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Cradle-to-Gate Sustainability Assessment of Centralised versus Decentralised Additive Manufacturing for Wind Turbine Blade Mould Production

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Abstract

Additive Manufacturing (AM) has emerged as a transformative technology in the production of wind turbine blade moulds, enabling greater design flexibility, mass customisation, and on-demand responsiveness. This study presents a comparative environmental sustainability assessment of centralised and decentralised AM supply chains for wind turbine blade mould manufacturing across four European regions centred on Luxembourg. A cradle-to-gate Life Cycle Assessment (LCA) framework is employed to quantify carbon footprint (CFP) and water footprint (WFP) across the stages of raw material acquisition, manufacturing, and transportation. The turbine blade moulds are produced using two composite materials: ABS+20%CF and ABS+20%GF, both selected for their mechanical performance and printability in AM applications. Geospatial routing data obtained from third-party mapping and navigation platforms are utilised to estimate regional transport distances and routes, thereby enabling a spatially explicit evaluation of environmental trade-offs between centralised and decentralised supply chain configurations.

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1. Introduction

Additive Manufacturing (AM) has emerged as a transformative technology in sustainable production, offering notable advantages in material efficiency, design complexity, and decentralized fabrication [12]. Its application in the manufacturing of wind turbine blade moulds enables the production of large-scale, geometrically complex components while reducing material waste and shortening lead times. Fibre-reinforced thermoplastics, particularly acrylonitrile butadiene styrene (ABS) filled with 20% glass fibre (ABS+20%GF) or 20% carbon fibre (ABS+20%CF), are increasingly employed in AM due to their enhanced thermomechanical properties [35]. ABS+20%GF offers a

balance of impact resistance and thermal stability, while ABS+20%CF exhibits superior stiffness and heat deflection performance, qualities essential for the durability of moulds in wind energy applications [1,3].

Life Cycle Assessment (LCA) provides a rigorous framework for quantifying cradle-to-gate environmental indicators such as carbon footprint (CFP) and water footprint (WFP) [67]. Within this framework, supply chain structure, centralized versus decentralized, has significant implications for environmental performance. Centralized systems consolidate mould production at a single facility and distribute finished products to various end-users, benefiting from economies of scale but often incurring substantial transport-related emissions. In contrast, decentralized systems leverage

the flexibility of AM to shift manufacturing closer to the point of use, reducing transport intensity and enabling localized sustainability gains [2,8].

This study systematically evaluates the environmental performance of centralized and decentralized AM supply chains for wind turbine blade mould production across four representative European regions. By integrating cradle-to-gate LCA with geospatial transport data and incorporating key design parameters derived from multidisciplinary design optimization (MDO), the analysis quantifies and compares the CFP and WFP of ABS+20%GF and ABS+20%CF moulds under varying supply chain configurations [89]. This approach reveals the coupled effects of material selection and logistical structure on environmental outcomes, offering data-driven insights to support sustainable production strategies and circular economy initiatives in the context of large-scale AM.

This study integrates geospatial distance data with cradle-to-gate LCA to evaluate CFP and WFP under centralized and decentralized supply chain models for large-format additive manufacturing. In the centralized model, moulds are fabricated at a single facility and transported to end-users via Euro 4 road freight (7.5-16.0 ton trucks), ferries, and medium-haul air cargo [8]. In contrast, the decentralized model ships only raw materials to local sites for on-demand production. This analysis quantifies the trade-offs between long-distance logistics and localized manufacturing, supporting environmentally optimized supply chain design.

This study presents a systematic evaluation of the environmental sustainability of wind turbine blade mould production using AM under both centralized and decentralized supply chain models. The research aims to quantify the CFP and WFP across raw material extraction, production, and transportation stages using a cradle-to-gate LCA framework. By comparing the environmental impacts of centralized and decentralized AM configurations across four European regions anchored by a geographic reference point in Luxembourg the study seeks to determine the optimal production setup that minimizes environmental burdens. Additionally, it evaluates the material efficiency and environmental potential of Large Area Additive Manufacturing (LAAM) using ABS+20%GF and ABS+20%CF, analyses trade-offs between supply chain flexibility and ecological impact, and offers strategic recommendations for aligning AM deployment with regional logistics capacity, circular economy goals, and sustainable industrial practices.

2. Materials and Methodology

2.1. Mould Configuration: Design, Material Choice, and Manufacturing Strategy

This study investigates the environmental sustainability of wind turbine blade mould fabrication using LAAM with fibre-reinforced ABS composites under varying supply chain configurations. Specifically, ABS+20%CF and ABS+20%GF were selected not only for their enhanced mechanical and

thermal properties but also for their representative differences in forming behaviour and environmental performance during LAAM processes. ABS+20%CF offers improved rigidity and thermal conductivity, which are critical for dimensional precision and efficient heat dissipation during the curing of large moulds [1011]. In contrast, ABS+20%GF provides superior impact resistance and thermal stability, making it more suitable for applications involving repeated thermal cycling and mechanical handling [12]. By systematically comparing the CFP and WFP of these two materials across centralized and decentralized supply chain models, this study aims to uncover the coupling relationships between material selection, manufacturing mode, and environmental impact, providing a knowledge base for sustainable mould production strategies in the wind energy sector.

2.2. Data of ABS-Based Blade Moulds and Geospatial Comparison of Supply Chain Models

This study evaluates wind turbine blade mould manufacturing using large area additive manufacturing processes under centralized and decentralized configurations. The methodology builds upon prior work by Daareyni et al. [8], leveraging their validated design strategies and manufacturing parameters as foundational inputs to ensure methodological consistency across supply chain scenarios. The analysis considers subsystem-level variables including toolpath length, number of tools, shell thickness, top thickness, and side thickness. Country-specific CO₂ emission intensities (e.g., Egypt: 0.57, Iceland: 0.028 kg CO₂e/kWh) and transport emission factors for road (2.42×10^{-4}), flight (9.32×10^{-4}), and ferry (1.19×10^{-4}) are integrated to capture geographic and logistical variation. The environmental evaluation aims to minimise embodied energy from processing and transport, manufacturing time, mould mass, CFP and WFP. The design space includes two fibre-reinforced thermoplastics ABS+20%GF and ABS+20%CF used within a fixed build envelope ($1365.0 \times 960.0 \times 960.0$ mm³), and defined print parameters (layer height: 3.8 mm; nozzle diameter: 7.6 mm; print speed: 279.4 mm/s) [8]. The mould mass for ABS+20%GF ranged from 456.4 to 829.0 kg, while ABS+20%CF ranged from 319.3 to 783.7 kg [8]. Figure 1 illustrates the material and production flow of these moulds under centralized and decentralized supply chain configurations. In the centralized model, raw materials are shipped to a single facility for mould fabrication, followed by distribution to end users via multimodal transport. For long-distance logistics (≥ 1000.0 km), cargo flights are combined with truck transport to ensure efficiency, while trucks are primarily used for shorter distances (< 1000.0 km). Ferries are employed for cross-sea routes. In the decentralized model, raw materials are delivered directly to local manufacturing sites, enabling on-site mould production. This flow chart provides a structured representation of transport choices and production stages for environmental performance comparison.

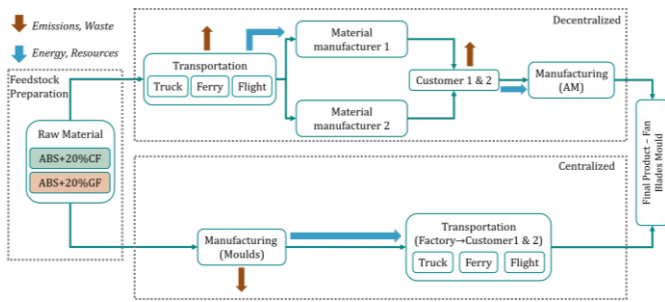


Fig. 1. Material and production flow of ABS-based blade moulds in centralized and distributed supply chains.

To assess the environmental performance of different supply chain strategies for wind turbine blade mould production, Europe was divided into four regions radiating from a central reference location Luxembourg. This spatial framework enabled a cradle-to-gate LCA comparison of centralized and decentralized models by integrating geolocation data from Google Maps and Great Circle Map to quantify transport distances and routes across raw material extraction, manufacturing, and distribution stages. In the centralized model, wind turbine blade moulds are fabricated at a single production facility and then transported to both the nearest and farthest wind farms to the mould manufacturer in each region. For instance, in region 1, Vestas supplies Middelgrunden Offshore Wind Farm in Denmark (nearest)

and Havøygavlen Windpark in Norway (farthest); in region 2, Vestas serves Rampion Offshore Wind Farm in the UK (nearest) and the under-construction Hafið Wind Farm in Iceland (farthest). In Region 3, LM Wind Power supplies the GEROA Precommercial Project in Spain (nearest) and Aftissat Wind Farm in Morocco (farthest), while Region 4 includes Vestas-supplied Monteforte Wind Farm in Italy (nearest) and Jabal Elzyt Wind Farm in Egypt (farthest). Although centralized production benefits from manufacturing efficiency, it incurs higher transport emissions due to extended logistics pathways. In contrast, the decentralized configuration maintains fixed wind farm locations but redistributes manufacturing across multiple local facilities: two mould material (ABS+%GF and ABS+20%CF) manufacturers are strategically positioned closer to each wind farm within each region. Raw materials are transported to these local sites, where additive manufacturing is conducted on-site, thereby minimizing finished product transportation. This distributed production strategy improves logistical responsiveness and reduces environmental burden associated with long-distance deliveries. For consistent comparison, two decentralized manufacturing locations per region were selected based on proximity to Luxembourg, enabling geographically contextualized sustainability assessment.

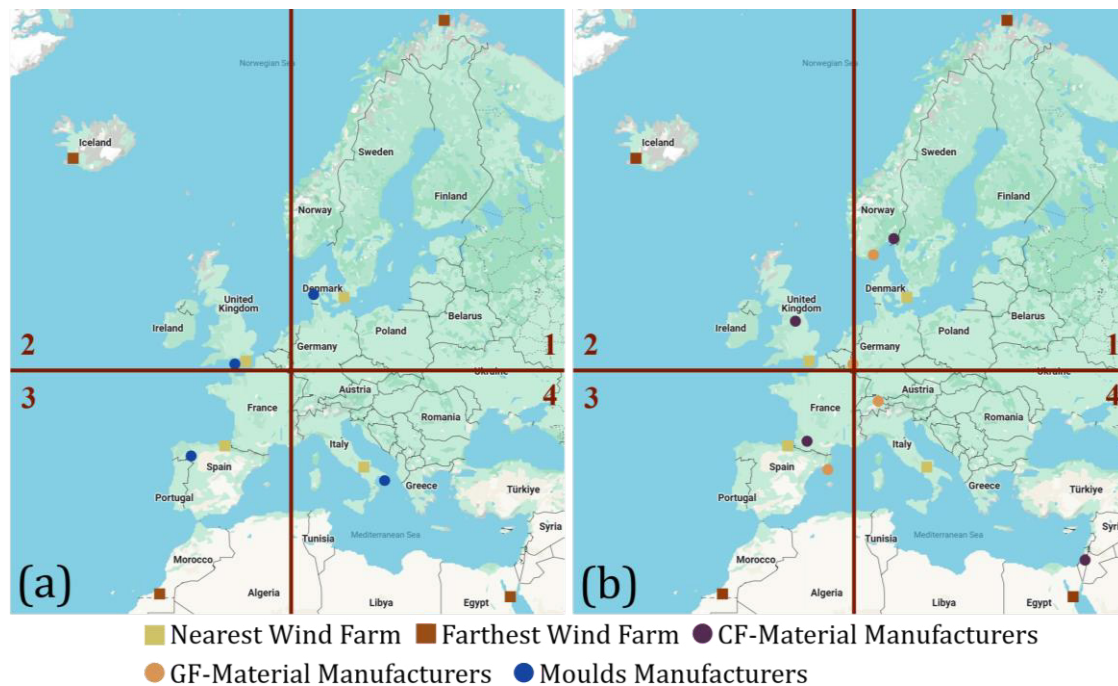


Fig. 2. Geographical division and supply chain routing framework for centralized and decentralized blade mould production in Europe. (a) Centralized. (b) Decentralized.

2.3. Calculation, and LCA indicator

This study utilized a structured analytical framework is employed to assess the environmental impact of LAAM-based wind turbine blade moulds manufacturing. This approach divides the life cycle into three key stages: raw material

production, additive manufacturing, and transportation. At each stage, environmental indicators including CFP, WFP, and embodied energy, which are quantitatively evaluated using a set of dedicated parametric equations. These equations systematically incorporate variables such as component mass (m_p), transportation distance (D), embodied energy (E), and process-specific intensity factors (e.g., C_R , m_w , μ_F , G , N , B),

ensuring a comprehensive and scientifically robust assessment.

Rather than treating the environmental impacts as aggregated values, the framework enables disaggregated, stage-specific calculations to enhance accuracy and traceability. CFP is computed via Equation 1, WFP through Equation 2, and energy consumption through Equation 3. This methodological distinction allows for clearer interpretation of how each life cycle phase contributes to the overall footprint. To calculate the environmental impacts associated with additive manufacturing processes, a rigorous analytical framework is established, explicitly addressing CFP, WFP, and E. Equation 1 systematically quantifies the CFP through three critical phases: raw material production (C_R), additive manufacturing processes (C_P), and transportation (C_T).

$$\begin{aligned} C_R &= \frac{m_p}{\mu_R} \times c_R \\ C_P &= \frac{E}{X} \times m_w \\ C_T &= \frac{m_p}{\mu_R} \times D \times \mu_F \end{aligned} \quad (1)$$

Similarly, Equation 2 precisely determines the WFP across raw material production (W_R), additive manufacturing (W_P), and transportation (W_T).

$$\begin{aligned} W_R &= \frac{m_p}{\mu_R} \times G \\ W_P &= \frac{E}{X} \times B \\ W_T &= \frac{m_p}{\mu_R} \times D \times N \end{aligned} \quad (2)$$

Lastly, Equation 3 rigorously evaluates the embodied energy related to raw material production (E_R) and transportation (E_T), providing a comprehensive measure of energy impacts across these vital stages.

$$\begin{aligned} E_R &= \frac{m_p}{\mu_R} \times e_R \\ E_T &= \frac{m_p}{\mu_R} \times D \times Y \end{aligned} \quad (3)$$

Table 1 illustrates the carbon intensity of electricity generation across selected countries in 2023, measured in grams of CO₂ equivalent per kilowatt-hour (gCO₂e/kWh). To maintain data consistency and analytical relevance, the most recent available values were adopted. For countries lacking 2023 data specifically Iceland the 2022 values were used as substitutes. The resulting dataset highlights significant variation in carbon intensity across regions. For instance, Morocco (0.63 gCO₂e/kWh) and Egypt (0.57 gCO₂e/kWh) remain among the highest emitters, while Iceland (2022: 0.028 gCO₂e/kWh) and Norway (0.03 gCO₂e/kWh) demonstrate exceptionally low-intensity power systems due to their reliance on renewable energy sources. Intermediate values are observed in countries such as Italy (0.331 gCO₂e/kWh), the United Kingdom (0.238 gCO₂e/kWh), Spain (0.174 gCO₂e/kWh), and Denmark (0.152 gCO₂e/kWh) [13].

Table 1. Evolution of carbon intensity in power generation for 8 countries [13].

Country	Carbon Intensity (gCO ₂ e/kWh)
Denmark	0.152
Egypt	0.57
Iceland (2022)	0.028
Italy	0.331
Morocco	0.63
Norway	0.03
Spain	0.174
United Kingdom	0.238

The carbon intensity values presented in Table 1 serve as critical input parameters for evaluating the environmental performance of wind turbine blade mould manufacturing under different geographic contexts. By reflecting regional disparities in electricity generation profiles, these data enable more spatially accurate assessments of embodied emissions within cradle-to-gate life cycle models [14]. This approach is particularly relevant for additive manufacturing processes, where energy consumption plays a significant role in overall environmental impact [15].

3. Result and Discussion

3.1. Calculation result

Figure 3 presents the environmental impacts associated with the production of wind turbine blade moulds using ABS+20%GF and ABS+20%CF across centralized and decentralized additive manufacturing supply chains in four European regions: Northeast (I), Northwest (II), Southeast (III), and Southwest (IV). The analysis focuses on regional variations in CFP and WFP. Across all regions, decentralized configurations consistently exhibit higher CFP and WFP than their centralized counterparts, with the largest disparities observed in the Southeast and Southwest. For instance, in Figure 5(a.I), the centralized model achieves reductions of approximately 44.0% in CFP and 46.8% in WFP compared to the decentralized model, primarily due to optimized logistics and shorter transport distances. Notably, ABS+20%CF exhibits similar environmental trends to ABS+20%GF. In regions such as the Northeast, where centralized facilities are located closer to end users, the performance gap between the two supply chain models is less pronounced. More broadly, regional differences in CFP and WFP are evident, with the more centralized Northeast and Northwest regions demonstrating significantly lower environmental impacts than the more distributed Southeast and Southwest. These differences are largely attributed to variation in transport modes (e.g., road, air, ferry) and differences in regional manufacturing efficiency.

Within the same region, comparisons between ABS+20%CF and ABS+20%GF under both supply chain configurations reveal consistent trends. On average, the CFP of ABS+20%CF moulds are 185.4% higher than

ABS+20%GF in centralized scenarios and 184.1% higher in decentralized scenarios. However, for WFP, the trend reverses, with ABS+20%CF exhibiting 22.9% and 24.0% lower water footprints in centralized and decentralized models, respectively. These findings highlight the higher carbon intensity but lower water demand of carbon fibre-reinforced composites relative to their glass fibre counterparts. Consequently, incorporating flame-resistant fibres or modifying carbon composite manufacturing techniques may help reduce CFP in future applications [16].

Figure 4(a–d) illustrates the embodied energy associated with the mould production process across centralized (a, b) and decentralized (c, d) models for ABS+20%GF and ABS+20%CF, categorized by different mass levels. In all scenarios, raw material production accounts for the majority of energy use, followed by transportation, while the manufacturing process contributes minimally. Under

centralized configurations, total embodied energy is significantly lower, with ABS+20%GF reaching approximately 7×10^5 MJ at 800 kg and ABS+20%CF reaching about 20×10^5 MJ. Conversely, decentralized models exhibit greater energy demand and variability, with ABS+20%CF surpassing 35×10^5 MJ due to its high material energy intensity and increased transportation requirements.

Overall, centralized supply chains demonstrate superior median performance in both CFP and WFP with lower variability, suggesting greater environmental robustness under diverse geographic and operational conditions. These results underscore the environmental benefits of centralized strategies in large-area additive manufacturing (LAAM). Nonetheless, decentralized models offer enhanced flexibility, making them more adaptable to region-specific demands and logistical constraints.

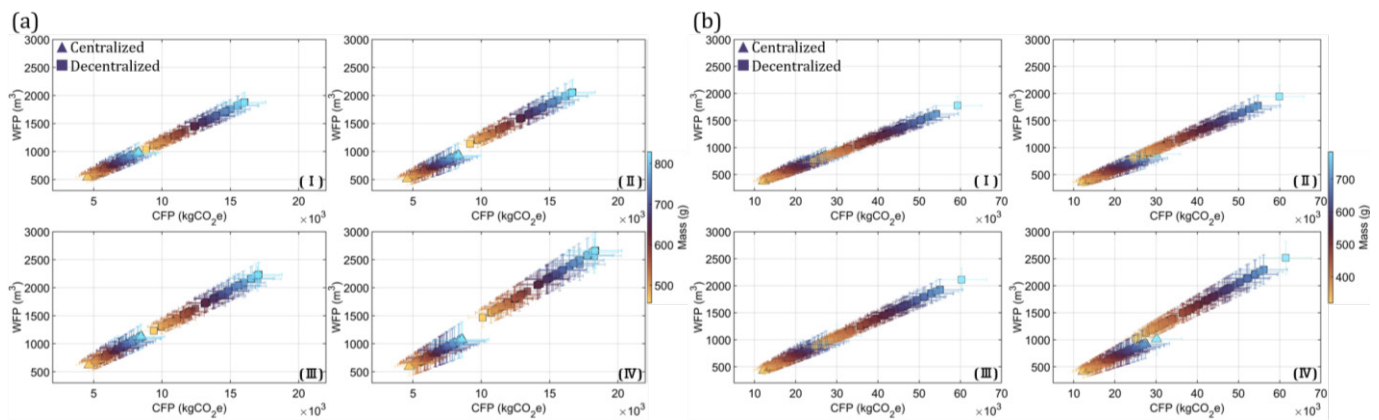


Fig. 3. Comparison of centralized and decentralized supply chains for ABS+20%GF (a) and corresponding results for ABS+20%CF (b) mould.

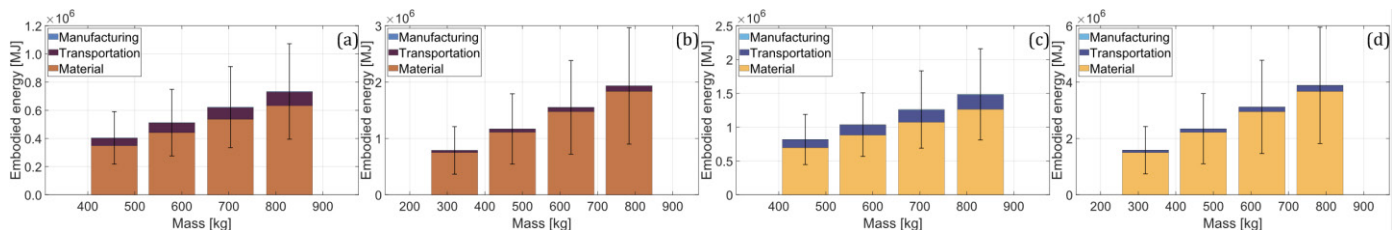


Fig. 4. (a) Total embodied energy for ABS+20%GF with centralized supply chain. (b) Total embodied energy for ABS+20%CF with centralized supply chain. (c) Total embodied energy for ABS+20%GF with decentralized supply chain. (d) Total embodied energy for ABS+20%CF with decentralized supply chain.

3.2. Analysis of the CFP and WFP

Figure 3(a) and (b) present a comparative analysis of the carbon footprint (CFP) and water footprint (WFP) associated with centralized (C) and decentralized (D) additive manufacturing supply chains for ABS+20%CF wind turbine blade moulds. In Figure 3(a), the centralized configuration consistently demonstrates lower CFP values, stabilizing around 9×10^3 kgCO₂e with narrow uncertainty bands, indicating stable environmental performance. In contrast, decentralized models exhibit significantly broader CFP distributions, ranging from approximately 16×10^3 to 18×10^3 kgCO₂e, with greater variability across all regions. This disparity is primarily attributed to increased logistical

complexity and fragmented transportation inherent in decentralized supply chains. With respect to WFP, centralized systems typically report values between 1000.0 and 1200.0 m³, whereas decentralized configurations show a substantial increase, with peak values ranging from 2200 to 2600.0 m³. These findings suggest that centralized manufacturing yields lower and more stable environmental burdens due to its streamlined logistics and higher process efficiency. Decentralized models, by contrast, are characterized by elevated CFP and WFP values, driven by dispersed transport routes and greater reliance on localized, water-intensive processes. The results challenge the widely assumed environmental benefits of decentralization and underscore the necessity for region-specific planning.

In Figure 3(b), the same trends persist, albeit with overall increases in both CFP and WFP. The average CFP for centralized configurations increases by approximately 101%. For example, in Figure 3(b.I), the decentralized model exhibits a 98.6% higher CFP compared to its centralized counterpart, while in Figure 3(b.IV) representing Southeast Europe the difference escalates to 104.4%. These increases are primarily driven by longer transport distances between production facilities and wind farm sites, with long-haul air freight serving as the dominant transport mode. Conversely, Region I (Northeast Europe) relies mostly on short-haul flights, with a maximum transport distance variation of approximately 3147.0 km (1699.2 nmi). Such spatial transport disparities are key contributors to the elevated CFP values. Additionally, within the same region, the WFP under decentralized conditions rises by up to 147.6%. Collectively, these results emphasize the trade-offs between carbon and water impacts and highlight that centralized additive manufacturing offers a more consistent and environmentally advantageous pathway for large-scale wind turbine blade mould production. While decentralized models provide logistical flexibility, they impose significantly higher environmental costs. Aligning supply chain structures with regional infrastructure and sustainability objectives is thus essential for improving the environmental performance of LAAM.

4. Conclusion

This study finds that centralized AM supply chains are environmentally more sustainable than decentralized ones for wind turbine blade mould production in Europe. Centralized models consistently achieve lower CFP due to optimized transport routes and economies of scale. Although decentralized production offers faster response and local adaptability, it incurs significantly higher CFP as a result of fragmented logistics and greater reliance on multimodal transport. Using a cradle-to-gate LCA, the study quantifies CFP and WFP for ABS+20%GF and ABS+20%CF, with centralized systems showing lower environmental impact, especially in regions with strong industrial infrastructure and proximity to end users.

Three key findings further support this conclusion: (I) AM with ABS+20%GF and ABS+20%CF offers strong potential for material efficiency and emissions reduction, particularly under centralized logistics; (II) decentralized production, while flexible, is environmentally costly in regions with long distances and reliance on air freight; (III) supply chain design should align with regional logistics capacity, environmental goals, and circular economy principles.

Overall, this research highlights the need for region-specific strategies when deploying AM for large-scale composite tooling. Centralized supply chains offer more consistent and lower-emission solutions, while decentralized systems, though adaptable, present higher environmental trade-offs. This study provides a structured LCA-based framework for evaluating and improving AM supply chain

sustainability. Future work should consider end-of-life phases, cost analysis, and real-world validation to inform policy and industry decision-making.

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