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Investigating the impact of sustainability in the production of aeronautical subscale components

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Abstract

The aim of this paper is to investigate the impact of sustainability aspects in the production of aeronautical subscale components by comparing the traditional riveted versus the innovative Laser Beam Welding (LBW) process in industrial conditions. We adopt a quantitative assessment methodology for both processes, by taking into account a series of manufacturing scenarios with six multi-dimentional aeronautical subscale components in different annual production rates (mass production). The results reveal that the exploitation of the LBW technology can provide weight savings up to 28 %, by exploiting lower density Al-Cu-Li alloys, while the time savings during the manufacturing process can be up to 67 %. Furthermore, the total manufacturing cost of the LBW process can be reduced up to 40 % for the case of long structures, when compared to the corresponding riveted structures. In terms of environmental friendliness, the LBW process results to increased CO_{2e} emissions by 124 % during the manufacturing process when compared to the riveting process. However, this difference is lower than 60 % when longer structures with smaller count of stringers are used. Finally, despite the high carbon footprint emission during the manufacturing phase, when the life cycle of aircrafts is assessed, the LBW joining process can contribute to lighter components, resulting to less weighted aircrafts whose engines consume less fuel, contributing in that way to energy and GHG emissions reductions.

Keywords: Sustainability; carbon footprint; laser beam welding; riveting; ABC costing; Al-Li alloys.

1. Indroduction

The introduction of sustainable production processes in industries is rapidly increasing worldwide. Indeed, the need for sustainable and especially environmetal-friendly products and goods is increasingly receiving attention among consumers and indicates that market forces will require improved and innovative ways of dealing with economic, environmental and social aspects. Sustainability factors need to be considered during the preliminary stages of product design and must be taken into account during

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the life cycle perspective (raw materials, production, distribution, usage, maintenance, end of life) of a product (Hallstedt et al., 2015; Mayyas et al., 2012). In the short term, sustainability requirements may increase the cost (material cost, manufacturing cost, testing and assessment cost, etc.) in some cases, however in the long term they exhibit a positive impact on financial performance and competitive advantage (Mayyas et al., 2012; Yang et al., 2010), while at the same time companies with environentally friendly production processes can improve their position to face challenges and costs resulting from current and future carbon footrpint regulations (Urban and Chiang, 2016).

According to Hallstedt et al., (2013) the long term cost benefits can be achieved by companies that manufacture products that are produced during a long period of time and need to be supported or maintained for much longer after the production process has ended. An early adopter of the aformentioned sustainability strategy, is the aviation sector since its products have an average a life cycle of more than 20 years. Furthermore, since aviation is currently the second largest consumer of transport fuel globally (Huang et al., 2016), it is necessary for the aircraft industry to adopt certain sustainability practices that will result to the production of lighter weight aircraft and consequently to energy and greenhouse gase (GHG) emissions reduction (Immarigeon et al., 1995).

Today, the world's aircrafts consume 250 millions tons of oil equivalents and comprise 12 % and 9 % of global transport sector energy use and GHG emissions, respectively (Huang et al., 2016). Furthermore, global aircraft use is projected to triple by 2050, due to rapid growth of the commercial aerospace and increasing globalization. Indeed, in terms of passengers, air traffic has been doubling every 15 years in the past, and is expected to double again in the next 15 years. To this end, a growing number of aircraft industry companies such as Airbus, Boeing and General Electric have recognized the need for adopting sustainable manufaturing processes as a business opportunity (Hallstedt et al., 2015). They are trying to replace the conventional manufacturing processes such as the riveting process, with innovative additive processes such as the Laser Beam Welding (LBW) process in order to reduce the high "buy-to-fly" ratio (the mass of raw material needed per unit mass of finished component) and produce lighter weight aircrafts (Allwood et al., 2011). The weight savings that are achieved by LBW aircraft components proceeded mainly from the removal of fasteners and sealants. Indeed, The laser beam utilizes the flow of high power photons as a heat source. The laser beam locally melts the location of the structures that will be joined; fastening is achieved from the common solidification of the joined structures with or without the use of additional filler wire material. On the other hand, riveting joining technology is a semi-permanent method, which creates an assemby (which consists of two components) by using a series of materials (intermediate rivets, lock bolts and sealant), which seems to increase the total weight of final structure (Wilson et al., 2012).

Aluminum alloys are widely used as a primary material in aircraft structures for many decades because of their high stiffness-to-weight and strength-to-weight ratios (Starke and Staley, 1996). Aluminum alloy producers focus their research efforts on developing lighter alloys, with higher damage tolerance capabilities and the ability to be efficiently welded. The latest focal point of such a development was lithium containing aluminum alloys due to their lower density, higher specific strength and rigidity, better corrosion and fatigue crack growth resistance properties, when compared to conventional aluminum alloys, e.g. 2024 (Al-Cu-Mg) (Alexopoulos et al., 2013; Dursun and Soutis, 2014; Rioja and Liu, 2012). Lithium (Li) is the lightest metallic element and therefore its addition results to global weight reduction of fixed geometrical dimensions of a structural element; it was calculated that when 1 wt % Li was added to Al and its alloys, its density is reduced by 3 % and the modulus of elasticity is increased by almost 6 % (Heinz et al., 2000; Lavernia and Grant, 1987). Second generation Li-containing aluminum alloys, e.g. 2090, 8090, etc. were developed in the decades of 80s and 90s and generally presented superior damage tolerance capabilities than conventional Al-Cu-Mg alloys and several drawbacks; the most important disadvantage was anisotropy of the mechanical properties between the sheet rolling directions (Blankenship and Starke, 1993, 1992). During the last years, third generation aluminum - lithium alloys, e.g. 2198 and 2196 were developed to replace the conventional alloys 2024 and 2524 in aircraft structures where damage tolerance is the critical design factor. Preliminary results showed that aluminum alloy 2198 was found to be superior to 2024 both in fatigue (Alexopoulos et al., 2013) and corrosion behavior (Alexopoulos et al., 2016b). It was found that the use of high strength Al-Cu-Li alloys instead of conventional Al-Cu-Mg alloys, e.g. 2024, can reduce the structural weight by 3 to 5 % (Alexopoulos et al., 2016a) and increase the rigidity by 20 % (Murphy et al., 2007).

The aim of the present article is to compare the sustainability of typical aircraft subscale components. To this end, the traditional riveted versus the innovative LBW process is evaluated, in industrial conditions (mass production). This work is the continuation of a previous study (Alexopoulos et al., 2016a), where a direct comparison between the LBW and the riveting process is made in laboratory scale (serial production), for the case of manufacturing a typical four-stringer aeronautical subscale component. In the present work, we have adopted a quantitative assessment methodology for both processes, by taking into account four criteria that are related to: a) the weight of components, b) the manufacturing cost, c) the lead processing time and, d) the equivalent carbon dioxide (CO_{2e}) emissions during the manufacturing process of aeronautical subscale components. In order to determine the ideal shape of subscale components which can minimize the carbon footprint and the total manufacturing cost, in industrial conditions, we have developed a integrated approach which contains the comparison of a series of manufacturing scenarios with six multi-dimentional aeronautical subscale components in different annual production rates.

The paper is structured as follows: the next section presents the dimensions of the six different structures under consideration as well as the materials used for the manufacturing of aeronautical subscale components. Furthermore, in this section, both the laser beam welded and the riveting manufacturing processes, are briefly described. Subsequently, the third section contains the theoretical background as well as the methodology followed for the cost and carbon footprint evaluation, while the analysis and discussion of the results are presented in the fourth section, respectively.

2. Description of materials and manufacturing processes

2.1. Compared structures and materials

The aeronautical subscale components used for the comparison between the LBW and the riveting process are presented in Table 1. Structure A1 is a four-stringer subscale component with nominal dimensions 742 mm x 384 mm with a sheet thickness of 3.2 mm. Structure B1 has eight stringers and is double in width than Structure A1, while Structure C1 has the same number of stringers with Sructure A1, but is double in length than structure A1. Taking into account the research work of Dittrich et al., (2011) for lower skin thicknes in order to fully exploit the enhanced damage tolerance capabilities of the third generation Al-Cu-Li alloys, we have decided to include in this study some additional structures with reduced sheet thickness in order to calculate the effect on the weight, manufacturing cost, lead processing time and CO_{2e} emissions of the manufactured aeronautical subscale components.

The materials used for the manufacturing of the laser beam welded subscale component were all aircraft aluminum alloys. Third generation aluminum - lithium (Al-Cu-Li) alloy 2198-T3 with nominal thickness 1.6 mm and 3.2 mm and Al-Li "L" shape profile 2196-T8 (1.6 mm thickness) was used for skin and stringers of the LBW component, respectively. In addition, skin to stringer filler welding wire of AA4047 with nominal diameter of 0.8 mm was used. The chemical composition of the investigated materials is summarized in Table 2. The materials were delivered in sheet form at T3 condition and L profile at T8 condition, respectively (Starke and Staley, 1996).The materials used for the construction of the riveted component were similar to the previous research work of the group study (Alexopoulos et al., 2016a), with aluminum alloys 2024-T3 (3.2 mm thickness) and "Z" shape profile of 7075-T73511 (1.6 mm thickness), for the skin and stringer, respectively. Furthermore, for the skin to stringer joining rivets of aluminum alloy 2017 W (solid solution) with 4 mm diameter as well as lock bolts rivets of titanium alloy Ti6Al4V with 4 mm diameter were required. The chemical composition of these materials that are widely commercially available can be easily found on handbooks and on specific articles focusing on aircraft materials, e.g. (Starke and Staley, 1996), (Heinz et al., 2000) and (Dursun and Soutis, 2014), etc.

Currently, the possibility to use the same shape stringers for two different joining processes remains rather limited. The main advantage of exploiting weldable aluminum alloys in aircraft structures is the possibility to use "L" shape instead of "Z" shape stingers in LBW structures and therefore essentially reduce structural weight. To this end, in a previous article of the authors (Alexopoulos et al., 2016a), several structural scenarios were considered and the theoretical weight of the B1 demonstrator was calculated. Besides the two realistic scenarios considered (riveted with AA2024 and LBW with AA2198), two other hypothetical scenarios were also examined: the possibility to (a) rivet the third generation Al-Cu-Li 2198 alloy (with the use of "Z" stingers) and to (b) LBW the Al-Cu-Mg 2024 alloy (with the use of "L" stringers). For the first case, a small (3 %) weight saving is obtained mainly due to the lower density of the Al-Cu-Li alloys whereas for the second case, a larger weight decrease is noticed mainly due to the absence of sealants, intermediate rivets and lock bolts rivets of the laser beam welded component. For the latter case, "L" shape stringers were used, instead of the "Z" shape stringers that have a significant effect of the component's weight due to the less material used. The last case is a theoretical approach as AA2024 is considered non-weldable and therefore "L" shape stringers cannot be used. Overall, manufacturing of the 4-stringer LBW stiffened panel with Al-Cu-Li alloys shows an approximate 20 % weight saving when compared with the riveted panel due to the above defined parameters.

The authors acknowledge that for a proper comparison of the different joining technologies, the produced parts should have to fulfil the same design prerequisites. Several design prerequisites should be considered for a specific aircraft structure according to the location being used, e.g. stiffness, compressive strength, fatigue crack growth, etc. that are mainly set by the aircraft manufacturer. As AA2198 is newly developed, the aircraft manufacturers are currently using the same thickness sheets to replace the conventional AA2024 sheets so as not to essentially change the already established process manufacturing lines. In a recent research article (Kashaev et al., 2015) it was demonstrated that the laser beam welded four-stringer specimen (specimen width of 740 mm, total length of 1250 mm with a center notch of 165 mm in length and the stringer distance for the four- stringer specimens was 175 mm) takes approximately 20 per cent more load than the reference riveted specimen. Additionally, by comparing the reference and welded specimen, the higher modulus of the stiffened panel is visible, and the ultimate stresses are on the same level. To fully take advantage of the higher mechanical properties, a parametric study of changing the material thickness or re-designing the aircraft stiffened component to fully take advantage of the high damage tolerance capabilities of the third generation Al-Cu-Li alloys should be performed. All these parametric steps before manufacturing are in-house information for the aircraft manufacturers and cannot be easily found in the open literature; additionally, the aircraft manufacturers are very cautious when changing their production lines of manufacturing mainly due to installation costs. To this end, for the case of the present article it is not straight forward to produce aircraft structures responding to absolutely the same design prerequisites to directly compare their sustainability potential.

2.2. Manufacturing processes

Riveting has been the state of the art joining technology for aircraft fuselage many decades now (Wilson et al., 2012), nevertheless, the introduction of advanced welding methods (i.e. LBW), as an alternative joining processes to riveting in the manufacture of primary aircraft structure is very promising (Xiao and Zhang, 2014). The following sections describe shortly of the two joining processes.

2.2.1 Riveting process

The riveting manufacturing process takes place in three work stations, while each work station consists of one sub process, as it can be seen, in Figure 1. The first sub process includes seven different activities which are intended to prepare both the skin and the stringers for the main, riveting process. The continuous improvements in modern machine tools, along with the development of new tool materials and tool geometries, have produced a constant increase in the cutting conditions (i.e. speed and feed rate), (López de Lacalle et al., 2001). Similarly, to the LBW process, Activity 1.1 and 1.2 aim at configuring the skin and stringers to the required dimensions with milling processes, while Activity 1.3 deals with the amendment of the burrs, which are created during the milling process. Subsequently, in Activity 1.4, a specialized technician drills the necessary holes on the skin by exploiting the already manufactured stringer's pilot holes. Additionally, a V-groove is manufactured at the rivet holes at the outer skin surface. Before the final assembly via riveting, both stringer and skin must be cleaned, to remove any kind of dirt, grease, chips, etc. Thus, Activity 1.5 deals with the cleaning of raw materials, which takes place in an already heated tank that contains alkaline solution. Finally, the last activity (Activity 1.6), deals with the rivet's heat treatment, for the rivets to obtain the required mechanical properties combination. During the second sub-process, all the necessary activities for the skin/stringer assembly as well as the fastening process via riveting takes place. More specifically, Activity 2.1 deals with the skin/stringer assembly and with the placement of intermediate AA2017 rivets in their holes. The second activity of current sub process aims at fastening the above formed assembly, while during the last activity (Activity 2.3) the lock bolts rivets are fastened at the outer holes of the subscale component. The third sub process of conventional manufacturing process deals with the structure's final inspection before dispatching to customers. However, the current sub process has not been considered as previously mentioned since the quality control method used is not the same as the corresponding method of LBW process.

2.2.2 Laser beam welding process

The welding was performed using a large scale laser welding facility equipped with a movable processing head (Figure 2a) and two 3.5 kW CO_2 lasers (with beam quality K ≈ 0.76, beam parameter product BPP = 4.4 mm mrad and beam focus diameter d ≈ 130 μm) (Enz et al., 2012). The facility has been installed in HZG Institute in cooperation with AIRBUS Germany and it facilitates an up-scaling of the welding process from coupon specimens up to complete fuselage panels with dimensions of 8500 mm x 3000 mm.

The Laser head is connected to two CO_2 Laser sources that are placed over the welding frame with maximum power of 3500 Watt each (Figure 2b). Attached to every CO_2 Laser source is a cooler device that cools the source as well as a fume device that removes fumes produced during the welding process. The flexible laser system is designed for two-sided simultaneous welding of longitudinal stringers (Figure 2c). Additional components of the laser head are the two coils of filler material, filler material guides as well as the entire measurement technology that controls the weld during the process. The management and control of the welding process is performed in the control station, which is a room with the control panel. This room has a direct visual contact to the laser hall and to the welding frame, enabling a specialized user to monitor the main welding process.

The T-joints of skin and stringer were welded simultaneously from both sides of the stringer as well as successively from each side of the stringer. The incident beam angle of both lasers was constantly at 22°. The filler wire AA4047 and the shielding gas helium were supplied from each side of the stringer in front feeding mode. The welding equipment and joint configuration used in this study are shown in Figure 2c. To retain the position of skin and stringer during welding a vacuum unit for the skin and a mechanical clamping device for the stringer were used.

As it can be seen in Figure 3, LBW manufacturing process is also divided into three work stations/sub processes, while each sub process includes multiple related activities. During the first sub process all the necessary activities for the preparation of raw materials before the main laser beam welding process, take place. Activities 1.1 and 1.2, deal with the cutting of skin and stringers to the required dimensions to be welded, while Activity 1.3 aims at removing aluminum alloy material from the skin surface, to prevent pore formation in the welds. The same task is necessary to be performed for the case of stringers, where they are milled on both longitudinal sides and at the bottom side as well. Finally, Activity 1.5 deals with the cleaning of skin and stringers, where a technician, by using a cloth and ethanol, eliminates moisture, oil, grease and dust from the materials' surface to achieve high weld quality as the latter induce structural defects to the weld pool. The second sub process includes all the necessary activities for the skin/stringer joining via the LBW process. During the Activity 2.1, a technician places the skin on a vacuum clamping table for the vacuum pressure to start (Activity 2.2), while the same activity is repeated, according to the number of the remaining stringers. The last sub process of LBW process includes the necessary activities for the quality evaluation of the welded joints. It is important to mention that current sub process has not been considered since the quality control method used is not the same as the corresponding method of riveting process.

2.2.3 Defects – risk assessment

Several processes include the possibility to manufacture a subscale component with defects. To this end, a small-scale risk analysis is performed in this section, embracing several processes that involve risks during manufacturing. The discrepancies from manufacturing of the ideal subscale coupon without defects are identified and estimated based on their initial risk in Table 3.

In Process 1.3, the LBW technician places the skin on the working table and grinds the skin surface at the four material stripes that afterwards the stringers will be laser beam welded. There is a possibility the technician to apply greater force than the appropriate and therefore the grinding depth of the skin to be higher than the defined depth of 50-150 μm to form a small crenellation, thus influencing the local mechanical properties of the coupon. Likewise, in Process 1.4, during the surface finish stage of the stringer, there is a possibility that the milling depth and height may be higher than expected due to wrong fixation of the stringers on CNC milling machine. This defect has similar impact on the local mechanical properties of the sub-scale like formed crenellations on the skin surface.

In Process 1.5, the longtime exposure of the skin/stringers to atmospheric conditions, after the cleaning process, might endanger the welding process and the quality of the weld. Usually a surface oxide layer grows on the unprotected metal surface with exposure time. This oxide layer it degrades the efficiency of the welded joints by introducing porosity to the welded seam.

In Process 2.1, a specialized technician carries and places the skin on the vacuum clamping table. Every edge of the skin must be coincident exactly at the outside edge of each suction block. The main risk is when the two skin sides are not perpendicular to the ones of the vacuum table (misalignment of skin to suction block table). If the skin is not positioned correctly on the suction blocks, then the skin will be misaligned accordingly to x and y axes of the laser head and vacuum won't be applied properly.

During the stringer's positioning at the clamping rollers (Process 2.3), there is a possibility that the vacuum clamping device will not apply the proper pressure. The pressure that should be applied is strongly dependent to the stringer's thickness. The technician realizes a stringer's misalignment or deformation while the stringer is being clamped. Additionally, in the similar following Processes (2.4, 2.5 and 2.6), there is also a possibility the technician not to correctly position the stringer on the top of the skin's surface and/or the laser head not to be positioned at the correct distance to weld the stringer. Therefore, there is the possibility the stringer to be placed in a misaligned position before being LBWed. Finally, in the same Processes, three different cases (defects) might occur during LB welding:

1. the stringer is misaligned due to its length,
2. there is a gap between the surface of the skin and the stringer due to wrong grinding of the skin, and
3. the stringer is curved when compared to surface of the skin due to insufficient pressure applied by the vacuum clamping rollers.

To mitigate the initial risk of above cases, the LBW technician should check the position of clamping rollers on the stringer and the applicable pressure. Checking with hand tools does not induce a serious problem in the performance, although the result could be significant. Between the last two misalignment cases, there is also another risk that should be mentioned, referring to risks on possible thermal distortions of the structure during the welding process.

In Process 2.3, as the laser beam melts locally the skin and stringer, the filler wire feeder delivers AA 4047 filler simultaneously to both sides of the stringer. There is a probability for no constant wire filler feeding rate that could result to non-uniform welding. A non-uniform welded panel has definitely high cost for the manufacturer since these welded panels are unacceptable, unrepairable and therefore are rejected. Additionally, in the same process, if the filler wire spools are exposed for a long-time period to atmospheric conditions, there is a possibility for surface oxide layer to be formed on the filler wires that will introduce defects (mainly porosity) in the welded seams.

Finally, during the laser welding main process, the vacuum system is continuously operating. The vacuum system is the most important operating system of LBW process since it clamps the skin on the vacuum table. If the sheet is not properly vacuumed, there is a possibility the welded panel to be endangered due to various parameters, such as to be moved or tilted and therefore cannot be properly welded due to incomplete fusion and other possible defects.

3. Costing and carbon footrpint calculation methodoly

This section describes the methodology adopted to calculate the manufacturing cost as well as the carbon footprint emissions for the two manufacturing processes in discussion. The economic evaluation for both manufacturing processes is based on the Activity Based Costing (ABC) method, while for the environmental evaluation the authors have adopted the PAS2050[1] standard.

3.1. Cost calculations

3.1.1 Theoretical bachground: Activity-based costing (ABC)

In the aviation industry, production cost estimation is of significant importance since aircraft production cost accounts for around 32% of the Airplane Life Cycle Cost (LCC) (Zhao et al., 2015). In industrial environment, traditional cost systems may cause significant cost distortions and lead to poor results, as well as all overhead costs are allocated to products on the basis of a single cost driver that is closely related to production volume (Yang et al., 2016). In addition to traditional costing system, Activity-Based Costing (ABC) has become a popular cost estimation method in manufacturing environment, due to the improved accuracy of product cost information in activity level (Schulze et al., 2012). ABC method was introduced by Kaplan and Cooper in the 1980s, as an alternative to overcome the shortcomings of traditional cost accounting systems (Spedding and Sun, 1999). The main advantage of ABC in contrast to alternative accounting systems is that it can allocate the overhead costs of a company in proportion to an activity's direct costs (Langmaak et al., 2013). To this end, a significant amount of companies have adopted this method for product costing in both manufacturing and business applications, (Alexopoulos et al., 2016; Curran et al., 2004; Pantelakis et al., 2009; Pantelakis and Baxevani, 2002; Spedding and Sun, 1999; Tapeinos et al., 2012; Tsai and Lai, 2007), including the manufacturing of joint products

[1] Publicly Available Specification (PAS) 2050 specifies requirements for the assessment of the life cycle GHG emissions of goods and services based on key life cycle assessment techniques and principles. This PAS is applicable to organizations assessing the GHG emissions of products across their life cycle, and to organizations assessing the cradle-to-gate GHG emissions of products (BSI, 2011).

(Tsai, 1996). The wide range of applications is the outcome of the benefits resulting from the use of the method. Indeed, according to Tsai et al. (2013), there are four key benefits in the ABC method:

1. accurate identification of product cost, especially overheads,
2. more precise information about value-added and non-value-added costs via the identification of cost drivers,
3. direct allocation of costs to products or processes that consume resources, and
4. identification of non-value-adding costs.

By taking into consideration Figure 4 (Tsai and Lai, 2007), it is necessary to adopt a two-stages procedure for the allocation of resources to cost objects. Initially, the resources are assigned to activities by using the resource drivers (factors which are used to measure the consumption of resources by the activities) and then, resources traced to each activity become cost elements. The activity cost pool is composed by a set of cost elements, while the cost of activity center / or sub-process is composed by related activities/ or activity cost pools. In the second stage, the cost elements of each activity are divided to cost objects, by using the activity drivers (factors which are used to measure the consumption of activities by the cost objects).

By following a bottom-up analysis, each manufacturing process was divided in multiple sub-processes and consequently each sub process was divided in multiple activities. Finally, to be aligned with the guidelines of ABC method, the resources have been identified, as well as the resource and activity drivers which were necessary for the cost assignment.

3.1.2 Cost calculation methodology

The comparison between the LBW and the riveting processes in terms of manufacturing cost, was conducted through the development of a cost model which is based on the ABC method. The model can estimate the total manufacturing cost of both manufacturing processes in activity level. All the neccessaray equations that were used for the calculation of total manufacturing cost are described in detail, in this section, while all equation elements units of measurement are defined at the Nomenclature section (Table 4).

Before presenting the equations, it is worth mentioning that specific assumptions have been taken into consideration in order to reflect typical industrial conditions. According to Alexopoulos et al. (2016), the assumptions that have been adopted are as follows: a) one year comprises of 227 working days, one working day counts for 7.5 working hours (one shift), and the employer's contribution (e.g. insurance cost) on gross salary is 35%, b) the depreciation period for industrial equipment is 10 years, and finally, c) a serial asynchronous production line for the manufacturing of panels is followed, which means that the work stations/sub processes are independent (can run in parallel), so their operation in not coordinated. The smooth operation of a serial asynchronous production line requires the existence of available physical space (buffer) for the temporary storage of semi-final panels (Urban and Chiang, 2016). Last but not least, it is worth mentioning that the collection of primary data, such as the operating time of equipment, as well as the working times of employees, were defined with direct observation and timing of the cycle work by engineers.

By taking into account the ABC method specificities as well as the aformentioned assumptions, a number of mathematical equations were developed in order to estimate the total manufacturing cost for the two manufacturing processes under investigation. More specifically, based on eqn 1, the total manufacturing cost (*TMC*) per manufacturing process consists of the following components: energy consumption (*EC*), material (*MC*), labor cost (*LC*), and depreciation charge (*DC*) of used fixed assets. However, in this case study the depreciation charge has not taken into account, for the calculation of total manufacturing cost, as the equipment used for the manufacturing of riveted aeronautical subscale components has already been depreciated. On the other hand, we have examined the impact of depreciation cost to the total manufacturing cost, for the case of the laser beam welded aeronautical subscale components

$$TMC = EC + MC + LC + DC, \tag{1}$$

The energy component (*EC*) depends on the energy consumption of the equipment that used for the manufacturing processes of the aeronautical subscale components. The energy cost from the operation of equipment is calculated according to the formula:

$$EC = EC_{\mathrm{PR}} + EC_{MP} = \left(\sum_{\mathrm{i}=1}^{n} IC_{\mathrm{PRi}} \cdot PC_{\mathrm{PRi}} \cdot T_{\mathrm{PRi}} + \sum_{\mathrm{j}=1}^{k} IC_{\mathrm{MPj}} \cdot PC_{\mathrm{MPj}} \cdot T_{\mathrm{MPj}}\right) \cdot CE\ , \tag{2}$$

where EC_{PR} is the energy cost for the first sub process (preparation), EC_{MP} is the energy cost for the second sub process (main process), IC_{PRi} is the installed capacity at the i machine/equipment of first sub process (in kWh), PC_{PRi} is the capacity range percentage of the i machine/equipment of first sub process, T_{PRi} is the operating time of i machine/equipment of first sub process (in hours). IC_{MPi}, PC_{MPi} and T_{MPi} are the corresponding equation elements for the main process (second sub process), while *CE* is the cost of electricity (in €/kWh).

The first sub process of LBW process includes four machines; a sheat cutting machine and a circualar saw machine is used for the cutting of skin and stringers, while a grinding belt machine and a CNC milling machine are necessary for the final grinding of skin and the surface finishing of stringers, respectively. During the second sub process, only the equipment of laser beam welding system consumes energy. The LBW system includes a vacuum system, laser heads, a mobile laser beam welding frame, CO_2 laser coolers, as well a control room with electrical monitoring devices.

When compared to the LBW manufacturing process, the first sub process of riveting process requires a shear cutting machine for the cutting of skin, a CNC milling machine, for the milling and drilling of stringers, a vibrating tank for the deburring of stringers, an electric drill for the V-grooving of stringers' holes, as well as a freezer, a furnace and heat elements for the heat treatment of intermediate rivets. In contrast to the LBW process, the second sub process of riveting process includes less energy demanding equipment. Indeed, the main process requires a conventional riveting machine for the intermediate rivets and a special riveting machine for the lock bolts rivets. The material cost depends on the characteristics of materials as well as the cost of consumables used on each manufacturing process. Thus, the energy cost for both joining technologies can be calculated by exploiting eqn 3:

$$MC = MC_{\mathrm{PR}} + MC_{MP} = \left(\sum_{\mathrm{i}=1}^{n} W_{\mathrm{PRi}} \cdot P_{\mathrm{PRi}} + TC_{\mathrm{PR\_CONS}}\right) + \left(\sum_{\mathrm{j}=1}^{k} W_{\mathrm{MPj}} \cdot P_{\mathrm{MPj}} + TC_{\mathrm{MP\_CONS}}\right), \quad (3)$$

where MC_{PR} is the material cost for the first sub process (preparation), MC_{MP} is the material cost for the second sub process (main process), W_{PRi} is the weight of material i which is used during the first sub process (in kg), P_{PRi} is the purchase price of material i (in €/kg), $TC_{\mathrm{PR\_CON}}$ is the total cost of consumables which is used during the first sub process (in €), while, W_{MPi}, P_{MPi} and $TC_{\mathrm{MP\_CON}}$ are the corresponding equation elements for the main process (second sub process). A detailed analysis for the materials used for the two investigated manufacturing processes, are provided in section 2.1.

The level of automation in a manufacturing processes has a significant impact in the final definition of the labor cost, which is calculated based on the formula shown below:

$$LC = LC_{\mathrm{PR}} + LC_{MP} = (TH_{\mathrm{PR}} \cdot CH\_T + STH_{\mathrm{PR}} \cdot CH\_ST) + (TH_{\mathrm{MP}} \cdot CH\_T + STH_{\mathrm{MP}} \cdot CH\_ST + ENGH_{MP} \cdot CH\_ENG) \quad (4)$$

where LC_{PR} is the labor cost for the first sub process (preparation), LC_{MP} is the labor cost for the second sub process (main process), TH_{PR} is the technician's labor hours for the first sub process (preparation), CH_T is technician's labor cost per hour, STH_{PR} is the skilled technician's labor hours for the first sub process (preparation), and CH_ST is the skilled technician's labor cost per hour. Furthermore, TH_{MP}, STH_{MP}, are the corresponding equation elements for the main process (second sub process). In addition, $ENGH_{\mathrm{MP}}$ is the enginner's labor hours for the main process (second sub process) and CH_ENG is the engineer’s labor cost per hour. Finally, the depreciation charge of fixed equipment comprises of a significant cost which it is necessary to be allocated in the total cost of final products that can be calculated by using eqn 5:

$$DC = TC_{\mathrm{EQUIP}}/(DP \cdot N_{\mathrm{PS}}) \, , \tag{5}$$

where, TC_{EQUIP} is the purchase price of equipment for each manufacturing process (in €), DP is the depreciation period (in years) and N_{PS} is the annual production rate for the investigated aeronautical subscale components.

3.2. Carbon footprint calculation

3.2.1 The PAS 2050 standard

Carbon dioxide (CO_2) is the main Green House Gas (GHG) emitted by powered aircrafts. More specifically, aircraft emissions contribute negatively to climate change by increasing the concentrations of GHGs in the atmosphere (Anger, 2010), which depend on the fuel use. According to Grote et al. (2014), the engines of aircrafts, consume in excess of 5 million barrels of oil in a daily basis, as the resulting CO_2 emissions emitted by aircraft engines is of concern. Indeed, aviation emissions have been increased considerably, from 1940 until today and currently the sector accounts for 4.9 % of total worldwide emissions (Lee et al., 2009). By taking into account that the commercial fleet is going to be doubled in size from 19,890 airplanes today to 39,780 by 2031 (Boeing, 2012), due to the increase in demand for air transport, it is evident that the aviation emissions will be increased tremendously, if the aircraft industry does not use innovative manufacturing processes and new recyclabe materials, in order to produce more sustainable aircrafts.

Since sustainability is of great concern during the manufacturing process, we evaluated the environment impact of LBW and riveting processes. For the assessment of a manufacturing process in terms of environmental impact, a series of parameters such as, Acidification, Photochemical ozone, Eutrophication, etc. (European Union, 2010) can be taken into consideration, but in our case, we decided to use the GHG emissions, since it is one of the most common parameter for product life cycle assessment (LCA). To this end, we calculated the carbon footprint for both manufacturing processes by following the guidelines of the Publicly Available Specifications (PAS) 2050 standard. The PAS 2050, builds on the existing ISO 14040 and 14044 standards for product life cycle assessment (LCA) and further specifies them for the evaluation of the GHG emissions of goods and services (BSI, 2011). By monitoring the

GHG emissions during the manufacturing proces, a company have the ability to develop measures in order to minimize emissions across the entire supply chain.

By taking into consideration the guidelines of the PAS 2050, we identified four basic steps for calculating the carbon footprint of a product. More specifically, the first step deals with the building of a high-level process map which is necessary to include all materials, activities and processes that contribute to the chosen product's life cycle. During the second step, all the relevant boundaries for the carbon footprint analysis must be determined. The key principle for system boundaries is to include all "material" emissions generated as a direct or indirect result of a chosen product being produced. The third step aims to the collection of more specific data following the requirements and recommendations of the PAS2050 standard, which enable the assessment of the carbon footprint in more detail. Two types of data are necessary to calculate the carbon footprint: a) activity data and b) emission factors. Activity data refers to all the material and energy amounts involved in the product's life cycle, whereas, emission factors provide the link that converts these quantities into the resulting GHG emissions: the amount of greenhouse gases emitted per 'unit' of activity data. Finally, the last step is related to the development of the necessary equation for the carbon footprint calculations per activity.

3.2.2 Carbon footprint calculation methodology

The carbon footprint emissions is the basic criterion for the environmental evaluation of the two investigated manufacturing processes. To this end, following the guidlines of the PAS2050 standard, we have calculated the carbon footprint emitted during the manufacturing phase of the two investigated joining technologies ("door to door" approach) and without taking into consideration prior or following phases of the supply chain.

Because of the direct depedence of carbon footprint emissions to the energy consumption of manufacturing processes, it is observed that energy cost and carbon footprint are linearly dependent. Indeed, in the case of energy cost, the energy consumption is multiplied by the cost of electricity, whereas in the case of carbon footprint emissions, the energy consumption is multiplied by the emission factor. Thus, the carbon footprint is calculated as an energy metric, as it can be seen in eqn 6:

$$CF = CF_{\mathrm{PR}} + CF_{MP} = \left(\sum_{\mathrm{i}=1}^{n} IC_{\mathrm{PRi}} \cdot PC_{\mathrm{PRi}} \cdot T_{\mathrm{PRi}} + \sum_{\mathrm{j}=1}^{k} IC_{\mathrm{MPj}} \cdot PC_{\mathrm{MPj}} \cdot T_{\mathrm{MPj}}\right) \cdot EF \,, \qquad (6)$$

where, CF_{PR} is the carbon footprint for the first sub process (preparation), CF_{MP} is the carbon footprint for the second sub process (main process) and EF is the emission factor. In this study, the emmision factor used for the carbon footpring is based on the German electric grid.

4. Results and discussion

In this section, a comparison between the two manufacturing processes takes place. In order to conduct an integrated comparison, we take into account four criteria that are related to: a) the weight of panels, b) the lead processing time, c) the manufacturing cost and, d) the CO_{2e} emissions during the manufacturing process of aeronautical panels. The evaluation results of both manufacturing processes are presented below.

4.1. Weight comparison

The weight calculations for the six different aeronautical subscale components are based on the geometrical dimensions of the examined panels, as well as on the density and the corresponding amount of the involved materials. By considering Figure 5, we argue that the LBW structures, made of innovative materials are lighter, when compared to the riveted structures, which incorporate conventional aluminum alloys. In the A1, B1, and C1 cases where the thickness of skins is 3.2 mm, the weight savings is almost 20 %, while in the A2, B2 and C2 cases where the thickness of skin is 1.6 mm, the corresponding saving is 28 %, respectively. Factor such as: a) the lower density of the innovative Al-Cu-Li alloys, b) the absence of sealants, intermediate rivets and lock bolts rivets of the laser beam welded component, c) and the “L” shape stringers used, instead of the “Z” shape stringers have a significant effect on the component’s weight due to less material used, resulting in such noticeable weight difference. It is also worth mentioning that if the proposal of Dittrich et al., (2011) for lower thickness of skin (from 3.2 mm to 1.6 mm) is adopted, then the manufactured structures can be lighter (up to 33 %) and more sustainable, since the production of lighter weight aircrafts, will reduce the fuel usage and therefore, the GHG emissions respectively.

4.2. Process duration comparison

The results which are presented below take into account the standard time for each activity which, according to Zandin (2001), refers to the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method. The standard time is calculated as the product of observed time, the performance rating factor and the personal, fatigue, and delay (PFD) allowance. By adopting the aforementioned methodology, we have estimated the cycle time for the preparation and the manufacturing of the aeronautical panels under investigation.

Figure 6 shows the process duration results, where it is obvious that the LBW process is less time consuming, when compared with the riveted process. The time savings for the LBW process varied between 51% and 67%, for all the investigated scenarios. This difference is due to the activities 1.2 and 1.4 respectively of the riveting process, which deal with the drilling, V-grooving and the additional configuration of skins and stringers. Indeed, the large duration of these activities, due to the intensive labor work, in combination with the absence of these activities from LBW process, are the principal reasons for this noticeable difference. Furthermore, by observing the results of the calculations performed, it is worth mentioning that there is a noticeable difference, when structures B (B1, B2) and C (C1, C2) are compared in terms of process duration. In specific, the process duration for the manufacturing of LBW structures C1 is 0,35 hours less, when compared with the corresponding riveted structure C1. Similarly, the difference for the LBW structure B1 is 1,34 hours less than the riveted B1, while the difference for the corresponding structures C2 and B2 is almost the same with the structures C1 and B1. These two structures (B and C) cover the same surface (almost 0.57 m^2), but have different geometrical dimensions, as well as different count of stringers. This means that in the case of structures with eight stringers (B1 and B2) the set-up movements of laser heads are eight, whereas in case of longer structures with four stringers (C1 and C2) the corresponding movements are only four. Thus, it is evident that the process duration for the latter case is reduced, while a better utilization of the laser heads speed is achieved.

Additionally, when comparing the LBW structures A1 with B1 and A1 with C1 respectively, it can be observed that the manufacturing process of longer LBW structures is less time consuming (almost 63 %), than the corresponding structures which are double in width and have bigger count of stringers. Indeed, for the LBW structure B1, the process duration is 93% more than the LBW A1, while the corresponding difference is almost 30 %, when a comparison between A1 and C1 takes place. So, it is resulted that the LBW technology can provides high volumes of stiffened panels (structures) when deals with long structures which have small count of stringers.

By taking into consideration the cycle time per sub process as well as the constraints of the two manufacturing processes, we have calculated the annual production rate per aeronautical panel and per manufacturing process, using three hypothetical scenarios. The first scenario presents the annual production rate using only one shift per working day, the second includes two shifts per working day, while the last includes three shifts per working day. Table 5 provides a detailed presentation of results obtained concerning the three scenarios. As it can be seen, even though the LBW process has less time-consuming sub processes, yet it has a lower annual production rate, for the first two structures. In particular, in case of structure A, the production rate for the LBW structures is lower by 25% for the first scenario, 17% for the second and 15% for the third scenario when compared with the corresponding riveted structures. On the contrary, the percentages for the case of structure B are 13% for all the investigated scenarios. This is because during the sub process "II" of the LBW process only one panel can be produced, so the welding of the next panel cannot be started, until the welding of the last panel is completed. On the contrary, during the sub process "II" of the riveting process more than one panel can be manufactured simultaneously. Indeed, during the main process one panel can be prepared for riveting, while another may be riveted with intermediate rivets and a third one can be riveted with lock bolts rivets at the same time. Therefore, during the riveting process most activities can run in parallel. As for the third long structure, it seems that a higher annual production rate can be achieved by adopting the LBW process. To this end, it is worth mentioning that for the third scenario, the LBW structures which are produced on an annual base, are higher by 147% than the corresponding riveted structures. In this case, the difference of annual production rate between the two joining technologies seems noticeable, since manufacturing of long welded structures embraces a better use of the laser equipment.

4.3. Cost comparison

Figure 7 shows the indicative calculated energy cost which is required during the manufacturing of the six structures by the LBW and riveting processes. As it can be seen, the LBW process includes energy demanding activities, which increase the total energy cost of the innovative joining technology. This difference is noticeable for structure B, since the energy cost of the LBW process is higher by 122 % for structure B1 and 124 % for structure B2, when compared with the conventional joining technology. The main reason for this high difference is the high energy consumption of LBW equipment. Also, it is worth mentioning that a small reduction in energy cost has been observed for LBW structures B2 and C2, when compared with the corresponding riveted structures, because of the lower energy consumption which is observed during the joining of the airframes. In the case of structures B1 and B2, this difference is almost 2 %, while for structures C1 and C2 the corresponding difference is just 1 %. It is evident that lower thickness skin requires lower power of laser heads during the welding, to avoid damage to the skin. As a final point, based on our calculation, for the case of riveted process, no essential energy savings can be observed from the extrapolation to double size structures, while for the case of the LBW process, the manufacturing of the LBW structure C (C1 and C2) requires almost 28 % less energy cost than the manufacturing of the LBW structure B (B1 and B2), for all investigated scenarios.

Figure 8 shows that the material cost of the LBW structures is lower, when compared with the respective cost of the riveted structures, despite the higher purchase price of the Al-Cu-Li alloys. This difference is higher for the structures with a thickness of 1.6 mm. In specific, the material cost of the LBW structures is lower by 32 % for the structure A2, 34 % for the structure B2 and 33 % for the structure C2, when compared with the corresponding riveted structures. This is mainly due to the high material cost of intermediate rivets, sealants and lock bolts contrasting the filler wire and protective welding gas (Helium) which present lower cost. More specifically, by adopting the LBW process the material cost can be reduced up to 11 % for skin with thickness 3.2 mm, while the corresponding reduction is at least 32 %, when exploiting the lower skin thickness. Considering the geometrical dimensions of structures, it seems that the long structures with 4 stringers (C1 and C2) have lower material cost, than structures with smaller length and eight stringers (B1 and B2). This is due to the fact that in the case of riveted structures, less lock bolts rivets (the cost of lock bolts rivets is higher, when compared with the respective cost of intermediate rivets) are used, while in the case of LBW structures a smaller number of excess stringers goes to scrap.

Considering the labor hour for each type of worker as well as the corresponding labor cost per hour, we have calculated an indicative labor cost which is required for the manufacturing of the six aeronautical panels (Figure 9). The results show that the labor cost for the riveting process is higher (up to 32 %) than the corresponding cost of LBW process. In particular, the reduced labor cost for the LBW structure A1 is 35 %, for the A2 is 34 % and for the A3 is 35 %, when compared with the corresponding riveted structures. Regarding structures A2, B2 and C2 the savings amount to 34 %, 32 %, and 52 %, respectively. This is expected since the riveting process is labor intensive, requiring several manual labor hours, while the LBW process is semi-automated and thus it requires less labor hours. When comparing the labor cost for the aeronautical structures with different thickness of skin, the results show that structures with lower skin thickness require lower labor cost. This is mainly due to the fewer labor hours which are required during the preparation of raw materials, as well as the standard time for the drilling of a skin with thickness 3.2 mm which is more than the corresponding activity for the lower skin thickness. Also, comparing the LBW structures A (A1 and A2) with C (C1 and C2), it seems that the manufacturing of a structure with double surface requires almost 20 % more labor cost, while comparing the LBW structures A (A1 and A2) with B (B1 and B2), the corresponding percentage exceeds 50 %, for all investigated scenarios.

As mentioned above, since the equipment used for the riveting process has already been depreciated and considering that the depreciation cost for LBW process is high, we decided to examine the impact of depreciation cost to the total manufacturing cost of structures, separately. To this end, we have calculated the total manufacturing cost by taking into account the energy, material and labor cost. Figure 10 depicts the total manufacturing cost per square meter for the six aeronautical panels. As it can be seen, the riveted panels are more expensive when compared with the corresponding LBW panels, while the highest contribution on the total manufacturing cost is made by the material cost, followed by the labor and energy cost, respectively. When taking into consideration the six investigated structures, it is evident that for the cases that the thickness of structures is 3.2 mm, the LBW process is cheaper by 20 to 27 % than the corresponding conventional manufacturing process. Nevertheless, in case the thickness of structures is 1.6 mm the innovative joining technology seems to be more competitive by 32 to 40 %, than the riveting process. More specifically, the LBW structure C1 is more cost effective than the LBW structure B1, because provides double structures' surface with almost 14 % less manufacturing cost. Similarly, the corresponding difference between the LBW structures C2 and B2 is up to 18 %. To this end, considering the aforementioned results, it is evident that the aviation industry can achieve essential cost savings, by implementing the LBW joining technology to long structures (i.e. structures C1 and C2).

By taking into account the above evaluation of manufacturing processes, it is concluded that structure C2 with nominal dimensions 1484 mm x 384 mm x 1.6 mm is the ideal solution for mass production in industrial conditions. To this end, we have examined the impact of depreciation cost to its total manufacturing cost, to evaluate the competitiveness of the innovative joining technology in industrial conditions. Because of the high investment cost for LBW equipment, it is vital to investigate whether a high production rate can reduce the total manufacturing cost per aeronautical structure, thus achieving economies scale. Based on the annual production rates that are presented in Table 5, we have calculated the depreciation cost for three hypothetical scenarios. The results obtained, are presented in Figure 11. During the first scenario which embraces an annual production rate of 1135 panels, the depreciation cost impacts the total manufacturing cost by almost 370 €. If the shifts per working day are two, the annual production rate is 2270 panels, while the corresponding depreciation cost per panel is almost 210 €. Finally, the last scenario includes three shifts per working day. In this case the annual production rate is increased further, reaching 3405 panels, whereas the depreciation cost is reduced by 135 € resulting in a decrease of the total manufacturing cost of LBW panel almost by 75 €.

4.4. Carbon footprint comparison

Following the guidelines of PAS 2050 standard, we have calculated the equivalent carbon dioxide (CO_{2e}) emissions for the two manufacturing processes, in order to examine the environmental friendliness of the two technologies that may ensure a sustainable life cycle of the final product. Figure 12, shows that the environmental impact of the LBW process is higher, when compared with the corresponding riveting process, because of the high energy consumption of LBW equipment. GHG emissions were calculated based on the "door to door" approach, i.e. the carbon footprint of the manufacturing processes that are being performed within the industry. To this end, higher GHG emissions of the LBW structures were expected due to the stage II of the process that is the laser beam welding itself. It is well known that this stage is energy demanding process. Nevertheless, the results of a previous study (Alexopoulos et al., 2016a) have shown that the LBW structure is more environment friendly, in the present article it is observed that in industrial conditions, a higher amount of equivalent carbon dioxide (CO_{2e}) emissions is emitted during manufacturing such LBW structures. In our previous study we examined the economical and environment impact during the manufacturing of a single structure (laboratory scale) in terms of serial production, while in the present work we have examined the corresponding impact for mass production. To this end, in the first case the set-up costs and emissions were allocated only in one structure, while in the second case the corresponding cost as well as the CO_2 emissions of each activity have been divided into several structures.

In terms of CO_{2e} emissions, the extrapolation to double size structures (from A to B and from A to C) is almost the same for the riveted process, while for the LBW process the manufacturing of structure C emits almost 28 % lower CO_{2e} emissions than the structure B. More specifically, during the manufacturing of LBW structures A1, B1 and C1 an increased amount of carbon footrpint (i.e.114 %, 124 % and 61 % respectively) is emitted, when compared to the corresponting riveted structures. Similar results are derived for the structures A2, B2 and C2 respectively. By comparing the structures in terms of carbon footprint, we can observe that the structure C2 has the smallest environmental impact. Indeed, during its manufacturing process 13.137 kg CO_{2e} is emitted for the case of riveting process, while 21.020 kg CO_{2e} is emitted for the LBW process. Nevertheless, it is notable to mention that although the LBW process is less environmental friendly, it creates lighter components that when used in aircrafts can minimize fuel consumption, thus in terms of product life cycle assessment, LBW is a sustainable manufacturing process.

The last part of this discussion deals with the effect of the different materials on the GHG emissions. In the present article, the GHG emissions were calculated based on the manufacturing processes only, and therefore in the present article the exploitation of different materials affects the manufacturing costs only (that include purchase cost) and not the GHG emissions. A complete life cycle assessment of the investigated aircraft sub-components will be calculated on a follow-up article of the authors.

5. Conclusions

The findings of the present work can be summarized below as follows:

1. Exploitation of the laser beam technology in manufacturing aeronautical subscale welded components can provide weight savings up to 28 %, when lower density Al-Cu-Li alloys are being used.
2. Time savings during LBW manufacturing process can be up to 67 %, especially for the welded structures with long welded seams.
3. LBW process seems to be more energy demanding than the respective riveting process. Welding of structures with long seams reduces the demanded energy by almost 60 % (i.e. comparison of C1 and C2 structures). LBW structures with double welded length (i.e. C1 and C2) require almost 28 % less energy cost than the corresponding structures (i.e. B1 and B2) with more stringers. Welding of long seams is essentially encouraged to avoid the set-up time of the new stringers to be welded.
4. Labor cost is significantly lower (up to 32 % for all the investigated structures) than the corresponding cost of riveted structures; this can be explained by the fact that riveting requires more manual labor hours than the LBW process which is semi-automated. Production of long LBW structures can reduce labor cost up to 20 % for structures with thickness 3.2 mm, while the benefits can be even higher (up to 50 %) for the low thickness investigated.
5. Material cost for the LBW structures is 12 % lower on average than the riveted structures, while this difference is up to 32 %, when the structures with a thickness of 1.6 mm are considered.
6. Total manufacturing cost can be reduced up to 40 % for the case of long structures with low thickness (structure C2) investigated. However, if depreciation cost of the LBW infrastructure is considered, then this technology turns to be more expensive than the traditional riveting technology.
7. Double in length LBW structures emit 28 % less CO_{2e} emissions than the corresponding double in width structures and this is dealing with preparation and set-up of the laser welding process.
8. LBWed structures seems to emit more CO_{2e} emissions during their manufacturing process than the respective riveted; however, when considering the life cycle of aircrafts, the laser beam technology can essentially contribute to decrease CO_2 emissions and therefore considered as a more cleaner technology. The presented technology can essentially contribute to manufacture light-weight components, therefore lower fuel consumption can be achieved and in this way the environmental impact and GHG emissions of aircrafts can be essentially reduced.

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List of tables

Table 1. Characteristics and schematic representation of aeronautical subscale components

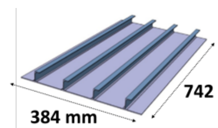
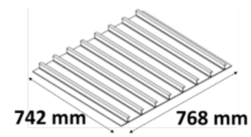
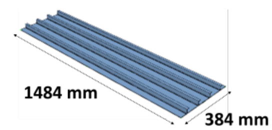
Structure	Length (mm)	Width (mm)	Thickness (mm)	Count of Stringers	Photo
A1	742	384	3.2	4	
A2			1.6		
B1	742	768	3.2	8	
B2			1.6		
C1	1484	384	3.2	4	
C2			1.6		

Table 2. Chemical composition (wt %) of the used aluminum alloys

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ag	Li	Zr	Al
AA2196 (stringer)	0.03	0.06	2.88	0.32	0.34	0.01	0.02	0.02	-	1.7	0.11	bal.
AA2198 (skin)	0.03	0.05	3.33	0.03	0.32	0.05	0.02	0.02	0.27	0.98	0.14	bal.
AA4047 (filler wire)	12.0	0.8	0.3	0.15	0.1	-	0.2	-	-	-	-	bal.

Table 3. Possible defects (risks) during manufacturing of the stiffened panels

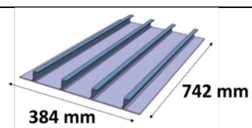
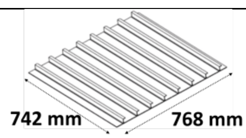
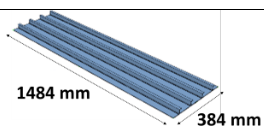
Process	LBW Activity	Description of defects (risks)	Estimated Initial Risk		
Preparation	Activity 1.3	During the sheet's surface finishing, there is a possibility the grinding depth to be higher than the expected.	Low	**Medium**	High
	Activity 1.4	During the surface finish of the stringer, there is a possibility the milling depth and height to be higher than it is expected because of the stringers fixation on CNC milling machine.	Low	**Medium**	High
	Activity 1.5	Long time exposure of the skin/stringers to atmospheric conditions after the cleaning process.	Low	**Medium**	High
Main Process	Activity 2.1	While the sheet positioning on the vacuum table, the two sheet sides are not perpendicular to the vacuum table.	Low	**Medium**	High
	Activity 2.3 (2.4, 2.5, 2.6)	During the placement of the stringer on the top of skin's surface, there is a possibility the stringer to be placed in a misaligned position before being LBWed.	Low	Medium	**High**
	Activity 2.3 (2.4, 2.5, 2.6)	If the filler wire spools are exposed for long time to atmospheric conditions, there is a possibility for surface oxide layer to be formed on the filler wires.	Low	Medium	**High**
	All activities	During the LBW process, there is a possibility the vacuum system to fail.	Low	**Medium**	High

Table 4. Nomenclature

Symbol	Description
CE	cost of electricity (in €/kWh)
CF	carbon footprint emissions (in kg)
CF_{MP}	carbon footprint for the second sub process (main process)
CF_{PR}	carbon footprint for the first sub process (preparation)
CH_ENG	engineer's labor cost per hour
CH_ST	skilled technician's labor cost per hour
CH_T	technician's labor cost per hour
DC	depreciation charge
DP	depreciation period (in years)
EC	energy cost
EC_{MP}	the energy cost for the second sub process (main process)
EC_{PR}	energy cost for the first sub process (preparation)
EF	emission factor
$ENGH_{MP}$	engineer's labor hours for the main process (second sub process)
IC_{PRi}	installed capacity at the i machine/equipment of first sub process (in kWh)
IC_{PRj}	installed capacity at the j machine/equipment of second sub process (in kWh)
LC	labor cost
LC_{MP}	labor cost for the second sub process (main process)
LC_{PR}	labor cost for the first sub process (preparation)
MC	material cost
MC_{MP}	material cost for the second sub process (main process)
MC_{PR}	material cost for the first sub process (preparation)
N_{PS}	annual production rate
PC_{PRi}	capacity range percentage of the i machine/equipment of first sub process
PC_{PRj}	capacity range percentage of the j machine/equipment of second sub process
P_{PRi}	purchase price of material i (in €/kg)
P_{PRj}	purchase price of material j (in €/kg)
STH_{MP}	skilled technician's labor hours for the second sub process (main process)
STH_{PR}	skilled technician's labor hours for the first sub process (preparation)
TC_{EQUIP}	purchase price of equipment for each manufacturing process (in €)
TC_{MP_CON}	total cost of consumables which used during the second sub process (in €)
TC_{PR_CON}	total cost of consumables which used during the first sub process (in €)
TH_{MP}	technician's labor hours for the second sub process (main process)
TH_{PR}	technician's labor hours for the first sub process (preparation)

TMC	total manufacturing cost
T_{PRi}	operating time of i machine/equipment of first sub process (in hours)
T_{PRj}	operating time of j machine/equipment of second sub process (in hours)
W_{PRi}	weight of material i which used during the first sub process (in kg)
W_{PRj}	weight of material i which used during the second sub process (in kg)

Table 5. Annual production rate per aeronautical structure for laser bean welding and riveting processes.

Structure	Shifts per working day	Annual production rate: LBW structures	Annual production rate: Riveted structures	Difference: LBW – Riveted structures
	1	1135	1507	-372
	2	2497	3012	-515
	3	3859	4519	-660
	1	681	780	-99
	2	1362	1561	-199
	3	2043	2342	-299
	1	1135	769	366
	2	2270	1541	729
	3	3405	2310	1095

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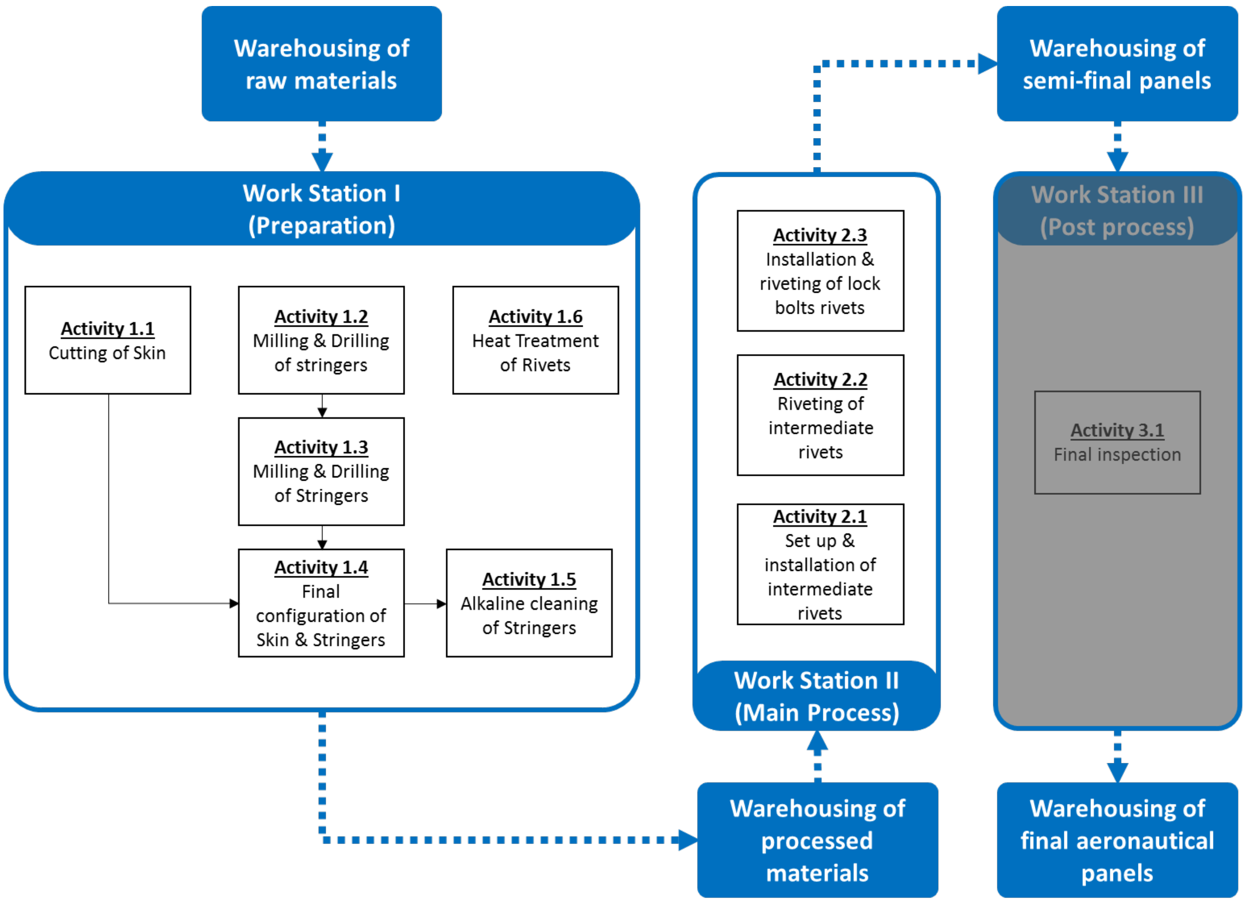

Fig. 1. Schematic flow diagram of the riveting process of the aeronautical subscale components.

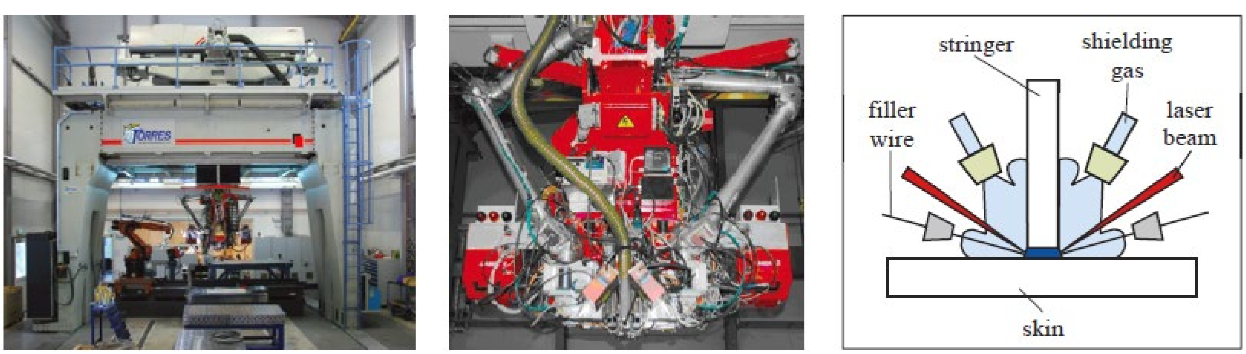

Fig. 2. (a) Laser welding facility; (b) laser processing head; (c) schematic diagram of the joint configuration. Source: (Enz et al., 2012)

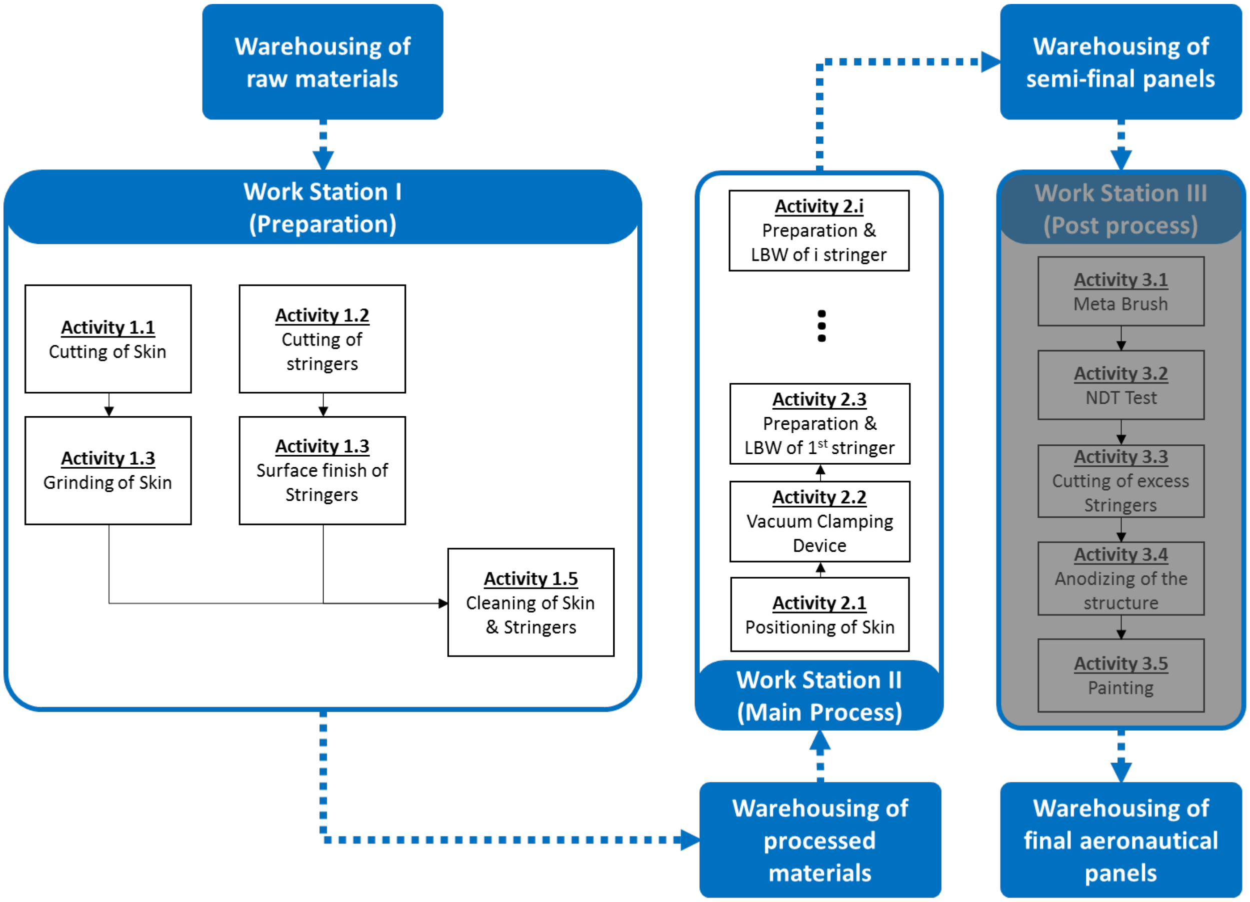

Fig. 3. Schematic flow diagram of the laser beam welding process of the aeronautical subscale components.

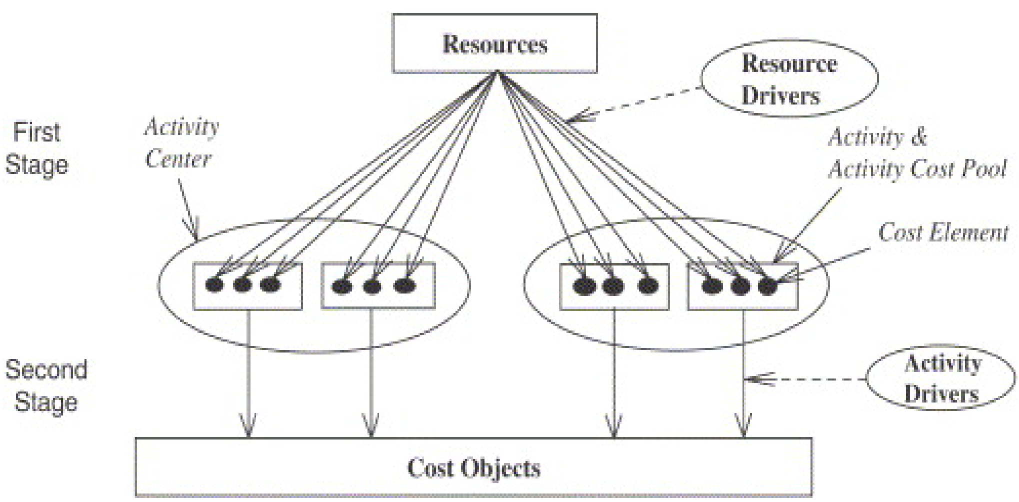

Fig. 4. Cost assignment view of Activity Based Costing (ABC) method. Source: (Tsai and Lai, 2007)

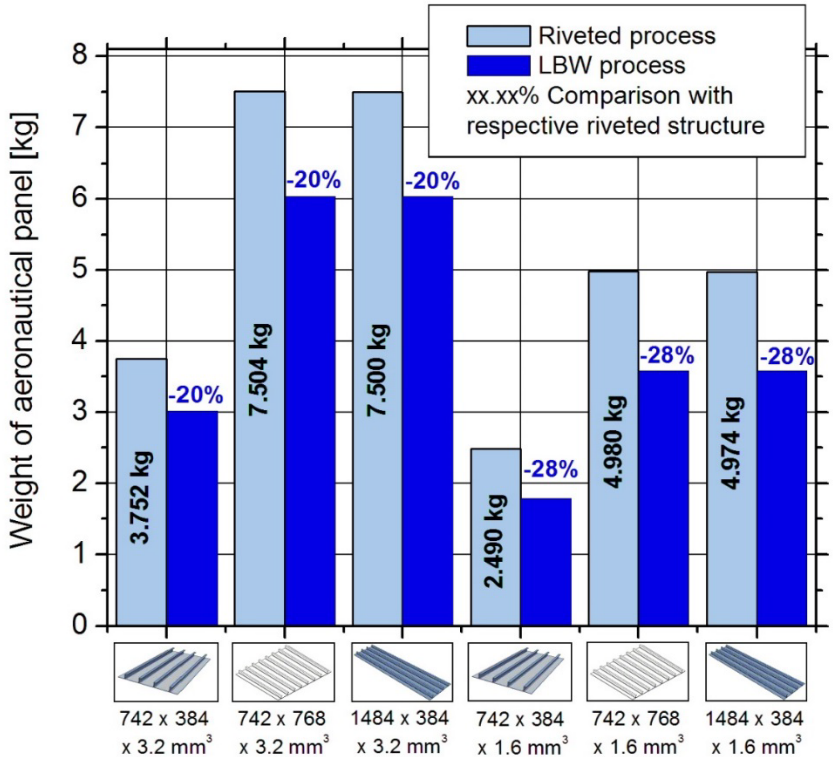

Fig. 5. Weight per aeronautical panel of the laser bean welding and riveting processes.

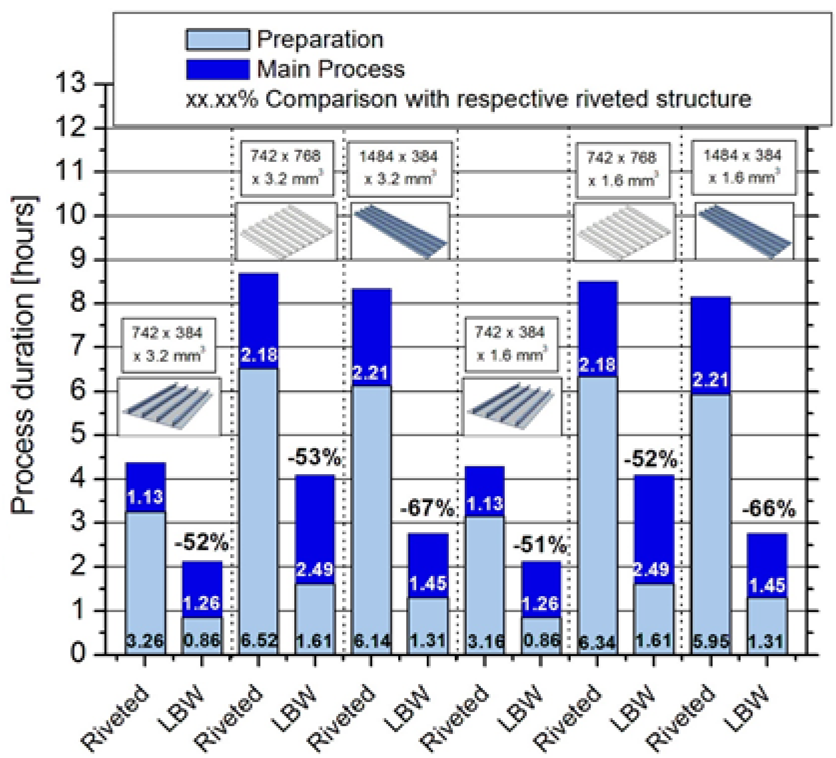

Fig. 6. Process duration per aeronautical panel per sub-process for laser bean welding and riveting processes.

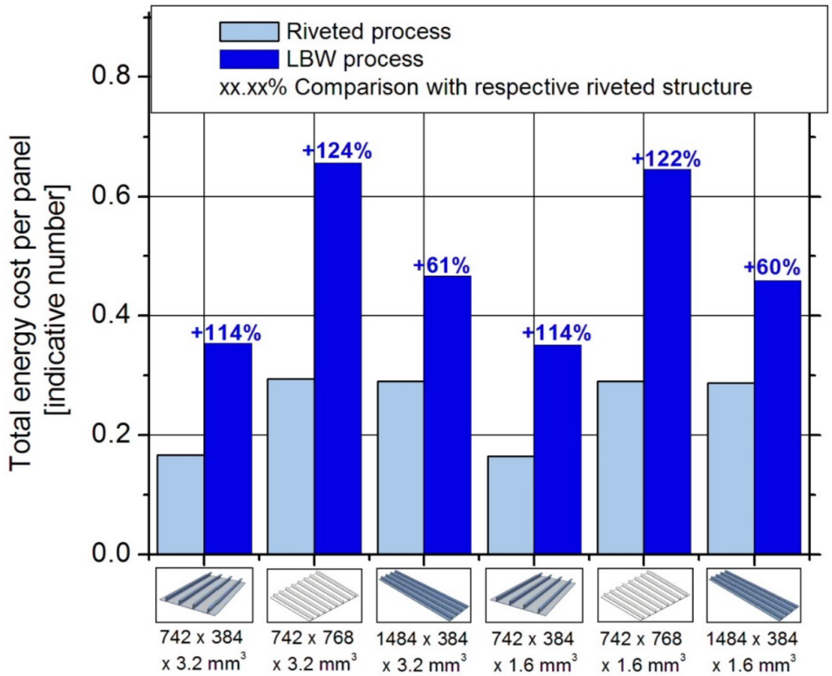

Fig. 7. Energy cost per aeronautical panel for laser bean welding and riveting processes.

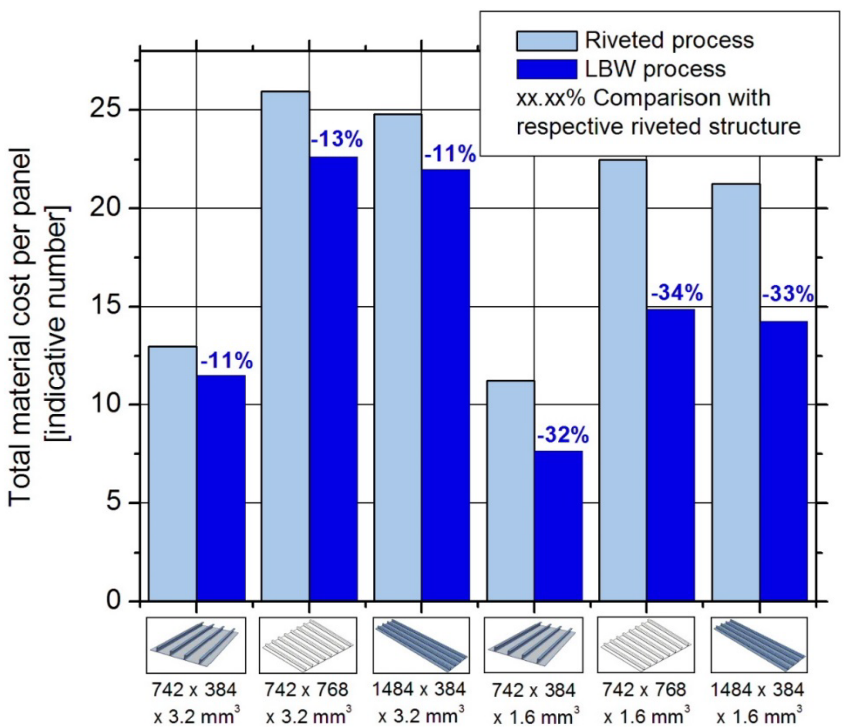

Fig. 8. Material cost per aeronautical panel for laser bean welding and riveting processes.

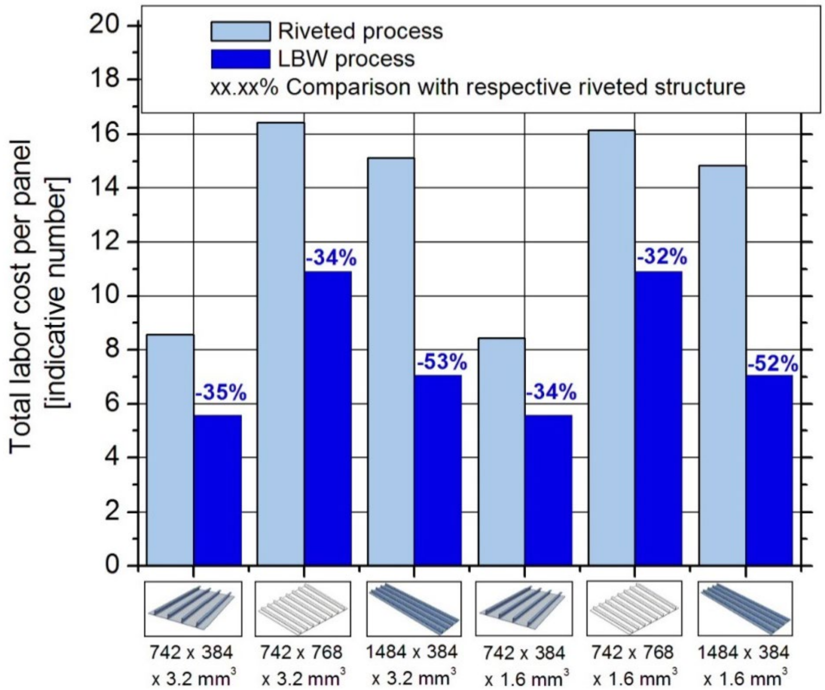

Fig. 9. Labor cost per aeronautical panel for laser bean welding and riveting processes.

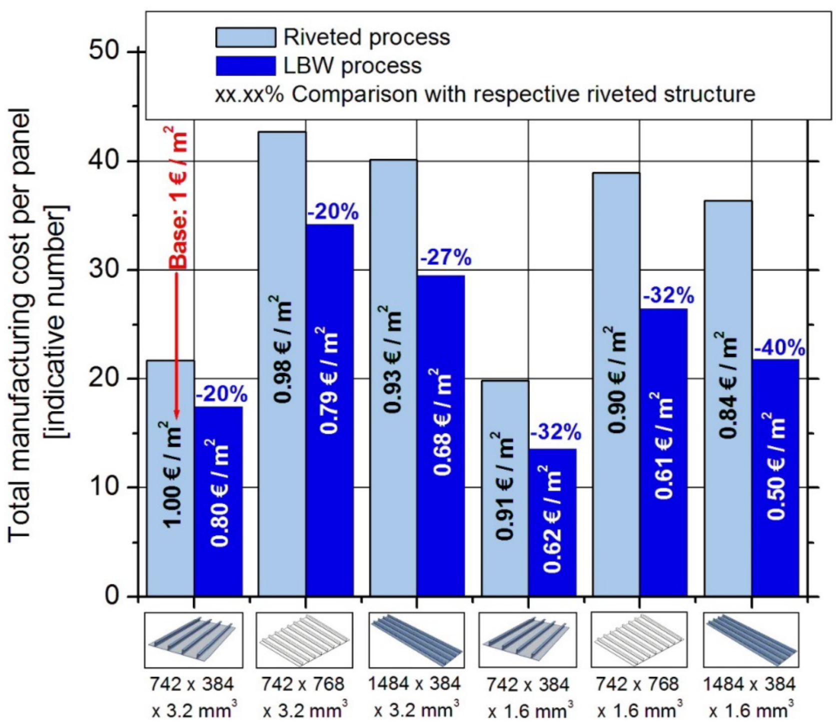

Fig. 10. Total manufacturing cost per aeronautical panel for laser bean welding and riveting processes.

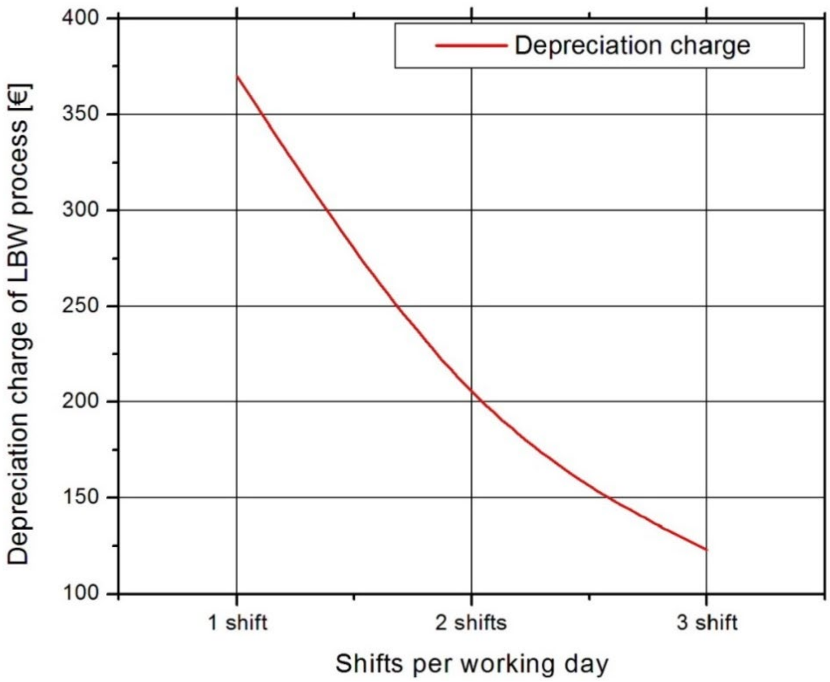

Fig. 11. Depreciation charge of LBW structure (C2) with nominal dimensions 1484 mm x 384 mm x 1.6 mm for different annual production rate

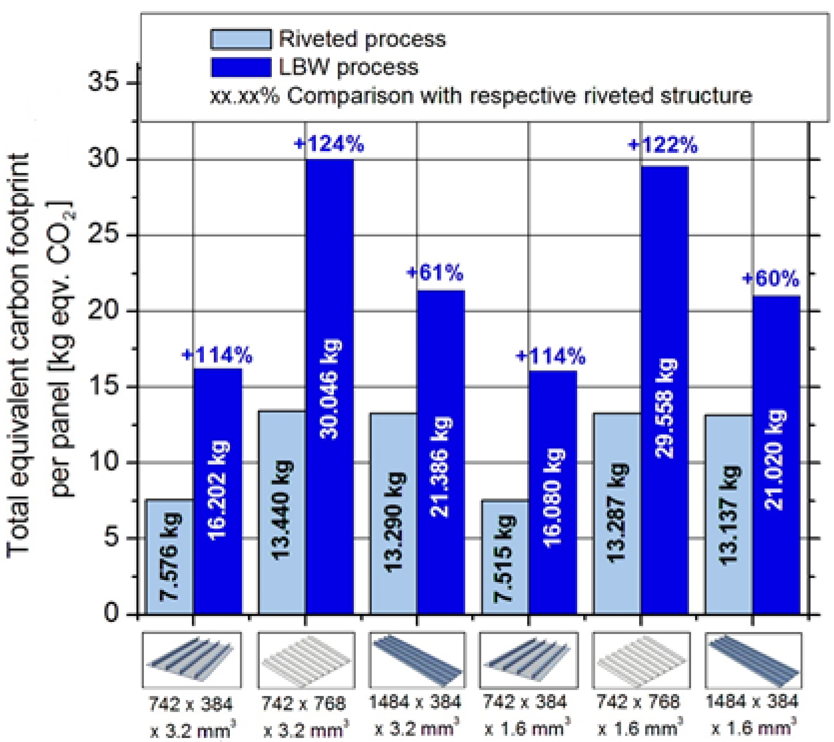

Fig. 12. Total equivalent carbon footprint per aeronautical panel for laser bean welding and riveting processes.