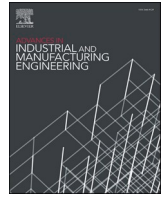




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Impact of additive manufacturing on titanium supply chain: Case of titanium alloys in automotive and aerospace industries

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ABSTRACT

Additive manufacturing (AM) is a promising technology for designing complex metallic pieces for different sectors with resource and time effectiveness. Titanium (Ti) is an essential critical material for AM development. AM can produce intricate and cost-effective components with Ti alloys for the transportation sector which would not be possible with conventional manufacturing (CM) technologies. This study assesses the impact of AM on the life cycle of Ti and its alloys by using review (numerical data, case examples) and dynamics simulation modelling. This article quantifies potential environmental benefits and examines aspects related to using Ti alloys in the automotive and aerospace industries. Mass flow, energy consumption and related greenhouse gas (GHG) emissions are assessed by making a comparison between subcategories of AM including binder jetting (BJT), directed energy deposition (DED), electron beam-based powder bed fusion (EB-PBF), and laser-based powder bed fusion (L-PBF) and CM processes including forging, milling, machining, and die casting. The results show that the AM subcategories considered potentially reduce manufacturing phase energy consumption and GHG emissions except for L-PBF. The findings highlight that an inclusive consideration of all life cycle phases is needed to fully identify potential benefits of AM for industries. Also, the scenario analysis in this study proposes the opportunity for saving mass and minimizing energy consumption and GHG emissions by optimizing the structural design and manufacturing processes for Ti components.

1. Introduction

Mass reduction in the transportation sector is one of the key means leading to achieving better performance, fuel efficiency, cost-effectiveness, and diminished greenhouse gas (GHG) emissions (3D Systems Corporation, 2018; Joost, 2012). The need to move people and goods by air, land, rail, or inland water and sea transport must be satisfied in a way that is efficient, safe, economical, and with minimal environmental impact. The introduction of lightweight materials such as titanium (Ti), aluminium (Al), carbon fiber reinforced polymer (CFRP) used either as single, composite, or hybrid material have offered transport industries the possibility to minimize mass, improve performance, resource and cost efficiencies. A lighter structural component in

transport application enhances performance and reduces the collision energy. Also, this reduces the likelihood of deformation and passenger injury in case of an accident (Hyundai Motor Group, 2019; Vehicle Technology Office, 2014). Weight reduction increases performance diminishes fuel consumption, and consequently reduces GHG emissions. Lightweight strategies are critical indicators of better performance in the transport industry (Najmon et al., 2019). Along these lines, light weighting, part downsizing and consolidating for lightweight materials such as Ti and its alloys enhance material efficiency. New manufacturing methods that allow optimized product design planning are promising potential solutions geared towards achieving efficient use of raw materials, increasing fuel economy and mitigating GHG emissions in the transportation sector (Ganesh Sarvankar and Yewale, 2019; Gloria et al.,

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2019). The ability to downsize components by, e.g., 20% in mass could result in about 12%–16% reduction in carbon dioxide (CO₂) emissions. The use of Ti in automotive engine valves and exhaust systems can reduce their weight by, respectively, 70% and 50% (Wagner and Schauerte, 2007). Ti alloys in the transportation sector, especially in the niche segments of the automotive industry (e.g., sports and luxury cars), can satisfy requirements such as space limitations, maintaining mechanical properties and corrosion resistance at elevated temperatures (Jones et al., 2012; Lenntech, 2021; Popov et al., 2021). Pure Ti is rarely used in industrial additive manufacturing applications because it is highly flammable and spontaneously combustible.

Achieving such objectives has been a challenge for the various transportation industries. Parts of automobiles, aircrafts, trains, or ships made in a traditional way of traditional materials are either bulky, difficult to manufacture, environmentally unsustainable or too expensive. Neither do traditional materials offer the properties required to effectively function in a harsh chemical environment and at high temperatures (high specific strength, corrosion resistance and springiness). Design-related limitations such as limited number of available manufacturing methods, tools and fixtures do not allow the transportation industry to utilize product designs that are capable to offer optimized products, weight reduction, durable products, and improved life cycle resource and costs efficiencies. One manufacturing technology that enables such benefits as well as other types of environmental effectiveness is additive manufacturing (AM) (Böckin and Tillman, 2019). AM can create optimized and lightweight components that cannot be obtained with conventional manufacturing (CM) processes. CM method can be defined as a manufacturing process in which parts are produced by removing or forming material. CM processes can be

sub-classified into subtractive and formative processes. There are four main types of CM methods including machining, injection moulding, forming, and joining methods. All these types of processes require direct contact of tools and fixtures with the processed material/workpiece and are characterized by higher scrap rate. AM offers opportunities to reduce raw material, manufacture lattices, topology or hybrid optimized parts and internal conformal flow channels (Putra et al., 2020; Tan et al., 2020).

This study aims to conduct a comprehensive assessment of flows of Ti and Ti alloys together with mass, energy and related emissions for CM and AM in automotive and aerospace industries. The modelling uses data only from raw material production and the manufacturing phase and hence it does not account for flows from the use or end of life phases. To achieve this aim, a novel dynamic simulation model is developed to carry out environmental analysis of several AM processes, such as binder jetting (BJT), directed energy deposition (DED), electron-beam based powder bed fusion (EB-PBF), and laser-based powder bed fusion (L-PBF) as well as CM processes including forging, milling, machining, and die casting. This study attempts to assist transportation industries, Ti suppliers, and stockholders in shifting toward solutions aimed to face economic challenges and comply with environmental regulations binding in the manufacturing sector. This is augmented by suggesting actions based on the 2030 Agenda for sustainable development goals (SDGs) such as SDG 7 (to ensure access to affordable, reliable, sustainable and modern energy), SDG 12 (to ensure sustainable consumption and production patterns) and SDG 13 (mitigation of climate change). The main objective of this study is to make progress in research towards above mentioned SDGs, with a contribution to optimizing manufacturing technologies and processes to identify better the potential benefits of AM by energy saving

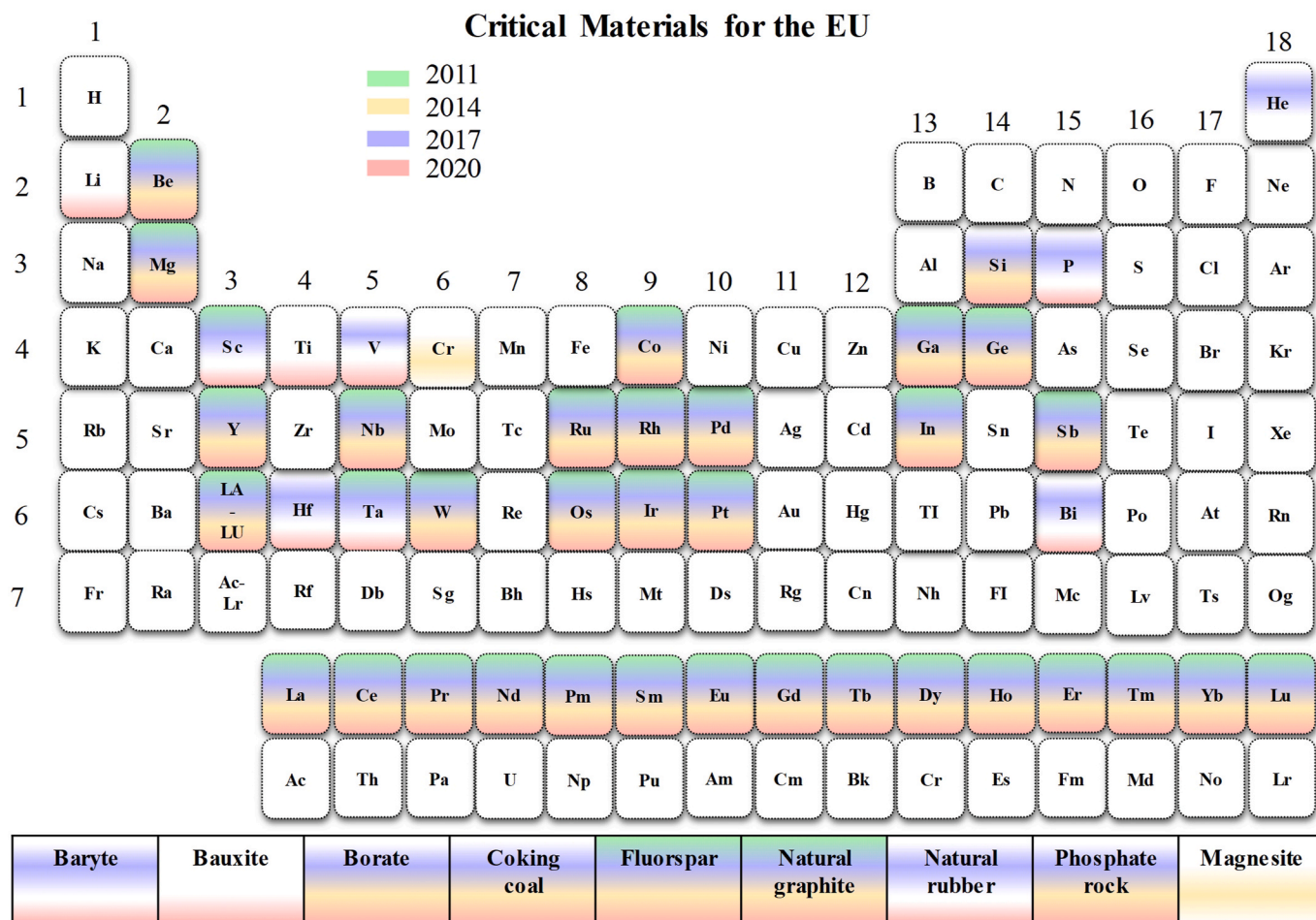


Fig. 1. Primary solutions for addressing the issue of critical raw materials (Popov et al., 2021).

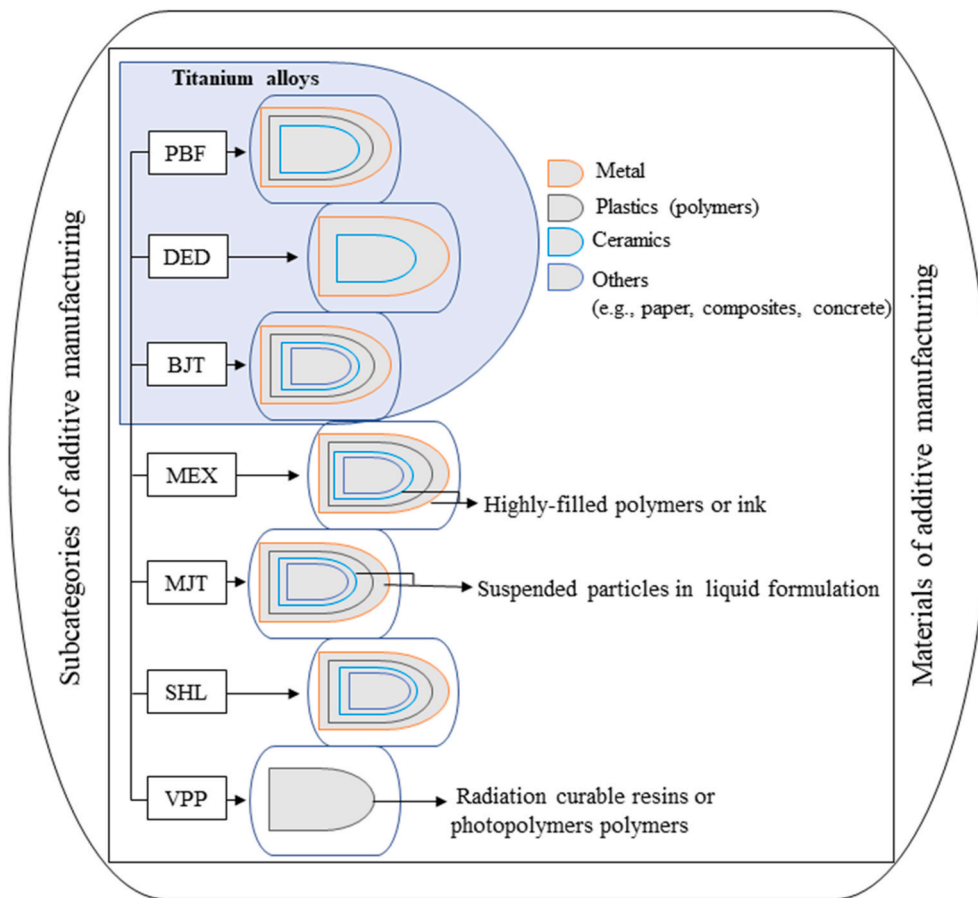


Fig. 2. Classification of AM and application materials (Diptanshu et al., 2019; Gonzalez-Gutierrez et al., 2018; Li et al., 2020; Niu et al., 2020).

and mitigation of GHG. Our quantitative analysis fills the knowledge gap for the case of selected AM components in aerospace and automotive industries. The work considers AM technologies for selected Ti alloy components and analyses their energy consumption and GHG emission footprints of CM technologies for the same components. Our findings are significant for assessing the role of AM technologies in helping manufacturers to save energy and to achieve GHG emissions goals. Moreover this work indicates the opportunities for optimization of manufacturing technology.

2. Literature review

Ti is a naturally occurring shiny transition metal with low thermal conductivity. It is rarely used in its elemental form. Ti alloys are resistant to the elevated temperature. It is a material with a silvery appearance (Gerdemann, 2001; Lenntech, 2021). Ti alloys are low density compared to other materials with similar structural properties. The commonly used Ti alloys have similar structural properties as comparable engineering material (stainless steel) at a halved weight (Donachie and M, 2000; Fujii et al., 2003). The high strength-to-weight ratio, good corrosion resistance and favorable mechanical properties of Ti alloys at the elevated temperature make them a preferred option for applications in aerospace, electric power plants and heat exchangers manufacturing (Hartman et al., 1998; Yamashita et al., 2002).

Ti and its alloys are classified as expensive based on the cost per kilogram in comparison to similar metals. The high costs are as result of energy requirement for natural Ti extraction and melting processes (Froes, 2015). Primary Ti requires ten-fold the energy needed to process comparable steel (Digital Alloys, 2019). The energy requirements as well as difficulty of manufacturability result in the use of Ti and its alloys

only in high-performance applications (Advanced Refractory Metals, 2019a). Ti and its alloys potentially can reduce the total mass of a vehicle component by 40–55% (Vehicle Technology Office, 2014). Application of Ti alloys is limited to CM, especially for those applications that require extensive machining. For instance, Ti–6Al–4V also known as Ti64 or Grade 5 makes up about half of total global Ti consumption (Kuttolamadom et al., 2010; Liu and Shin, 2019; Supra Alloys, 2022). It is mostly used for niche applications including aerospace, chemical and medical sectors requiring e.g., superior biocompatibility and high corrosion resistance.

Other new grades of Ti alloys e.g., aluminum-iron-titanium (Ti–Al–Fe) alloys offer cost-effectiveness easy processability (e.g., machinability and castability) with similar superior properties like traditional Ti–6Al–4V (Advanced Refractory Metals, 2019a; Allison et al., 1987; Liang et al., 2018). The automobile sector has improvised advanced CM methods (e.g., forming) designed for steel manufacturing to create Ti parts for benefits such as cost reduction, ease of manufacturing and improved performance.

CM methods such as casting, and machining are the most traditional methods used to manufacture Ti alloys. These CM processes require preformed ingots or large volumes of molten raw material and energy. It leads, due to low performance of CM processes, to considerable mass and energy losses. The buy-to-fly (BTF) is the weight ratio of raw material and finished component. Most of CM methods for Ti processing require a minimum BTF ratio of 8:1, while BTF for AM is 1.5:1 (Liu et al., 2018). Therefore, AM offers a new way to create complex and versatile Ti alloy product design. Also, AM offers design flexibility that ensures minimizing of required material for near-net shapes with minimal additional processing. Surplus Ti alloy powder removed from a build stage in the case of a powder bed AM systems can be remixed several times with

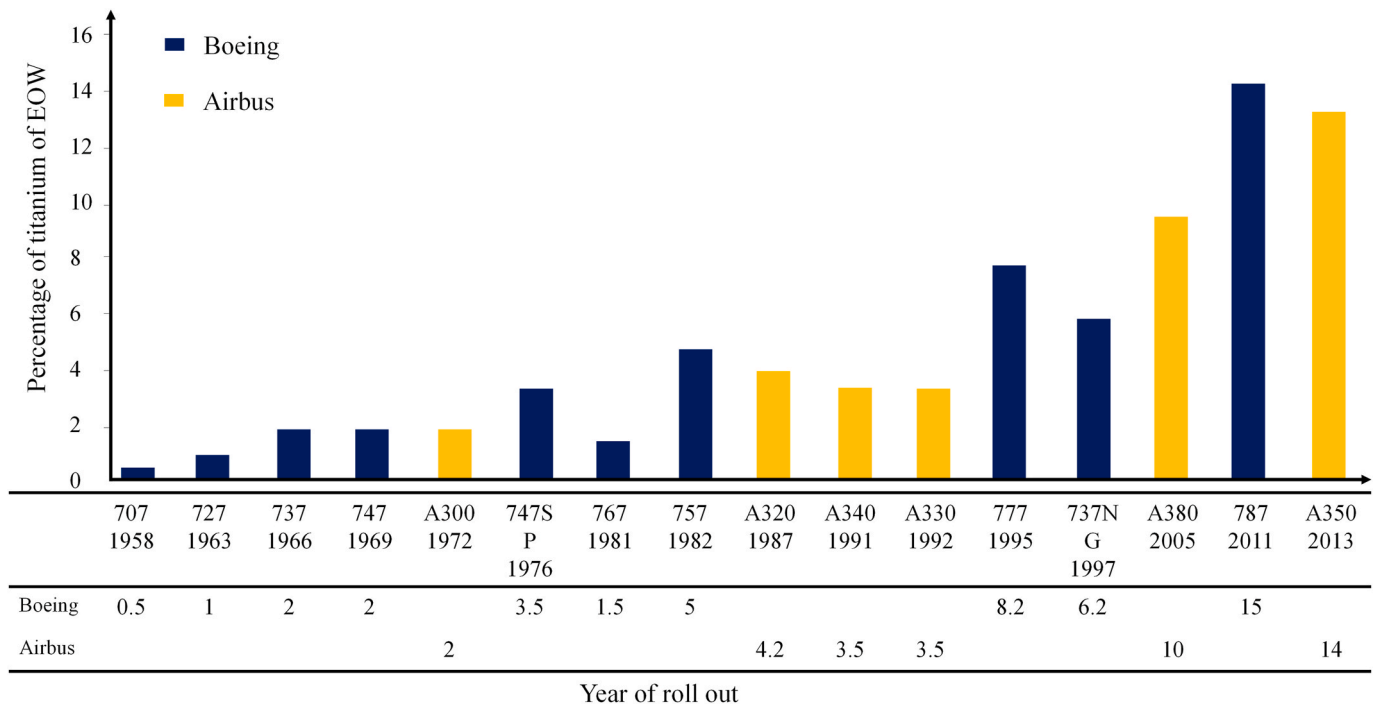


Fig. 3. Share of Ti in Boeing and Airbus aircraft as a percentage of operating empty weight (OEW), updated with data quoted in (Boyer, 2010; Gloria et al., 2019; Whittaker and Sam Froes, 2015).

virgin feedstock for new builds. This reduces the uptake of virgin material and as well as wastes (Harkin et al., 2020).

New ways of manufacturing Ti and its alloys are imperative to avoid future scarcity of this material. Ti has recently been listed as a critical raw material (CRMs) in the category low (Lewicka et al., 2021) by the European Union (Popov et al., 2021). CRM is defined as “any substance used in technology that is subject to supply risks, and for which there are no easy substitutes” (US Energy Protection Agency, 2014). The assessment of the criticality of materials can be based on their importance for environmental implications, the risk of supply and vulnerability to supply restrictions (Golroudbary et al., 2022; Quinteros-Condoretty et al., 2021; Rizzo et al., 2020). The criticality of material is determined by the assessing body, for a particular location and time of assessment. Fig. 1 shows the classification of critical raw materials by EU according to a study by Popov et al. (2021).

As Fig. 2 shows, Ti was first listed as CRM on the European Union chart in 2020. It is an indication that the efforts are needed to ensure its availability. The raw material scarcity can be tackled by optimizing product design (for material efficiency, increased durability, extending service life), recycling, reducing waste and pollution, using new materials and new manufacturing methods, (Brundtland, 1987; Popov et al., 2021; Rizzo et al., 2020).

The United Nations (UN) Member States in 2015 adopted the 2030 agenda for sustainable development including seventeen main goals referred to as sustainable development goals (SDGs). The SDGs provide a shared blueprint for all UN member states to achieve a better sustainable future in the following areas: people, the planet, prosperity, peace and partnership by 2030 (UN, 2020a). Five of the SDGs are closely linked to manufacturing including (1) Decent work and economic growth (UN, 2020b), (2) affordable and clean energy (UN, 2020c), (3) industry, innovation, and infrastructure (UN, 2020c), (4) responsible consumption and production (UN, 2020d), and (5) climate action (UN, 2020e). This study is focusing on above mentioned targets that seek to create economic productivity through diversification, productive activities, creativity and innovation, and materials. This review focused on the suitability of AM and CM to enhance downsizing, durability and recyclability of Ti components. The review also provided data on current and

future trends in Ti application, as well as the production and deliveries of automobiles and commercial aircraft.

2.1. Additive manufacturing

AM is a “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” (ISO/ASTM, 2021). AM is an emerging manufacturing method that allows building lightweight and original structures with improved functionality and reliability to meet stringent structural requirements for different industrial applications. AM provides the potential to create lightweight, downsized and intricate geometrical internal passages formed with materials for transport applications. Such optimized designs allow for minimizing fuel consumption, maximizing other component efficiency, and consequently reduction of overall emissions in use phase (Gebler et al., 2014; Lindemann et al., 2012). The use of AM to manufacture components in, e.g., aerospace can improve mechanical properties due to optimized and intricate designs. ISO/ASTM (2021) divides AM into seven (7) sub-categories including bed fusion (PBF), DED, material extrusion (MEX), BJT, material jetting (MJT), sheet lamination (SHL) and vat photopolymerization, (VPP) (ISO/ASTM, 2021). PBF can further be classified into EB-PBF and L-PBF based on the thermal energy source. DED also can be classified based on the form of feedstock; wire-based (Wire DED) and powder-based (Powder DED) or on the source of thermal energy used; laser-based, electron-beam or arc-based DED (Sing et al., 2020). The AM subcategories and the applicable processes for manufacturing Ti components are shown in Fig. 2.

AM processes such as PBF, DED and BJT offer the possibility to create complex structures with lattice infills and topology optimization with Ti (Hryha and Riabov, 2021). The AM subcategories enable the development of optimized and lightweight components, something that would not be achievable within CM processes. Designing optimized parts that can take the full advantage of AM such as topology and lattice optimization, as well as internal conformal cooling channels, part consolidation and downsizing potentially reduce the raw material and energy consumption rates.

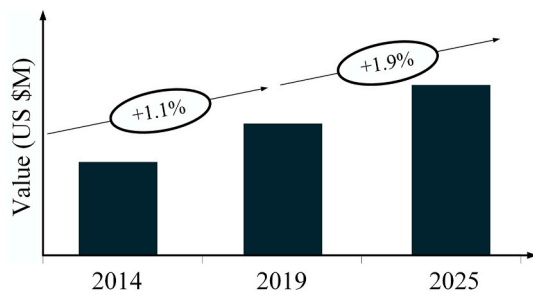


Fig. 4. Representation of growth of Ti value in the global automotive market, the data retrieved from (Lucintel, 2020).

The optimization of structural design with the replacement of lattice and topology structures must be planned to successfully manufacture the components. A lattice and topology structure can comprise a variety of geometry features and unit cells (when lattice is used) (Flores et al., 2020). The type of design optimization determines their feasibility for metal-based AM processes. Adopters of AM need to understand the rules of design for additive manufacturing (DfAM) and ensure that they are applied in digital design and actual manufacturing of the components. Certain steps can be taken to ensure that components can be printed failure-free at reduced resource consumption and diminished discharge of waste and emissions. Critical considerations are necessary to ensure the selection of the right DfAM rules, build orientation of the unit cell or topologized regions, process parameter optimization (several), and the intending post-processing method (e.g., heat treatment, polishing, machining) as these are decisive for the successful production of components.

2.2. Application of Ti alloys

Several sectors such as transportation or medicine use Ti and its alloys because of their unique characteristics. Global safety and environmental concerns require a safer and better performing transportation sector that could secure economic benefits and minimize negative environmental impacts. The aerospace has been using Ti alloys for over 50 years (Boyer, 2010; Farinia Group, 2014) in engine and airframe components due to their lightweight, strength, corrosion resistance, space limitation and resistance to high operating temperatures (Boyer, 2010; Gloria et al., 2019; Zhu et al., 2018). Ti components were first introduced in 1980 for automotive engines in Formula One racing cars. The material turned out to be appropriate for automotive suspension and exhaust systems but, due to its excessive cost, it was used exclusively in sports and luxury cars segment. The use of lightweight materials in the transportation sector was driven by benefits such as the possibility to downsize components, improve fuel consumption and safety, reduction of CO₂ emissions, and others. Figs. 3 and 4 show the trend exhibited using Ti in the automotive and aerospace sectors.

Figs. 3 and 4 show the total use of Ti regardless of the manufacturing method; however, CM is a potential source of these data. AM continues

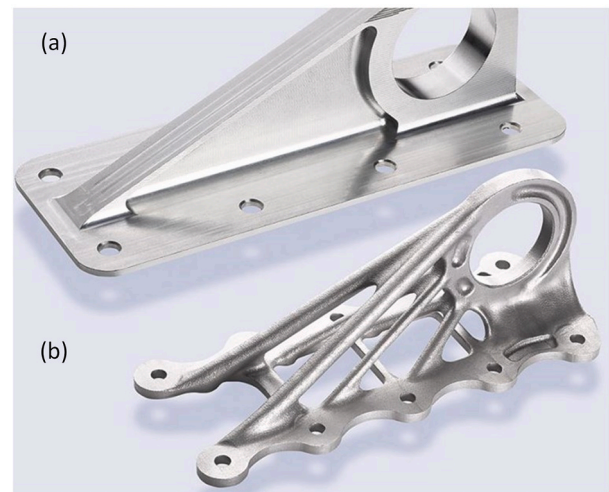


Fig. 6. Examples of Ti cabin bracket Airbus A350 XWB manufactured using (a) CM and (b) AM.

to emerge as an option to make functional components for the automotive and aerospace industries (Böckin and Tillman, 2019; Kellens et al., 2017). The share of Ti in transportation applications continues to grow as seen in Figs. 3 and 4 due to its properties such as reducing weight, heat and corrosion resistance. The trend to use Ti in aircraft was observed only on the example of Boeing and Airbus deliveries as these two manufacturers have expressed their commitment to replacing the existing CM parts and new components with AM components. The share of Ti in the total mass of an average commercial aircraft is 17% (Zhu et al., 2018). Boeing 787 and Airbus A 350 have the largest mass of Ti, 15% (Giurgiutiu, 2015; Gloria et al., 2019) and 14% (Whittaker and Sam Froes, 2015), respectively. Ti can be used in engines, airframes, suspension and exhaust components for improved performance, fuel efficiency, corrosion resistance and other reasons (Advanced Refractory Metals, 2019b; Yamashita et al., 2002).

2.3. Industrial cases of Ti alloy components in AM in automotive and aerospace sectors

The application of AM for Ti alloy parts in the transport industry does not only enhance mass efficiency, fuel consumption and emissions reductions but also reduces overall lifecycle costs. AM manufactured structural parts are estimated to save for instance up to three million USD per plane by substituting some of the conventionally manufactured (CM) parts on the 787 Dreamliner with AM manufactured Ti alloy parts. Brake disc and suspension spring are two of the heaviest Ti alloy components in automobiles. Lightweighting using Ti automobiles components is a potential driving force fuel economy, where about 6%–8% fuel economy improvement is feasible per 10 kg weight reductions. Planning of the manufacturing processes that considers the limitations of AM can

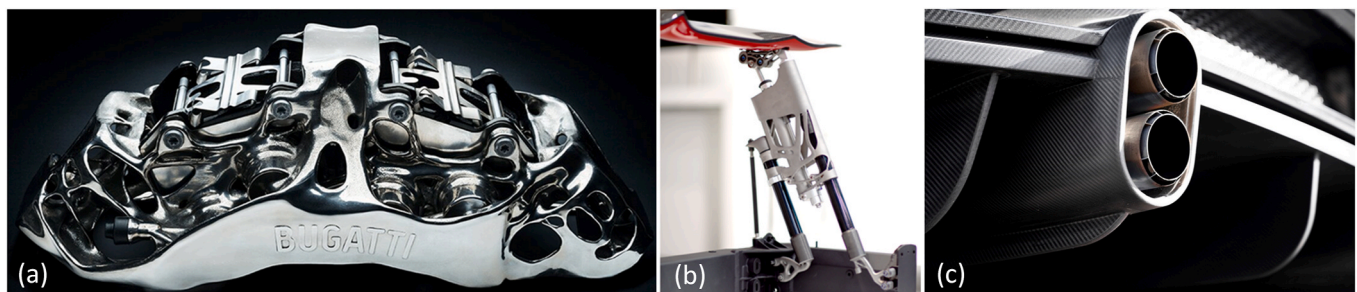


Fig. 5. Examples of Bugatti Ti components in automotive sector (a) eight-piston monobloc brake caliper (b) active spoiler bracket and (c) tailpipe trim covers.

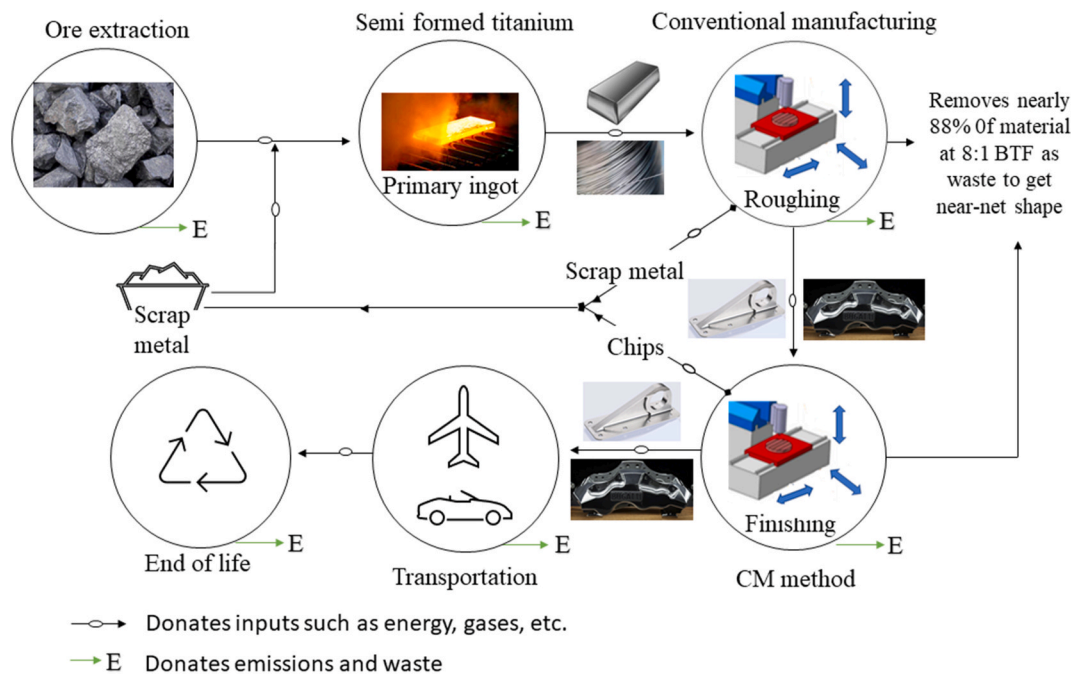


Fig. 7. Value chain for CM Ti parts.

help identify ways to eradicate manufacturing phase errors and reduce its costs. Examples of cases of CM and AM for Ti components in automotive and aerospace applications are shown in Figs. 5 and 6.

Currently, brake calipers are made from cast iron or Al. Prospects to print calipers with AM includes enhanced performance, material savings, cost and lead time reductions. The potential of reducing the structural weight of vehicles and aircraft components via AM directly improves operational costs. This is because AM parts contribute to the superior profile and overall mass reductions (Kaur and Singh, 2021; Saliyu et al., 2019). Studies have also shown that lightweight parts boost fuel efficiency as well other weight reduction benefits including lowered fuel consumption and related CO₂ emissions over the entire lifecycle (Gebler et al., 2014).

2.3.1. Cost efficiency for Ti alloys components

The production of the Ti alloy precursor used in CM and AM (powder based) are same, however, the process streams split for the pre-shaped block or powder Ti alloy. The Ti alloy powder used in PBF is produced from either the semi-finished or preformed wire into the required feedstock in a process called atomization. Atomization is the process of forming metal powder by breaking down molten metal with the assistance of high-speed fluid (e.g., air, inert gas, or water) into metal droplets. The feedstock used in PBF is produced either through gas atomization or plasma atomization (Daraban et al., 2019; Dawes et al., 2015; Popov et al., 2021). ASTM F3049-14 (ASTM F3049-14, 2014) defines the characteristics which are required of metal powder (feedstock) used for powder-based AM machines (ASTM F3049-14, 2014). The properties of the precursor and the used atomization process influence the different required properties of the powder (Hryha and Riabov, 2021; Popov et al., 2021).

In AM, cost reduction using Ti alloys can be attained by means of mass reduction (52.5%), higher material recovery rates (96%), reduced number of processing steps and shorter time (54.3%) (Flores et al., 2020; Nyamekye et al., 2017; Zhu et al., 2018). The material recovery rate given here is the amount of powder that can be recovered from the build platform of powder bed fusion. AM offers the possibility of building near net shapes, reusing excess powder [57], and reducing the processing steps via integrated product design. It can reduce the amount of virgin powder for each new build. The BTF of Ti for CM means that to be able to

conventionally manufacture a component one needs material input mass that is eight times higher than the weight of the final component whereas the AM method requires material input that is only about 1.5 times bigger than the final component weight (Farinia Group, 2014). The use of AM and proper design rules offer the potential to design optimization (e.g., topology, lattice, webbing) and the exact deposition of raw material during production. Studies have shown that AM makes it possible to manufacture components at higher material efficiency levels and improved cost efficiency by way of low raw material consumption and lightweight components (Flores et al., 2020).

The aerospace industry is required to reduce its emissions to be able to operate within the allocated emission limits (European Commission, 2021). There are strict compliance fines and fees that airlines must pay if they generate more emissions and are not able to stick to the allowable emission limits. Another source of cost reduction for transportation adoption of AM is maintaining safety superior performance. Weight reductions in these applications have the potential to influence fuel consumption, fuel economy and emissions. Weight reduction correlates with improved fuel consumption and reduced emissions in transport applications. Studies show that weight reduction by 1.0% or 10% in automotive industry improves fuel consumption by, respectively, 0.7% or 8.0% (Vehicle Technology Office, 2014; Yamashita et al., 2002). A study into the benefits of automobile weight reduction shows that 5.0% reduction of the weight of an average 1500 kg saloon car (75 kg) can improve fuel efficiency by 1.5% and engine performance by 4.5% (Hyundai Motor Group, 2019). In another study AZoNetwork (2001) demonstrated that weight reduction in automobiles can save fuel cost up to about 10 euros depending on the segment. Steinegger (2017) estimates that any weight reduction of an aircraft can save up to 0.03 kg of fuel for every 1000 km, which is equivalent to about 3.0 cents. This, when translated into lifetime savings, is about 25,000 kg reduction in CO₂ emissions for indefinite service life (Additive-X, 2019). For instance, it is estimated that about 1000 kg of CO₂ is generated annually for every 1000 kg of weight in airspace. The aerospace sector can generate fuel savings thus reducing annual kerosene expenses and emissions using lightweight AM parts.

2.3.2. Process chain and flow analysis of CM and AM for Ti components

Ti alloys used in CM often take the form of a preformed bar, plate,

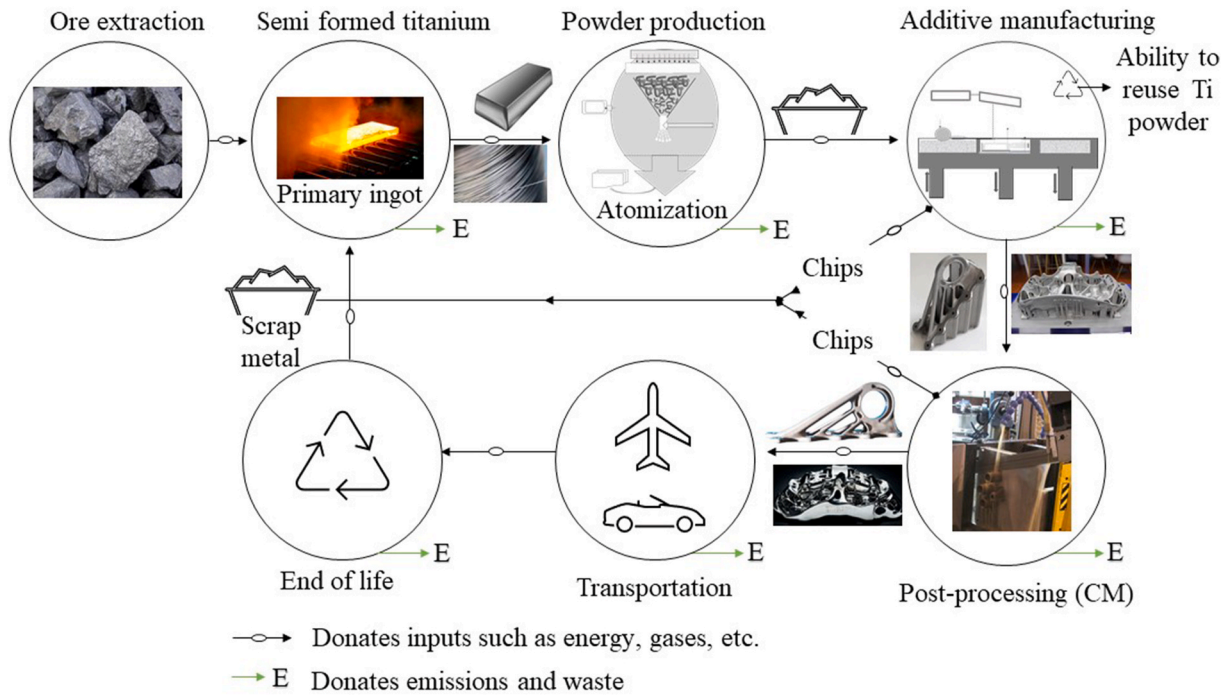


Fig. 8. Value chain for AM Ti parts.

billet, or powder whereas AM uses powder (for example L-PBF, DED) or highly filled polymers with metals (ME). Both CM and AM have a series of necessary phases that take place to produce the final components. Figs. 7 and 8 compare CM and AM process chains.

The value chains for CM and AM are respectively shown in Figs. 7 and 8. As can be seen from Fig. 8, CM processes (e.g., sawing, wire cutting) complement PBF for the removal of the build parts from the building platform.

Production of the raw material, referred to as ‘ingot’, needed as input into both CM and AM processes is similar as such the total energy consumption is same for the primary material (ingot) production phase. The raw material used in AM requires further processing into powder or wire thereby adding to the total energy consumption. The total energy consumption for the processing of materials is referred to as embodied energy. Ti-6Al-4V is the common Ti alloy is used in AM components manufactured for automotive and aerospace applications. Baumers et al. (2017) estimated that 528.90 MJ/kg of embodied energy is needed to produce Ti-6Al-4V plate (Baumers et al., 2017). Ti is often produced as a combination of virgin ingot and about 21%–23% of recycled material. Baumers et al. (2017) estimates that the embodied energy for processing the recycled material ranges between 221 and 244 MJ/kg (Baumers et al., 2017). Ti powder or wire used in AM is produced via atomization (gas or plasma atomization) or metal is drawn into a wire of required characteristics and properties needed to ensure good build ability (Kazybek and Perveen, 2019). Gas atomization can be applied to any form of Ti as input (e.g., a bar, plate, or scrap metal) while plasma requires only Ti wire as input (Hryha and Riabov, 2021). The atomization of Ti into powder is estimated to consume about 31.7 MJ/kg. The total embodied specific energy to produce Ti-6Al-4V powders is 560.60 (MJ/kg) (Baumers et al., 2017; Liu et al., 2018). A new feedstock production that uses plasma and recycled Ti are promising to reduce atomization energy (TCTMAG, 2019).

2.3.3. An evaluation of energy consumption for different CM and AM subcategories suitable for Ti

Scenario assumptions based on BTF ratio can be used to handle material and energy comparisons in a supply chain analysis. Studies have shown that the ratio of Ti alloy input (Ti6Al4V grade 5) to the

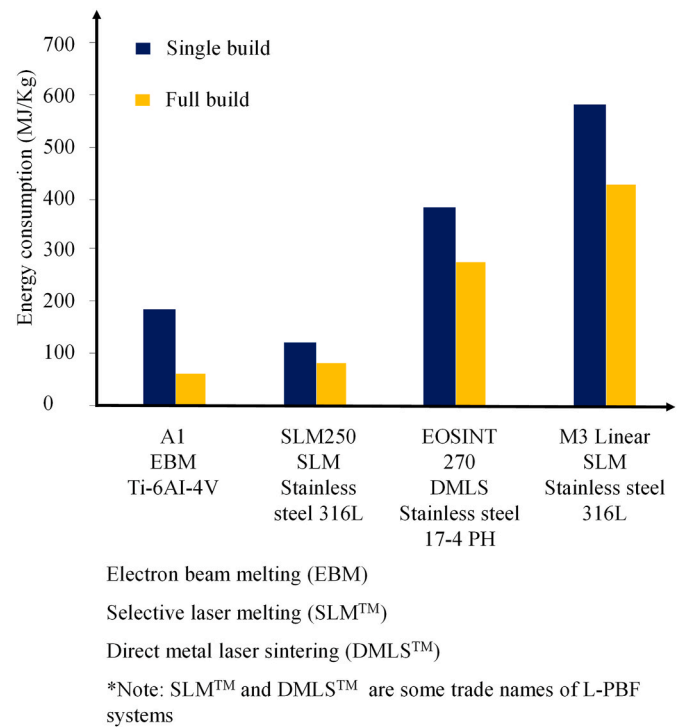


Fig. 9. Effect of build platform utilization and material type on Specific Energy Consumption (SEC), adapted from (Baumers et al., 2011; Liu et al., 2018).

output (final product) is about 8–15:1 (Caiazza et al., 2017; Liu et al., 2018). AM offers improved material efficiency because of a lower BTF ratio of about 1.5:1 (Huang et al., 2016; Liu et al., 2018). The use of AM can result in about 35–55% mass reduction in automobile and aircraft applications (Huang et al., 2016). The processing energy consumption in AM includes energy used for actual building and the post-processing energy usage. Energy consumption for post-processing varies

depending on the AM subcategory, complexities of support removal, the finish machining, and post-build processing needed for the intended application. The rate of energy consumption for diverse AM systems differs. The feedstock type, part design, processing speed, platform utilization rate and necessary auxiliaries, process gas, all contribute to differences in consumption. Fig. 9 shows an example of variations in energy consumption rates for EB-PBF and three different L-PBF systems.

Part design and build platform utilization rate are two options available in AM by which the energy consumption can be controlled. Maximization of platform usability boosts process efficiency as the same energy consumed for layering powder, heating system, moving powder recovery, controlling process gas and the required start up material can remain unchanged regardless of the number of parts on the build platform. This prediction suggests that making larger quantity of parts will reduce the per part energy consumption compared to a situation when a smaller quantity of parts is built in a cycle. This literature has shown that AM can be used to create cost-effective Ti alloy components of near-net shape requiring exact quantity of materials with a BTF of 1:1.5 and the possibility to reuse or recycle surplus feedstock. However, the manufacturing phase energy consumption is high compared to CM methods. There are also vast discrepancies in the compared AM sub-categories that raise concerns for further development. This study identifies practicalities such as DfAM, design optimization, maximizing of build platform for combined identical and non-identical build to reduce high SEC in L-PBF. The study shows that despite the ease of manufacturability and material saving offered by AM, the transport industry has yet to optimize its usage of resources for all possible replaceable components. This study aims to indicate AM manufactured Ti components potential in aerospace and automotive sectors including better resources efficiency wastes and emissions reduction.

3. Materials and methods

3.1. Materials

In this study, the United States Geological Survey (USGS) (Ober, 2020), European Commission (EU Commission, 2017), Statista database (Gullen and Plungis, 2021; Statista, 2021), other studies including the review of data (Liu et al., 2018; Sherman, 1980; Wagner and Schauerte, 2007), and industry-based data (Airliners, 2017; Bugatti Automobiles S. A.S., n. d.; Forecast International, 2021) are used as the primary data sources. The study uses system dynamics modelling (Forrester, 1997) to investigate industrial case studies from automotive and aerospace sectors concerning the use of Ti, energy flows and related emissions for applying CM and AM. The goal of these case studies was to deepen the knowledge on how AM and Ti alloys offer optimized designs and lightweight parts for automotive and aerospace applications. The data considered for automotive was limited to the sports and luxury cars segment as these segments currently utilize Ti alloy parts. Sports and luxury vehicles commonly containing Ti alloy parts include connecting rods, engine intake and exhaust valve, valve spring, valve spring seat, valve retainers, suspension spring, exhaust system and muffler, brake calipers, active spoiler bracket, and tailpipe trim covers. Ti alloy application in component systems of light weighting aircraft includes engine (functional and auxiliary), propulsion systems (functional), and nacelle systems (auxiliary).

3.2. Methodology

We applied the system dynamics simulation methodology, according to the concept of material flow analysis (MFA) and life cycle assessment (LCA), to manufacturing processes of the selected cases of aerospace and automotive industries. This study includes scenario modelled cases of airplane manufacturing performed to assess how AM saves raw materials and mitigates environmental impact of production and post-consumer use. Scenario A corresponds to 6% of AM Ti alloy parts at

Table 1
Description of variables of the proposed dynamic model for Ti supply chain.

Variable	Term	Type of variable	Group
$GS(t)$	Global primary Ti stock	Stock	Endogenous
$GIA(t)$	Global annual production rate of ilmenite and leucosene from mining	Auxiliary	Endogenous
$GRA(t)$	Global annual production rate of rutile from mining	Auxiliary	Endogenous
$GTS(t)$	Global annual production rate of Ti slag from mining	Auxiliary	Endogenous
$GT(t)$	Global annual production rate of Ti from mining	Flow	Endogenous
$TPS(t)$	Total processed Ti stock	Stock	Endogenous
$TPA(t)$	Annual production rate of Ti sponge metal from processing	Flow	Endogenous
$TPD(t)$	Annual production rate of Ti dioxide pigment from processing	Flow	Endogenous
β	The efficiency of production rate of Ti sponge metal from processing	Auxiliary	Exogenous
α	The efficiency of production rate of Ti alloy from Ti dioxide pigment from processing	Auxiliary	Exogenous
$GMT(t)$	Global stock of manufactured products including primary Ti	Stock	Endogenous
δ_i	Coefficient of global Ti used in industry 'i' ($i=1,2, \dots,7$) including paints, polymers, aerospace, handheld objects, alloys, automotive, other industries	Auxiliary	Exogenous
v_i	Coefficient of global Ti demand for industry 'i' ($i=1,2, \dots,7$) including paints, polymers, aerospace, handheld objects, alloys, automotive, other industries	Auxiliary	Exogenous
$MP(t)$	Annual manufacturing rate of Ti in industry 'i' ($i=1,2, \dots,7$) including paints, polymers, aerospace, handheld objects, alloys, automotive, other industries	Flow	Endogenous
$MD(t)$	Annual demand rate for Ti in manufacturing sector of industry 'i' ($i=1,2, \dots,7$) including paints, polymers, aerospace, handheld objects, alloys, automotive, other industries	Flow	Endogenous
$CSM(t)$	Total stock of Ti manufacturing by method 'k' in sports and luxury cars ($k=1,2$) including conventional and additive manufacturing	Stock	Endogenous
$CAM(t)$	Annual rate of Ti manufacturing by method 'k' in sports and luxury cars ($k=1,2$) including conventional and additive manufacturing	Flow	Endogenous
φ_{kj}	Coefficient of global Ti manufacturing by method 'k' ($k=1,2$) including conventional and additive manufacturing used in component 'j' ($j=1,2, \dots,10$) of sports and luxury cars included connecting rods, engine intake and exhaust valve, valve spring, valve spring seat, valve retainers, suspension spring, exhaust system and muffler, brake caliper, Active spoiler bracket, and tailpipe trim covers	Auxiliary	Exogenous
$CSC(t)$	Total stock of collected Ti manufactured by method 'k' in sports and luxury cars industry ($k=1,2$) including conventional and additive manufacturing	Stock	Endogenous
$CAC(t)$	Annual rate of collecting Ti manufactured by method 'k' in sports and luxury cars industry ($k=1,2$) including conventional and additive manufacturing	Flow	Endogenous
e_k	Efficiency of collecting of waste including Ti manufactured by method 'k' in sports and luxury cars industry ($k=1,2$) including conventional and additive manufacturing	Auxiliary	Exogenous
$RAC(t)$	Annual rate of recycling of Ti manufactured by method 'k' in sports	Flow	Endogenous

(continued on next page)

Table 1 (continued)

Variable	Term	Type of variable	Group
Y_k	and luxury cars industry ($k = 1,2$) including conventional and additive manufacturing Efficiency of recycling of waste including Ti manufactured by method 'k' in sports and luxury cars industry ($k = 1,2$) including conventional and additive manufacturing	Auxiliary	Exogenous
$CMS(t)$	Total stock of Ti manufacturing by method 'k' in aerospace industry ($k = 1,2$) including conventional and additive manufacturing	Stock	Endogenous
$CMA(t)$	Annual rate of Ti manufacturing by method 'k' in aerospace industry ($k = 1,2$) including conventional and additive manufacturing	Flow	Endogenous
ω_{kj}	Coefficient of global Ti manufacturing by method 'k' ($k = 1,2$) including conventional and additive manufacturing used in component 'j' ($j = 1,2,3$) of airplane included engine (functional and auxiliary), propulsion systems (functional), and nacelle systems (auxiliary)	Auxiliary	Exogenous
λ_{fl}	Coefficient of energy consumption for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by method 'l' ($l = 1,2,3, \dots, 8$): CM method including forging, milling, machining, and die casting or additive manufacturing method including BJT, DED, EB-PBF and L-PBF.	Auxiliary	Exogenous
$ECA(t)$	Annual rate of energy consumption for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by processes 'l' ($l = 1,2,3, \dots, 8$): CM processes include forging, milling, machining, and die casting or additive manufacturing method including BJT, DED, EB-PBF and L-PBF.	Flow	Endogenous
$ECS(t)$	Total stock of energy consumption for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by processes 'l' ($l = 1,2,3, \dots, 8$): CM processes including forging, milling, machining, and die casting or additive manufacturing method including BJT, DED, EB-PBF and L-PBF.	Stock	Endogenous
τ_{fl}	Coefficient of GHG emissions for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by processes 'l' ($l = 1,2,3, \dots, 8$): CM processes including forging, milling, machining, and die casting or additive manufacturing processes including BJT, DED, EB-PBF and L-PBF.	Auxiliary	Exogenous
$GCA(t)$	Annual rate of GHG emissions for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by processes 'l' ($l = 1,2,3, \dots, 8$): CM processes include forging, milling, machining, and die casting or additive manufacturing processes including BJT, DED, EB-PBF and L-PBF.	Flow	Endogenous
$GCS(t)$	Total stock of GHG emissions for processes of Ti in case 'f' ($f = 1,2$) including automotive and aerospace industries by processes 'l' ($l = 1,2,3, \dots, 8$): CM processes include forging, milling, machining, and die casting or additive manufacturing processes including BJT, DED, EB-PBF and L-PBF.	Stock	Endogenous

BTF 1.5:1 for components and 94% of CM Ti alloy parts at BTF 8:1 for components. Scenario B corresponds to 50% of both AM and CM Ti alloy components.

This study proposes a dynamics model consisting of global Ti flows, the respective resource use and emissions. We divided the variables of the dynamic model into two groups including endogenous and exogenous variables to specify model boundaries. Endogenous variables affect and are affected by other system components and parameters, while exogenous variables are not directly affected by the system. The group and type of all variables are specified in Table 1.

The model is composed of two main parts: (i) an extractive stage which includes mining and processing of Ti and (ii) a production stage of manufacturing components including Ti for sports and luxury cars as well as lightweight aircraft components. In the extractive stage, mining includes production of ilmenite and leucoxene, rutile, and Ti slag globally. Also, processing focuses on Ti sponge metal and Ti dioxide pigment. The production stage focuses on the manufacturing of automotive and airplane components among other industrial applications of Ti such as paints, polymers, handheld objects, alloys, and other industries.

The model consists of two types of equations (state and rate) for quantifying the stock and flow of a given system. The stocks (state equations) existing in the mass flows of the model analyze the dynamic behavior of the mining and processing of Ti as well as automobiles and commercial aircrafts production over time. The flows (rate equations) correspond to the production of Ti, manufacturing of products, energy resources, and the related emissions. Table A1 provides details of the dynamic model and data sources used.

Equation (1) corresponds to the global stock of primary Ti ($GS(t)$) over the period ' t_0-t ' where ' t_0 ' is the initial year and ' t ' is the final year. $GT(t)$ presents annual production rate of Ti from mining which calculated by Equation (2); $TPA(t)$ stands for annual production of Ti sponge metal from processing (Equation (3)) and $TPD(t)$ stands for annual production rate of Ti dioxide pigment from processing (Equation (4)). $GIA(t)$ corresponds to global annual production rate of ilmenite and leucoxene from mining, $GRA(t)$ is global annual production rate of rutile from mining, and $GTS(t)$ is the global annual production rate of Ti slag from mining. Coefficient of Ti metal and alloy are given by β and α , respectively.

$$GS(t) = \int_{t_0}^t (GT(t) - TPA(t) - TPD(t)) dt + GS(t_0) \tag{1}$$

$$GT(t) = GIA(t) + GRA(t) + GTS(t) \tag{2}$$

$$TPA(t) = \beta * GS(t) \tag{3}$$

$$TPD(t) = \alpha * GS(t) \tag{4}$$

Equation (5) describes the global stock of total processed Ti, $TPS(t)$, in the period ' t_0-t ' by a time integral of summation of annual production of Ti sponge metal and Ti dioxide pigment minus summation of annual manufacturing rate of Ti, $MP(t)$, in industry ' i ' ($i=1,2, \dots, 7$) including paints, polymers, aerospace, handheld objects, alloys, automotive, other industries (Equation (6)). The coefficient of global Ti used in industry ' i ' is given by δ_i .

$$TPS(t) = \int_{t_0}^t (TPA(t) + TPD(t) - MP(t)) dt + TPS(t_0) \tag{5}$$

$$MP(t) = \sum_{i=1}^7 \delta_i * GT(t) \tag{6}$$

Equation (7) represents the global stock of manufactured products including primary Ti ($GMT(t)$) in the period ' t_0-t ' by a time integral of

summation of annual manufacturing rate of Ti ($MP(t)$) minus the sum of annual demand rate for Ti in manufacturing sector of industry 'i' ($MD(t)$) (Equation (8)). The coefficient of global Ti demand for industry 'i' is given by v_i .

$$GMT(t) = \int_{t_0}^t (MP(t) - MD(t))dt + GMT(t_0) \tag{7}$$

$$MD(t) = \sum_{i=1}^7 v_i * GMT(t) \tag{8}$$

Equation (9) represents the global stock of Ti manufacturing ($CSM(t)$) in sports and luxury cars industry by method 'k' ($k=1,2$) including conventional and additive manufacturing in period ' t_0-t ' by a time integral of annual rate of Ti manufacturing by method 'k' ($CAM(t)$) (Equation (10)) minus annual rate of collecting Ti manufactured by method 'k' ($CAC(t)$) (Equation (11)). φ_{kj} stands for coefficient of global Ti manufacturing by method 'k' used in component 'j' ($j=1,2, \dots, 10$) of sports and luxury cars included connecting rods, engine intake and exhaust valve, valve spring, valve spring seat, valve retainers, suspension spring, exhaust system and muffler, brake caliper, active spoiler bracket, and tailpipe trim covers. The efficiency of collecting waste including Ti manufactured by method 'k' in sports and luxury cars industry is given by q_k .

$$CSM(t) = \int_{t_0}^t (CAM(t) - CAC(t))dt + CSM(t_0) \tag{9}$$

$$CAM(t) = \sum_{k=1}^2 \sum_{j=1}^{10} \varphi_{kj} * GMT(t) \tag{10}$$

$$CAC(t) = \sum_{k=1}^2 q_k * CSM(t) \tag{11}$$

Equation (12) represents the global stock of collected Ti manufactured of type 'k' ($CSC(t)$) in sports and luxury cars industry in period ' t_0-t ' by a time integral of annual rate of collecting Ti manufactured by method 'k' ($CAC(t)$) minus annual rate of recycling of Ti manufactured by type 'k' ($RAC(t)$) (Equation (13)). The efficiency of recycling of waste including Ti manufactured by method 'k' in sports and luxury cars industry is shown by Y_k .

$$CSC(t) = \int_{t_0}^t (CAC(t) - RAC(t))dt + CSC(t_0) \tag{12}$$

$$RAC(t) = \sum_{k=1}^2 Y_k * CSC(t) \tag{13}$$

Equation (14) represents the global stock of Ti manufacturing by method 'k' ($CMS_k(t)$) in the aerospace industry in period ' t_0-t ' by a time integral of annual rate of Ti manufacturing in the aerospace industry by method 'k' ($CMA(t)$) (Equation (15)). ω_{kj} corresponds to the coefficient of global Ti manufacturing by method 'k' used in component 'j' ($j=1,2,3$) of airplane included engine (functional and auxiliary), propulsion systems (functional), and nacelle systems (auxiliary).

$$CMS(t) = \int_{t_0}^t (CMA(t))dt + CMS(t_0) \tag{14}$$

$$CMA(t) = \sum_{k=1}^2 \sum_{j=1}^3 \omega_{kj} * CMS(t) \tag{15}$$

Considering all mass flows over time, the environmental assessment (energy and related GHG emissions) is given in an identical form in the

model. Every manufacturing method consumes energy obtained from different sources and generates relevant GHG emissions (S.M. Zahraee et al., 2020; Seyed Mojjib Zahraee et al., 2020).

In the production stage, the manufacturing of components containing Ti is analyzed separately. Total cumulative amount of energy consumed for processes of Ti in case 'f' ($f=1,2$) including automotive and aerospace industries by processes 'l' ($l=1,2,3, \dots, 8$): CM processes including forging, milling, machining, and die casting or additive manufacturing processes including BJT, DED, EB-PBF and L-PBF. λ_{fl} stands for coefficient of energy consumption for processes of Ti in case 'f' by method 'l' ($l=1,2,3, \dots, 8$): CM method including forging, milling, machining, and die casting or additive manufacturing method including BJT, DED, EB-PBF and L-PBF.

$$ECS(t) = \int_{t_0}^t (ECA(t))dt + ECS(t_0) \tag{16}$$

$$ECA(t) = \sum_{f=1}^2 \sum_{l=1}^8 \lambda_{fl} * (CAM(t) + CMA(t)) \tag{17}$$

The GHG emissions model is principally related to energy consumption and therefore the structure of both models are identical. Total stock of GHG emissions for processes of Ti and its annual rate are provided in Equation (18) and Equation (19), respectively. τ_{fl} corresponds to the coefficient of GHG emissions for processes of Ti in case 'f' ($f=1,2$) including automotive and aerospace industries by processes 'l' ($l=1,2,3, \dots, 8$): CM processes including forging, milling, machining, and die casting or additive manufacturing processes including BJT, DED, EB-PBF and L-PBF.

$$GCS(t) = \int_{t_0}^t (GCA(t))dt + GCS(t_0) \tag{18}$$

$$GCA(t) = \sum_{f=1}^2 \sum_{l=1}^8 \tau_{fl} * ECA(t) \tag{19}$$

4. Results and discussion

The results presented in this study are based on supply chain stages, including mining, processing, and manufacturing. Therefore, this article focuses on the contribution of AM to global mass saving of Ti and energy resource efficiency in those stages of the supply chain. Also, the related GHG emissions are presented for the processes taking place in those stages. It should be noted that a considerable contribution of AM as shown in the review analysis of this study comes mostly from the use phase of a product. For instance, part consolidation and downsizing potentially enhance the use phase performance, fuel consumption, and the overall lifecycle costs and emissions. We are investigating the impact of AM on the use phase and a closed-loop supply chain of Ti and Ti alloys as future research.

4.1. Assessment of mass saving on global scale for Ti CM and AM

The addition of mass savings and fuel efficiencies with the use of Ti over the entire lifecycle of automobiles and aircrafts can result in considerable savings of raw materials and energy as well as reduction of waste and emission flows. This study estimates such savings related to Ti manufacturing focusing on global niche automobiles (luxury and sports cars) and commercial aircraft deliveries and production. The main reason for considering luxury and sports cars is that these two vehicle types have the highest percentage of Ti applications. Luxury cars "have an average mass of about 2200 kg, a passenger/cargo volume larger than 3.4 m³ and an average footprint of about 5 m²" (Statista, 2020a). Sports cars "include passenger cars of an average mass of around 1565 kg and

Table 2

Tabulation of global Ti consumption (in tonne) with CM and AM for luxury and sports cars.

Component	Component weight CM	Raw material BTF 8:1	Component weight AM	Raw material BTF 1.5:1
Connecting rods (8)	2777.7	22221.3	2362.6	3543.8
Engine Valve (16)	229.6	1837.1	172.2	258.3
Valve spring (16)	318.0	2543.6	194.3	291.5
Valve Spring Seat (16)	13.3	106.0	8.8	13.3
Valve retainers	176.6	1413.1	123.7	185.5
Suspension spring (4)	3002.9	24023.0	2252.2	3378.2
Exhaust System and Muffler	24023.0	192184.3	18026.1	27039.1
Brake caliper (4)	8545.0	68359.7	6403.2	9604.8
Spoiler bracket (2)	5623.8	44990.2	2638.6	3957.8
Tailpipe trim covers	3367.2	26937.6	2042.4	3063.6
Total	48077.0	384616.0	34224.0	51336.0

average footprint of about 4.1 m² (Statista, 2020b).

Table 2 shows the potential of reducing Ti consumption in the automotive sector should AM replace CM in eight main components in luxury and sports car segment, assuming BTF of 8:1 for CM and 1.5:1 for AM according to (Liu et al., 2018).

The calculated values do not consider all components that could be replaced with Ti, example. Turbo chargers and pistons. Total savings on raw material resulting from replacing CM with AM based on assumptions adopted for this study are close to 333.2 kt. The total weight of the components listed above in Table 2 is about 48.1 kt and about 34.2 kt

respectively for CM and AM. The assumption applied to all these components of luxury and sports cars in 2019 would mean about 1.4 kt weight saving from all the segments of produced cars (552,000 cars). The main attributes of AM for automobiles and aircraft Ti components are illustrated in Fig. 10.

Considering aerospace industry, Huang et al. (2016) estimate in a study that about 10.7 kt of OEW aircraft can potentially be replaced with Ti. The study also estimates that the replacement of CM with AM for Ti components can potentially reduce mass (380–820 kg) of OEW aircraft. Table 3 summarizes the material saving potential of AM for the

Table 3

Tabulation of global Ti alloy consumption with CM and AM for aerospace.

Assumption	Mass (tonne, t)
Commercial passenger empty plane 110 t	
Total Ti alloy at 15%	16.5
Assumption of AM replacing 6% of Ti alloy components	0.9
Assumption of AM replacing 50% of Ti alloy components	8.3
Assume every plane has 16,500 kg of Ti alloy	
Total estimate of total commercial passenger planes in 2019 was about 1243 units	
Amount of Ti alloy used for 2019 deliveries	20509.5
CM Ti alloy for components at 94%	19278.9
AM Ti alloy for components at 6%	1230.6
AM Ti alloy for components at 50%	10254.8
Estimate of raw material required for AM and CM based on assumptions of this study	
Raw material needed with 94% CM for Ti at BTF 8:1	154231.4
Raw material needed with 6% AM for Ti at BTF 1.5:1	1845.9
Raw material needed if AM were used for 50% of all Ti components	15382.1
Ti alloy removed as waste (kg)	
Estimate of Ti waste at BTF 8:1 if 100% of the share of Ti alloy components are made with CM	43566.5
Estimate of Ti waste at BTF 8:1 if 94% of the share of Ti alloy components are made with CM	115673.6
Estimate of Ti waste at BTF 8:1 if 50% of the share of Ti alloy components are made with CM	171783.3

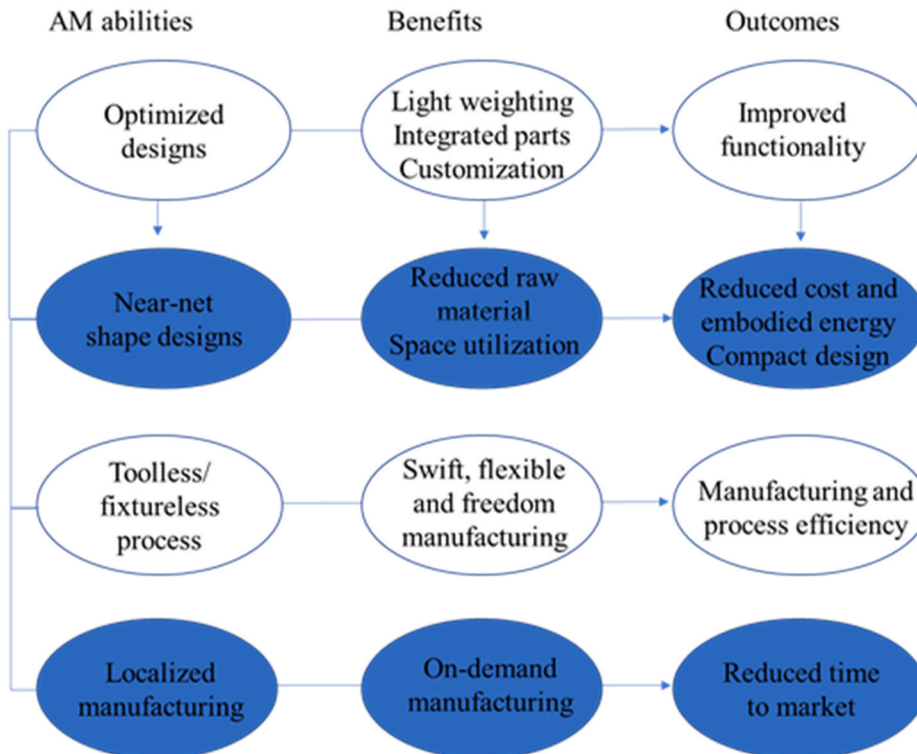


Fig. 10. Attributes of the integration of AM and Ti for niche transport applications.

Table 4
Energy consumption and GHG emissions of Ti (kg) production.

Type	Energy (MJ/kg Ti)	GHG emissions (kg CO ₂ eq/kg Ti)	Reference
Ingot	317–361	31–35.7	(Allwood et al., 2011; Norgate et al., 2007)
Powder	346–390	31.2–35.9	(Allwood et al., 2011; Norgate et al., 2007)
Recycled	78–96	4.7–5.7	Ashby (2012)

Table 5
Energy consumption and GHG emissions for CM and AM processes of Ti alloys.

Processes	Subcategory	Energy (MJ/kg)	GHG emissions (kg CO ₂ eq/kg)	Reference(s)
CM Process				
Forging		48.5–58.7	3.3–4.0	Senyana and Cormier (2014)
Milling		4.5–9.5	0.3–0.6	Dahmus and Gutowski (2004)
Machining		27.4–81.5	1.9–5.5	(Dahmus and Gutowski, 2004; Ezugwu and Wang, 1997)
Die casting		62–72	4.2–4.9	(Ezugwu and Wang, 1997; Kruzhanov and Armhold, 2012)
AM Process				
BJT		11.16		Digital Alloys (2019)
DED	Wire DED	84.6		Digital Alloys (2019)
PBF	EB-PBF*	61–177	4.1–12.0	Baumers et al. (2011)
	L-PBF (varying)	263.5–489.8	7.5–306	(Digital Alloys, 2019; Huang et al., 2016)

aerospace industry.

The total weight saving potential offered by AM results in additional weight saving. Weight reduction achieved for the above listed components may also positively impact the weight of other components in dynamic application. Every saving in weight corresponds to savings in

fuel and every saving in fuel consumption corresponds to the reduction of emissions such as CO₂.

4.2. Global trends of Ti CM and AM

Given the growth of demand for Ti alloy posed by luxury and sport cars manufacturing, we analyzed the global mass flow of Ti in this segment between 2010 and 2050. Results show an increase in the use of Ti alloys in both methodologies: CM (from around 40 kt in 2010 to 68 kt in 2050) and AM (from around 29 kt in 2010 to 48 kt in 2050). Moreover, the results estimate on average around 40% higher proportion of Ti alloy used by CM compared to AM. It is worth noting that the detailed analysis suggests around 15% reduction of the manufacturing rate as well as 11% reduction of the recycling rate of Ti from the automotive industry in 2019–2020 due to the negative effect of Covid-19 pandemic on the supply chain.

As estimated, the availability of Ti used in CM and AM for recycling will reach around 53 kt and 38 kt in 2050, respectively. The pattern of behavior observed for Ti available for recycling is oscillation. One of the main reasons for this trend in Ti flows recycling is the delay mechanism within the system which affects the lifespan of the car and the collection stage. The analysis of mass flows shows that it is possible to obtain significant amounts of Ti from end-of-life vehicles reaching up to 79% in 2050. This result highlights the importance of applying circular economy strategies to Ti in the automotive industry. It is worth noting that the existing technologies for Ti recovery is expensive and energy intensive, however, we cannot ignore the continuous use of Ti in new and innovative applications, some of which could contribute to the circular economy strategies.

Moreover, the global trend of using Ti for aircraft components is examined by considering two given scenarios. Scenario A corresponds to 6% of AM Ti at BTF 1.5:1 for components and 94% of CM Ti at BTF 8:1 for components. Scenario B corresponds to 50% of both AM Ti and CM Ti components. According to the results, the total amount of Ti alloys in aerospace manufacturing will reach up to 32.2 kt in 2050. It is worth noting that it is expected that there will be fewer orders for new commercial aircraft in the next three years (2020–2023) than in the pre-COVID-19 era, which will surely impact the use of Ti in the manufacturing sector in the years to come.

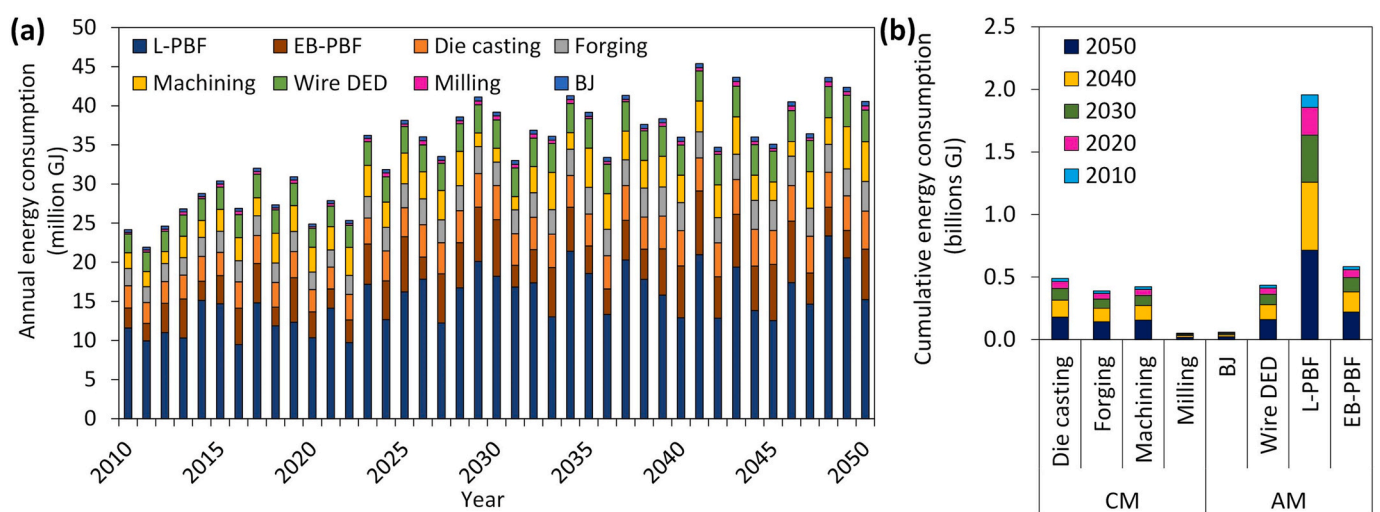


Fig. 11. Global energy consumption of CM including forging, milling, machining, die casting vs. AM including BJT, Wire DED, EB-PBF, L-PBF (varying machine systems) for potential application of Ti in sports and luxury cars manufacturing. a) Annual energy consumption. b) Cumulative energy consumption in 10-year interval.

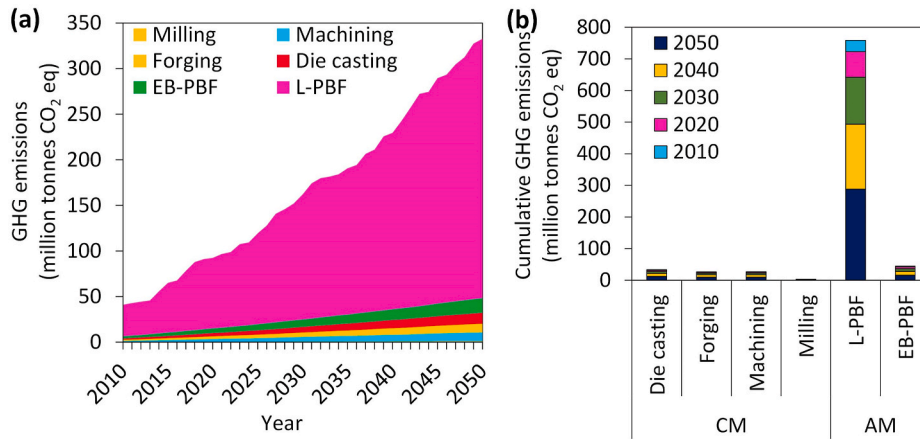


Fig. 12. Global greenhouse gas emissions of CM including forging, milling, machining, die casting vs. AM including EB-PBF, L-PBF (varying machine systems) for application of Ti in sports and luxury cars manufacturing. a) Annual GHG emissions. b) Cumulative GHG emissions in 10-year interval.

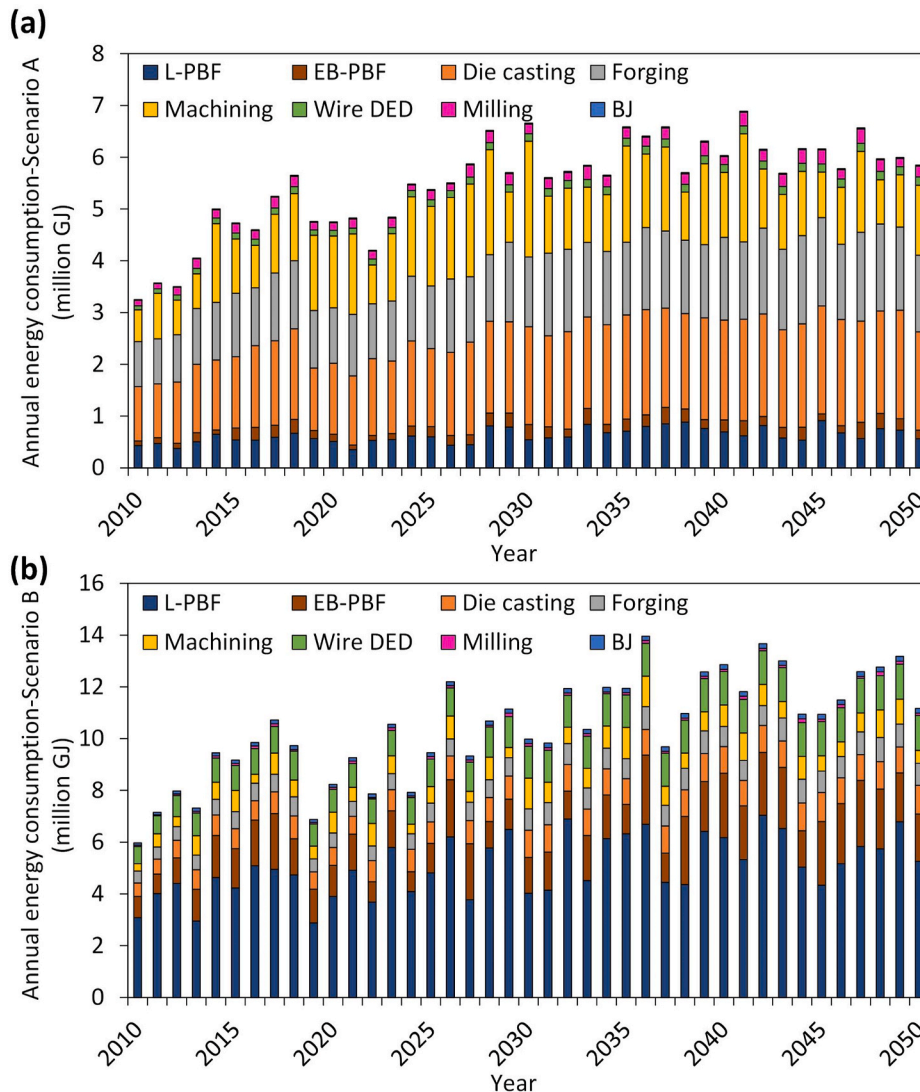


Fig. 13. Global annual energy consumption of CM including forging, milling, machining, die casting vs. AM including BJT, Wire DED, EB-PBF, L-PBF (varying machine systems) for potential application of Ti alloys in airplane manufacturing. a) Scenario A: AM Ti components at 6%. b) Scenario B: AM Ti components at 50%.

4.3. Energy flow and related emissions analysis

4.3.1. Assessment of energy consumption in environmental analysis for CM and AM

The SEC in the production of raw materials, removing or adding materials to form final components and the CO₂ equivalent (CO₂ eq) emissions during production are shown in Table 4 and Table 5. SEC is defined as the energy required to produce a unit volume of input material measured in MJ/kg of Ti.

The comparison of energy consumption presented in Table 5 shows higher SEC for AM than for CM. High energy consumption is reported in L-PBF systems compared to BJT, DED and EB-PBF systems due to high energy intensities required by the laser system to melt and fuse Ti alloy powder (Digital Alloys, 2019; Liu et al., 2018). The fast-building rate of BJT enables components manufacturing with minimal energy consumption (Desktop Metal, 2021). In their study, Martin Baumers et al. (2017) state that low raw material consumption in AM potentially compensates for high SEC during the actual building and post processing phase in AM (Baumers et al., 2017). This is the effect of embodied energy reductions from raw material savings for optimized designs in AM which otherwise would not be feasible in CM (Liu et al., 2018; Mani et al., 2014). High SEC in PBF AM systems can potentially be offset with the right selection of product design optimization, processing parameters values and utilization of the build platform (Kellens et al., 2017; Liu et al., 2018). The comparison of carbon emissions shows that AM generates higher emissions than CM. The outcome is the opposite, however, when material savings and efficiencies in the use phase offered by AM components come into play. This comparison, when extended to cover the phases of the value chain, shows reductions in AM compared to CM.

To assess the global environmental impact of the application of Ti alloys in sports and luxury cars manufacturing, Figs. 11 and 12 present global energy consumption and GHG emissions for Ti alloy flows in the automotive industry. Annual and cumulative energy consumption of Ti is respectively assessed and compared between CM and AM in Fig. 11a and 11b. Detailed calculations show that 73% of total energy consumption corresponds to L-PBF which, as discussed above, is due to high energy intensities required to drive the laser units and followed by other processes such as machining (8%), EB-PBF (7%), die casting (6%), forging (5%), and milling (1%). Noteworthy, 85% contribution of L-PBF as energy intensive process technology in manufacturing stage comes in the use phase and waste management of end-of-life products. For example, due to the peculiarities of the fundamental AM process, including flexible realization of a complex shape, it has an enormous potential for improving the efficiency of material use, with positive environmental impact benefits in the phase of product use and their disposal. Also, the analysis of trends over the period 2010–2050 shows that the growth of energy consumption for each process separately would be 61% for BJT, 71% for Die casting, 72% for Forging, 152% for machining, 152% for milling, 69% for wire DED, 31% for L-PBF and 151% for EB-PBF. Accordingly, Fig. 12a shows that the L-PBF is the largest contributor to GHG emissions among the compared manufacturing methods. Model estimation indicates that 86% of total GHG emissions of Ti alloy manufacturing corresponds to L-PBF while other methods account for much smaller GHG emissions: EB-PBF (5%), Die casting (4%), Machining (3%), Milling (less than 1%). Cumulative GHG emissions in a 10-year interval are shown in Fig. 12b. Considering the growth of GHG emissions for each method over a long-term perspective, the finding gives a new insight into the development of low carbon emission technologies in the manufacturing of Ti in the sports and luxury cars segment.

In the case of the aerospace industry, Fig. 13 shows global annual energy consumption for diverse types of manufacturing in different scenarios. By applying scenario A, the highest energy intensive process interestingly is die casting with 32% of total energy consumption for Ti manufacturing, followed by forging (25%), machining (23%), L-PBF (10%), milling (4%), wire DED (3%), EB-PBF (3%), and BJT (less than

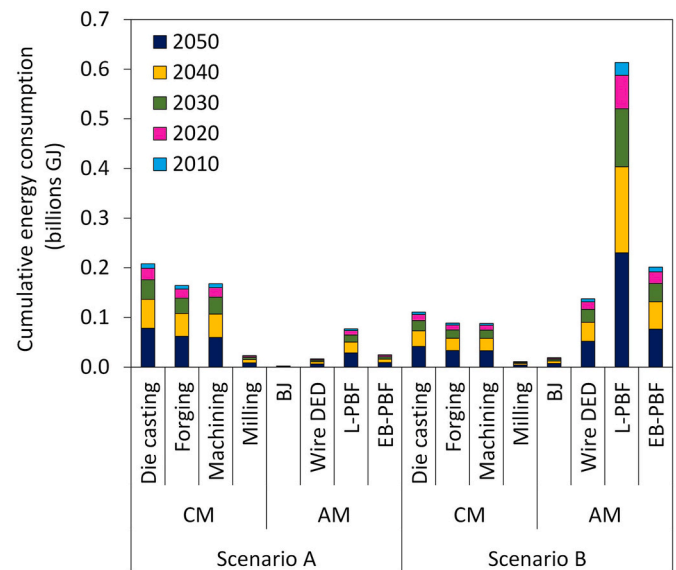


Fig. 14. Global cumulative energy consumption of CM including forging, milling, machining, die casting vs. AM including BJT, Wire DED, EB-PBF, L-PBF (varying machine systems) for potential application of Ti in airplane manufacturing.

1%). However, results for scenario B show that the highest energy intensive process is L-PBF accounting for 47% of total energy consumption of Ti manufacturing, followed by EP-PBF (16%), wire DED (12%), die casting (10%), forging (8%), machining (4%), BJT (2%) and milling (1%). Also, scenario analysis shows that it is possible to reduce energy consumption by 0.2 billion GJ just by applying scenario A compared to scenario B. This finding highlights the necessity of balancing the proportion of use of different methods of Ti manufacturing in terms of less consumption of energy through the process.

The cumulative energy consumption in the manufacturing stage is shown in Fig. 14. Noteworthy, this result does not consider the overall life cycle energy consumption through all stages of supply chain. The high energy consumption in L-PBF is mostly due to the slow build rate and high energy intensities required to drive the laser units. Current L-PBF machine systems continue to offer innovations such as multiple laser systems and stacking which potentially reduce high energy intensities. As a result, there is a probability that in future using new technologies of AM for combined parts manufacturing can reduce the overall energy and raw material consumption. High energy consumption seen in Fig. 14 for scenario B for L-PBF (approximately 2.2 billion GJ) can be downplayed if such energy efficient innovations continue to emerge as the AM processes grow towards the 50% application projection. The ability to build components using the exact quantity of raw materials needed also saves the embodied energy. Thus, including the overall life cycle energy saving potential that can be obtained by using lightweight, optimized, better functioning AM Ti components can potentially offset energy consumption and cost.

Given the emissions connected with energy sources through the application of Ti in airplane manufacturing, Figs. 15 and 16 show annual and cumulative GHG emissions in different scenarios. The results indicate that in scenario A, the highest GHG emissions take place for L-PBF (43% of total GHG emissions through Ti manufacturing), followed by die casting (20%), machining (17%), forging (16%), milling (2%), and EB-PBF (2%). For scenario B, the results show a significant increase in the amount of GHG emitted by L-PBF (up to 87%) while GHG emissions from other processes are much smaller: EB-PBF (5%), die casting (3%), machining (2%), forging (2%) and milling (less than 1%). This finding is indicative of the significant potential of different AM processes, except for L-PBF, in saving energy and reduction of GHG emissions.

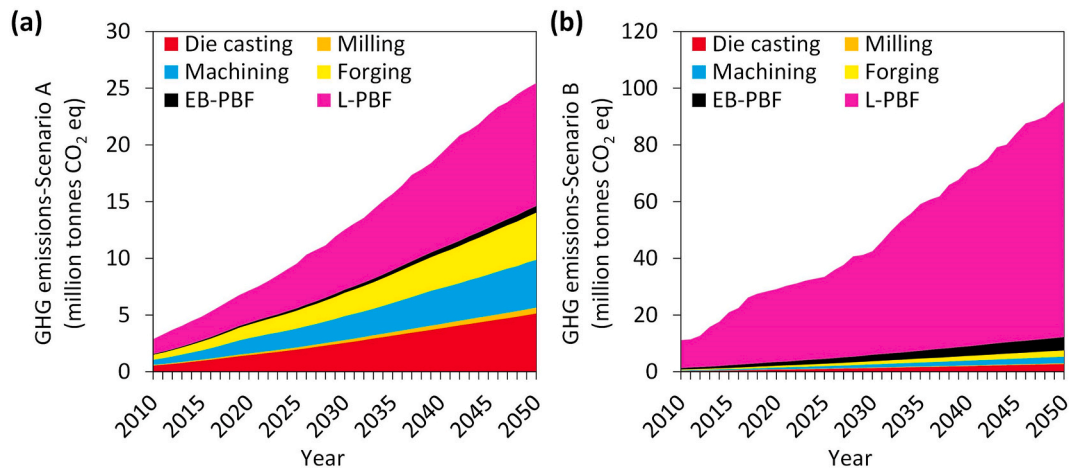


Fig. 15. Global annual greenhouse gas emissions of CM including forging, milling, machining, die casting vs. AM including EB-PBF, L-PBF (varying machine systems) for application of Ti in airplane manufacturing. a) Scenario A: AM Ti components at 6%. b) Scenario B: AM Ti components at 50%.

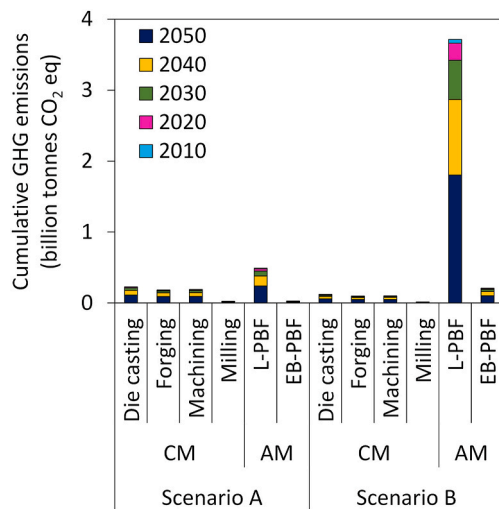


Fig. 16. Global greenhouse gas emissions of CM including forging, milling, machining, die casting vs. AM including BJT, Wire DED, EB-PBF, L-PBF (varying machine systems) for potential application of Ti in airplane manufacturing.

5. Conclusions

The findings of this study can assist automotive and aerospace industries, Ti suppliers and stockholders in adopting solutions adequate to economic challenges and environmental regulations concerning the manufacturing sector. Our detailed assessment of Ti alloy application in additive manufacturing in the automotive and aerospace industries provides a better understanding of the potential pros and cons of AM from a material and environmental perspective compared to CM. The model provides a novel interdisciplinary approach to the quantitative assessment of manufacturing technologies for identifying opportunities for optimization of AM. It can lead to broader environmental, social and economic benefits. The results give a new insight into developing additive manufacturing processes in automotive and aerospace industries in line with actions geared towards achieving the 2030 Agenda for SDGs. To ensure sustainable consumption and production patterns (SDG 12), the analysis has revealed amount of mass savings at a global scale for Ti in CM and AM processes. Moreover, to address sustainability of energy (SDG7) and the mitigation of climate change (SDG 13), the results have shown a comparison for energy consumption and GHG emissions

between different processes of CM and AM.

The results show systematically that the L-PBF manufacturing process is the biggest energy consumer and GHG emitter in both studied cases. However, other AM processes such as BJT, Wire DED and EB-PBF are responsible for lower energy consumption. Noteworthy, decision makers need to consider the entire value chain of AM to identify its benefits which are the largest during the use phase of the components. The findings of this study demonstrate the relevance of optimization of manufacturing process technologies with a view to improve the overall energy and emission saving potential. The scenario building analysis suggests that there is a possibility to reduce the total cumulative energy consumption by optimizing the use of manufacturing technologies. For instance, the flexibility of design optimization and reduced quantity of raw material can offset high energy consumption in the manufacturing phase reported for L-PBF. The limitation of the study is the lack of detailed analysis of recycling end-of-life components including Ti, in aerospace and automotive industries. It is due to the limited availability of data on material flows and its environmental impact through the processes. Therefore, for a future study, it is suggested to develop an optimization model that would incorporate diverse CM and AM processes to minimize energy consumption and environmental emissions. Also, it is recommended to develop the model of this study for closed supply chain of Ti by considering its circularity through recovery and reuse of material. Further research will be needed in the near future to update the findings of this study and to assess the technological progress, especially on corrosion-resistant aluminum alloys applied in the aerospace and automotive industry.

Competing financial interests

The authors declare no competing financial interests.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1

The framework of the dynamic model of Ti and data sources.

Stage of supply chain	Equation	Data sources
Mining	Eq. (1), Eq. (2), Eq. (3), Eq. 4	United States Geological Survey (USGS) (Ober, 2020), European Commission (EU Commission, 2017)
Processing	Eq. (5), Eq. 6	United States Geological Survey (USGS) (Ober, 2020), Statista database (Gullen and Plungis, 2021; Statista, 2021), European Commission (EU Commission, 2017)
Production and manufacturing	Eq. (7), Eq. (8), Eq. (9), Eq. (10), Eq. (11), Eq. (14), Eq. (15), Eq. (16), Eq. (17), Eq. (18), Eq. 19	Statista database (Gullen and Plungis, 2021; Statista, 2021), Other studies (Airliners, 2017; Allwood et al., 2011; Ashby, 2012; Baumers et al., 2011; Boyer, 2010; Dahmus and Gutowski, 2004; Digital Alloys, 2019; Ezugwu and Wang, 1997; Forecast International, 2021; Gloria et al., 2019; Golroudbary et al., 2022a, 2022b; Huang et al., 2016; Kruzhanov and Arnhold, 2012; Liu et al., 2018; Lucintel, 2020; Norgate et al., 2007; Rahimpour Golroudbary et al., 2019; Senyana and Cormier, 2014; Sherman, 1980; Wagner and Schauerer, 2007; Whittaker and Sam Froes, 2015)
Recycling	Eq. (9), Eq. (10), Eq. (11), Eq. 12	United States Geological Survey (USGS) (Ober, 2020), Other studies (Allwood et al., 2011; Ashby, 2012; Baumers et al., 2011; Dahmus and Gutowski, 2004; Digital Alloys, 2019; Ezugwu and Wang, 1997; Huang et al., 2016; Kruzhanov and Arnhold, 2012; Norgate et al., 2007; Senyana and Cormier, 2014)

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