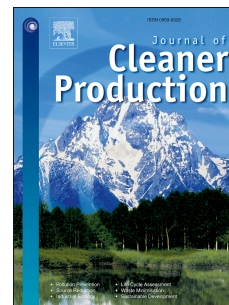


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Specific Energy Consumption based Comparison of Distributed Additive and Conventional Manufacturing: From Cradle to Gate Partial Life Cycle Analysis

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Abstract

The additive manufacturing (AM) paradigm, especially in the distributed manufacturing setting, is a novel paradigm that can bring production of components closer to the consumers, at potentially lower economic and environmental costs. In this paper, we present a comparative analysis of AM with conventional manufacturing (CM) from the energy consumption perspective to assess under what conditions AM is better—a key gap in the area. Leveraging an energy consumption survey between CM and AM supply chains, this paper analyzes the significance of transportation in a cradle-to-gate partial life cycle analysis. Though the decentralization of AM has been discussed in energy consumption assessments, it has not been discussed in terms of how the distributed components and their transportation would affect the two supply chains' scenarios. This gap motivated this research to conduct energy efficiency assessment of AM and its comparison with CM in a distributed supply chain. Our analysis showed that transportation contributed 3x to 4.5x increase in the overall energy impact in CM compared to corresponding transportation in the AM setting. In effect, from our analysis, for every three CM parts, the transportation energy consumption approximately equaled the energy needed to manufacture one similar part in AM. Our analysis leverages the solid-to-envelope ratio “ α ”, defined as the volume of solid material within a part's envelope. Based on our analysis, AM would be the preferred production method for α values falling within the range of 0.08 to 0.22 (8-22% of raw material efficiency in CM). Hence part geometry, where AM has greater potential for energy savings by reduction in the amount of material waste, is a good indicator for using AM over CM for energy efficiency. We also discuss several future directions for better assessment of AM versus CM under different settings and upcoming innovations such as Industry 4.0.

Keywords: Additive Manufacturing, Distributed Manufacturing, LCA Comparison, Energy Consumption, Carbon Impact, Industry 4.0.

1 Introduction¹

Greenhouse gases and resource scarcity are impending crises that require greater sustainability efforts in the manufacturing industry to satisfy growing consumption rates. According to the Netherlands Environmental Assessment Agency, fossil-fuel combustion was responsible for 89% of total CO₂ emissions in 2020. Contributing to these emissions were electricity/heat generation, manufacturing industries, and road transport at 36%, 17%, and 16% respectively [1]. The U.S. Department of Commerce defines sustainable manufacturing as “the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources”. Additionally, researchers surveying 189 articles on the definition of sustainable manufacturing found that most of them included a potential to decrease energy consumption [2]. As supply-chains and production facilities steadily become widely connected via Internet of Things (IoT), the future of industrial production with Industry 4.0 envisions connected smart factories adopting technologies, such as industrial internet, smart manufacturing, and cloud-based manufacturing [3, 4]. The advent of these concepts to digitize manufacturing processes seek to optimize output while addressing several aspects of sustainability—energy consumption will be one such significant aspect.

A key component in the future of manufacturing and Industry 4.0 is Additive Manufacturing (AM) [5]. AM is the manufacturing method in which the part is manufactured by successively adding more material to the previous layer or the substrate. AM is supposed to generate less material waste since it only uses as much material as needed, whereas conventional manufacturing (CM) may form a part by machining off feedstock material creating scrap metal which may then be recycled. A high volume of scrap presents manufacturers with laborious and time-consuming steps in their supply-chain to store, sell, and/or recycle. While AM production offers simplifications to the supply-chain by reducing waste, it also holds the potential to reduce greenhouse gas emissions and reliance on global transportation logistics as components are more readily available to be printed at the point of use, which reduces the need of having a sophisticated multi-supplier, multi-component supply chain. Further, manufacturing happens without extra tooling, assembly, and additional personnel training [6]. Contributing to the sustainability benefits, AM could increase overall value if it can provide greater environmentally and economically efficient manufacturing in a decentralized setting [7], as opposed to the centralized productions where few production facilities meet the global demand for one specific product.

Environmental benefits of AM supply-chains are, however, only explicitly identified under certain conditions such as when AM enables a large amount of energy savings and low material usage [8, 9] or when its energy mix is sourced from more renewable and less carbon-based resources [9-11]. In the future, “production on demand” will play a greater role in manufacturing to meet the ever-volatile needs

¹ An earlier version of this paper is available in the non-peer-reviewed archive SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4250944.

Abbreviations Used: AM, Additive Manufacturing; CED, Cumulative Energy Demand; CM, Conventional Manufacturing; DMS, Decentralized Manufacturing System; EC, Energy Consumption; EDF, Electric Ducted Fan; EBM, Electron Beam Melting; FSF, Formed Solid Feedstock; LBM, Laser Beam Melting; LCA, Life Cycle Assessment; MCDM, Multi-Criteria Decision Model; PBF, Powder Bed Fusion; RC, Remote Control.

of the world—goods which are “produced on demand” will meet the demands of greater individuality, customer-specific product variants, and short delivery times [12]. In their work, Matt et al. [12] demarcated the evolving concept of “distributed manufacturing systems” (DMS) in eight types ranging from simple to visionary concepts. In its most visionary approach, they stated that their Type 8 DMS could revolutionize industrial production through the wider use of 3D printers connected to distributed cloud services. Products could then be manufactured and assembled in distributed networks of authorized printing labs or small factories with qualified staff for final assembling and finishing treatments. They also developed a list of trends towards the greater adoption of evolved DMS. These included sustainability needs, rising logistics costs, greater customization needs by the mass of consumers (mass customization), democratization of design, market and customer proximity, strategic use of resources, and processes that can benefit the local economy (regionalism and authenticity).

Similar to how we define the CM supply-chain for our comparison, Matt et al. [12] also defined the simplest DMS (Type 1) as sufficient for today’s requirements. This is where a company firmly defines a standardized product where its production sites are geographically dispersed in different markets and countries. Type 2 introduces modularity in scalable configurations; Type 3 adds a certain level of variability in production; Type 4 introduces intelligent and digitally networked manufacturing systems; and Type 5 refers to cases where a company hires a production provider for industrial contract manufacturing rather than investing in the development of production sites. In this paper, we define our distributed CM supply chain as a combination of Type 1 and Type 5, while we also explain the scenario in Section 3, wherein those service providers may produce components at different geographical locations, which must then come together to be assembled at a centralized location with qualified personnel prior to shipping to a specific market.

Contributions: This is the first paper which focuses on distributed metal AM, bringing to the fore the length of the supply chain and corresponding impact on transportation cost, from an energy consumption perspective. The main aim of this research is to conduct an energy efficiency assessment of AM and its comparison with CM in a distributed supply chain. The comparative analysis focuses on energy consumption using a partial life cycle assessment—focusing only on energy consumption per mass of material of the part. We surveyed the specific energy consumption metrics from the cradle-to-gate of the supply-chains for stainless-steel parts in both AM and CM processes. Scientifically, there has been a growing amount of research in AM as a sustainability alternative to CM, on account of its material savings and reduction of environmental impacts in the use phase (the operational stage of a product's life cycle). The focus has been on the many ways of assessing AM’s energy consumption as an indicator of environmental/carbon impact, by collecting and calculating the overall composites of energy consumption from each phase of the methodologies’ scopes. We consider in our assessment the most recent indicator model for comparing AM and subtractive manufacturing scenarios from an energy consumption standpoint. The solid-to-envelope ratio (α), described in Section 2.3, used in our analysis, enables the generalization of the critical geometric point at which the energy savings of AM outweigh the energy requirements of the conventional supply chain. Another novelty in this paper’s assessment is in the nature of the functional unit, a part requiring distributed components. This increases the transportation steps in the conventional supply chain, which can be reduced in the AM supply chain. What follows from this work is the quantification of the amount of impact that transportation has on the overall energy consumption and its impact as a parameter of the α indicator.

Overview of Sections: To illustrate the need for a more complete understanding of AM as an environmentally friendly strategy in these future manufacturing supply chains, a literature review of past life cycle analysis (LCA) comparisons is summarized in Section 2. Upon identifying the open research gap in quantifying the distributed supply chain comparison, Section 3 defines the distributed manufacturing supply-chains in greater detail and illustrates how the comparison between AM and CM needs to be reassessed through the lens of such a distributed supply-chain. For comparative analysis, we propose small and adaptable AM facilities located close to the final consumer that meet the local demand for different products, compared to CM in its centralized assembly setting. Section 4 defines and presents our partial LCA methodology and introduces the equations used to perform impact assessment with the solid-to-envelope ratio α used in past studies [8, 13, 14]. Section 5 details how metrics were gathered from our energy consumption survey to form the impact assessment. Then, in Section 6 we present results, by supplying data to the impact assessment based on a real-world application where multiple components come together to form a single part in the simulated distributed supply-chain.

2 Systematic Literature Review on Sustainability Assessment Themes of AM

There exists a broad range of LCA methods assessing the sustainability and environmental aspects of AM. In what follows, we illustrate four common themes in AM sustainability assessments. The first subsection of the surveyed literature presents the consensus that the production energy consumption has the most significant impact. Next, Subsection 2.2 follows our surveyed sustainability assessments of the AM supply chain from cradle-to-gate and cradle-to-grave. We noticed that cradle-to-gate assessments did not include the use-phase, while cradle-to-grave assessed the LCA with use-phase included. This distinction was not made in publications prior to Kokare et al. [15], who recently presented the cradle-to-gate and cradle-to-grave distinctions in their survey of AM LCAs. Hence, past LCAs that did not consider the use-phase have been partial LCAs, as they only went from cradle-to-gate. Those that accounted for the part's lifetime in the use-phase were denoted as cradle-to-grave. The assessments of AM in the cradle-to-grave life cycle showed a significant reduction of impacts as categorized in Table 1, such that some authors suggest assessment on a part-by-part basis [16].

Contributing to the growing field of AM sustainability research are the addition of assessment indicators for selecting the impact categories of significance [17-19] and, uniquely for the AM domain, AM-specific indicators [13, 20, 21] which consider the geometric properties of a part. To account for greater industries and components, these impact category choices, methods of filtering, and the AM-specific indicators have been integrated in past AM LCAs as illustrated in Table 0. Subsections 2.3 and 2.4 emphasize the importance of presenting this work as the next stage in comparing AM with CM within an extended (distributed) supply chain, while incorporating the latest AM-specific measures or metrics to assess the environmental impacts and performance of AM processes. The objective is to integrate the previous AM-specific indicator into a comparative model to accurately forecast AM's sustainability performance from an energy consumption perspective. As discussed, this aspect is crucial as it encompasses the majority of the environmental impacts associated with this manufacturing method. Additionally, using the indicator will give concrete observational assertions for what sort of products, given their “solid-to-envelope” ratio, will be better or worse between the two assessed AM and CM scenarios.

Table 1. Systematic Review of LCA Methods, Indicators, and Impact Categories Assessed in the Scope of Sustainable AM. Relevant themes addressed in bold font are addressed in this paper's assessment for an energy consumption review using the solid-to-envelope ratio tool for comparing AM and CM in distributed parts supply chains.										
Authors	Scope	Functional Unit	Use Phase	DMS	Metal	Compares w/ CM	Impact Categories	Special Indicators for scoring, filtering	Comparison Indicators	Result
Faludi 2016 [22]	Cradle-to-gate and gate-to-grave	Complex turbine	N	N	Y aluminum	N	ReCiPe ² Midpoint H Europe 18 Impact Categories	ReCiPe Europe Midpoint H single scoring	N/A	Operational electricity caused the majority of embodied impacts.
Li 2016 [10]	Cradle-to-gate	A lever	Y	Y	Y	Y	Cost, and Carbon Emissions	N/A	Differences in Cost and Carbon Emissions	Cost is dominated by transportation and carbon emissions dominated by raw material. AM supply chains are indeed superior.
Priarone 2016 [8]	Cradle-to-grave	Three different product shapes with varying cavities	N	N	Y titanium	Y	Energy demand and CO2 emissions	Carbon Emissions Signature proposed by Jeswiet and Kara 2008 [19], solid-to-cavity ratio [23]	Impact Comparisons	Solid-to-cavity ratio showed correlation to signifying the best manufacturing strategy.
Huang 2016 [24]	Cradle-to-gate	5 aerospace parts	N	N	Y titanium and aluminum	Y	Energy demand and CO2 emissions	Buy-to-fly ratio	Impact comparisons	These energy savings are primarily due to the reductions in resource production energy use attributable to the lower buy-to-fly ratios of AM processes and the reduced mass associated with the AM components' advanced lightweight geometries. In addition, the modular nature of AM could enable cost effective distributed manufacturing, which if adopted on a wide scale could lead to even greater impacts.
Paris 2016 [20]	Cradle-to-grave	Turbine blade	N	N	Y titanium	Y	10 impact categories from Simapro and CML 2 Baseline 2000	Cumulative Exergy Demand, Shape factor, & Ratio factor (Comparison)	Developed their own indicators for making environmental and	For parts above the geometric quantity (shape factor) $K = 7$, EBM is always the best option due to lower material usage from EBM compared to milling.

² <https://www.rivm.nl/en/life-cycle-assessment-lca/recipe>

									geometric assessments	
Cerdas 2017 [16]	Cradle-to-grave	Eyeglasses frame	N	Y	N	Y	8 Impact categories	N/A	Impact comparisons	In a DMS, the production process and material used drive the environmental impact. CMS driven less by material. No indication of whether one is better than the other.
Kafara 2017 [25]	Cradle-to-grave	Mold cores	Y	N	N	Y	ReCiPe Midpoint H Europe 18 Impact Categories [18]	The ReCiPe Endpoint H Method was used to normalize, weight and combine these 18 impact categories to a single score	Impact comparisons	AM is in comparison to conventional methods a cost and time effective method for small-scale production and customized products.
Mami 2017 [21]	Cradle-to-gate	Titanium door stop	Y	N	Y	Y	Resources, Ecosystem quality, human health, climate change	Eco-efficiency composite trade-off	Eco-efficiency comparison	The optimized 3d printing scenario showed impact reduction of 20% for all impact categories, by reducing the weight of the part by 20% from the CM scenario.
Walachowicz 2017 [9]	Cradle-to-gate	Repair of one burner tip	N	N	Y super alloy	Y	All ILCD recommended impact categories at midpoint level	CML2001-APr in GaBi LCA software and database	Impact Comparisons or none	Primary energy consumption and GHG emissions can be reduced if it substitutes a manufacturing process with a low degree of material utilization far from near-net shape manufacturing.
Kamps 2018 [26]	Cradle-to-gate	Low or high-volume gear wheel production	N	N	Y steel	Y	Energy and cost	Cost-and-energy efficiency	Breakeven point between production size and cost between AM and CM	Mere substitution not suitable, must consider use phase or optimized design to prove cost and energy efficiency of LBM. Breakeven point for energy was 12 parts until CM is more eco-efficient.
Watson 2018 [13]	Cradle-to-grave	A part made from a billet of raw material	N	N	Y	Y	Energy	Solid-to-envelope ratio (alpha)	Critical solid-to-envelope ratio threshold	Offers a tool that can be used to discriminate between manufacturing processes purely from an energy consumption perspective.
Bockin 2019 [27]	Cradle-to-gate	Theoretical weight reduction 25% of engine automotive	N	N	Y	Y	Fossil fuels and greenhouse gases global warming	Energy Priority Strategies, Eco-indicator 99, and Environmental Development of Industrial Products (weighting methods).	Impact Comparisons	Use phase and material choice are critical indicators of AM's performance, ambiguous conclusion.
Fredrikson 2019 [28]	Material, powder, and production processes	Manufacture r details	N	N	Y super alloy	N	Energy use and emissions	Ashby 5 step method [17]	Ashby 5-Step Method [17]	Large energy consumption embodied in material.
Ahmad 2019 [14]	Cradle-to-gate	one unit of steel washer with 3	N	N	Y steel	Y	Carbon emissions and energy consumption	alpha [13]	Impact Comparisons	Alpha, as an indicator for energy consumption and carbon emission, is more

		varying geometries								useful in AM than CM. EBM has lower impact overall tested geometries.
Lunetto 2021 [29]	Cradle-to-gate	Fixed number replicas of the same unit	N	N	Y titanium	Y	Cumulative energy demand, cost and CO2 emissions	Solid-to-cavity ratio [23] & cumulative energy demand	Break even surfaces for energy demand, cost, and CO2 metrics	EBM did not show clear advantages in cost, CO2, or energy demand.
Gao 2021 [30]	Cradle-to-grave	Various AM methods	Y	N	Y titanium and steel	N	Energy demand and CO2 emissions	None	Impact comparisons	<i>From the standard point of energy efficiency and LCA studies, wire feedstock materials are more attractive than powder-based feedstock materials since the printing rate of the wire-based metal AM is faster than that of the powder-based AM process.</i>
Rupp 2021 [11]	Cradle-to-gate	Pump impeller spare part	N	Y	Y	Y	CO2 emissions	Buy-to-fly-ratio	Impact comparison	The buy-to-fly ratio is the key driver when it comes to emission reduction.
Reis 2023 [31]	Cradle-to-gate	3 three different geometries: a gear, cylinder and S-shaped geometries	N	Y	Y steel	Y	human health, ecosystems, and resources.	Buy-to-fly ratio	Both midpoint and endpoint indicators from the ReCiPe method were aggregated and converted to endpoints [18]	WAAM was the best ecological option due to its better material utilization for all the geometries produced, proving to have a 12% environmental impact reduction in geometry 1 production, 45% in geometry 2, and 47% in geometry 3 relative to CNC Milling.
Tran 2023 (this paper)	Cradle-to-gate	One part comprised of 7 distributed components of varying geometries assembled at a single location.	N	Y	Y steel	Y	Energy demand	alpha [13]	Critical alpha ratio [13]	AM showed significantly lower energy consumption compared to traditional manufacturing. While transportation had a minimal impact on overall energy consumption, it contributed 3.5-4 times higher transportation costs in the CM scenario. This factor becomes crucial if other phases of the distributed supply chain rely on renewable energy sources while transportation does not.

2.1 Operational Energy Consumption Is Most Impactful

According to Faludi et al. [22], energy consumption has a significant impact on manufacturing industries. This impact is further emphasized in AM when compared to the higher carbon emissions associated with CM processes [32]. As described in this subsection, this is due to the relatively higher energy consumption in AM processes compared to conventional methods. Considering these

observations, the next crucial step is to evaluate the energy competitiveness of AM in the distributed manufacturing scenario. This evaluation should also address the identified gaps in the themes related to sustainability assessment in AM—such as extending the current works' methods to future setups, parts, and functional units. By undertaking this analysis, we can gain a comprehensive understanding of the energy performance and sustainability implications of AM, paving the way for greater informed decision-making in the manufacturing industry.

LCA studies from 2010 such as Baumer et al. [33, 34] analyzed the resource consumption and carbon impact of AM systems, comparing their results with others (Morrow et al. [23] and Kellens et al. [35]). The results of their energy analysis admittedly were not congruent with each other due to different machine parameters and part geometries studied. The reasons for the discrepancy in specific energy consumption metrics (SEC) in kWh/kg were primarily due to process rate as a function of layer thickness and capacity utilization. In turn, establishing a higher rate of deposition by setting certain machine parameters and fitting more components to be built in the chamber were suggested as ways to reduce energy consumption and carbon footprint. Gutowski et al. [36] reaffirmed the observed relationship between the energy consumption rate (J/kg) and the process rate (kg/hr) for manufacturing process innovations. The study showed that smaller process rates led to higher SEC. Yet, the bulk of LCA studies pertaining to the AM energy consumption used these metrics due to the gap in reported empirical studies on metal AM machines.

In 2015, studies began to explore the question of how AM could enable more sustainable models of production and consumption via product and process redesign, make-to-order components, and “closing the loop” (recyclability). Faludi et al. [22] conducted an LCA to measure the environmental impacts of selective laser melting (SLM). They showed that among all the energy required to build an AM part, such as the energy to produce powder, supporting hardware, and energy to process AM, the last had the most significant footprint. Additionally, out of all case study instances studied for observed impacts, only two were *not* dominated by the process electricity consumption, which demonstrates the outsized impact of electricity needs.

One of the first papers to compare the carbon emissions between SLM and its CM counterpart in a centralized and decentralized aspect was by Li et al. [10]. In the centralized model, manufacturing takes place at a centralized location and in the decentralized model, manufacturing takes place near the end user. Li et al. [10] Were inconclusive regarding AM's role in being environmentally friendly but suggested that it may reduce carbon emissions by replacing lengthy conventional supply-chain structures requiring many tiers of transportation costs. The paper is one of the early explorations on the impact of AM on supply chain performance using system dynamics. The paper increased the understanding of where costs and carbon emissions were being generated for both conventional and AM-based spare part supply chains. They found that the dominant source of carbon emissions came from raw materials due to indirect energy use while the dominant source of economic cost came from transportation. Though the raw material dominated the carbon impact, the authors stated that it was still debatable whether AM supply chains were environmentally superior to conventional supply chains and that it was somehow determined by the characteristics of the CM methods. In subsequent studies, certain geometric factors such as the

solid-to-cavity ratio were utilized as metrics to quantify the extent to which adopting AM could effectively reduce environmental impacts within a supply chain. In the next subsection, we discuss the different geometric indicators, their differences, and the one we chose for our analysis of AM and CM from the distributed supply chain perspective.

2.2 Weight Reduction Reduces Life Cycle Impacts in the Use Phase

In 2017-18, analyses performed in a survey of AM's sustainability by Colorado et al. [37] showed that studies pertaining to environmental aspects were most prolific in 2018—double the number of publications compared to 2016. Huang et al. [24] redesigned additively manufactured aircraft components to assess the carbon and energy impact of AM. They estimated that redesigned AM aerospace components could consume only 33-50% of the energy of their CM counterparts, while also reducing a significant amount of fuel consumption during their use. Mami et al. [21] showed over a 20% impact reduction across all their defined impact categories by reducing the weight of the aerospace door stop functional unit. Taking the use phase into account, the 20% reduction in weight contributed to a 20% reduction across their measured resources, ecosystem quality, human health and climate change impact indicators. Their sensitivity analysis showed that, for lower productivity levels, the optimal scenario relied on the chosen tradeoff between environmental impacts and cost reduction, bringing another perspective from the eco-efficiency indicator metric.

Subsequently, a greater number of LCA comparison studies between AM and CM appeared. For instance, Priarone et al. [8] compared different geometries being manufactured by milling—a CM process and the electron beam melting (EBM—an AM process. They evaluated these two paradigms using the term “solid-to-cavity”, defined as the mass of the final part as a fraction of the solid feedstock, to suggest that weight reduction and geometries that carry a lower ratio would have lower energy demands and carbon footprint. Their study proposed 3 product shapes for comparison but did not provide an absolute condition for CM or AM to supersede the other in one geometry. Kamps et al. [26] also performed an LCA comparison for steel gears while additionally finding a breakeven point in economic cost between hobbing and laser beam melting (LBM) for a given production size. They also corroborated the finding [26] that designs for minimizing the weight of components were a good criterion for cost and energy efficiency in AM.

2.3 Using Geometric Indicators to Discriminate Between Manufacturing Processes for Lesser Environmental Impacts

To ensure accurate assessment of AM production scenarios, it is crucial to utilize appropriate AM-specific indicators/tools, particularly those proposed in the existing literature. Growing acknowledgment by researchers highlights part geometry as a key indicator in AM assessment, especially when comparing with CM. To solidify their impact, implementations and observations from different scenarios become crucial, emphasizing the next essential step in exploring AM's energy competitiveness and sustainability implications. Based on our literature survey, we found various quantities to measure the effectiveness and economy of material utilization in a manufacturing or supply chain process (material efficiency): solid-to-cavity, buy-to-fly, shape (K), and alpha (α) ratios. To make the distinction between each of these quantities, we explain with the following example: let's say one has a cube-shaped billet with a total mass of 100 grams (about 3.53 oz). Within this billet, 50% of the volume is the solid material required for the desired part, and the other 50% is waste (cavity).

The solid-to-cavity ratio refers to the ratio between the solid mass and the cavity mass of the product. It is commonly used in the field of manufacturing, particularly in the case of injection molding [23]. In our example, the solid-to-cavity ratio would be $\text{Solid mass} / \text{Cavity mass} = 50 \text{ grams} / 50 \text{ grams} = 1$. Similar to the solid-to-cavity ratio, the buy-to-fly ratio is a term commonly used in the aerospace industry to describe the ratio between the weight of the raw material purchased and the weight of the final part or component produced. It is also known as the material utilization ratio. For a high buy-to-fly ratio of 10:1, it denotes that only 10% of the bought material mass is used in manufacturing the part. Given the example, the buy-to-fly ratio is 100 grams:50 grams, or 2:1, denoting half the material was used to produce the part. The issue arises here that for the same example, where 50% of the material is a waste, the solid-to-cavity and buy-to-fly ratios are 1.0 and 2.0, respectively. This could be misleading as the ratios may imply equal useful and wasted material in the first case but double the waste in the second case. Additionally, these terms are measured in mass which does not accurately represent the volumetric nature of the feedstock to product relationship.

Another indicator that addressed the volumetric nature of machining operation has been suggested by Paris et al. [20] as the shape factor $K = \text{volume of raw material required in milling process} / \text{volume of the part}$ [20]. The shape factor K provides a ratio that compares the volume of feedstock in the milling process to the volume of the part. A lower value of K indicates a more efficient process, as it suggests that less material is wasted relative to the volume of the final part. In our example, the K factor would be 1, which is still not intuitive in understanding that only 50% of the volume is being used from the billet for the part. To avoid confusion, it's better to use the term "solid-to-envelope ratio" suggested first by Watson and Taminger to compare energy consumption between AM and CM [13]. It represents the volume of solid material within the part's envelope. This ratio is a valuable variable for determining the most energy efficient manufacturing method, whether conventional subtractive manufacturing or AM, in terms of total energy required to produce the final product. It's represented by the symbol " α ." This ratio is useful when assessing the energy impact between additive (AM) and subtractive (CM) technologies since a lower α signifies a smaller envelope indicative of AM's competitiveness in contrast to CM, where a higher amount of material removal (scrap volume) would be anticipated. In our example, the $\alpha = 50 \text{ grams} / 100 \text{ grams} = .5$. This ratio is a more intuitive quantity to denote the raw material efficiency and, consequently, more readily available to be integrated into AM and CM comparison models. In this paper, we define this variable to solve for the threshold point of when one manufacturing technology will be more energy efficient than the other. That is, if α is lower than α_{crit} then AM will be more energy efficient than CM and vice versa.

Although past literature has called for a "part-by-part" assessment of AM's supply chain performance [16], more recent literature allowed some of these strategic indicators to assess the most sustainable (or economical, etc.) manufacturing between AM and CM using comparative quantities, such as breakeven surfaces or critical threshold. These indicate how environmentally competitive metal AM processes can be compared to conventional counterparts. Their conclusions and methods are therefore more generalized and applicable to a broader range of parts. Kamps et al. [26] considered this strategy based on the volume of production [26], and Lunetto et al. on the deposition rate of a particular AM process [29]. To the best of our knowledge, this is the first paper to integrate Watson and Taminger's

critical alpha quantity [13], the more intuitive and practical indicator quantity, in the comparison between AM and CM distributed supply chains.

2.4 Supply Chain Consequences

Moreover, surveys from Huang et al., Kellens et al. and Baumers et al. [24, 35, 38] called for greater insight into supply-chain consequences where the environmental impacts may potentially be reduced by a decentralized AM production. Recently, Pilz et al. [39] in 2020 noted that future assessments of the environmental impact of decentralized and centralized supply-chains should be more deeply explored based on their literature review on the logistical performances between AM and CM. Though AM can decrease the distances of transporting products, more comprehensive research is needed in quantifying AM's potential in reducing further carbon impact via reducing supply-chain and logistical operations. This is especially pertinent as prior work noted that economic cost was dominated by transportation, while carbon emissions were dominated by raw material [10]. Rupp et al. [11] compared the LCAs of AM and CM components using a “buy-to-fly” coefficient in their decentralized AM and centralized CM impact analysis. They described the “buy-to-fly” coefficient as a weight ratio between the feedstock material and the final product and a significant indicator for determining a supply chain's competitiveness. However, their analysis neither took into full account the impact of coefficients due to supply-chain changes nor critical coefficients thresholds as to when such coefficient may favor AM over CM.

2.5 Existing Gaps in Current Literature

Based on our chronological review of metal LCA methods comparing AM to its conventional counterparts, it is evident that use of AM may indeed reduce carbon footprint by reducing material and energy inputs in their lifecycle. Even though there has been some demonstration of environmental benefits through shorter transportation distances, most of the LCA studies in the literature were done for polymer AM machines as that has been the most mature technology in AM. One of the first studies placing metal AM in a simple decentralized model had been reported by Li et al. [10]. Yet, their analysis did not account for the complex and tiered nature of more complex distributed scenarios as we defined in Sections 1 and 3. Past LCA studies including the solid-to-envelope ratio have also not addressed how an advanced distributed AM supply-chain could reduce the transportation steps and hence achieve greater bias towards AM. Huang et al. [24] acknowledged that there existed and still exists an open research gap to quantify the cost effectiveness of more complex distributed manufacturing models. Based on the lack of a more accurate representation of metal AM in distributed manufacturing settings, a review of past LCA studies motivated this paper to assess the LCA comparison of AM and CM inclusive of advanced supply-chain scenarios. Reasons for this present gap in literature may be due to the lack of technological maturity and adherence to past supply chain models. However, as described in the next section, prominent industry leaders and various enterprises are embracing novel business paradigms to integrate distributed manufacturing systems within their extensive supply networks.

Though the literature is lacking discussion on societal indicators integrated in AM LCAs, the current interest calls for AM in more distributed networks. What is needed first are more observations on AM's varying supply-chains scenarios and their impacts, under holistic supply-chain considerations. After a thorough review of published literature on comparative studies of AM's and CM's supply chain characteristics, we found that most studies analyzed specific cases, examining the manufacturing of a particular product shape using a specific AM process. As a result, these findings cannot be generalized to other product shapes or products manufactured by other AM techniques [15].

Building upon the state-of-the-art methods, this paper leverages the previously published assessments of AM's environmental impact and conducts an energy consumption assessment from the cradle-to-gate life cycle. As a result, the LCA in this paper technically refers to “partial” life cycle assessment as discussed in Section 2. Specifically, we use for our assessment the alpha-critical variable defined earlier for indicating the geometric threshold where a certain supply chain scenario can tip the balance from one to another type of manufacturing based on energy efficiency. We have performed this assessment from a commercial product standpoint. For CM the subtractive methods are assumed in the example parts which allow us to better compare our findings with past work. We do not consider the use phase, and topological optimizations required for AM, or assume that the part is used in a transportation application. Hence, this study assesses the AM supply chain's so-called “paradigm shifting” potential to replace the CM under conservative assumptions and with the flexibility to extend it to other geometry of parts.

3 A Case for Distributed Additive Manufacturing

The manufacturing industry is increasingly working on the implementation of sustainable manufacturing and business practices for energy and resource-saving systems [7]. Currently, manufacturers may source production components from multiple offshore locations to economically achieve desired production quality at the minimum cost. The supply chain disruptions due to COVID-19 started a trend for domestic manufacturing, which has accelerated with many countries on-shoring their production. In both contexts, as the cooperation between different enterprises evolves and becomes more collaborative, they will be better prepared to handle volatile demands and product variants required to remain competitive. This is particularly true in markets where customer demands, and product variations are increasingly volatile. As noted by Matt et. al [12], the future of production is pointing to a shift away from mass production to individual and micro production. Distributed manufacturing can be of two types, as demonstrated through examples from shoe and the furniture industry. In the first type, it involves distributing the manufacturing sites of the complete product close to the end user. This can be enabled by AM technology, which shortens the supply chain. Nike and Adidas have implemented this first type as responsive manufacturing facilities: Adidas' Speedfactory³ and Nike's Flex factory respectively, allowing them to respond swiftly to changing demands in the e-commerce and social media era. In the second type, distributed manufacturing may refer to assembling the parts close to the end user, where parts are manufactured at various locations and then transported to be assembled near the destination. Many

³ <https://report.adidas-group.com/2021/en/group-management-report-our-company/global-operations.html>

furniture products are an example of this method, where manufacturers often produce parts at various locations and then assemble them close to the end user. Many automotive products are produced using this approach as well, where manufacturers often produce/source automotive components from various specialized factories and then assemble them at their final production facility. In this current study we primarily consider distributed AM for Type 1, while CM may resemble Type 2 of distributed manufacturing. Our goal for studying AM and CM in the distributed manufacturing scenario is motivated by the increasing need for logistical coordination and the creation of autonomous manufacturing sites capable of producing parts adaptively, and on-demand at the user location.

Defined as autonomous agents working together with their own various machines and tools, the subsystems in the DMS run in parallel at different geographical locations to economize the benefits of outsourcing through corresponding intelligent operation planning systems [7, 40]. DMS research and planning of distributed manufacturing facilities have been an ongoing effort for over two decades. We adapt the DMS paradigm to this LCA comparison to assess the future evolution of manufacturing sustainability. In conjunction, rising logistics costs, mass customization, open innovation of design, proximity to point of consumption, and production at the place of critical resources are among some of the increasing trends for DMS production [12]. Studies from Durão et al. [41] presented one such scenario of AM used in the DMS setting, which included activities such as defining customer orders, supplying raw materials, machine setup/scheduling, etc. But there has been no LCA study comparing the carbon footprint impact of centralized manufacturing over the carbon footprint of DMS. While the AM technology is conducive to DMS, at this point of its maturity it may be expensive to be localized to all useful locations. As noted in previous studies by Pereira et al. [42], this is due to the current lack of automation, and machine costs including trained personnel, in this developing production process. With the continuing focus of innovation, we foresee these costs going down significantly in the future. Next, we elaborate on the need for this comparative LCA study to address greater production freedom of AM under the paradigm of DMS.

AM has the potential to play a key role in DMS due to its unique advantage in achieving complex geometrical attributes without extra tooling. Studies have shown that AM components still suffer from “design fixation”, hindering engineers from creating innovative designs in examples such as prosthetics, aircraft brackets and airducts, etc. Design fixation is defined as the unintentional adherence to a set of traditional ideas or concepts that hinder the final output to already known solutions [43]. As previously mentioned in Section 2, past studies compared AM to its conventional counterparts in a fixed setting with one component. Yet, with the different shapes and internal structures that may be produced using the same machine at a single location, multiple component parts in DMS bring up a compelling case for an investigation into AM under the DMS paradigm. The methodologies of past LCA comparison studies for AM have yet to consider the added transportation and assembly costs from a DMS standpoint. Therefore, defining AM in explicitly unique supply-chains is the next step needed for envisioning its true utility and its true impact assessments. When AM’s conceptual opportunities are compared to in this way against traditional manufacturing, design fixation is avoided at the logistical level.

When components cannot be easily fabricated as a single part, conventional machining techniques fabricate the components in sections to be assembled via welding, riveting, bolting together, etc. at a different location. This is particularly true when an enterprise’s in-house production of a component is more costly than when it is outsourced, requiring that component to be made at some offshore location to

later be assembled for the finished part. AM provides a significant application to the manufacturing supply-chain by being able to combine multiple assemblies into one monolithic part or significantly reduce the number of components needed to be assembled [44-46].

Studies have shown that AM can significantly reduce the number of distributed assembly operations incurred from traditional manufacturing systems, particularly those in aerospace industry. Shapiro et al. [44] used an example of an Airbus 3D printed aluminum part for the Eurostar E3000 satellite. When fabricated as one single monolithic part, compared to the conventional way, the AM part weighed 35% less, was 40% stiffer and did not need the assembly operations of fastening 44 rivets. Moreover, Galati et al. [45] redesigned computer numerical control (CNC) machined components for a high-precision flying probe to be produced using powder bed fusion (PBF). They were able to reduce the weight of a bracket by 10% and increase stiffness by 50%. They also redesigned rails to reduce weight by 30% simultaneously reducing the number of components from sixteen to three. Though studies have provided some validation of AM to remove most assembly operations, it still shows some limitations in its ability to produce monolithic rigid body joints. These limitations were due to poor surface quality, poor mechanical properties, and residual material leftover upon building as illustrated by Cuellar et al. [47]. Though AM was shown to be steps away from realizing the non-assembly paradigm, current research efforts suggest that development of alternative designs and materials are underway [29].

As the development of AM continues, its underlined advantages, such as: a) building the same or similar component in one build cycle without extra tooling, b) more effective use of materials, c) reducing the assembly line and other supply chain logistics, etc., will become clearer. This makes the case for deeper analysis of AM's efficacy and the identification of the manufacturing conditions where AM supersedes CM, particularly in terms of reduction in carbon footprint, which is focus of this paper.

4 Methodology

4.1 Assumptions

With significant research and advancement being made in AM technology, the technology is getting more mature, and it can be assumed that the post processing needs such as heat treatments, achieving quality control, dimensional tolerance, support removal, etc., would be minimized in the future. Even in CM, the need for quality control and post processing treatments remains, making it impossible to differentiate between AM and CM with regards to post-process treatment and quality control. For most applications, the quality control aspect is not energy intensive anyway and therefore is not considered in this work. Hence, this paper focuses solely on comparing the overall production cost between AM and CM, assuming that pre-process trial runs and adjustments for the quality of the finished product in AM have been achieved, and the process parameters for producing quality products are already set.

Although the advantage of AM for complex and intricate parts is well-known, for this study, we are considering parts that can be both manufactured easily with AM or CM. If final assembly would be required for the produced part, it is assumed that the energy for assembling, and quality check will be the same in AM and CM. Therefore, it does not need to be considered as a factor into our LCA.

The geometry and complexity of the part for baseline comparison is assumed to be the same for both in our study, while also being reasonably simple, not requiring multiple quality runs etc. The cost to setup CM or AM facilities are not considered and is beyond the scope of this paper.

We assumed that data in the reported literature about energy consumption is consistent in all different publications. The reported literature numbers for energy consumption are secondary energy, meaning electrical power consumption rather than primary energy. The difference between the two is that electricity is produced from primary energy and that there exists energy waste due to transmission, power generation efficiency, and storage of energy consumption as well as electric grid distribution. Although we do not report primary energy consumption, in this comparative study, comparing secondary energy consumption is adequate, assuming the energy loss factors from primary to secondary energy in both AM and CM are similar. In what follows, we assume a decentralized and distributed production chain for AM in the LCA comparison given the outlook that industrial companies are entering emerging markets with the consideration that social and environmental responsibility as well as economic efficiency will be heavily valued [7, 48].

4.2 Life Cycle Analysis Method

According to the LCA phases defined in Section 2, here we define our i) goal and scope, ii) life cycle inventory analysis, and iii) life cycle impact assessment methods accordingly. With reference to the scope of the LCA, the decentralized setting in AM shortens the supply-chain primarily by reducing the transportation distances of raw materials and finished components. Manufacturing is therefore decentralized in the sense that *all* components can be manufactured at the point of use using the powder feedstock. The goal of this novel comparative LCA study is to quantify the energy consumption at each phase of the two supply-chains for a clear understanding of decentralized AM's competitiveness against its centralized CM counterpart, where multiple components are manufactured in a centralized setting and assembled if needed at specific location(s). The scope of our analysis will indicate whether transportation costs will play a significant role in the overall energy impact.

In the LCA, it is not enough to only consider energy consumption, however, we adopt the same framework and consider solely energy consumption because it is the most impactful. We discuss a few reasons for this impact in addition to what we mentioned in Section 2.

1) **Energy policy.** Energy is constantly rising. This increasing energy cost of the products and materials will be passed on to the consumers. According to the multi-criteria decision making (MCDM) framework, which has been combined with LCA in past investigations and developments in environmental and societal indicator frameworks [49], any artefact of investigation for policy making must be comprehensive. In this context, LCA frameworks have been critiqued in recent studies on account of its categories of indicators being all quantitative, lacking indicators with qualitative measurements. As a result, authors in [49] have combined the LCA framework with MCDM for assessing the energy consumption metrics of past studies. This is important because policies created with focus only on energy consumption, without regard to other important aspects, such as societal well-being and fairness, will struggle to be sustainable. For example, past energy consumption studies on the effect of energy policies on housing conditions in Southern

Mediterranean Europe [50, 51] showed that singularly reducing energy usage resulted in an unequal distribution of discomforts to residents. This calls for evidence-based policy that holistically considers the design space.

Energy's role as a powerful policy indicator is crucial, especially in major agreements like the Paris Agreement, where it shapes sustainability and climate change policies. Decisions regarding cleaner technologies, energy efficiency, and renewable sources are essential in transitioning to a low-carbon, resilient, and sustainable economy. 2) **Green House Gas (GHG) Participation** of manufacturing industries is critical in GHG discussions as they consume the most energy [32]. The manufacturing sector is also one of the primary users of fossil fuels to transport and manufacture materials and products. The burning of fossil fuel is the largest contributor to GHG. As a result, energy consumption is measured here to generalize the overall quantitative measures. Future studies may also consider qualitative studies of AM, such as societal and economic impacts, which is beyond the scope of this work. 3) **Generalizing Measures.** Quantitative measures could be partially represented by energy consumption measured for each unit such that all CO₂ indicators (raw material, manufacturing and transport) are accounted for. To do so, we account for the SEC in the equations presented in Table 2. Based on those expressions, we solve for the alpha critical for the two distinct supply chains representing AM and CM.

The cradle-to-gate scope of our analysis of the AM and CM production systems focuses on the complete production process from mining the ores to the delivery of the finished product to the consumer. The production modes of AM include mining, powder production, transportation, AM processing, assembly of the components (if required), and delivery of the product. The CM production modes are mining, production of ingots/billets, transportation of solid feedstock, the CM process (milling, turning, etc.), assembly (if required), and final component delivery.

Based on the DMS scenario, we present and discuss results for the overall comparison between the two competitive manufacturing technologies - CM and AM. In our inventory analysis, we consider the impact of transportation cost as a function of the number of end users, the effect of each component's α_{crit} (defined in Subsection 2.2), and an overall energy cost comparison for a representative part.



Figure 1. Details of each component's solid-to-envelope ratio (indicated by the value of Alpha) and manufacturing method. In order to produce the overall part, each component must be manufactured according to specialized CM methods, compared to a single additive method in the PBF process. Lower alpha values for larger components increases the likelihood for more energy efficient production in AM.

Our inventory analysis phase quantifies energy and material inputs for both production modes of each component within the AM and CM manufacturing system's scope to produce the part. For our distributed manufacturing scenario, we selected a 90 mm electric ducted fan (EDF) to power a Freewing F-15C Eagle Super Scale high performance drone [52]. To compare the two production systems, the EDF for a remote control (RC) airplane constitutes the functional unit of the LCA. As illustrated in Figure 1, it is made up of seven different parts requiring assembly to form the whole product. In our LCA, we considered each of its parts' supply chain distances, transport modes, solid-to-envelope ratio, volume of its feedstock envelope, and manufacturing method. In this comparative study, we do not consider complex, intricate, or proprietary products and perform energy analysis between AM and CM for simple parts only. The EDF is a good model example as its dimensions were suitable for manufacturing via current metal AM machines while also being suitable for an AM industry application. The RC airplanes and their components, such as the EDF, are part of the global Remote-Control Products Hobby market, which is expected to reach 2 billion dollars in 2027 according to Transparency Market Research [53]. The

demand for RC airplanes is an example of how spare components are likely pushing companies to adapt to the best supply-chain model to meet customer requirements and alleviate the difficulty of forecasting the demand and storage [10].

In our inventory analysis phase, we have considered scopes 1, 2, and 3's impacts on the carbon footprint, respectively denoting direct-energy required for processing, indirect-purchased energy, and indirect-upstream/downstream value chain emissions as defined by ClimatePartner [54]. Scope 1 emissions occur from the process of actual manufacturing, scope 2 concerns the indirect emissions from creating the raw material, and scope 3 considers the impact in delivering the raw material to manufacturing and the product to user. In our CM scenario, the components are designed and manufactured at the Horizon Hobby LLC enterprise locations. Mentioned as one of the key players in RC products by Transparency Market Research, they are located in Shanghai, China; Barsbüttel, Germany, and Ontario, California (USA) [53]. From each of these locations, the components are sent to be assembled in Champaign, IL, USA, where Horizon Hobby headquarters is based before shipping to the final user location. In the AM scenario, these designs are sent digitally to be manufactured and assembled at the same final user location in Las Cruces, New Mexico USA. The closest AM powder manufacturer to the final user location (Las Cruces, NM) is found in Philadelphia, Pennsylvania according to the Global Steel Powder Market Report 2021 (Courtesy: Market Info Reports) which presented several leading producers of steel powder. For the CM system's feedstock, and according to the same report, producers of stainless-steel plates and rods have locations in Beijing, China, Stockholm, Sweden, and Ghent, Kentucky, USA.

Table 2. Impact Assessment Equations		
LCA Stage	Equation	Definition
Feedstock AM EC_{FAM}	$\sum_{n=1}^{\# \text{ components}} [\alpha \cdot V_t \cdot \rho \cdot SEC_{Powder}]$	Amount of energy (kWh) required to manufacture the metal powder for a specific number of same-design components to be built (# components). The SEC for powder creation is multiplied by alpha, envelope volume (V_t) and density of the material (ρ).
Feedstock CM EC_{FSM}	$\sum_{n=1}^{\# \text{ components}} [V_t \cdot \rho \cdot SEC_{FSF}]$	Amount of energy required to manufacture the metal formed solid feedstock (FSF) for a specific number of same-design components to be built.
AM Production EC_{AM}	$\sum_{n=1}^{\# \text{ components}} [\alpha \cdot V_t \cdot \rho \cdot SEC_{AM}]$	Amount of energy required to manufacture a specific number of same-design components in AM.
CM Production EC_{SM}	$\sum_{n=1}^{\# \text{ components}} [(1 - \alpha) \cdot V_t \cdot \rho \cdot SEC_{SM}]$	Amount required to produce a specific number of same-design components in CM. $(1 - \alpha)$ represents the amount of material that needs to be removed from the envelope, envelope volume (V_t) and density of the material (ρ).

Transportation (General) EC_T	$\sum_{n=1}^{\# locations} [Mass_{Transport} \cdot d_n \cdot SEC_{Transport_n}]$	Amount of energy required to transport material across different modes of transportations d_n with varying $SEC_{Transport_n}$ according to transport mode.
AM Feedstock Transportation $EC_{T_AM_FEED_MFG}$	$\sum_{n=1}^{\# locations} [\alpha \cdot V_t \cdot \rho \cdot \# of parts \cdot d_{AMFEEDMFG_n} \cdot SEC_{Transport_n}]$	From AM feedstock factory location to AM manufacturing location ($d_{AM_FEED_MFG_n}$)
CM Feedstock Transportation $EC_{T_SM_RAW_MFG}$	$\sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of parts \cdot d_{SMFEEDMFG_n} \cdot SEC_{Transport_n}]$	From CM feedstock factory location to CM manufacturing location ($d_{SM_FEED_MFG_n}$)
AM Assembly Transportation $EC_{T_AM_FEED_MFG}$	$\sum_{n=1}^{\# locations} [\alpha \cdot V_t \cdot \rho \cdot \# of parts \cdot d_{AMMFGASSY_n} \cdot SEC_{Transport_n}]$	From AM manufacturing location to AM assembly location ($d_{AM_MFG_ASSY_n}$)
CM Assembly Transportation $EC_{T_SM_MFG_ASSY}$	$\sum_{n=1}^{\# locations} [\alpha \cdot V_t \cdot \rho \cdot \# of parts \cdot d_{SMMFGASSY_n} \cdot SEC_{Transport_n}]$	From CM manufacturing location to CM assembly location ($d_{SM_MFG_ASSY_n}$)
AM Part Transportation $EC_{T_AM_ASSY_USER}$	$\sum_{n=1}^{\# locations} [\alpha \cdot V_t \cdot \rho \cdot \# of parts \cdot d_{AMASSYUSER_n} \cdot SEC_{Transport_n}]$	From AM assembly location to final user ($d_{AM_ASSY_USER_n}$)

CM Part Transportation $EC_{T_SM_ASSY_USER}$	$\sum_{n=1}^{\# locations} [\alpha \cdot V_t \cdot \rho \cdot \# of parts \cdot d_{SM_ASSY_USER_n} \cdot SEC_{Transport_n}]$	From CM assembly location to final user ($d_{SM_ASSY_USER_n}$)
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Following Watson and Taminger [13], we present the energy consumptions for AM ($EC_{AMTotal}$) and CM ($EC_{SMTTotal}$) production systems, including the transportation energy, in Equations 1 and 2:

$$EC_{AMTotal} = EC_{Mining} + EC_{FAM} + EC_{T_AM_FEED_MFG} + EC_{AM} + EC_{T_AM_MFG_ASSY} + EC_{ASSY} + EC_{T_AM_ASSY_USER} \quad (1)$$

$$EC_{SMTTotal} = EC_{Mining} + EC_{FSM} + EC_{T_SM_FEED_MFG} + EC_{SM} + EC_{T_SM_MFG_ASSY} + EC_{ASSY} + EC_{T_SM_ASSY_USER} \quad (2)$$

Table 2 presents the equations for each term included in Equations 1 and 2, following the production modes within the scope of our LCA. We remove the energy consumption for mining (EC_{Mining}) and assembly operations (EC_{ASSY}) in Equations 3 and 4 if CM and AM share the same processes and plant operations during those phases (described in Section 5). Additionally, the AM components in our scenario are not built as one part but must be assembled from the same designs and thus require the same assembly operations as their CM counterparts. For future works, Equations 1 and 2 may be used and built upon for impact assessment or solving for the cross-over point α_{crit} .

$$EC_{AMTotal} = EC_{FAM} + EC_{T_AM_FEED_MFG} + EC_{AM} + EC_{T_AM_MFG_ASSY} + EC_{T_AM_ASSY_USER} \quad (3)$$

$$EC_{SMTTotal} = EC_{FSM} + EC_{T_SM_FEED_MFG} + EC_{SM} + EC_{T_SM_MFG_ASSY} + EC_{T_SM_ASSY_USER} \quad (4)$$

α_{crit} is solved by setting $EC_{AMTotal}$ and $EC_{SMTTotal}$ equal. First, all the terms that contain α are moved to the one side of the equation; since α is a constant and the argument of each summation that contains this constant only have multiplications, it is possible to solve for α , which results in a solution to α in order to find α_{crit} , seen in Equation 5. From Equation 5, we see that α_{crit} increases when distances for any AM transportation step decreases and distances from manufacturer to assembly and assembly to user for CM increase. When α_{crit} is large, there is a greater chance that AM is better than CM for carbon footprint.

$$\begin{aligned}
\alpha_{crit} = & \left\{ \sum_{n=1}^{\# parts} [\rho \cdot V_t \cdot EC_{FSM}] + \sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of part \cdot d_{SMFEEDMFG_n} \cdot EC_{Transport_n}] + \sum_{n=1}^{\# parts} [\rho \cdot V_t \cdot EC_{SM}] \right\} \\
& \div \left\{ \sum_{n=1}^{\# parts} [EC_{FAM} \cdot V_t \cdot \rho] + \sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of parts \cdot d_{AMFEEDMFG_n} \cdot EC_{Transport_n}] + \sum_{n=1}^{\# parts} [\rho \cdot V_t \cdot EC_{AM}] \right. \\
& + \sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of parts \cdot d_{AMMFGASSY_n} \cdot EC_{Transport_n}] + \sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of parts \cdot d_{AMASSYUSER_n} \cdot EC_{Transport_n}] \\
& + \sum_{n=1}^{\# parts} [\rho \cdot V_t \cdot EC_{SM}] - \sum_{n=1}^{\# distances} [V_t \cdot \rho \cdot \# of parts \cdot d_{SMMFGASSY_n} \cdot EC_{Transport_n}] \\
& \left. - \sum_{n=1}^{\# locations} [V_t \cdot \rho \cdot \# of parts \cdot d_{SMASSYUSER_n} \cdot EC_{Transport_n}] \right\} \quad (5)
\end{aligned}$$

5 Data Gathering

The energy consumption of AM and CM per phase (referenced in Section 4) of this paper's LCA is surveyed. From ore extraction to transportation of the final product, this section discusses each stage and the process of gathering data from the literature. The origin of our functional unit comes from its feedstock material which is either metal powder (AM) or solid feedstock (CM). The manufacturing of AM and CM feedstock shares the same process of extracting metal from the ore or using recycled material. The ore or the recycled material with the desired composition is melted together in an electric arc furnace before being placed in a refining vessel to reduce impurities [55]. Because we assume the sourced metal (stainless steel) is the same in manufacturing the component, the energy consumption for this phase is the same whether AM or CM is utilized. Hence, there is no impact on calculation for differential energy consumptions and on α_{crit} .

However, the creation of raw ingot (stainless steel) is not the final step in feedstock material preparation. For AM, atomization is required to produce metal powder. While for CM, the stainless-steel ingot is required to be shaped into rod, plate or tube. Atomization is the commonly used method to produce metal powder for AM. Morrow et al. [23] categorized atomization as either direct or indirect depending on what the unprocessed metal source is. Direct atomization takes the molten steel directly from the metal refining facilities; on the other hand, indirect atomization remelts metal parts from the forming process to be shaped. Based on our survey, the estimated EC (energy consumption) for atomized H13 steel powder varies depending on how many steps are taken to produce it. The direct route EC is 15 MJ/kg (4.16 kWh/kg) while the indirect route EC increases to 26 MJ/kg (7.22 kWh/kg) [23], due to the extra forming steps.

Reusability of loose powder after each build cycle by collecting and then sieving it into recycled powder is a promising application to reduce feedstock material consumption in AM-PBF (Powder Bed Fusion) technology. Slotwinski et al. [56] studied the difference between virgin powder and recycled powder where after eight build cycles the change in elemental concentration was negligible. Yet, the powder size distribution after the fourth reuse may change because of the creation of larger particles due to laser fusion [56]. Based on later research using industrial powder recycling strategies, where recollected and sieved powder were mixed with varying proportions of virgin and ‘several times’ recycled powder, Jacob et al. [57] showed that even for powder recycled up to 11 times, the mechanical tensile strength, hardness, chemical composition, and density were not significantly compromised. They also noted that further research should strategize tracking the recycled powder based on exposure time over the number of builds for cases where powder recycling may significantly affect the sensitive material properties. Given the increasing trend of recyclability we assume optimal and full powder recycling strategies where the higher recyclability of powder permits us to fully recycle powder in our powder feedstock energy quantifications.

The feedstock material production for CM takes the fresh metal from the refining facilities and uses a forming process to shape the metal into plates, rods or tubes. Morrow et al. [23] presented EC metrics for steel plates production while describing the process to include plates and rods. The square and circular thick plates are common for milling while the rod is the most common shape for turning. They described this forming process as “casting and working” and calculated an EC of 20MJ/kg (5.5 kWh/kg). While the energy consumption to specifically produce rods was not found in our literature survey, the data presented by Morrow et al. [23] is general enough to be used for rods and plates. Since most of the energy consumption goes to casting to turn the metal into a liquid, the specific energy consumption after cutting or rolling the feedstock into the desire shape is assumed to be an insignificant difference. As a result, no matter the shape, the specific metal forming process does not change the specific energy consumption of the feedstock gathered by Morrow et al. [23].

The next phase of our impact assessment is processing the feedstock material to build the desired product or component. For AM, three different metal PBF systems were studied for data gathering: Concept Laser M3, EOS EOSINT M270, and ReaLizer SLM250 as shown in Table 3. Also, two different CM processes are presented: turning and milling. We surveyed energy consumption for two turning systems: Doosan Machine PUMA 2500Y and Anyang CKJ6163, and for five milling-based systems: Production Machine Center (PMC), 1998 Bridgeport, 1988 Cincinnati Milacron, Mori Seiki NV1500 DCG, and VMC850 CNC machine.

Table 3. Specific Energy Consumption for Additive Manufacturing

Machine	Material	Layer Thickness	SEC (kWh/kg)	Reference
EOSINT M 270	Stainless Steel 17-4 PH	20 μm	66.94 (full build) 94.1 (single component)	Baumers, 2011 [39]
Concept Laser M3 Linear	Stainless steel 316L	30 μm	117.5 (full build) 163.33 (single component)	Baumers, 2011 [39]
SLM 250	Stainless steel 316L	50 μm	35.50 (full build) 48.85 (single component)	Baumers, 2011 [39]
Concept Laser M3 Linear	Stainless steel 316L	30 μm	26.89	Kellens, 2010 [18]
SLM 250	Stainless steel 316L	50 μm	31	Baumers, 2010 [15]

Table 4. Specific Energy Consumption for Conventional Manufacturing (Turning)				
Subtractive Method	Machine	Material	SEC (kWh/kg)	Reference
Turning	Doosan Machine PUMA 2500Y 4 Axis	Stainless Steel AISI 316L	1.69	Nyamekye, P. (2017) [58]
Turning	Anyang CKJ6163	Stainless Steel 304	0.23– 2.75	Zhao, G. (2020) [59]

Baumers et al. [60] and Kellens et al. [35] both measured the EC of the Concept Laser M3 Linear AM machine using stainless steel 316L material at 30 μ m layer thickness per pass. The Concept Laser M3 Linear uses a 200W or 400W fiber laser and has a build chamber of 350 $\times$ 350 $\times$ 300 mm. Baumers et al. [60] measured the EC for building a single component versus the EC for building as many components that can fit in a build bed (full build) for different machines and materials. Their results showed that using a full build was more energy efficient in Selective Laser Melting and Electron Beam Melting (EBM) processes; this is attributed to the energy consumed during the operation phases which does not depend on the size of the batch, or how many components are made in the operation, such as generating an inert atmosphere and the preheating and cooling processes. They also reported that the Concept Laser M3 Linear using SS 316L had an EC of 423 MJ/kg (117.5 kWh/kg) in a full build and an EC of 588 MJ/kg (163.33 kWh/kg) for a single component. Kellens et al. (2010) [35] did not state the number of components that the printed batch contained but mentioned that the energy consumed to produce 0.409 kg was 11 kWh, which translates to an EC of 26.89 kWh/kg. Baumers et al. [60] used an EOSINT M 270 to study the capacity impact in the energy consumption. This machine had a 200W laser and a build platform of 250 mm x 250 mm x 215 mm. They reported that building a single component had an EC of 339 MJ/kg (94.1 kWh/kg), while a full build of six components consumed 241 MJ/kg (66.94 kWh/kg).

The SLM 250, with a build volume of 250mm x 250 mm x 300 mm, was also studied by Baumers et al. [33] to compare the EC of SLM and EBM; the calculated value was 31 kWh/kg using a full build. A year later, Baumers et al. [60] included this machine in the study to contrast a single component build with a full build. The single component required 106 MJ/kg (29.44 kWh/kg) and a full build required 83 MJ/kg (23.05 kWh/kg). We note the high variance among the full builds EC in these studies. Both studies describe the same process parameter. Yet, Baumers et al. [60] stated they excluded power draw from the chiller in the SLM250 machine, which lowered the EC of the SLM machine. In order to fairly measure the SLM250 for our energy analysis, we cross-referenced disparate data from two studies by Baumers et al. [33] [60] to calculate the true EC. It was reported that the chillers used an external power source of approximately 0.6 kW [60]. Baumers et al. [33] affirmed chiller energy consumption was included in almost all the results, except for the mean real power consumed. Using this mean real power consumed kW (excluding chillers), the build time reported and the total energy consumed kW (including chillers) from Baumers et al. [33] and the EC kWh/kg (excluding chillers) from Baumers et al. [60], we recalculated the true EC. From our calculations a single component and a full build demanded 48.85 kWh/kg and 35.5 kWh/kg, respectively.

Table 3 presents the EC for the different machines from these studies. The significant difference between these EC values illustrates the need for future work to obtain more detailed energy consumption analyses in metals AM. Even when comparing the energy consumption for the same machines, different studies show disparate results. These are due to the difference in the unspecified 3D printing parameters, along with the different geometry and desired properties of the components. Identification of the variables affecting the EC of AM and how they affect the manufacturing is an open research area. We note that for our analysis, to use the reported data, same manufacturing conditions and process parameters are assumed.

Turning data was collected from two turning machines (lathes) in Table 4. The Doosan Machine PUMA 2500Y was used by Nyamekye et al. [58] to compare the energy consumption of AM and CM. This 4 axis CNC machine was able to perform 4 different operations such as turning, drilling, milling, and cutting. The total energy recorded was 3.24 MJ to reduce the 0.71 kg envelop to a 0.18 kg final component. Dividing the energy consumption by the scrap metal (input minus output) the resulting energy consumption was 6.11 MJ/kg (1.698 kWh/kg). Another machine, Anyang CKJ6163 with a Guangzhou CNC System was used by Zhao et al. [59]. They developed a prediction model for this machine with a 2.9% error rate according to the experimental results. Energy consumption and material volume removal data from the experiments were used to calculate the EC in KJ/mm³. Depending on process parameters such as depth of cut, feed rate, spindle speed and tool flank wear, the EC can vary from 0.23 kWh/kg to 2.75 kWh/kg for stainless steel 304, an order of magnitude difference.

Table 5 presents milling data from 5 different machines. Dahmus and Gutowski [61] utilized three of them to analyze the energy requirements for metal removal. The Production Machining Center (PMC) included auxiliary equipment systems such as lubricant and chip recovery systems that may require more energy than the machining operation [61]. The energy consumed per volume of material removed was 60 kJ/cm³ for steel. Using the density of the steel as 8050 kg/m³ and converting the J to kWh results in an EC of 2.07 kWh/kg. The other two machines that Dahmus and Gutowski [61] analyzed were automated milling machines: the 1998 Bridgeport and the 1988 Cincinnati Milacron. Like the PMC, these automated milling machines have auxiliary systems such as coolant pumps and tool changers, yet they lack the chip handling, computers, cutting fluid handling equipment and lubrication systems found with the PMC. Also, the automated milling machines were less capable than the PMC and consumed less energy. The EC for the 1998 Bridgeport was 0.34 kWh/kg and for the 1988 Cincinnati Milacron was 0.69 kWh/kg.

The next reported study used a micromachining center where Mori Seiki NV1500 DCG was used. Diaz et al. [62] measured the power and material removal rates for 1080 stainless-steel. The power demand was a total of 1567W, and the material removal rate was 44 mm³/second. This data can be used to calculate the energy per removal volume to be 35.61 J/mm³. Considering the material density of 7.86 g/cm³, the EC can be calculated to be 4.53 MJ/kg (1.258 kWh/kg).

Yu et al. [63] created a prediction model for the energy consumption of the VMC850 CNC machine with stainless steel 304 under varying process parameters. They generated a data set of 25 tests from milling experiments; the EC varied from 12.252 J/mm³ to 391.019 J/mm³ representing differences emanating from a broad range of milling parameters. We calculated the EC in the common units with a density of the stainless steel 304 of 7.85 kg/cm³; the EC values in kWh/kg ranged from 0.43 to 13.8 kWh/kg.

Following the manufacturing of single components, assembly is the next stage in the LCA. Butala and Mpofu [64] described an assembly

Subtractive Method	Machine	Material	SEC (kWh/kg)	Reference
Milling	Production Machining Center (PMC)	Steel	2.07	Dahmus et Gutowski (2004) [42]
Milling	1998 Bridgeport automated milling	Steel	0.34	Dahmus et Gutowski (2004) [42]
Milling	1988 Cincinnati Milacron	Steel	0.69	Dahmus et Gutowski (2004) [42]
Milling	Mori Seiki NV1500 DCG	1018 Steel	1.258	Diaz et al. (2011) [43]
Milling	VMC850 CNC machining center	Stainless steel AISI 304	0.43 -13.8	Yu et al. (2021) [44]

system as the integration of individual components into a product, final or semi-finished. The energy consumption studied for this stage pertained mostly to the automobile industry and used an empirical approach to calculate the energy used by the entire assembly plant; this included the energy for lighting the factory, heating, ventilation and air-conditioning, painting systems, compressed air, and welding [65-67].

We assume that the assembly plant for AM and CM would have the same energy consumption when the number of components and plant operations and processes are similar. Based on this premise, Assembly EC (EC_{ASSY}) does not have an influence on calculation for energy consumptions and α_{crit} between AM or CM.

The last phase of impact assessments comes from transportation phases. The transportation process appears whenever the material (feedstock material, components or final product) needs to move from one location to another. Eom et al. [68] provided different transportation modes from which data can be gathered: water, rail and road. We gather the EC reported for USA as representative for all the transportation scenarios, including international transportation. Routes in correspondence to our scenario are described in the next section.

Transport Mode	SEC (kWh/kg-km)	Reference
Truck	7.81E-04	Eom et al. (2012) [49]
Rail	7.96E-5	Eom et al. (2012) [49]
Water	1.29E-04	Eom et al. (2012) [49]

feedstock material, except when using the upper bounds of metrics. In what follows, we discuss the transportation and solid-to-envelope threshold α_{crit} in detail.

6 Experiment/ Results

The equations and comparison models were implemented in Python; with the data stored in excel sheets. Our results for the EDF manufacturing consumed less energy across the board for AM under the surveyed lower, median and upper EC values. Feedstock material costs were much higher in CM due to the amount of feedstock material needed to be machined compared to AM, while in AM production costs were much higher in processing the

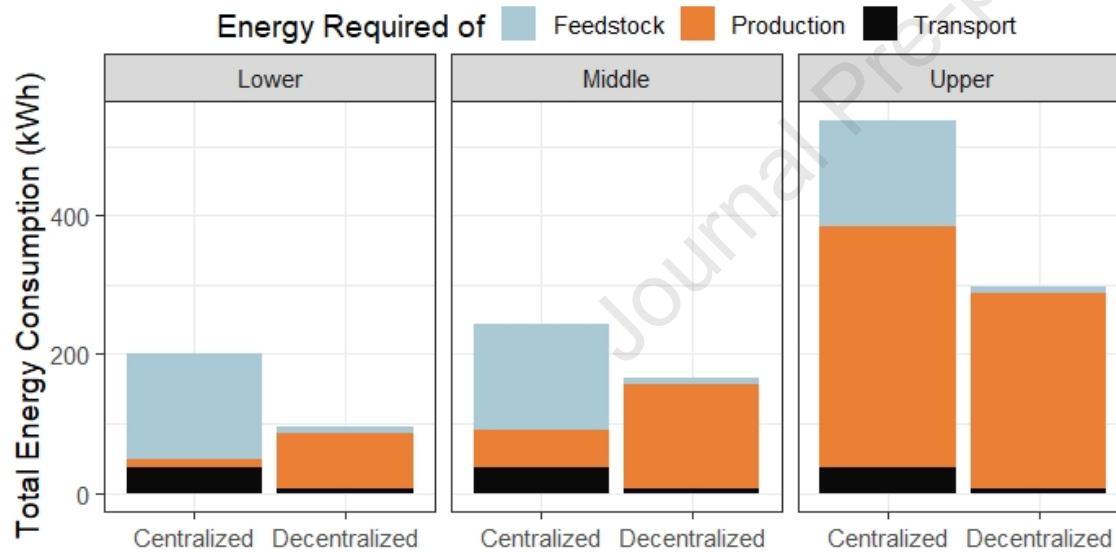


Figure 2. Direct comparisons using lower, median and upper production energy consumption values from the surveyed literature. Based on the energy values taken, the CM scenario (centralized assembly line) transportation costs showed a greater impact on the overall energy consumption ranging between 3-4.4 times that of the AM scenario (decentralized manufacturing and assembly lines).

At first sight the simulation results from Figure 2 show that, in the AM scenarios, transportation cost is minute compared to its overall energy consumption. In contrast, transportation presented a greater proportion in the CM scenarios induced by the two additional transportation steps per component (transportation of production to assembly line, and transportation of assembly line to the final consumer). Based on our illustrated distributed manufacturing scenario, the CM transportation costs were higher by a factor of 6.4 compared to AM for all three EC ranges. Because transportation costs do not change, between the lower, middle and upper EC metrics used in Figure 2, the CM scenario consumed 32.2 kWh in transportation costs while in AM it was 5.7 kWh. In terms of proportion of overall costs between the two systems, transportation's impact were 3 times higher in the CM scenario for the lower bounds by contributing 6.1% (5.8 kWh of 95.6 kWh) to the overall EC in AM and 18.4% (37.2 kWh of 202 kWh) in CM. In the middle EC range, CM's transportation impact was 4.4 times greater by contributing 15.2% to its overall EC (37.2 / 244 kWh) and only 3.5% (5.8 / 166.8 kWh) in AM. For the upper bounds, CM's transportation proportion was 3.4 times higher at 2.1% (5.8 / 281.3 kWh) compared to 6.9% (37.2 / 536.8 kWh) of the total EC. This proportionality remains as the number of clients grow, with the difference in transportation growing linearly. If the ratio of transportation costs grew in relation to the overall system's energy consumption impact, then that difference would increase exponentially which our study does not show. Instead, as will be discussed in the following section, we examine the difference in transportation impact by the number of components manufactured per iteration of distribution when multiple clients are involved.

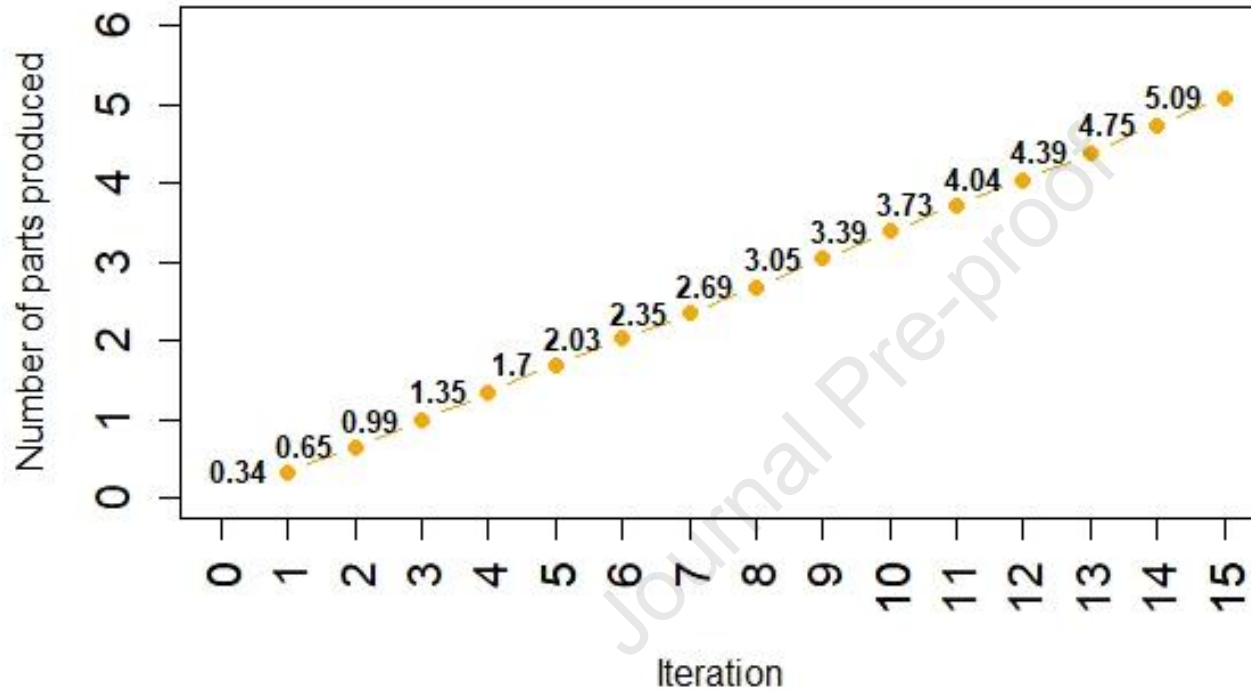


Figure 3. Number of parts accumulated in AM equal to the carbon impact of transportation (per production of an electric ducted fan) in the CM distributed supply chain. After being produced at each of their distinct locations, the complexity and carbon footprint of the CM supply chain increases due to many components need to be transported (for assembly and then delivery to final consumer). The increase is measured by the energy consumption equal to the number of components made in AM (on the y-axis) per iteration of a single CM part. After three CM iterations, the energy consumption from solely transportation logistics accumulated to equal about one (.99) part compared to AM's simplified supply-chain.

6.1 Transportation Results

Based on our analysis, the comparison for one component makes it difficult to analyze the distributed manufacturing setting since transportation does not reveal its cumulated impact until product shipment reaches multiple clients. Though we found that the proportional impact of transportation to the whole CM scenario did not increase when the number of components and/or clients increased, we quantified the impact in terms of the number of parts cumulated from the carbon footprint savings of the AM scenario over the CM scenario. While all AM components can be manufactured, assembled, and delivered at a single location, the CM components incur extra energy costs for transporting the components for assembly and delivery. Figure 3 shows the number of parts accumulated equal to the extra energy costs from the CM supply-chain's transportation logistics. In addition to our first client in Las Cruces, New Mexico, we added four additional clients located in the United States with distances ranging from 600-2800 miles; in San Francisco, CA, Chicago, IL, Miami, FL, and Twin Falls, ID. Additionally, we increased the demand per client to three EDF's which translates to 15 iterations of our LCA (five client locations requesting three parts each). Illustrated in Figure 3, the difference in total CM and AM transportation costs ($CM_{Transport} - AM_{Transport}$) is divided by the total energy consumption of AM to produce the component ($ECAM_{Total}$). This gives the additional number of components that can be built with AM if AM is chosen in place of CM. We found that after the 15th iteration, the difference in transportation cost resulted in an accreted energy consumption equal to approximately five EDF's in the AM scenario. The transportation proportion of the AM system ranged from 3.83-6.05% between each of the iterations while in CM it ranged from 17.61-18.40%. This results in a CM transportation proportion of about 3.0-4.5 times higher than its AM counterpart in the decentralized distributed scenario between each iteration. Despite the greater proportion of transportation consumption in the CM, we found that the proportion of transportation impact in relation to the whole CM scenario did not increase when the number of components and/or clients increased. The linear results are the same when the same analysis is applied to all other energy impact analysis including feedstock and production energy consumptions—leading to the conclusion that neither of the three energy impacts, including transportation, would outgrow another as the number of clients and/or components increased. In what follows, we examine α_{crit} and how it is affected with and without transportation.

6.2 Alpha Critical Threshold Analysis

Table 7. Alpha Critical Thresholds for Each Bounds			
Part name	α_{crit} , Lower EC (kWh/kg) from CM, and AM machines.	α_{crit} , Median EC (kWh/kg) from CM, and AM machines.	α_{crit} , Upper EC (kWh/kg) from CM, and AM machines.
Double Fan,	$\alpha_{crit} = 0.1852$ 0.43 (VMC850 low power) 35.5 (SLM 250)	$\alpha_{crit} = 0.1213$ 2.07 (PMC) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.1528$ 13.8 (VMC850 high power) 117.5 (Laser M3 Linear)
Bottom Housing	$\alpha_{crit} = 0.1744$ 0.43 (VMC850 low power) 35.5 (SLM 250)	$\alpha_{crit} = 0.1172$ 2.07 (PMC) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.1501$ 13.8 (VMC850 high power) 117.5 (Laser M3 Linear)
Top Housing	$\alpha_{crit} = 0.1744$ 0.43 (VMC850 low power) 35.5 (SLM 250)	$\alpha_{crit} = 0.1172$ 2.07 (PMC) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.1501$ 13.8 (VMC850 high power) 117.5 (Laser M3 Linear)
Main Shaft	$\alpha_{crit} = 0.2186$ 0.23 (Anyang CKJ6163) 35.5 (SLM 250)	$\alpha_{crit} = 0.1381$ 1.69 (Doosan PUMA) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.0873$ 2.75 (CKJ6163 high power) 117.5 (Laser M3 Linear)
Nose Cone	$\alpha_{crit} = 0.2186$ 0.23 (Anyang CKJ6163) 35.5 (SLM 250)	$\alpha_{crit} = 0.1381$ 1.69 (Doosan PUMA) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.0873$ 2.75 (CKJ6163 high power) 117.5 (Laser M3 Linear)
Spacer	$\alpha_{crit} = 0.185196$ 0.43 (VMC850 low power) 35.5 (SLM 250)	$\alpha_{crit} = 0.1213$ 2.07 (PMC) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.1528$ 13.8 (VMC850 high power) 117.5 (Laser M3 Linear)
Warhead Fan Motor	$\alpha_{crit} = 0.1852$ 0.43 (VMC850 low power) 35.5 (SLM 250)	$\alpha_{crit} = 0.1213$ 2.07 (PMC) 66.94 (EOSINT M270)	$\alpha_{crit} = 0.1528$ 13.8 (VMC850 high power) 117.5 (Laser M3 Linear)

As illustrated in Table 7, each component's α_{crit} value for lower, median, and upper bounds were calculated with metrics coming from the different listed machines. Based on the different manufacturing energy consumption metrics assumed for each bound, there is a significant variance in α_{crit} between the bounds. In the lower bound scenarios, α_{crit} is .174-.219 for the median, .117-.138, and for the upper, .087-.153. This indicates that prior LCA studies comparing the lower EC metrics between AM and CM would result in a greater α_{crit} threshold and hence more likely conclude AM as the better production method for lowering carbon impact. Between the three bounds of energy consumption, the turning method displayed the largest range in α_{crit} between .087 to .219. Figure 4 orders our scenario's

components in descending α values to depict each components' individual energy impact. Noticed in Figure 4 for the components manufactured by turning machines, we see that even when the Nose Cone and Main Shaft components carry a low α , its finished components still required less energy than AM machines. This is due to their respective α values (.155 and .112) to be greater than the .087 allowance indicated by α_{crit} in the turning method for the upper bound scenarios. However, the results would be different in the lower bound scenarios where α_{crit} is .219. Though most of the components performed better in the CM scenarios, the overall analysis shown in Figure 2 still proved AM to be better since the Bottom Housing and Top Housing were the largest components requiring the greatest specific energy consumption while also being the most AM efficient component.

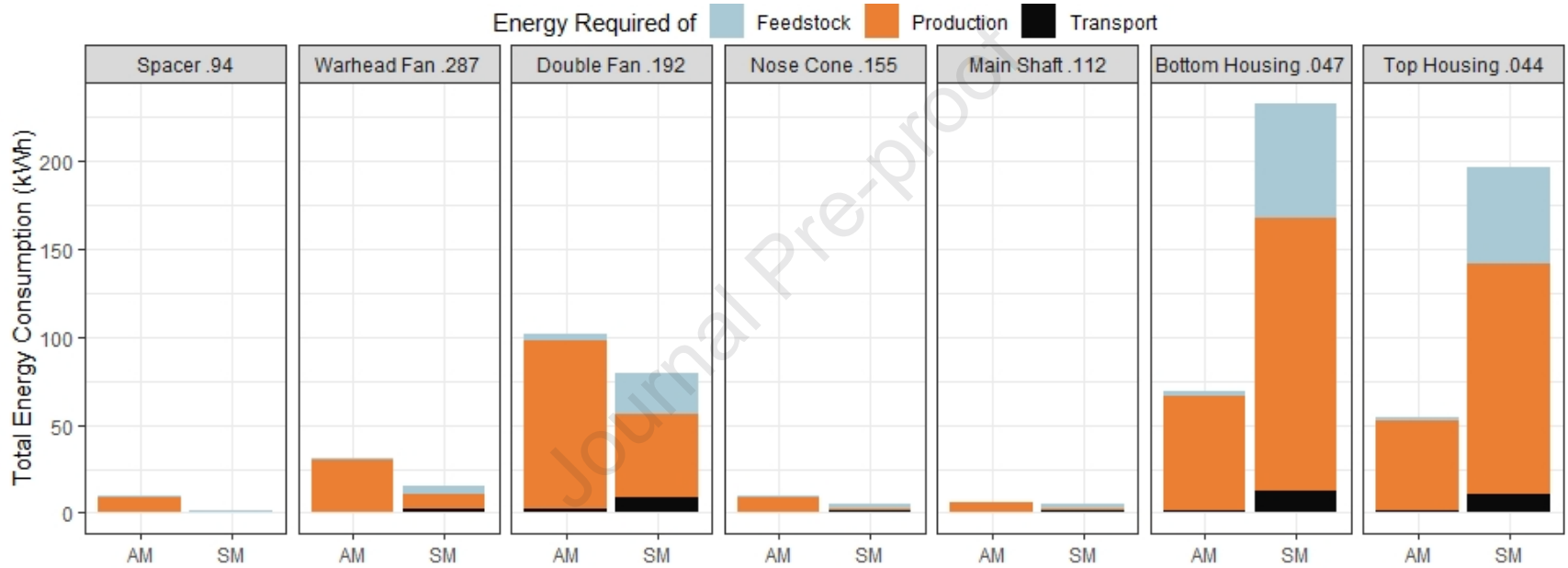


Figure 4 displays the facets of each component in descending order of α to illustrate its effect on the performance of the comparisons. The nose cone and main shaft were manufactured using the turning method while all others used the milling method in the CM scenario.

In Figure 5 we plot α_{crit} for the spacer component, since it is the component that can be redesigned to reduce volume of the component without modifying the volume of the envelope, generating different values of α . Its CM system is milling and upper bound metrics are used for SECs. From here we can study the relationship between the transportation cost and α_{crit} by plotting the energy consumption as a function of α . According to the figure, α_{crit} is the point where the AM and CM energy consumption curves for one specific scenario, intersect. As shown in Figure 5, we see when transportations steps are included (bringing the manufactured components to the assembly

lines and from the assembly lines to the final consumer in the CM scenario), the α_{crit} cross-over point happens at higher values (indicated by the intersection of yellow lines). The analysis suggests that as conventional supply-chains get lengthier and collaborative, the additional transportation steps would make components manufactured with an AM supply-chain more likely to be more energy efficient.

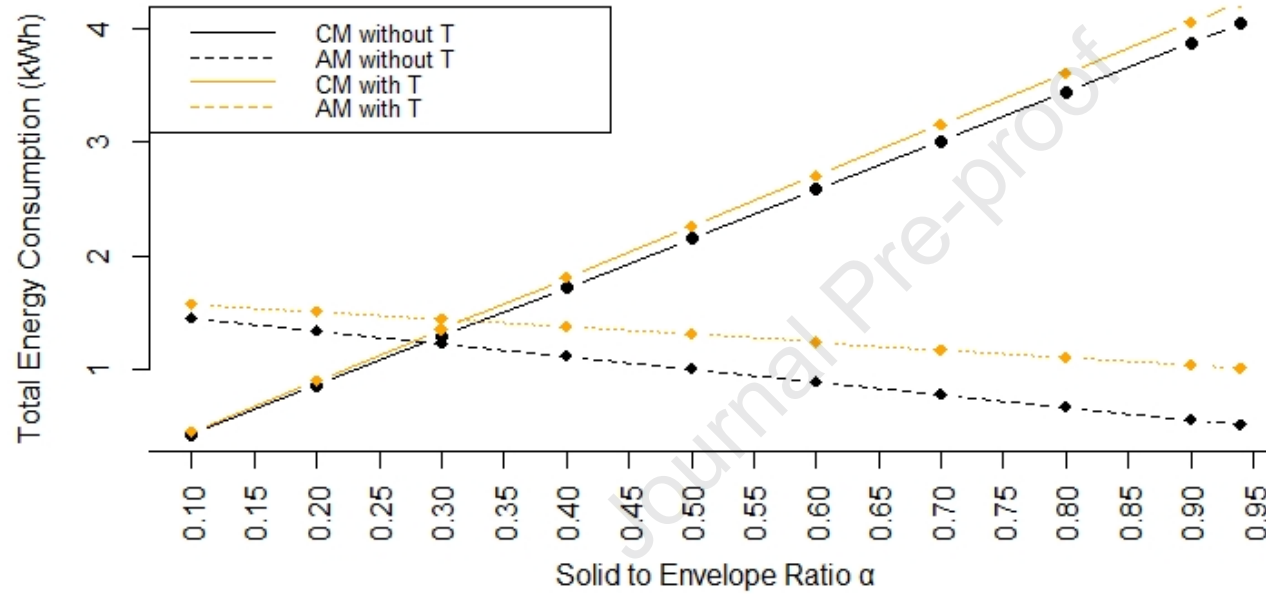


Figure 5 plots the energy consumption as the solid-to-envelope ratio α increases. With and without transportation costs, the cross-over points (α_{crit}) are indicated by the crossings of the black and yellow lines (respectively). As shown, when transportation costs are included, the additional transportation costs in the CM supply chain result in a higher α_{crit} value.

7 Discussions and Conclusions

In this paper, we conducted a cradle-to-gate partial LCA comparing AM and CM in a distributed supply chain setting. Our study did not consider the use phase, topological optimizations, or assumed the part's application in transportation, instead only focusing on energy

consumption. Despite these assumptions, our research explores the potential paradigm shift of the AM supply chain, potentially replacing conventional methods for stainless steel parts in the distributed manufacturing scenario. By clarifying relevant terminologies and their application in related works, we pave the way for future analyses on various supply-chain impacts. This work represents an initial step in a novel framework that accounts for transportation in distributed manufacturing. Our analysis revealed a linear relationship between transportation costs and locations/components manufacturing. If the transportation costs increase super linearly, the significance of transportation in the centralized manufacturing scenario for CM would escalate more rapidly than the contributions of feedstock and manufacturing to the overall carbon footprint. Such scenarios may be noticed when individual manufacturing locations also increase the logistical complexity of the supply chain with other collaborating enterprises. While the proportion of transportation energy consumption did not grow significantly in our distributed manufacturing scenario for both AM and CM, the additional steps to distribute the components for assembly may still end up being significant when considering the economic cost or carbon footprint of transportation.

However, the additional transportation steps incurred from the gathering of CM's distributed components still accounted for about 33% of the overall energy costs in the AM scenario. This is significant, as with the total energy needed to transport three CM parts, one extra AM part can be built at the destination (ref. Figure 3). Transportation metrics in this study were also conservative without considering volume parameters which may often account for higher transportation costs. These conservative measurements could be replaced with the more realistic DHL Carbon Calculator [11] to see the exact effect of transportation costs in the distributed supply chain when volume is considered. Significant distances in complex supply chains have the potential to further increase α_{crit} , indicating that transportation costs not considered in previous energy studies could result in a significant energy undercount. For future work, quantifications of supply-chain structures where transportation steps increase super linearly could be analyzed, such as from the use of complex multiple-assembly lines that interact by sending the parts back and forth through different geographical locations—our study will serve as an important starting point for those real-world studies.

Further, if AM components go through a component redesign to maximize the productivity of this new technology (Section 3), then AM manufacturing can have an even smaller energy footprint. Outside of the design and “topology optimization” of AM components [44, 68-70], perhaps what is most positive on the outlook for AM is that it is still a nascent and developing technology where improvements are underway as noted in multiple studies [9, 24, 36]. Current research efforts are focused on developing efficient AM processes [71]. IoT frameworks are currently underway to collect real-time raw data from AM systems, combining material attributes, machine parameters, and design information for big-data processing [71]. We foresee these as important contributors in the future.

For future studies, supply chain comparisons considering supply chain design elements such as capacity utilization, location of facilities, inventory to meet demand, lead time, and transportation frequency [72] could all be used as parameters for more detailed and organization-specific analyses. Additionally, empirical studies for each of the industry specific assembly metrics are an open research gap. This is needed to analyze the reduction in energy impact with AM in comparison to CM. If assembly metrics could be quantified,

then additional statements could be made to compare the EC of conventionally assembled products with AM non-assembly products. Furthermore, metrics for metal AM energy consumption should be studied as it has been more than decade since the last in-depth quantification on metals AM machines. There is also need for studies to explore the DMS scenario from the context of sustainability. We intend to explore the concept of the triple bottom line (TBL) in the context of AM sustainability assessments. TBL is a framework, first acknowledged in a most recent survey of AM LCAs by S. Kokare et al. [15], that evaluates the economic, social, and environmental performance of a process or system. With the adoption of AM, we can create parts that are highly optimized and may conserve energy and material resources. However, more analyses are needed in considering this technology as a sustainable method of manufacturing using novel technologies from industry 4.0. For example, there could be pitfalls for the over-use of AI to automate processes, such as topological optimization, resource allocation, etc., in DMS scenarios. The use of the innovations in Industry 4.0 needs to be considered and assessed in the holistic context of sustainability.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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