Daša Krapež Tomec[1*], Leon Oblak[2], Manja Kitek Kuzman[2],
Branko Glavonjić[3], Teja Bizjak Govedič[4]

Environmental Assessment/Evaluation of 3D Printing and 3D Printing with Wood-PLA Composites - Case Study

Ekološka procjena/evaluacija 3D printanja i 3D printanja s drvo-PLA kompozitima – studija slučaja

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 25. 4. 2023.
Accepted – prihvaćeno: 1. 9. 2023.
UDK: 674.816
https://doi.org/10.5552/drvind.2024.0107

ABSTRACT • *In recent years, additive manufacturing has become a regular process in various industries, and consequently there is an increasing need to evaluate the environmental aspects of this technology and its associated materials. In this paper, comparative cradle-to-grave life cycle assessments between a conventional product and a 3D-printed alternative made of polylactic acid (PLA) and PLA-wood material were investigated based on the standard ISO 14044:2006. The environmental impact of each product was quantified for 18 categories. The goal of life cycle assessment (LCA) was to determine whether the use of 3D printed PLA/PLA-wood products can be a sustainable alternative to traditional metal products. The paper presents a case study in which a comparative LCA was conducted. The results show that a metal part manufactured using conventional subtractive processes (milling, drilling, welding, etc.) has a higher environmental impact compared to 3D-printed alternatives made from renewable materials. However, there are many sub-issues that need to be adequately addressed.*

KEYWORDS: *life cycle assessment; 3D printing; environmental impact; carbon footprint; wood-PLA composite*

SAŽETAK • *Posljednjih je godina aditivna proizvodnja postala redoviti proces u raznim industrijama, a posljedično se pojavila sve veća potreba za procjenom ekoloških aspekata te tehnologije i s njom povezanih materijala. U ovom su radu ispitane i uspoređene procjene životnog vijeka konvencionalnog proizvoda „od kolijevke do groba" te 3D isprintane alternative izrađene od polilaktične kiseline (PLA) i PLA-drvnog materijala na temelju standarda ISO 14044:2006. Utjecaj svakog proizvoda na okoliš kvantificiran je unutar 18 kategorija. Cilj procjene životnog vijeka takvih proizvoda (LCA) bio je utvrditi može li uporaba 3D printanih PLA/PLA-drvnih proizvoda biti održiva alternativa tradicionalnim metalnim proizvodima. U radu je prikazana studija slučaja u kojoj je pro-*

* Corresponding author
[1] Author is a PhD candidate at University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Ljubljana, Slovenia. https://orcid.org/0000-0003-1879-3830
[2] Authors are full professors at University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Ljubljana, Slovenia. https://orcid.org/0009-0008-8054-1945; https://orcid.org/0000-0002-3764-4681
[3] Author is full professors at University of Belgrade, Faculty of Forestry, Belgrade, Serbia. https://orcid.org/0000-0003-4293-4410
[4] Author is a research associate at University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Ljubljana, Slovenia. https://orcid.org/0009-0007-6794-9113

vedena komparativna procjena životnog vijeka – LCA. Rezultati pokazuju da metalni dio proizveden primjenom konvencionalnih subtraktivnih procesa (glodanja, bušenja, zavarivanja itd.) ima veći utjecaj na okoliš nego 3D isprintane alternative izrađene od obnovljivih materijala. Međutim, u vezi s tim postoje i mnoga potpitanja koja se moraju adekvatno riješiti.

KLJUČNE RIJEČI: *procjena životnog vijeka; 3D printanje; utjecaj na okoliš; ugljični otisak; drvo-PLA kompozit*

1 INTRODUCTION
1. UVOD

Three-dimensional printing (3DP) is a manufacturing process in which a product is built up layer-by-layer using a digital model. Since its introduction in the 1980s, additive manufacturing (AM) has been used primarily for rapid prototyping due to its ability to produce objects with complex geometries. Of these methods, FDM (Fused Deposition Modeling) or FFF (Fused Filament Fabrication) is the most researched and increasingly appreciated in the last decade and has become the manufacturing method for 3D printers. FDM 3D printers are now affordable and available to a community of do-it-yourself enthusiasts (Krapež Tomec and Kariž, 2022).

3D printing creates shifts in work patterns as the process is highly automated and human workers are only needed in pre- and post-processing (Lindemann *et al.*, 2012). Through 3D printing, chains are expected to become shorter by reducing the need for centralized manufacturing and tooling. Production-related energy requirements and CO_2 emissions are reduced by shortened processes and more direct manufacturing. This reduces the need for tooling, the need for handling, and it lowers indirect material-related energy through higher resource efficiency (Reeves, 2013).

Numerous perspective research articles on using wood in AM have already been published and are presented in (Krapež Tomec and Kariž, 2022). In this regard, it is also worth promoting life cycle assessment (LCA) analysis, a quantitative evaluation of the environmental impacts that occur during the life cycle of the product.

AM replicates biological processes by building products layer-by-layer. It is inherently less wasteful than traditional subtractive production methods and holds the potential to decouple social and economic value creation from the environmental impact of business activities. There are many potential sustainability benefits of this technology, from less material waste, energy efficiency, local production, carbon footprint reduction, to circular economy, optimized design and innovation driver; three of them stand out: (1) Improved resource efficiency - improvements can be realized in both the production and use phases, as manufacturing processes and products can be redesigned for AM; (2) Extended product life -achieved through technical approaches such as repair, remanufacture and refurbishment, and more sustainable socio-economic patterns such as stronger human-product affinities and closer producer-consumer relationships (Kohtala, 2015); (3) Redesigned value chains - shorter and simpler supply chains, more localized production, innovative distribution models and new collaborations (Ford and Despeisse, 2016).

Reeves (2012) has shown in a case study of a structural aircraft component that manufacturing-related energy demand and CO_2 emissions can be reduced by up to 75 %. 3D printing-induced light weighting also leads to usage savings, amounting to 63 % savings in energy and CO_2 emissions over the entire life cycle of the product. This shows that 3D printing has great environmental potential beyond just manufacturing of products.

3D printing enables a buy-to-fly ratio of nearly 1:1, leading to a significant reduction in resource requirements and manufacturing-related waste. Case studies show that up to 40 % of raw material-related waste can be avoided by 3D printing, while 95-98 % of non-melted raw material can be reused (Petrovic Filipovic *et al.*, 2011). Other indirect manufacturing inputs can be avoided as 3DP does not require auxiliary materials such as coolants, lubricants or other substances that are sometimes harmful to the environment.

In general, 3D printing methods have better environmental characteristics. In terms of low carbon emission, there are five primary environmental benefits: (1) Reduction of raw material requirements in the supply chain. This reduces the mining and processing of ores as primary materials. (2) Reduced need for energy-intensive manufacturing processes, such as casting, and wasteful/harmful materials, such as cutting fluids in CNC machining. (3) Flexibility in designing more efficient components with better operational performance. (4) Reduced weight of products, helping to improve carbon footprint when used in the vehicle they are integrated into, e.g. aircraft. (5) Parts could be manufactured closer to the point of consumption, reducing energy consumption in logistics (Peng, 2017). All five points speak in favor of our 3D-printed versions from PLA and PLA-wood.

Despite the potential increase in recycling rates, the materials used for AM are not necessarily more environmentally friendly than those used in traditional manufacturing. The only exception could be the biopolymer polylactic acid (PLA) (Faludi *et al.*, 2015).

Potential material savings may be partially offset by the relative toxicity of the material used for AM and the impact of energy consumption to produce the feedstock and the processing itself. Therefore, the full environmental performance of AM needs to consider the energy demand from a system perspective and not just the process itself (Faludi *et al.*, 2015).

Wood fiber/flour stands out as a premier choice among raw materials for manufacturing plant fiber-plastic composites. PLA, a compostable synthetic polymer made from a monomer feedstock derived from corn starch, is an acceptable substitute for petroleum-derived plastics. The integration of wood-based materials into AM has garnered considerable attention, primarily due to their dual advantages: a favorable ecological footprint and enhanced material attributes (Tao *et al.*, 2017).

However, little research has been done on the toxicity and environmental impact of AM processes and materials. Such effects may exist in the processing and disposal of materials used in AM processes (Ford and Despeisse, 2016).

The fact that there are not many papers studying environmental impact of 3D-printed PLA-wood products led us to perform a comparative LCA analysis for the existing conventional product (metal chair connector) and the 3D-printed alternatives made of biocompatible material PLA and PLA-wood blend material (according to manufacturer wood makes up to 40 %). This case study presents a comparative sequence LCA of a part produced by two different manufacturing processes - Conventional Manufacturing (with milling, drilling, welding) and 3D printing process (FDM – Fused Deposition Manufacturing). A specific part – a chair connector - made of metal is analyzed from cradle to gate. The LCA is analyzed to provide a framework to choose the most appropriate manufacturing process in terms of environmental impact.

Figure 1 Chair design – chair type: domestic seating for adults (Cvetko, 2020)
Slika 1. Dizajn stolice – tip stolice: kućni namještaj za sjedenje namijenjen odraslima (Cvetko, 2020.)

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 A case study: A chair connector
2.1. Studija slučaja: poveznik stolice

A metal connector from a modern chair for domestic use (Figure 1) was chosen for a case study. The chair consists of the following components:

- the shell of the seat and backrest are made of plastic composite material and represent the seat part of the

a) b) c)

Figure 2 a) 3D model of connector (SolidWorks), b) connector made of PLA material, c) connector made of metal (Cvetko, 2020)
Slika 2. a) 3D model poveznika (SolidWorks), b) poveznik od PLA materijala, c) poveznik od metala (Cvetko, 2020.)

Table 1 Three versions of connectors defined with material usage, printing time, material price and weight
Tablica 1. Tri verzije poveznika definirane utroškom materijala, vremenom printanja, cijenom materijala i masom

Version *Verzija*	**Material** *Materijal*	**Print time, h** *Vrijeme printanja,* h	**Material used, g** *Utrošak materijala,* g	**Price of material, €/kg** *Cijena materijala,* €/kg	**Weight, g** *Masa,* g
Metal connector / *metalni poveznik*	metal	/	no data	no data	1340
Optimized connector 2-PLA *optimizirani poveznik 2-PLA*	PLA	13 h 13 min	387	19.52 (7.03 per item)	360
Optimized connector 2-WPC *optimizirani poveznik 2-WPC*	PLA-W	14 h 58 min	444	30.50 (15.12 per item)	347

chair. The seat part, in which there are four upholstery nuts, is fixed to the metal connector with four M6×14 screws.

- another component of the chair is a metal connector used to attach four oak legs and the seat part. The four oak legs are screwed to the metal connector with eight M6×45 screws and nuts.

The materials included in this case study are an original metal-based, alternative 3D- printed part from polylactic acid and a 3D-printed part from a filament mixed with PLA and wood.

2.2 3D printing of PLA and wood-PLA connectors
2.2. 3D printanje PLA i drvo-PLA poveznika

The digital models of 3D parts were modeled in SolidWorks software (SolidWorks Corp., Waltham, MA, USA) and exported to STL format. The STL models were sliced and prepared for 3D printing in Z-Suite software (Zorttrax, Olsztyn, Poland).

Parts used for the LCA comparison with original metal connector (from Maxxim, Dipo, reference unknown) were printed on Zorttrax M-200 (Olsztyn, Po-

Table 2 Life cycle inventory database used for different versions of connector (SimaPro references written in both bold and italic letters)
Tablica 2. Baza podataka inventara životnog ciklusa koja se primjenjivala za različite verzije poveznika (SimaPro reference napisane su podebljanim i kurzivnim slovima)

	Life cycle inventory database / *Baza podataka inventara životnog ciklusa*		
Life cycle stage *Faza životnog ciklusa*	**Metal connector** *Metalni poveznik*	**3D-printed PLA connector** *3D isprintani PLA poveznik*	**3D-printed PLA-wood connector** *3D isprintani PLA-drveni poveznik*
Premanufacturing or raw material extraction *pretproizvodnja ili ekstrakcija sirovina*	- materials processing - input from nature: ***iron ore*** / *obrada materijala - ulaz iz prirode: željezna ruda* - transformation input: *electricity, medium voltage, SI* / *transformacijski ulaz: električna energija, srednji napon, SI*	***- polylactide, granulate*** / *polilaktid, granulat* - filament production – input: ***electricity, medium voltage, SI*** / *proizvodnja filamenta – ulaz: električna energija, srednji napon, SI*	***- polylactide, granulate*** / *polilaktid, granulat* ***- wood wool*** (as replacement for wood flour) / *drvena vuna (kao zamjena za drvno brašno)* - filament production – compounding – *electricity*, ***medium voltage, SI*** / *proizvodnja filamenata – kompaundiranje – električna energija, srednji napon, SI*
Manufacturing and processing *proizvodnja i prerada*	- product manufacturing – processes (***sheet rolling, milling, drilling, welding***) / *izrada proizvoda – procesi (valjanje lima, glodanje, bušenje, zavarivanje)* - *transport from processing site to manufacturing site:* ***transport, freight, lorry 16-31 metric ton, euro5*** / *prijevoz od mjesta obrade do mjesta proizvodnje: prijevoz, teret, kamion 16-31 metrička tona, euro5* ***- electricity, medium voltage, SI*** / *električna energija, srednji napon, SI*	- product manufacturing – 3D printing; input is ***electricity, medium voltage, SI /*** *izrada proizvoda – 3D ispis; ulaz je električna energija, srednji napon, SI*	- product manufacturing – 3D printing; input is ***electricity, medium voltage, SI /*** *izrada proizvoda – 3D ispis; ulaz je električna energija, srednji napon, SI*
Transportation *transport*	- transport from manufacturing site to distribution site ***transport, freight, lorry 16-31 metric ton, euro5*** / *prijevoz od mjesta proizvodnje do mjesta distribucije: prijevoz, teret, kamion 16-31 metrička tona, euro5*	- no transport – 3D printing takes place at manufacturing site / *nema transporta – 3D ispis se obavlja na mjestu proizvodnje* - distribution to individual consumer is excluded / *isključena je distribucija pojedinačnom potrošaču*	- no transport – 3D printing takes place at manufacturing site / *nema transporta – 3D ispis se obavlja na mjestu proizvodnje* - distribution to individual consumer is excluded / *isključena je distribucija pojedinačnom potrošaču*
Usage / *uporaba*	- all 3 products have the same use phase / *sva tri proizvoda imaju istu fazu uporabe*		
End-of-life or waste disposal *kraj životnog vijeka ili odlaganje otpada*	- wasted metal is melted down for reuse / *otpadni se metal tali za ponovnu upotrebu*	- wasted PLA is recycled for reuse (or abiotically degraded) / *otpadni PLA se reciklira za ponovnu upotrebu (ili se abiotički razgrađuje)*	- wasted PLA is recycled for reuse (or abiotically degraded) / *otpadni PLA se reciklira za ponovnu upotrebu (ili se abiotički razgrađuje)*

land). Pure PLA filament and PLA-wood filament (with up to 40 % wood flour content), both commercially available, were used. The diameter of the filament was 1.75 mm, the diameter of the print nozzle was 0.6 mm, the layer thickness was set to 0.4 mm and the infill to 40 %.

2.3 LCA methodology
2.3. LCA metodologija

The study applied the LCA methodology based on the standard ISO 14044:2006 following four major steps to quantify the difference in environmental impact between conventional metal connector and two 3D printed alternatives. A “cradle-to-gate” evaluation was conducted within the SimaPro 9.0 software, developed by PRé Sustainability, Amersfoort, 2019. Additionally, all phases to the end of the life cycle were also taken into consideration, based on data from scientific papers. SimaPro 3D printing is not supported by SimaPro, as it was not yet included in the library at the time of this study. The geography for the manufacturing and distribution phases were set in Slovenia at time horizon 2021. The process trees are presented in Figure 4 and the input information of the Life Cycle Impact Assessment (LCIA) in Table 2.

For consistency, it was assumed that the input mass of all three versions of chair connector is 1 kg of raw material.

It was also assumed that all transport is carried out by road with a truck (SimaPro reference: Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}). The geography for the manufacturing and distribution is set in Slovenia, where distances are short (typically less than 50 km) and no specific locations were determined (of manufacturing companies, etc.). For this study, it was assumed that the metal is processed by manufacturer A, while the metal part is formed by a nearby subcontractor and later distributed to a warehouse B (presumably in Kranj; halfway between Jesenice and Ljubljana - to negate the impact of distances between production sites, as they are fictitious). On the other hand, filaments are extruded by manufacturer B in Ljubljana and 3D parts are printed and assembled in warehouse B. In this sense, the 3D printing variants eliminate some manufacturing and transportation phases – considering that 3D printing can be produced at the same site where it is later assembled.

The classification and characterization processes were carried out according to the standard ISO 14040:2006. For the assessment of impacts, ReCiPe 2016 Midpoint (Hierachist) was applied to calculate the environmental impacts, and 18 impact categories were included in the LCA. Midpoint characterization factors are calculated based on a consistent environmental cause-effect chain, except for land-use and resources. Its regional validity is Europe; it is global for climate change, ozone layer depletion and resources. Its temporal validity is present time.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Life cycle impact assessment of three versions of chair connector
3.1. Procjena utjecaja na okoliš životnog vijeka triju verzija poveznika za stolicu

The results of the cradle-to-gate comparative LCA between the three types of chair connectors are shown in Figure 3, 4 and 5.

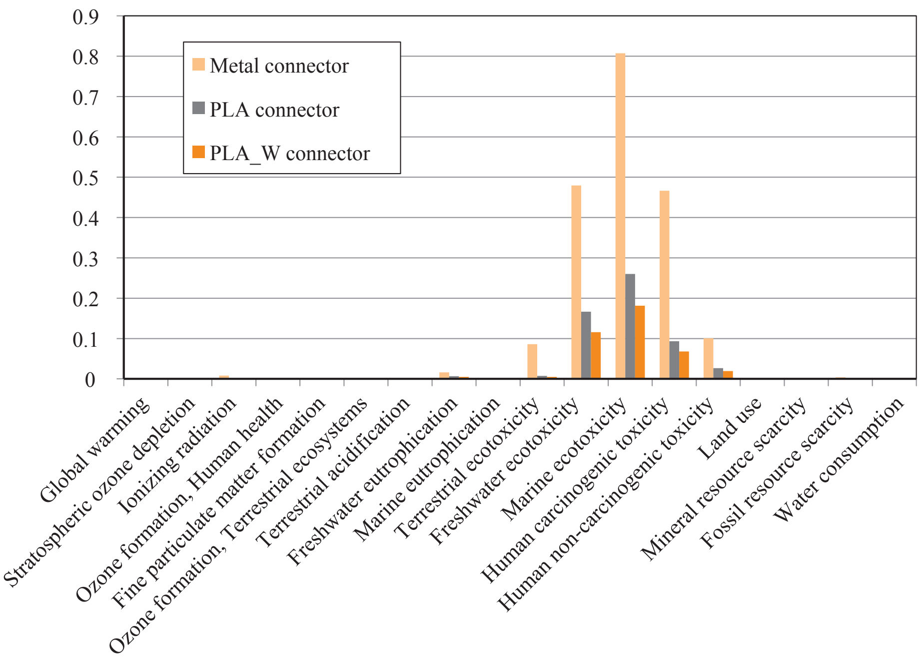

Figure 3 Impact assessment of 3 versions of chair connectors using ReCiPe 2016 Midpoint (H) method with normalization of results
Slika 3. Procjena utjecaja na okoliš triju verzija poveznika za stolicu primjenom metode ReCiPe 2016 Midpoint (H) s normalizacijom rezultata

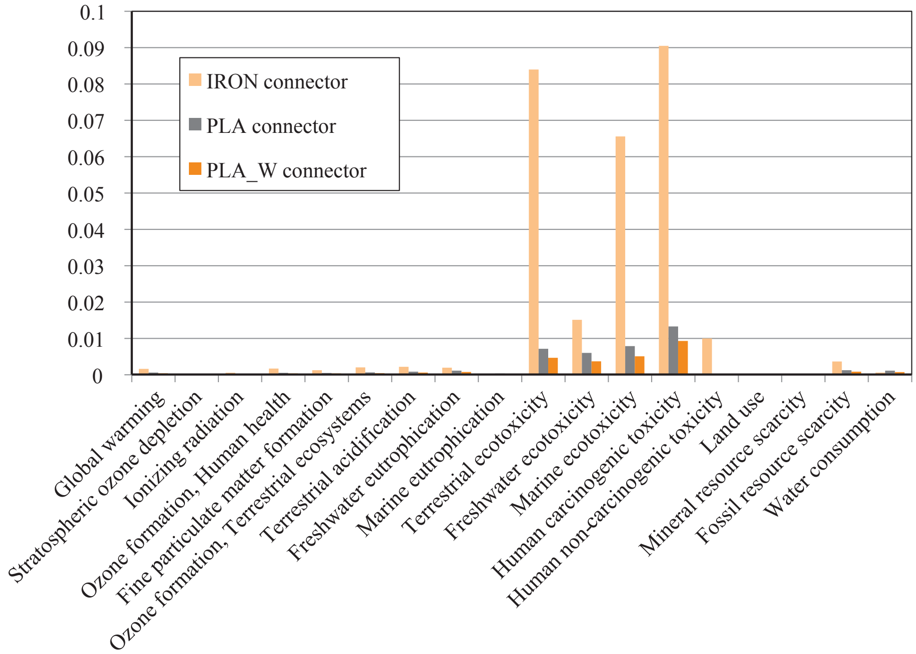

Figure 4 Impact assessment of 3 versions of chair connectors using ReCiPe 2016 Midpoint (H) method with normalization of results and excluded long-term emissions
Slika 4. Procjena utjecaja na okoliš triju verzija poveznika za stolicu primjenom metode ReCiPe 2016 Midpoint (H) s normalizacijom rezultata i isključenim dugoročnim emisijama

Normalization results can be used to compare different categories of impacts, as these impacts are individually converted by a multiplication factor to have all impacts in a single unit or ratio form.

Considering all three versions of connector, Freshwater and Marine ecotoxicity, and Human carcinogenic toxicity are the major environmental impacts. In all three impact categories, the metal connector has by far the highest values (70-80 %). As shown in Figure 5, this is due to operations related to processing of iron, part milling operation, high electricity usage and transport. When comparing the two 3D-printed versions, it is evident that the values of PLA-wood connector are 20 to 30 % lower than those of pure PLA connector.

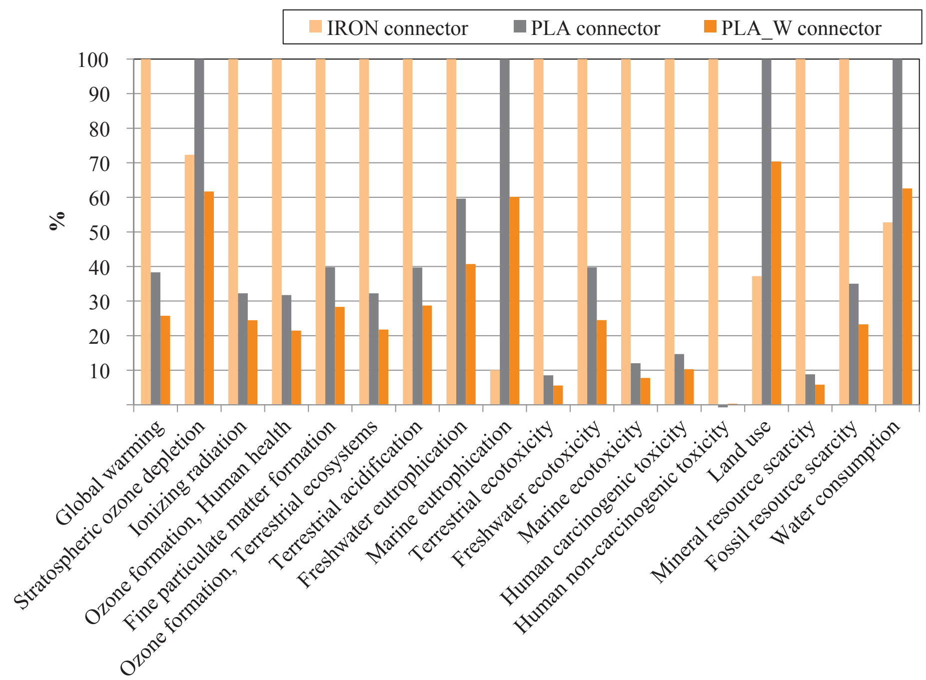

Figure 5 Impact assessment of 3 versions of chair connectors using ReCiPe 2016 Midpoint (H) method with characterization of results, excluding long-term emissions
Slika 5. Procjena utjecaja na okoliš triju verzija poveznika za stolicu primjenom metode ReCiPe 2016 Midpoint (H) s karakterizacijom rezultata i isključenim dugoročnim emisijama

Comparing all three versions of connector, when excluding long-term emissions, Terrestrial and Marine ecotoxicity, and Human carcinogenic toxicity are the major environmental impacts. In all three impact categories metal connector has by far (above 80 %) the highest values. Comparing the two 3D-printed versions, PLA-wood connector has around 30 % lower values than pure PLA connector. All three impact categories are defined by the use of electricity in 3D printing and also by the raw material used, i.e. PLA.

In Characterization, all results are plotted on a percentage scale.

The carbon footprint is the sum of greenhouse gas emissions caused directly or indirectly by an organization, product, service, or other activity that causes or contributes to greenhouse gas emissions over a period of time. It is defined in units of CO_2 equivalents (CO_2e) (Le Treut *et al.*, 2007). Impacts are calculated per unit of CO_2e of the six major greenhouse gasses (GHGs). The average of all these gasses causing global warming is known as Global Warming Potential (GWP) and is usually given in the time frame of 100 years.

The 3D-printed alternatives showed (Figure 5) 62 % (PLA) and 73 % (PLA-wood) lower GWP than the conventional metal part. However, the results of the cradle-to-gate life cycle assessments suggest that the 3D-printed PLA alternative may cause greater environmental impacts than the conventional products in some impact categories – Stratospheric ozone depletion, Marine eutrophication, Land use and Water consumption.

In terms of LCA, 3D-printed PLA-wood and PLA alternatives would be much more environmentally friendly compared to conventional products, although the environmental benefits might be insignificant from the manufacturer's point of view.

3.2 Life cycle interpretation (LCI)
3.2. Tumačenje životnog vijeka (LCI)

The aim of our case study was to determine with a quantitative analysis whether a 3D-printed product can be a sustainable alternative to the conventional connector from the manufacturing and material point of view.

3DP induces CO_2 emission reduction potentials over the entire lifecycle of a product. The life cycle of the connector component includes several phases, from raw material production/acquisition to the end-of-life phase of the connector. For each phase, the data from literature is described to estimate the environmental impacts throughout the connector life cycle.

The transportation of each material to the manufacturing site (which is assumed to be Slovenia) has also been considered (and described previously in subchapter "LCA analysis" of chapter Method and Materials).

3.2.1 Raw material phase
3.2.1. Faza sirovine

In iron ore processing, substantial solid waste, mainly slag, could be repurposed as secondary raw materials, aligning with circular economy principles. This also applies to energy waste from steelmaking. The most environmentally impactful stages are blast furnace and coke oven operations, driven by energy consumption and emission toxicity (Renzulli *et al.*, 2016). Raw materials (coal, pulverized coal, iron ore) are largely imported (Australia, South Africa, USA, Canada, Venezuela, Brazil, Mauritania).

Despite high initial production impacts, metal benefits from usage and end-of-life recycling, offsetting compared to non-metallic alternatives. A cradle-to-gate study is limited for LCAs involving metals, meanwhile cradle-to-grave provides comprehensive insights (ISO 14040/14044) (Santero and Hendry, 2016).

Metal production averages 20-25 MJ (5550-6950 Wh)/kg (Low-tech magazine, 2023), 6 kWh in SimaPro. Furthermore, crude PLA synthesis and filament conversion are considered, assuming 15 kg/hour production with 1 kWh/kg consumption and no extrusion waste.

For PLA-wood chair connectors, wood benefits (cost, renewability, recyclability, non-toxicity, reduced plastic use) attract manufacturers as a filler. Wood, cost-effective vs. petroleum/bioplastics, is combined with polymers for diverse performance (Ayrilmis *et al.*, 2019).

In raw material stage, metal connectors show higher environmental impact due to primary sourcing, meanwhile PLA and PLA-wood use renewable sources (plant-derived starch, trees).

3.2.2 Manufacturing phase
3.2.2. Faza proizvodnje

Observed sustainability challenges for the case-studied part include: (a) material and process standardization, (b) limited speed and reliability of AM technologies, (c) constrained quality and aesthetics of products, (d) cost efficiency and energy efficacy enhancement at higher production volumes.

From a sustainability standpoint, AM's additive nature reduces waste compared to subtractive techniques, despite potential higher energy intensity per unit. AM's make-to-order capacity aligns with better overall performance and dematerialization due to increased raw material utilization (Chen *et al.*, 2015).

AM's direct production from 3D CAD models eliminates tooling costs, promotes design sharing, customization, and faster prototyping. Energy intake involves electrical and material-based energy. AM's main environmental benefits over CNC machining are less waste and lower pollution, especially from metalworking fluids (Huang *et al.*, 2013).

While AM's energy consumption can be higher than conventional methods, benefits emerge from utilization rates. Sharing machines reduces environmental impact. Fused Deposition Modeling (FDM) shows lowest environmental impact per part with both high and low utilization (Ford and Despeisse, 2016).

3D printing's energy consumption surpasses that of injection molding, but it's relatively low in FDM. Material waste is minimized, but print time affects energy consumption. Lightweight 3D-printed designs reduce fuel costs during use (Gebler *et al.*, 2014).

In terms of production costs, 3D printing introduces shifts in the cost structure with a focus on machine costs. Material costs are case-specific but often comprise a smaller portion, although 3D printing materials are costlier, they pay off due to higher material efficiency (Reeves, 2008).

Comparatively, FDM 3D printing is cost-efficient below a break-even point, making it optimal for specific production volumes (Hopkinson *et al.*, 2006). 3D printing generates less waste than conventional methods, but supports and failed prints contribute to post-processing waste.

Hybrid manufacturing processes offer advantages such as improved surface quality and shorter production times. Integrating AM with traditional processes enhances these benefits (Ford and Despeisse, 2016).

3.2.3 Use phase
3.2.3. Faza uporabe

Concerning product use, the lightweight of a 3D-printed part must be highlighted. Both 3D-printed parts are approximately 4 times lighter than original metal part.

Optimized 3D-printed connectors were printed from polylactic acid (PLA) and wood-plastic composite and tested in the Furniture Testing Laboratory according to the requirements of the SIST EN 12520:2010 standard. The optimized 3D-printed connector made of PLA material met the requirements of the standard, and the connector made of wood-plastic composite did not, as a fracture occurred.

Observed sustainability challenges for the case-studied part are: (a) uncertain performance of product and component due to low maturity of technology and (b) uncertain performance of product and component over a longer lifetime.

3.2.4 Repair and remanufacturing phase
3.2.4. Faza popravka i ponovne proizvodnje

Another important segment is that of spare parts. If a part is broken and the replacement part is no longer manufactured by the industry, the entire object needs to be thrown away, resulting in various environmental impacts. However, if the spare part can be printed, the object will last longer and the process time for repair is reduced. This unequivocally contributes to sustainability objectives by mitigating waste generation and consequently reducing the associated carbon footprint.

Companies are beginning to discover the impact of using AM technologies to extend product lifecycles and close the loop (Ford and Despeisse, 2016).

3.2.5 End-of-life phase
3.2.5. Faza kraja života

In the end-of-life phase, metal's negative environmental impact turns positive due to its recyclability advantage. The highest value recovery occurs locally during manufacturing when unused AM material (powder or resin) is reclaimed. One the other hand, approximately 95-98% of metal powders can be reused (Petrovic Filipovic *et al.*, 2011).

Ford and Despeisse (Ford and Despeisse, 2016) noted that AM can integrate in situ recycling to divert waste to new applications. Simplified recycling systems are feasible with increased PLA use and reduced plastic variety. PLA's recyclability without quality loss enables closed material loops (Chen *et al.*, 2015).

'Biodegradable' materials decompose based on conditions. Composting is a controlled process. According to EN 13432, 'compostable' means 90 % conversion in industrial composting within 6 months. PLA degrades rapidly under these conditions, but takes decades in the wild, contributing to pollution (3Dnatives, 2023).

PLA degradation mechanisms include hydrolysis, thermal degradation, and photodegradation. Slow ambient degradation is observed, and PLA persists in certain environments (Bagheri *et al.*, 2017; Karamanlioglu and Robson, 2013).

AM enhances material recycling efficiency, raises awareness, and promotes recycled material acceptance.

4 CONCLUSIONS
4. ZAKLJUČAK

Industrial sustainability is a persistent priority, with growing emphasis on enhancing production efficiency and environmental harmony. Sustainable development seeks to reduce the ecological impact of manufacturing, a pursuit achievable through AM.

The focal point of this case study revolves around the comprehensive evaluation of diverse materials and manufacturing methodologies employed in the fabrication of a chair connector, uniting four oak legs with the seat component. This project aimed to assess the environmental life cycle of 3D-printed parts comparing the result with conventional metal part.

It was found that a metal part, manufactured with conventional technologies, has a higher environmental impact compared to 3D-printed alternatives from renewable materials.

These observations are due to the fact that the 3D printing uses significantly smaller amount of material as it is an additive manufacturing- in other words, it generates less waste during manufacturing, it is possible to optimize geometries and create lightweight components that reduce material consumption during manufacture and energy consumption during use, it reduces transportation in the supply chain and an inventory waste due to the ability to manufacture spare parts on demand.

In addition, it was found that the material used can strongly influence the environmental footprint in other impact categories, leading to important tradeoffs. Challenges in AM with biodegradable materials, such as wood composites, include processing issues during extrusion and part fabrication, particularly with respect to part dimensional stability and material brittleness depending on the degree of stress on the wood components, as well as effects on polymer crystallization behaviour during processing (Gardner and Wang, n.d.). In certain cases, the mechanical and physical properties of the printed parts can approach the property range of conventional wood composites such as particleboard, fiberboard, and wood-thermoplastic composites. With the proper incorporation of wood fibers, nanocellulose and continuous fiber printing, this could even be improved.

However, there is still an open question of PLA material environmental impact. It is, nevertheless, a renewable material, derived from natural, plant-based starch. Furthermore, it is advertized as biodegradable although studies (Bagheri *et al.*, 2022; Castro-Aguirre *et al.*, 2016; Karamanlioglu and Robson, 2013; Rezvani Ghomi *et al.*, 2021) show that its degradability is either abiotic (with hydrolysis, thermal- or photo-degradation) or very slow.

As for AM in general, it is still in its early stages and requires further research to reduce material and machine costs, create faster and more accurate printing processes, and operate autonomously (Gopal *et al.*, 2023).

The case study of a wooden chair with three different connectors is based on several assumptions, and future work (additional LCA analysis and comparison) is needed to better understand the environmental impact of 3D-printed products. This approach aligns with the principles of the European Bauhaus framework, a paradigm endeavouring to synthesize sustainability, aesthetic considerations, and innovative approaches.

Acknowledgements – Zahvala

The authors acknowledge the support of the Slovenian Research Agency (ARRS) within the framework of research program No. P4-0015 "Wood and lignocellulosic composites".

5 REFERENCES
5. LITERATURA

1. Ayrilmis, N.; Kariz, M.; Kwon, J. H.; Kitek Kuzman, M., 2019: Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials. International Journal of Advanced Manufacturing Technology, 102 (5-8): 2195-2200. https://doi.org/10.1007/s00170-019-03299
2. Bagheri, A.; Aghareb Parast, M. S.; Kami, A.; Azadi, M.; Asghari, V., 2022: Fatigue testing on rotary friction-welded joints between solid ABS and 3D-printed PLA and ABS. European Journal of Mechanics – A/Solids, 96: 104713. https://doi.org/10.1016/J.EUROMECHSOL.2022.104713
3. Bagheri, A. R.; Laforsch, C.; Greiner, A.; Agarwal, S., 2017: Fate of so-called biodegradable polymers in seawater and freshwater. Global Challenges, 1 (4): 1700048. https://doi.org/10.1002/gch2.201700048
4. Castro-Aguirre, E.; Iñiguez-Franco, F.; Samsudin, H.; Fang, X.; Auras, R., 2016: Poly(lactic acid) – Mass production, processing, industrial applications and end of life. Advanced Drug Delivery Reviews, 107: 333-366. https://doi.org/10.1016/j.addr.2016.03.010
5. Chen, D.; Heyer, S.; Ibbotson, S.; Salonitis, K.; Steingrímsson, J. G.; Thiede, S., 2015: Direct digital manufacturing: definition, evolution and sustainability implications. Journal of Cleaner Production, 107: 615-625. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.05.009
6. Cvetko, M., 2020: Optimizacija 3D tiskanega veznika za stol. University of Ljubljana.
7. Faludi, J.; Bayley, C.; Bhogal, S.; Iribarne, M., 2015: Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. Rapid Prototyping Journal, 21 (1): 14-33. https://doi.org/10.1108/RPJ-07-2013-0067
8. Ford, S.; Despeisse, M., 2016: Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of Cleaner Production, 137: 1573-1587. https://doi.org/10.1016/j.jclepro.2016.04.150
9. Gardner, D. J.; Wang, L., n.d.: Additive Manufacturing of Wood-based Materials for Composite Applications. SPE Automotive Composites Conference & Exhibition, October.
10. Gebler, M.; Schoot Uiterkamp, A. J. M.; Visser, C., 2014: A global sustainability perspective on 3D printing technologies. Energy Policy, 74 (C): 158-167. https://doi.org/10.1016/j.enpol.2014.08.033
11. Gopal, M.; Lemu, H. G.; Gutema, E. M., 2023: Sustainable Additive Manufacturing and Environmental Implications: Literature Review. Sustainability, 15 (1). https://doi.org/10.3390/su15010504
12. Hopkinson, N.; Hague, R.; Dickens, P., 2006: Rapid Manufacturing: An Industrial Revolution for the Digital Age. John Wiley & Sons, Ltd. https://doi.org/10.1002/0470033991
13. Huang, S. H.; Liu, P.; Mokasdar, A.; Hou, L., 2013: Additive manufacturing and its societal impact: A literature review. International Journal of Advanced Manufacturing Technology, 67 (5-8): 1191-1203. https://doi.org/10.1007/s00170-012-4558-5

14. Karamanlioglu, M.; Robson, G. D., 2013: The influence of biotic and abiotic factors on the rate of degradation of poly(lactic) acid (PLA) coupons buried in compost and soil. Polymer Degradation and Stability, 98 (10): 2063-2071. https://doi.org/10.1016/j.polymdegradstab.2013.07.004
15. Kohtala, C., 2015: Addressing sustainability in research on distributed production: An integrated literature review. Journal of Cleaner Production, 106: 654-668. https://doi.org/10.1016/j.jclepro.2014.09.039
16. Krapež Tomec, D.; Kariž, M., 2022: Use of Wood in additive manufacturing: Review and future prospects. Polymers, 14 (6): 1174. https://doi.org/10.3390/POLYM14061174
17. Le Treut, H.; Somerville, R.; Al, E., 2007: Historical Overview of Climate Change Science.
18. Lindemann, C.; Jahnke, U.; Moi, M.; Koch, R., 2012: Analysing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In: Proceedings of Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference at: Austin, TX, USA, Volume 23.
19. Peng, T., 2017: Energy modelling for FDM 3D printing from a life cycle perspective. International Journal of Manufacturing Research, 11 (1): 1. https://doi.org/10.1504/ijmr.2017.10003722
20. Petrovic Filipovic, V.; Gonzalez, J.; Ferrando, O.; Gordillo, J.; Puchades, J.; Portoles, L., 2011: Additive layered manufacturing: Sectors of industrial application shown through case studies. International Journal of Production Research, 49: 1061-1079. https://doi.org/10.1080/00207540903479786
21. Reeves, P., 2008: Additive Manufacturing – A Supply Chain Wide Response to Economic Uncertainty and Environmental Sustainability. Econolyst Ltd.
22. Reeves, P., 2012: Example of Econolyst Research – Understanding the Benefits of AM on CO_2. Econolyst Ltd.
23. Reeves, P., 2013: 3D Printing in Aerospace and Automotive. Econolyst Ltd.
24. Renzulli, P. A.; Notarnicola, B.; Tassielli, G.; Arcese, G.; Di Capua, R., 2016: Life cycle assessment of steel produced in an Italian integrated steel mill. Sustainability, 8 (8): 719. https://doi.org/10.3390/su8080719
25. Rezvani Ghomi, E.; Khosravi, F.; Saedi Ardahaei, A.; Dai, Y.; Neisiany, R. E.; Foroughi, F.; Wu, M.; Das, O.; Ramakrishna, S., 2021: The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. Polymers, 13 (11): 1854. https://doi.org/10.3390/polym13111854
26. Santero, N.; Hendry, J., 2016: Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21 (11): 1543-1553. https://doi.org/10.1007/s11367-015-1022-4
27. Tao, Y.; Wang, H.; Li, Z.; Li, P.; Shi, S. Q., 2017: Development and application of wood flour-filled polylactic acid composite filament for 3D printing. Materials, 10 (4): 339. https://doi.org/10.3390/ma10040339
28. ***Low-tech Magazine – Doubts on progress and technology, 2023: How much energy does it take (on average) to produce 1 kg of the following materials? (online). https://www.lowtechmagazine.com/what-is-the-embodied-energy-of-materials.html (Accessed Apr. 13, 2023).
29. ***3Dnatives, 2023: Is PLA filament actually biodegradable? (online). https://www.3dnatives.com/en/pla-filament-230720194 (Accessed Apr. 13, 2023).
30. ***SImaPro, 2021: Understanding electricity in SimaPro. (online). https://simapro.com/2019/understanding-electricity-in-simapro/ (Accessed Jan. 18, 2021).
31. ***SIST EN 12520:2010 Furniture – Strength, durability and safety – Requirements for domestic seating (CEN/TC 207/WG 1).
32. ***ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines (ISO/TC 207/SC 5).
33. ***SIST EN 310:1996 Wood based panels – Determination of modulus of elasticity in bending and of bending strength.
34. ***SIST-TS CEN/TS 14966:2006 Wood based panels – Small scale indicative test methods for certain mechanical properties.

Corresponding address:

DAŠA KRAPEŽ TOMEC

University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Jamnikarjeva 101, Ljubljana, SLOVENIA, e-mail: dasa.krapez.tomec@bf.uni-lj.si