

Sustainable Prosthetic Manufacturing: A Comparative Life Cycle Assessment of Centralized and Decentralized Additive Manufacturing Supply Chains in Europe

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Abstract. Additive Manufacturing (AM) has emerged as a transformative approach in prosthetic fabrication, offering personalized healthcare solutions alongside potential environmental advantages. This study investigates the environmental sustainability of centralized and decentralized AM-based supply chains for prosthetic production across Europe. Utilizing a Life Cycle Assessment (LCA) framework and cradle-to-gate methodology, the analysis quantifies carbon footprint (CFP) and water footprint (WFP) across raw material acquisition, manufacturing, and transportation stages. Geospatial data from Google Maps and Great Circle Map were employed to model distribution routes within four European regions centered on Luxembourg.

Centralized production was found to consistently outperform decentralized configurations in terms of environmental efficiency, largely due to reduced transportation-related emissions and resource use. In contrast, decentralized models, while offering increased responsiveness and customization, demonstrated elevated CFP and WFP values, particularly in regions with limited supplier accessibility or reliance on multimodal transport.

By revealing the trade-offs between supply chain configurations, this study contributes to the development of sustainable manufacturing practices in healthcare. The findings underscore the importance of strategic supply chain design, material selection, and integrated LCA in aligning AM processes with circular economy principles and global sustainability goals.

Keywords: Addictive manufacturing, Carbon footprint, Water footprint, Sustainability, Prosthetic, Cradle to gate, Life Cycle Assessment, Prosthetics, Supply Chain.

1 Introduction

Additive manufacturing (AM) is transforming prosthetic production by providing customized solutions and environmental benefits. Sustainable approaches - such as improving material efficiency, using biodegradable polymers and adopting energy-efficient methods - are in line with the principles of Our Common Future, which promotes ‘doing more with less’ and conserving energy [1]. In order to minimize environmental impacts, AM can use different metrics for LCA, which is one of the most common methods used by decision makers [2]. Ngo et al. found that sustainable AM can significantly reduce waste compared to traditional methods, highlighting the need for environmentally conscious innovation [3]. Overall, AM is advancing healthcare and supply chains while supporting long-term industrial sustainability.

In recent decades, AM has revolutionized production by enabling faster prototyping, reducing material waste, and greater design flexibility. These benefits align with the Sustainable Development Goals (SDGs) by promoting resource conservation, lowering environmental impacts, and advancing a circular economy [4, 5]. In prosthetic manufacturing, AM helps reduce carbon and water footprints compared to traditional methods. LCA studies on the cradle-to-gate stage show that AM significantly cuts emissions and water use by optimizing material use and minimizing waste [6, 7]. Evaluations of metal AM also reveal environmental benefits, especially when combined with design optimization, as noted by Pusateri and colleagues [8]. Additionally, AM’s ability to produce customized, patient-specific components reduces the need for multiple prototypes, saving both material and energy. This personalization improves patient outcomes and enhances sustainability by increasing efficiency and cutting waste [9].

Recent research has advanced sustainability-by-design through multidisciplinary optimization (MDO) frameworks that integrate design, materials, manufacturing, and environmental models within CAX workflows. For example, Daareyni et al. [10] combined parametric and generative design approaches with cradle-to-gate carbon and water footprint analysis in large-area additive manufacturing for compo-site tooling, revealing strong correlations between part mass and environmental impact, as well as trade-offs between mechanical performance and sustainability when selecting reinforcement materials. Similarly, Flores Ituarte et al. [11] applied an MDO framework to prosthetic socket design via material jetting, embedding life-cycle metrics and finite element analysis into parametric CAX models to enable real-time exploration of performance–sustainability trade-offs, and demonstrating how variations in stiffness requirements influence weight, manufacturing time, and environmental footprint. While these works demonstrate the benefits of early sustainability integration, they focus on single AM processes and cradle-to-gate scopes, without assessing how production geography, logistics, and electricity-mix variation shape impacts. This leaves a gap in linking CAX-based sustainability optimization with geospatial and supply chain analysis. Addressing this gap, the present study integrates distance-based data and LCA in both centralized and decentralized paradigms to assess the environmental trade-offs of different supply chain configurations, providing insights into sustainable supply chain design in advanced manufacturing.

The primary objectives of this study are to (I) assess the environmental impact of the prosthetic supply chain through carbon and water footprint analysis; (II) compare centralized and decentralized AM processes for the production of prosthetics in Europe; and (III) determine the optimal sustainable production configuration using geospatial analysis. Secondary objectives include (I) assessing the material efficiency and sustainability potential of AM processes; (II) analysing the impact of manufacturing flexibility and responsiveness inherent in decentralized production; and (III) providing recommendations for policy makers and industry stakeholders to advance sustainable practices and circular economy principles in healthcare manufacturing.

2 Materials and Methodology

2.1 Prosthetic design, material, and manufacturing method

This study builds upon the MDO results reported by Flores Ituarte et al. [11] for prosthetic socket design via material jetting additive manufacturing. The MDO results, specifically the mass of each optimized design and manufacturing energy consumption, serve as the primary input dataset for the present work. These results were generated using the design-to-manufacture modelling framework originally proposed by Flores Ituarte et al. [12], which decomposes the product development problem into material, design, and manufacturing disciplines, with explicit coupling models linking them.

In the original framework, the product design discipline employed a parametric, FEA-driven design automation of a representative prosthetic socket, enabling systematic variation of geometric parameters such as rigid region thickness and volume fraction. The material discipline modelled the behavior of a Stratasys J750 material jetting process combining two photopolymers, TangoPlus (Tp) for flexible zones and VeroClear (Vc) for rigid zones, to achieve tunable stiffness. The manufacturing discipline quantified the influence of build geometry on manufacturing time and total manufacturing energy consumption.

The present study directly reuses the optimized design dataset from Flores Ituarte et al. [11], which includes for each design: (i) mass, (ii) material composition, and (iii) embodied energy. This allows us to extend the prior MDO-based sustainability assessment beyond the cradle-to-gate scope by integrating these outputs with geospatial data and supply chain models. Specifically, our methodology incorporates distance-based transport modelling and centralized-decentralized production scenarios into a LCA framework to capture the environmental trade-offs of different supply chain configurations for prosthetic production.

2.2 Supply Chain Configurations and Environmental Assessment

Figure 1 compares a centralized and decentralized supply chain configuration. In the centralized model, finished prosthetic parts are transported from the prosthetic manufacturer to the customer by truck (3.5-7.5 ton Euro 4), ferry, and flight (medium haul dedicated freight). In contrast, the decentralized model emphasizes the transportation

of raw materials from the supplier to the customer, who then performs the AM process locally, potentially reducing emissions and resource consumption.

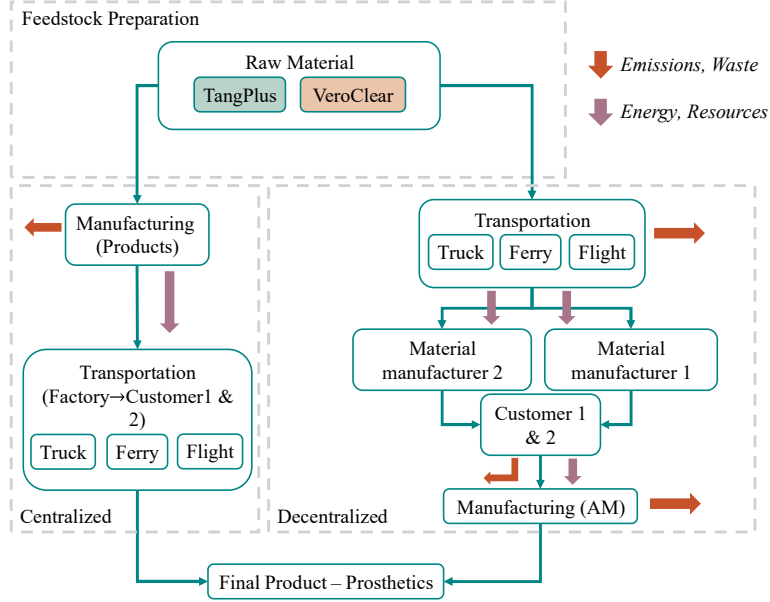


Figure 1. Sustainable manufacturing process chain for prosthetic production focusing on transportation and environmental flows (CFP/WFP).

Table 1 is the formulas used to calculate the CFP and WFP. The methodological steps for calculating the environmental sustainability indication involve the application of parametric equations to assess the CFP, WFP and energy consumption in the different life cycle stages of the manufacturing of a cavity repair by material jet additive manufacturing. As shown in Table 1, the total environmental impact is divided into three components: raw material extraction, AM process and transportation. Each component is modeled using mathematically formalized relationships involving variables such as component mass (m_p), transportation distance (D), embodied energy (E), and corresponding emission or water intensity factors (e.g., c_R, m_w, μ_F, G, N, B). Parameter values used in these calculations were obtained from rigorously validated and peer-reviewed technical databases and institutional publications, including Ansys Granta EduPack 2024R2, the European Commission's Primary Energy Factor Report (2017), the statistical data set in Our World of Data [13], and the data set in Greensleeves and Hoekstra for the UNESCO-IHE Water Footprint Report [14].

Figure 2 presents the carbon intensity of electricity generation from 2000 to 2023. In the present study, the latest available data were utilized to ensure the accuracy and relevance of the analysis. However, since data for 2023 were not available for Israel and Iceland, the corresponding values for 2022 were used as a replacement in those cases. These databases ensure methodological transparency, data traceability, and consistency with established practices in environmental life cycle assessment. As such, the

framework supports strong integration with MDO models aimed at improving the sustainability performance of prosthetic components.

Table 1. Equation for the calculation of CFP and WFP.

Aim	Equations	Explanation
CFP (Raw Materials)	$C_R = \frac{m_p}{\mu_R} \times c_R$	Carbon footprints during material manufacturing process.
CFP (Manufacturing)	$C_P = \frac{E}{X} \times m_w$	Carbon footprint during additive manufacturing process.
CFP (Transportation)	$C_T = \frac{m_p}{\mu_R} \times D \times \mu_F$	Carbon footprint during transportation process.
WFP (Raw Materials)	$W_R = \frac{m_p}{\mu_R} \times G$	Water footprints during material manufacturing process.
WFP (Manufacturing)	$W_P = \frac{E}{X} \times B$	Water footprint during additive manufacturing process.
WFP (Transportation)	$W_T = \frac{m_p}{\mu_R} \times D \times N$	Water footprint during transportation process.
E (Material)	$E_R = \frac{m_p}{\mu_R} \times e_R$	Embodied energy cost in raw material production.
E (Transportation)	$E_R = \frac{m_p}{\mu_R} \times D \times Y$	Embodied energy cost in transportations process.

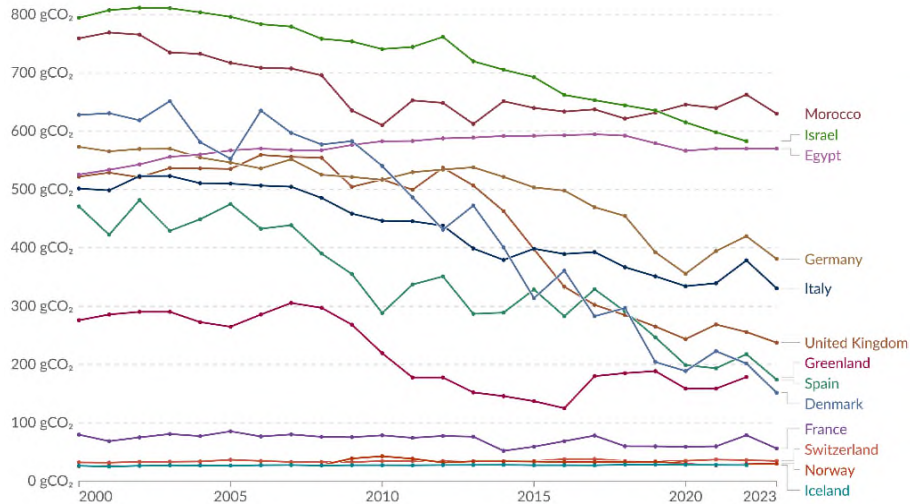


Figure 2. Carbon intensity of electricity generation 2000 to 2023 [13].

2.3 Supply chain implications: centralized and decentralized models

For this study, Europe was geographically divided into four regions, with Luxembourg as the central reference point. For each region, suppliers and customers were selected based on LCA and Cradle to Gate methodology. Using geospatial data from Google Maps and Great Circle Map, we calculate and track the carbon and water footprints associated with the raw material sourcing, manufacturing and transportation phases. Supplier and customer selection was guided by two different supply chain strategies: centralized and decentralized.

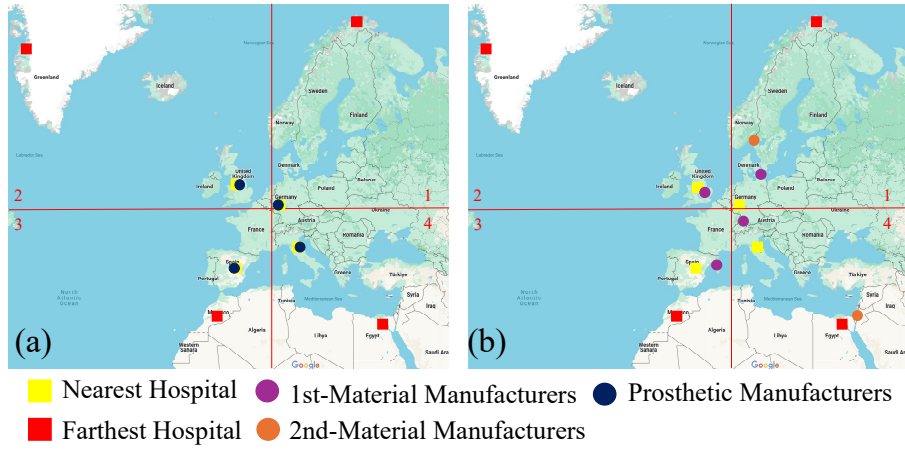


Figure 3. The map of the research. (a) Centralized. (b) Decentralized.

In the centralized model, prosthetic manufacturing facilities are responsible for producing the final product, which is then distributed to the nearest and farthest customer locations in each quadrant. Carbon and water footprints are systematically calculated to assess the environmental impact of production and distribution activities. This approach mirrors the traditional centralized supply chain configuration discussed by Khajavi, where centralized production typically benefits from economies of scale but entails higher transportation-related environmental cost. In contrast, the decentralized model involves replacing decentralized prosthetic manufacturers with decentralized raw material suppliers. Here, raw materials are shipped to a hospital located at the customer's site, where the final prosthetic product is manufactured using AM technology. This setup represents a shift towards distributed production, which Khajavi team argued has becoming increasingly feasible with advances in additive manufacturing to reduce inventory levels, shorten lead times and increase responsiveness [15]. To ensure the robustness of the dataset, two decentralized customers in each region were selected - one closest to the central reference point and one furthest away - to allow for a full comparison in the carbon and water footprint calculations.

3 Results and Discussion

3.1 Calculation results

Figure 4 (a-d) provides a comparative analysis of the trends in carbon and water footprints of centralized and decentralized supply chains for the production of prosthetic components in four different geographic regions on the map. In centralized supply chains, prosthetic components are produced in factories and then delivered to customers, with supply distances ranging from the nearest to the furthest customer. In contrast, decentralized supply chains involve local production at the customer site using materials supplied by nearby suppliers. Typically, there are two suppliers per customer, and all have a neighboring supplier. It is worth noting that both regions (3) and (4) have only one supplier for regional reasons.

The decentralized model also exhibits greater variability and data dispersion, particularly due to the logistical complexity associated with intermodal transport, including trucks (3.5-7.5 tons, Euro 4), ferries and medium haul dedicated freight flights. This complexity is more pronounced in areas with limited local suppliers. Overall, the results of the analysis indicate that centralized production is the environmentally preferred option due to its lower variability and smaller environmental footprint.

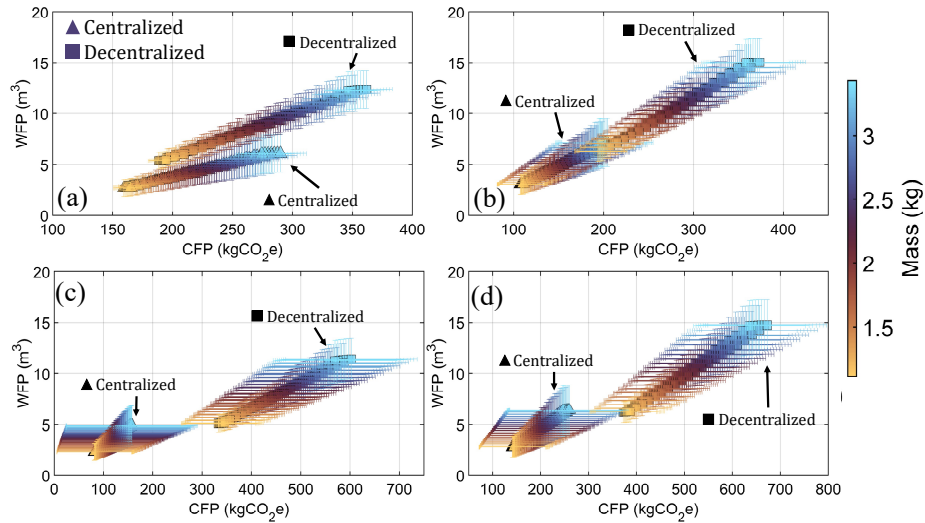


Figure 4. Comparative results for centralized and decentralized supply chain configurations.

(a) Region 1, (b) Region 2, (c) Region 3, (d) Region 4.

Table 2 presents the quantitative relationship between CFP and WFP for centralized and decentralized supply chains across four regions. Both CFP and WFP tend to increase with product mass. Overall, the average CFP of centralized supply chain is 171.50 kgCO₂e and the average WFP is 4.32 m³, whereas the decentralized supply chain has higher averages of 379.27 kgCO₂e and 9.38 m³. Thus, centralized supply chain corresponding to approximately 55% lower CFP and 54% lower WFP compared

to the decentralized supply chain. For Region 1, CFP values rise from 146.17 kgCO₂e to 246.46 kgCO₂e (a 68.61% increase), while WFP values escalate from 2.81 m³ to 6.34 m³ (a 125.93% increase). On average, CFP rises by 71.34% and WFP by 123.33% between the two mass extremes, the heaviest product (3.42 kg) and the lightest product (1.11 kg), illustrates a positive correlation between mass and environmental burdens. Within the decentralized supply chain, the heaviest product produces on average 502.66 kgCO₂e CFP and 13.39 m³ WFP, which are approximately 121% and 118% higher than those in centralized supply chain. The lightest product in decentralized supply chains in average produces 271.89 kgCO₂e CFP and 5.74 m³ WFP, increases of approximately 122% and 114% relative to centralized supply chain. These results show that the mass of the product and the type of supply chain have a strong effect on environmental impact with the centralized supply chains consistently lead to lower CFP and WFP than the decentralized ones.

The centralized model demonstrates a narrower and lower range of CFP values (centralized supply chain: Region 1, 159.37-289.99 kgCO₂e; Region 2, 107.41-204.33 kgCO₂e; Region 3, 81.34-157.67 kgCO₂e; Region 4, 141.1-259.73 kgCO₂e; with average values ranging from 122.30 to 227.93 kgCO₂e), with more environmentally efficiency. By contrast, the decentralized model generally presents higher CFP values (decentralized supply chain: Region 1, 188.49-361.71 kgCO₂e; Region 2, 193.52-373.70 kgCO₂e; Region 3, 333.10-602.52 kgCO₂e; Region 4, 372.45-672.73 kgCO₂e; with average values ranging from 271.89 to 502.66 kgCO₂e), indicating a greater environmental burden. Regarding WFP, the centralized model also records lower values. Therefore, it concluded that centralized supply chains are more environmentally stable and efficient.

Table 2. Comparison of centralized and decentralized supply chains for Carbon Footprint (CFP) and Water Footprint (WFP) across four European regions. SC: supply chain, R: region

SC Type	Avg CFP (kgCO ₂ e)	Avg WFP (m ³)	CFP Range (R1–R4)	WFP Range (R1–R4)	Lightest vs Heaviest (Avg. CFP)	Lightest vs Heaviest (Avg. WFP)
Centralized	171.50	4.32	R1: 159.37-289.99 R2: 107.41-204.33 R3: 81.34-157.67 R4: 141.1-259.73	R1: 2.67-6.12 R2: 3.02-7.15 R3: 2.26-4.89 R4: 2.77-6.4	122.30-227.93	2.68–6.14
Decentralized	388.86	9.72	R1: 188.49-361.71 R2: 193.52-373.70 R3: 333.10-602.52 R4: 372.45-672.73	R1: 5.4-12.38 R2: 6.3-15.04 R3: 5.07-11.42 R4: 6.2-14.74	271.89-502.66	5.74-13.39

4 Conclusion

This study demonstrates that centralized AM supply chains are environmentally more sustainable than decentralized models for prosthetic production in Europe. Centralized production enhances sustainability, while decentralized production offers advantages in terms of customization and productivity. However, centralized production could be more environmentally friendly due to fewer total transport distances. When assessed

through cradle-to-gate LCA indicators specifically CFP and WFP centralized configurations consistently exhibited lower environmental impacts due to optimized logistics and economies of scale.

AM processes show strong potential for material efficiency and sustainability, with centralised configurations particularly benefiting from simplified logistics and reduced environmental burdens. While decentralised production improves manufacturing flexibility and responsiveness, it also brings with it greater environmental impacts, especially in regions where suppliers rely on multimodal transport systems such as trucks, ferries and flights. These insights provide valuable guidance for policymakers and industry stakeholders in implementing sustainable manufacturing strategies in healthcare that promote circular economy principles through informed supply chain design and life cycle integration.

In conclusion, our analysis highlights a critical trade-off in supply chain design between CFP and WFP. Among all the regions assessed, decentralized supply chain models offer greater flexibility but tend to exert more significant negative environmental impacts. In contrast, centralized models are more environmentally friendly, albeit with reduced flexibility. These findings underscore the necessity for decision-makers to carefully balance competing environmental priorities when configuring supply chains, as optimizing one metric may come at the expense of another. Ultimately, the choice between centralized and decentralized models should be informed by context-specific sustainability objectives and resource constraints.

Future research should expand sustainable additive manufacturing for prosthetic production by evaluating wider environmental impacts beyond carbon and water footprints, to include indicators such as land use, energy intensity and air pollution. Further exploration of bio-based and biodegradable polymers in 3D printing is recommended to increase sustainability and reduce the ecological impact of prosthetic waste. In addition, the social economic dimensions of decentralized production, including healthcare accessibility, cost effectiveness and fair distribution in low-resource areas, are also worth studying. Dynamic supply chain modelling integrating real-time transportation and demand changes should also be investigated to optimize environmental outcomes under changing business conditions.

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