuracy, and, consequently, the economics of cutting operations. [18]

3.4 Economic and environmental aspects

To compare the costs of aluminium and steel, it is chosen to compare standard profiles, and custom profiles. For standard profiles, price data from Norsk Stål is collected to form a neutral image on the economic aspect. Norsk Stål stocks not the 6063-T6 alloy, but as an approximation alloy 6082-T6 will be used which according to Sapa is about the same price per kilo. The comparison is based on a standard profile contained both the respective aluminium and steel alloy, 40 x 40 x 4,0 mm, square tube.

	6063-T6	S355J2
Kg/m	1,61	4,30
Price/kg (NOK)	129,44	21,69

Table 2: Price comparison

This makes aluminium more than six times as expensive per kilo than steel. Comparing the price per meter, the price of aluminium is over twice as expensive. Hypothetically, if comparing the price against the weight saving in *Figure 8*, the steel section cost with prices form Norsk Stål (about) 666 NOK. The aluminium profile with 0% weight saving costs 3922 NOK, the aluminium profile with a 40% weight saving costs 2382 NOK and the aluminium profile with a 49% weight saving costs 2045 NOK.

According to Sapa, it is difficult to determine the cost of a custom profile without having produced it. Sapa has forwarded a price example of a custom profile that is used in structural applications. The custom profile cannot be imaged, but comprises a hollow profile which is 380 x 40 mm. The profile has a vertical support wall in the middle and flanges on each side for joining to the next profile. Goods thickness is 2 mm. The extrusion tool consists of a two-part die in steel and costs 30.000 NOK. This is described as a one-time investment. With alloy 6063-T6 the extrusions weight is approximately 5,6 kg/m. Sapa charges 35 NOK/kg, which makes the custom profile price 196 NOK/m.

According to Christensen, T. H. (2011) production of iron and steel is an energy-demanding process, and production of aluminium is an extremely energy-demanding process. Besides, production of iron and steel creates a large amount of tailing, and production of aluminium leaves large open scars in the landscape until residues are backfilled and vegetation re-established.

Metals such as steel and aluminium is in principle limited resources, but if they are recycled they can be classified as renewable resources. Recycled steel and aluminium scrap is an important part of the raw material used in the metal industry and is traded on the global marked. Recycled scrap metals are used in nearly all metal products. [17] According to Sapa (2015), 75 % of all aluminium ever produced, is still in use.

The main problem in steel and aluminium recycling is the cleanliness of scrap with respect to primary steel, other metals and alloys. This is a particular problem with post-consumer waste. Processes to separate different alloys apart and remove unwanted additions in the scrap metal may be an energy demanding and costly affair. When this is fulfilled, the clean metal scrap can be recycled without loss of quality, only with a slightly loss quantity.

The benefit of saving energy by using scrap must be weighed against the alloying metals associated with the scrap. Despite this, several studies have concluded that, from an environmental point of view that recycling is beneficial, and that the energy savings are so significant compared to virgin production, the recycling of metals is environmentally beneficial even when long-transport distances are involved. [17]

The tables below show electricity use and CO_2 emission for one tonne of produced aluminium and steel. [9]

	Virgin	Recycled
Electricity (kWh)	516	87,7
CO_2 (kg)	2308	164

Table 3: Steel production

	Virgin	Recycled
Electricity (kWh)	15950	140
CO_2 (kg)	4014	483

Table 4: Aluminium production

3.5 Environmental interaction

According to Bardal, E. (2004) five different main principles can be used to prevent corrosion:

- Appropriate materials selection
- Change of environment
- Suitable design
- Electrochemical, i.e. cathodic and anodic protection
- Application of coating

Corrosion is defined as the destruction or deterioration of a material because of reaction with its environment. Fontana, M. G. (1987) classifies corrosion into two main groups; wet corrosion and dry corrosion. Wet corrosion occurs when a liquid is present. A common example is corrosion of steel by water, and is the one relevant in this case. General corrosion or surface corrosion, is the most common corrosion type, which provides a uniform corrosion over the entire material. [16] When designing with corrosion-prone materials, it is obviously vital to know how fast the corrosion process is going to be. Aluminium, and most other materials, form oxidation barrier layers in just the same sort of way, but the oxidation layer on aluminium is a much more effective barrier than the oxide film on iron is. This results in that aluminium in general, oxides much slower than iron. [13]

Pitting is far the most common type of corrosion in aluminium, and is primarily an aesthetic problem which never affects the strength. It occurs only on the presence of an electrolyte containing dissolved salts, usually chlorides. The corrosion generally manifests as extremely small pits that, in the open air, reach a maximum penetrations of a minor fraction of the metals thickness. [9]

When it comes to steel, atmospheric corrosion rates can be reduced considerably by use of special low-alloy steels, such as S355 structural steel. However, when selecting materials within these groups, some kind of protection must be considered as an integrated part. This could be done by applying coatings on the metal surface, in order to make a barrier between the metal and the corrosive environment. [16]

The table below shows the results from a field exposure tests on untreated metals the Swedish Corrosion Institute has carried out, and shows the weight losses after eight years in marine- and urban atmospheres. [9]

	Marine	Urban
Aluminium (g/m^2)	7	2
Carbon steel (g/m^2)	933	676
Galvanised steel (g/m^2)	133	61

Table 5: Weight losses after eight years

However, it is also important that the materials in adjacent components are compatible. With regard to corrosion, compatibility often means that detrimental galvanic elements must be avoided. [16] This could result in galvanic corrosion and may occur where there is both metallic contact and an electrolytic bridge between different materials. The least noble metal in the combination becomes the anode and corrodes. In most combinations with other materials, aluminium is the least noble one and presents a greater risk of galvanic corrosion than most other structural materials. To provide this, the different materials must be electrically insulated from each other. [9]

3.6 Thermal characteristics

The strength of a material tends to fall quickly when a certain temperature is reached. This temperature limits the maximum operating temperature for which the material is useful. According to The Engineering ToolBox, the maximum operating temperature for steel is 500 – 650°C and for aluminium it is 150 – 250°C, which is far above the temperatures in the intended operating environment. [19]

Some properties of steel such as strength, elasticity, hardness, brittleness, and magnetism are at their highest point at very low temperatures and decrease with temperature rise. However, the resistance of steel to shock decreases significant with lowered temperatures. Certain ordinary carbon and low-alloy-content steels exhibit a loss of toughness when low temperatures near −40°C are reached, so that some of these steels are too brittle to use in impact service in cold climates. [19]

Tests and field use of aluminium and its alloys indicate that they are admirably suited for extreme-low-temperature service. Tests made to subatmospheric temperatures indicate that the tensile, yield, and impact strengths of all aluminium alloys increase at extreme low temperatures. Aluminium alloys retain ductility at these temperatures, corrosion resistance is enhanced, and there is no increase in brittleness. No special precautions regarding methods of handling at extreme low temperatures are required. [9][19]

4. FINDINGS

There are several assumptions about what defines low-volume production. Some define it as a production rate of 20-500 units per year, while others believe it does not depend on an annual production rate, but the characteristics of the product and production process. Low-volume production is described as a balancing act between features, cost, and speed, and requires designers to make compromises on aesthetics and material properties to accommodate this. Use of standard components instead of custom parts is described as an important aspect of low volume production. Client expectations and willingness from vendors may be challenging in this type of production. It is important to understand the challenges and limitations to optimize the product design in low-volume production.

According to the three largest trailer providers in Norway and Scandinavia's largest trailer provider, S355 structural steel is mainly used in similar products. This forms the basis of the comparison together with 6063 aluminium alloy which is according to Napic and Sapa, suitable for the purpose.

The strength of a material is defined as "the force per unit at failure". For structural constructions, strength is considered as the yield strength, where the material returns to its original shape and cross section when the tension ceases. The strength-to-weight ratio is a relationship defined as the strength of the material divided by its density. In this case, the aluminium alloy has about twice as high strength-to-weight ratio as the steel alloy. The modulus of elasticity of aluminium in general is about one third of steel. This gives about three times as high deflection in an aluminium structure as in a similar steel structure. If the dimension of the aluminium structure increases to derive the deflection, often the strength is not fully exploited. If increased dimensions is tolerated, calculations shows that it is possible with a weight reduction near 50%.

For steel structures, the use of commercial off-the-shelf parts, COTS, would be appropriate. It is interesting whether it would be economical to use COTS in an aluminium construction. Through extrusion technology for aluminium, own custom profiles are relatively cheap to develop. Customized profiles can potentially optimize the product's weight and strength, and save labor hours on further assembling. Fusion welding is dominant by joining both steel and aluminium constructions. The method is relatively cost effective and can be performed by the clients themselves. When purchasing profiles from Sapa, they offer to join them with friction stir welding at the factory. This gives stronger joints and is relatively inexpensive. However, by welding, a heat-affected zone that weakens the strength of the structure is establishes. Extruding own profiles enables the use of snap-fit joints. With snap-fit joints the profiles can be compressed together to form joints without loss of strength.

The machinability of a material indicates how easily a material can be machined. Aluminium is generally between four and five times easier to machine than structural steel. Machinability affects tool wear and speed, which again affects the economics of the manufacturing process.

Numbers from a neutral supplier show that aluminium COTS is over six times more expensive than steel COTS. According to Sapa, it is difficult to estimate the tool price for a custom profile, but operates with a significantly lower aluminium kilo price than the neutral supplier.

Extraction of both aluminium and steel temporarily destroys large rural areas. Aluminium extraction requires over 30 times more electricity and produces almost twice as high carbon emissions as steel. Steel and aluminium are basically limited resources, but can be considered renewable if they are recycled. Recycling of aluminium requires significantly less energy than new production, but still has a higher footprint than steel.

Both steel and aluminium oxidize, but aluminium oxidizes much more slowly than steel. Studies have shown that aluminium in urban environments oxidizes over 300 times more slowly, and in marine environments more than 100 times slower than steel. However, galvanic corrosion must be considered, as aluminium in humid environments oxidizes quickly in contact with, for example, steel.

Unlike most grades of steel, aluminium does not become brittle at low temperatures. In temperatures down to -40°C, some steel is so weakened that they are not suitable for construction. Tests made on aluminium show that its strength increases at extremely low temperatures.

5. FINAL REMARKS

The goal of this paper was to find the most optimal construction for the load bearing trailer structure based on mechanical properties and the economic aspect. The conclusion is not unambiguously because there are indications that compromises occur when choosing material.

By using COTS in structural applications with the same strength, significant weight savings can be made by choosing aluminium instead of steel, provided it is tolerated to increase the dimensions. However, cost per unit is significantly higher when using aluminium. Weight and price therefore become a compromise and must be considered. By using own extruded aluminium profiles, the cost per unit can be significantly lower, but the cost of the extrusion tool(s) must be incurred. Since the extrusion tool is s a one-time investment, this cost will be distributed to the number of manufactured units. In order to enable cost savings using own aluminium profiles, the production volume should be mapped. Potential savings in labor hours using own solutions should also be included to the calculation.

In the intended operating environment, the use of aluminium indicates advantages over the use of steel. Besides weight saving, aluminium will handle a wet climate without any need of corrosion protection. As previously mentioned, this must be considered as an integrated part of a steel structure. This leads to cost savings and possible savings in maintenance. However, this requires that aluminium never acts in direct contact with other metals. It is also conceivable that temperatures down to -40°C may occur in a user environment, which an aluminium structure as opposed to a steel structure, can withstand without a potential loss of strength. Strength loss can also be avoided using aluminium profiles with snap-fit solution, avoiding a loss of strength caused by joining. Tool wear and overall time spent on machining operations can also be reduced by using aluminium, as machinability is better. From an environmental perspective, steel is currently a greener choice in production, but in use as a part of a vehicle, movement can take place more environmentally effectively by weight reduction.

The recommendation for the client is to focus on the compromise between weight and price. With aluminium, the load bearing structure may become more expensive, but also enable weight savings. If weight is the critical factor, the production volume should be mapped. This determines whether it would be appropriate to develop custom aluminium profiles. Steel dominates the current market segments which gives a reason to claim that steel handles the intended use environment in a satisfactory manner, although aluminium can potentially handle this even better.

Based on the literature review on low-volume production, the segment shows trends to be a bit pre-intended and conservative. The claim that use of COTS instead of customer parts will be more cost-effective appears to be invalid when using aluminium. If low-volume production is defined as production of up to 500 units annually, it seems cost-saving not to use COTS, but rather use custom profiles.

REFERENCES

[1] Veststøl, H. (1998). Design methods for high-volume automotive structures: *Development of aluminium extrusion-based integrated seating systems* (Doctoral thesis). Trondheim: Norwegian University of science and technology (NTNU).

[2] S. Mayer and A. D. Seeds. (1994). BMW's Aluminium Light-Weight Prototype Car Project: *Comparison of Aluminium and Steel Performance*. SAE Technical Paper Series 940154.

[3] Jina, J., Bhattacharya, A., & Walton, A. (1997). Applying lean principles for high product variety and low volumes: *Some issues and propositions*. Logistics Information Management, 10(1), 5-13.

[4] Mellody, M. (2014). Limited Affordable Low-Volume Manufacturing: *Summary of a Workshop*. Washington, D.C.: National Academies Press.

[5] Javadi, S., Bruch, J. and Bellgran, M. (2016). Characteristics of product introduction process in low-volume manufacturing industries: *A case study*, 27(4), 535-559.

[6] Javadi, S. (2015). Towards Tailoring The Product Introduction Process For Low-Volume Manufacturing Industries (1st edition). Västerås, Sweden: Mälardalen University Press Licentiate Theses.

[7] Vallhagen, J., Madrid, J., Söderberg, R., Wärmefjord, K. (2013). An approach for producibility and DFM-methodology in aerospace engine component development. Procedia CIRP 11 2nd International Through-life Engineering Services Conference.

[8] Schneider, E. (2010). Turn down the volume. Mechanical Engineering, 132(4), 36-39.

[9] Sapa Profiler AB (2015). Design manual: *Success with aluminium profiles*. Stockholm: J&L Annonsbyrå AB

[10] Grauslund, S. (2009). Rør i Den Store Danske, Gyldendal. Available from: http://denstoredanske.dk/index.php?sideId=153984 (Retrieved: February 9th, 2017)

[11] Specific strength. (n.d.). Available from: http://www.manufacturingterms.com/Specific-strength.html (Retrieved: February 14th, 2017)

[12] Vollen, Ø. (2011). Mekanikk for ingeniører*: Statikk og fasthetslære.* (2nd edition). Bekkestua: NKI Forlaget AS

[13] Ashby, M. F., Jones D. R. H. (1980). Engineering Materials 1: *An introduction to their properties and applications*. (2nd edition). Department of Engineering, University of Cambridge. UK: Butterworth Heineman

[14] Ashby, M. F., Johnson, K. (2000). Materials and design: *The art and science of material selection in product design*. (3rd edition). Amsterdam: Elsevier

[15] Fontana, M. G. (1987). Corrosion engineering. (3rd edition). New York: McGraw-Hill

[16] Bardal, E. (2004). Corrosion and protection: *Engineering materials and processes*. London: Springer

[17] Christensen, T. H. (2011). Solid waste technology & management. New Jersey: Blackwell Publishing Ltd.

[18] Kalpakjian, S., Schmid S. R. (2009). Manufacturing Engineering and Technology (6th edition). New Jersey: Pearson Education.

[19] Roberts, P. W. (n.d.). Electrical and Mechanical Engineering: *Effect of Extreme Arctic Cold on Materials*. Available from: http://collections.dartmouth.edu/arctica-beta/html/EA02b-02.html (Retrieved: April 10th, 2017)