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Unveiling the Environmental and Economic Implications of Additive Manufacturing on Inbound Transportation

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Abstract: This study aims to investigate the impact of additive manufacturing (AM) on the sustainability of inbound transportation. By combining insights from existing literature and interviews with professionals in the additive manufacturing field, we present a comprehensive analysis of this subject. Drawing upon both literature review and interview perspectives, it is evident that AM significantly influences the sustainable dimension of transportation. A key attribute of additive manufacturing is its inherent efficiency, resulting in minimized waste generation during production. This stands in contrast to traditional manufacturing methods, which involve material reduction to achieve desired shapes. The streamlined process of additive manufacturing requires fewer raw materials, thereby reducing environmental impact. The transportability of filament powder in bulk form further contributes to these sustainability gains, reducing material volume and transportation frequency. Consequently, emissions associated with additive manufacturing-related transportation are lowered. Recycling of materials is also structured within a broader framework, deviating from the conventional model of product returns to manufacturers. Despite its potential, our empirical findings suggest that the adoption of additive manufacturing doesn't consistently lead to cost reduction compared to conventional methods. The applicability of additive manufacturing remains limited to specific product ranges. Nevertheless, cost savings can occur in the realm of inbound transportation due to factors such as reduced transportation frequency and the transport-friendly nature of raw material containers. Furthermore, the efficiency of raw material usage in additive manufacturing contributes to economic benefits. Unlike conventional manufacturing, additive processes don't require extensive raw material inventories. Economic considerations extend to the adoption of distributed manufacturing systems. While centralized systems minimize raw material transportation, they may increase transportation distance for the final products. Conversely, distributed systems increase raw material travel but decrease product transportation distance. The study underscores that while distributed manufacturing offers advantages, it impacts transportation costs. In essence, this study sheds light on the complex interplay between additive manufacturing and inbound transportation sustainability. It underscores how additive manufacturing's inherent efficiencies and material characteristics have ramifications for environmental and economic dimensions. Through a blend of theoretical insights and empirical evidence, this research contributes to the broader discourse on sustainable manufacturing practices.

Keywords: Additive manufacturing, inbound transportation, sustainability, environmental impact, transportation frequency

1. Introduction

Significant transformations are occurring in the manufacturing industry's production and delivery methods, owing to emerging changes. This evolution, known as Industry 4.0, is poised to reshape the manufacturing landscape through

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the adoption of digitalization. Industry 4.0 leverages advanced technologies to streamline processes, enhance flexibility, expedite production, new transportation modes, and reduce costs, representing a paradigm shift [1-3]. This concept revolves around integrating cutting-edge technologies into manufacturing, leading to more efficient operations, improved quality, and lowered costs. This research specifically delves into additive manufacturing (AM), commonly referred to as three-dimensional printing (3DP), within the context of this transformative framework. As contemporary society grows increasingly conscious of sustainability issues, businesses are developing a broader understanding of its significance. This prompts them to invest in novel technologies, driven by the realization that both industries and consumers prioritize sustainability when making product choices. AM is an emerging production technology widely regarded as more sustainable than conventional manufacturing methods. This perception stems from its capacity to recycle materials and products, enhance energy efficiency, reduce waste and material consumption. Consequently, manufacturing enterprises can wield this emergent technology to influence their ecological, societal, and economic footprint, thus advancing their overall sustainability. The impact of additive manufacturing on logistics sustainability has been investigated through various avenues. These include the exploration of greener logistics and supply chain practices [4], and the juxtaposition of the sustainability profiles of additive manufacturing and conventional production methods [5]. While extensive work conducted in the past decade to analyze AM's ecological influence on transportation, a scarcity of studies that specifically examine its sustainable impact on transportation still remains.

Existing literature suggests that additive manufacturing (AM) may influence transportation through factors such as production location, intermediary steps in the supply chain, and the optimization of transport capacity. However, there remains a research gap regarding the specific sustainability implications of AM on transportation. Transportation plays a vital role in sustainability due to its significant contribution to global carbon dioxide emissions and other factors [6]. Hence, this investigation aims to delve into the influence of AM on the sustainability of transportation. The scope of logistics under examination is restricted to a specific type of transportation, as it is more susceptible to AM's impact as opposed to its outbound counterpart. This is attributable to AM's capacity for reshaping the production network. Additive manufacturing holds the potential to substantially transform the manufacturing landscape, potentially sparking a new industrial revolution. It represents an innovative manufacturing technique that offers viable solutions in wide variety of industries, such that its current utilization is evident. In the conventional global manufacturing paradigm, semi-finished components are consolidated at assembly points before being dispatched along the supply chain. However, with additive manufacturing's capacity to produce items in close proximity to end consumers, this traditional model could render manufacturers redundant. Nonetheless, this shift towards production decentralization may not align optimally with sustainability objectives.

Additive manufacturing's ramifications on transportation remain substantial, primarily for transporting products employed in the AM. Transportation of finished goods is essentially limited to the movement from manufacturer to consumer. Remarkable changes, particularly concerning the pre-additive manufacturing transportation phase, are anticipated when contrasted with traditional production methods, one of which is the significantly abbreviated production timeline. As such, additive manufacturing has the potential to confer substantial sustainability advantages, particularly through the domain of unprocessed product transportation that transpires before the final product's production. Prominent manufacturers in the realm of 3D printing offer solutions tailored for various industries. Within the dental field, the production of aligners with exceptional precision and reduced delivery times is made possible through on-site 3D printing. Furthermore, its utilization extends to training, education, and the creation of artificial human body parts. These instances collectively underscore the increasing and evolving role of additive manufacturing across these sectors.

What goes unmentioned in the discourse of these companies are the potential sustainability advantages that additive manufacturing brings to the table. Amid escalating concerns surrounding carbon dioxide emissions and the consequent surge in record-breaking temperatures, coupled with the growing scrutiny of manufacturing's societal impact and economic incentives, the allure of additive manufacturing's sustainability benefits should not escape companies with a sustainability agenda. Additive manufacturing is regarded as an ecologically conscious manufacturing technology with respect to carbon emissions. Beyond cost reductions and energy conservation, this manufacturing approach holds the promise of curtailing carbon dioxide emissions. With an expanding array of companies embracing it, the cumulative impact will also amplify. While it's not anticipated to supplant mass production, the repercussions of additive manufacturing could indeed reverberate within the supply chains where it's employed. It becomes imperative for companies to grasp how additive manufacturing can pave the way for sustainability gains within their purview. Companies are progressively embracing 3D printing as a viable solution. Given the sustainability advantages it offers, comprehending the implications of this manufacturing technology on transportation becomes pivotal for gauging its impacts and maximizing potential sustainability dividends.

2. Literature Review

Over time, rapid prototyping evolved into additive manufacturing, which centers around the incremental layer-wise construction of products—marking a departure from traditional manufacturing methods that entail material removal to achieve form [7]. This transition brings about a range of advantages for products, including reduced weight, the incorporation of multiple materials, ergonomic design, and the optional integration of mechanisms. These advantages are harnessed through the enhanced complexity of shapes facilitated by additive manufacturing, enabling the production of both homogeneous and heterogeneous products through the same technology [8]. Consequently, variety of industries can leverage additive manufacturing to fabricate prototypes, models, parts, and end products. Certain sectors, like jewelry and toys, are exploring the application of additive manufacturing for their specific contexts [9]. However, while decentralized manufacturing reduces transportation requirements, the energy-intensive nature of additive manufacturing offsets some of these gains [10]. The ensuing sections of this literature review will delve deeper into the transportation aspect within the context of additive manufacturing. The decision of whether to involve in AM hinges on the adopting corporation's circumstances [11].

Additive manufacturing brings forth a multitude of benefits; nonetheless, it also confronts a range of challenges. These hurdles encompass several aspects, including engineers' insufficient familiarity with additive manufacturing, the absence of comprehensive regulatory frameworks and certification protocols for the technology, the technology's limited reliability, hurdles in harmonizing it with existing systems, as well as complexities in recycling materials for specific products [11]. [12] presents a broader perspective on these challenges, introducing reasons spanning variety of domains.

Additive manufacturing is poised to induce a transformation in transportation dynamics. Chief among its effects is the potential to relocate production sites in closer proximity to end-users, driven by the decentralization of manufacturing operations [13]. This decentralization offers ancillary advantages such as the potential to bypass intermediaries in the supply chain, and the prospect of reshoring production to high-wage nations [14, 15]. However, it's worth noting that centralized production systems can maximize transport capacity utilization, leading to reduced transportation costs [16]. Nonetheless, research has demonstrated that a clear preference between centralized and decentralized systems doesn't emerge when the sustainability perspective is taken into account [17]. [18] argues for a hybrid approach, considering the feasibility of securing profitability. The emergence of city-level hubs is a likely scenario, as they can adeptly manage material flows and possess requisite expertise [19]. Furthermore, additive manufacturing will curtail the necessity for extensive distribution and inventory management [20]. Unlike the semi-finished products typical of conventional manufacturing, additive manufacturing facilitates the bulk transport of input materials, such as raw materials, with minimal packaging requirements [21]. Apart from these aspects, [22] highlights that experts opine that additive manufacturing is unlikely to significantly impact delivery times, the development of transportation technologies, or traffic safety. Differing viewpoints are evident regarding the potential increase in transport volumes and the ensuing environmental consequences.

Additive manufacturing has ushered in a technological wave that has rippled across the manufacturing landscape, triggering multifaceted changes. As previously elucidated, it has the potential to prompt the decentralization of production, thus drawing manufacturing operations closer to end-users. This transformation also carries implications such as circumventing intermediaries, optimizing logistic capability utilization. While existing study has delved into the ramifications of additive manufacturing on transportation, it predominantly scrutinizes the journey between manufacturing entities and end-consumers or distributors, often neglecting a comprehensive exploration of sustainability.

Capitalizing on the sustainability paradigm often associated with additive manufacturing, we adopt a methodology akin to that of [23] to dissect its sustainability implications. This approach encompasses environmental, societal, and economic dimensions. In alignment with this methodology, we constructed a conceptual model, as depicted in Figure 1, that presents our research questions. Notably, our focus lies on IT interlinking suppliers and AM establishments. Evidently, preceding research underscores that AM inevitably alters IT dynamics within these units to a certain degree, aligning with the technology's broader impact on supply chain transportation. The research questions outlined therein encapsulate our endeavor to pinpoint the effects of AM on IT, anchored within the various sustainability facets.

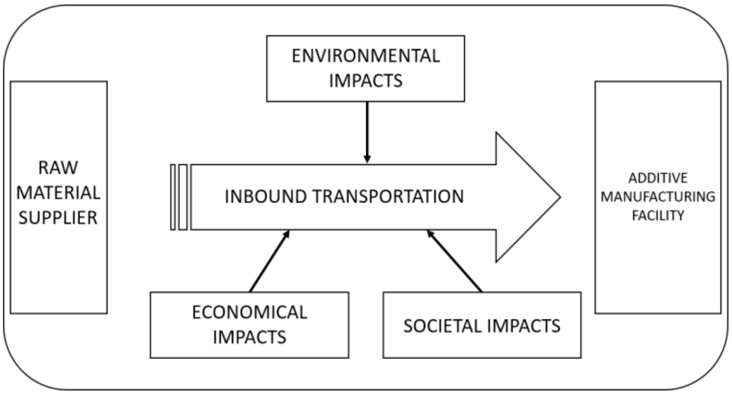

Fig. 1 – Sustainability paradigm

3. Methodology

3.1 Research Strategy and Design Framework

The research philosophy encompasses the foundational beliefs and premises that dictate the manner in which data pertaining to a situation's outcomes should be gathered, analyzed, and harnessed for research development. This philosophy is intrinsically linked to the origin, essence, and evolution of knowledge. Establishing a coherent, meticulously structured, and scientifically substantiated research study hinges on formulating fundamental presumptions about the research philosophy at the study's inception. The discourse encompassing research philosophy predominantly orbits around ontology and epistemology.

Within the realm of philosophical conjectures concerning the essence of reality, this study aligns itself with the ontology of relativism. This ontological stance underscores the supposition that multiple "truths" are contingent upon the observer's standpoint, temporal context, and spatial location. It is postulated that the vantage point and convictions of an observer, alongside varying companies utilizing additive manufacturing, bestow distinct shades to the perspective on sustainability and its impact. Similarly, the outlook regarding the way AM reshaping production facilities diverges within stakeholders. Consequently, the sustainability ramifications of AM are intrinsically linked to the observer's standpoint, encompassing both the outlook of participants and companies leveraging additive manufacturing. This view holds true within a specific milieu, during a designated timeframe.

In the pursuit of comprehending and operationalizing knowledge within both the tangible and societal realms, an epistemological standpoint is adopted. This endeavor aligns with the epistemology of social constructionism, a perspective founded on the premise that reality is forged through meticulous observation, with the observer constituting an integral part of the observed reality. This approach places emphasis on the manner in which individuals perceive their experiences, positing that reality is not a product of external objects, but rather a creation of human cognition. Given the objective of scrutinizing the influence of AM on the sustainability of IT, the present research adheres to the epistemological lens of social constructionism.

The crux of social constructionism lies in the notion that the researcher is an inherent constituent of the observed phenomenon. To this end, a multifaceted approach integrating a comprehensive literature review and qualitative data, in the form of interviews, is embraced. The purpose of this methodology is twofold: firstly, to cultivate a foundational comprehension of additive manufacturing and its ramifications for sustainability through scholarly discourse, and secondly, to amalgamate this foundational understanding with insights garnered from a select number of strategically chosen cases. These cases encapsulate stakeholder perspectives and are instrumental in facilitating a comparative analysis, thus paving the way for the formulation of a comprehensive theory that delineates the effect of AM on the sustainability of IT.

The process of theory development encompasses three distinct approaches: deductive, inductive, and abductive. Within the framework of this study, an inductive approach is embraced, characterized by the formulation of an original conceptual framework derived from pertinent scholarly literature, wherein a discernible area lacking in previous studies has been highlighted. The platform subsequently undergoes empirical validation and evaluation through insights gleaned from a limited pool of interview responses. In the realm of the inductive approach, the underlying assumption is that the empirical findings will fortify the connection between observed premises and eventual conclusions. Essentially, the process commences with meticulous observation, whereby theories are progressively cultivated and postulated in light of the gathered empirical evidence. These observations, deemed as substantiating evidence, eventually converge to affirm the veracity of the final conclusions.

The focal objective of the present work is to delve into the ramifications of AM on the sustainability of IT. This exploration is underpinned by qualitative empirical data ascertained through interviews. To establish a theoretical underpinning, a comprehensive literature review is undertaken to dissect the sustainability implications of additive manufacturing. The outcome of this review paves the way for the creation of a conceptual framework that addresses the identified research void and aligns with the overarching purpose. The research design serves as the blueprint that delineates and rationalizes the data collection, analysis, and interpretation strategies employed to address the research inquiries. The selection of the optimal research method hinges on a host of factors, including prior methodological choices and the prevailing epistemological stance. Additionally, a distinction exists not only in terms of epistemology but also in the researcher's level of involvement or detachment from the research subjects.

Given our alignment with the epistemological framework of social constructionism, as previously discussed, the decision to adopt an involved or detached research style necessitated consideration. Our approach aimed to strike a balance, as we aimed to identify and delineate impacts by conducting a series of interviews across various companies. Through these interviews, we sought to investigate how the integration of AM influenced the sustainability of IT within their unique contexts. To ensure the validity of our findings, it was imperative to not only gather information about the company's operational environment but also maintain objectivity in our analysis. As such, our research style encompassed elements of both detached and involved methodologies. In the landscape of case study methods, distinct approaches are discernible based on the epistemological foundations of positivism or constructionism. The positivist case study adheres to a predefined structure, wherein data analysis transpires across multiple cases to ensure rigor and validity. On the contrary, the constructionist case study places less emphasis on validity concerns, as the data analysis is primarily conducted within the boundaries of each individual case. An intermediate approach, harmonizing aspects of both positivist and constructionist epistemologies, emerges as a flexible research design that encompasses both cross-case and within-case analyses. This hybrid approach facilitates cross-case exploration while upholding the essence of a constructionist perspective, making it particularly suitable for our research objectives. Hence, the present study adopts a multiple case study methodology, involving the collection and analysis of data from several sources. Aligned with the tenets of constructionism, our chosen methodology recognizes that interviewees, serving as representatives of individual cases, may harbor divergent viewpoints on the impacts due to the distinct organizational contexts they operate within. Several example models enable us to build a nuanced understanding through various situations and to derive outcomes that offer insights into the degree of generalizability, bolstered by our meticulous attention to the contextual nuances that characterize each interviewee's setting.

3.2 Information Procurement

Primary data encompasses information that researchers gather directly from original sources, utilizing methods like surveys, observations, experiments, or interviews. This type of data is specifically collected for a particular investigation, acquired firsthand to involve their insights and generate experimental information. In our pursuit of primary data, we conducted interviews with individuals closely connected to transportation aspects within companies that incorporate additive manufacturing for production. To be more precise, we employed partially organized systematical discussions as our data collection method. This choice was congruent with our research design, as it allowed us to comprehend the contextual background of the interviewee. Semi-structured interviews offer participants greater latitude to introduce specific topics, as opposed to highly structured interviews. Given that our research aims to explore and discover, the semi-structured approach was apt. On the other hand, an unstructured interview format might divert discussions away from the targeted impacts we sought to investigate, rendering it less suitable for our purposes.

Considering the limited adoption of additive manufacturing within companies, our study's population remained constrained. Moreover, our research focused on a specific dimension within these companies—transportation. While locating companies that had embraced additive manufacturing was achievable through search engines, we also utilized snowball sampling to extend our pool of interviewees within the same organization. This approach facilitated a more comprehensive grasp of the company's context by allowing us to compare responses within the same entity and discern potential variations in perspectives. In our commitment to preserving the privacy of interviewees, we provided them with a statement outlining how the interview data would be treated before the commencement of the interview process.

3.3 Participant Identification

Given the aim of the present work to investigate the influence of AM on the sustainability of IT, our focus is on engaging experienced professionals closely associated with transportation within an additive manufacturing supply chain. Specifically, we sought out interviewees whose roles were intricately tied to inbound transportation within the context of AM. The proposed study views IT from the point of view of facilities utilizing additive manufacturing for production. It is important to emphasize that this perspective encompasses both product suppliers and manufacturers employing AM. Acquiring insights into how additive manufacturing impacts this material flow from these suppliers was crucial. Moreover, we gathered empirical data from workers at facilities incorporating AM in manufacturing processes. This allowed us to obtain firsthand accounts of how inbound transportation is directly affected by additive manufacturing. Given the relatively nascent adoption of additive manufacturing in the German market, the pool of potential interviewees was limited. Therefore, our sample was intentionally composed of both major German factories that have integrated AM as a component of their operations, as well as smaller and medium-sized German companies solely focused on additive manufacturing.

To initiate contact, selected companies or individuals of interest were contacted via email, providing an overview of the research topic and interview guidelines. In instances of no response in a week, another follow-up message was sent to gauge interest. Ultimately, we successfully secured participation from six interviewees utilizing AM. Utilizing snowball extracting, an additional interviewee was also included, extending from the primary interviewees as shown in Table 1.

Table 1 – Details of the experimentation

Attendee	Duty	Position	AM Exp.	Dialogue Info	Dialogue Type
Participant 1	Mnf. 1	Dept. Head	2 years	51 minutes	Google Meet
Participant 2	Spl. 1	Manager	5 years	33 minutes	Phone
Participant 3	Spl. 2	Manager	6 years	27 minutes	Phone
Participant 4	Mnf. 2	Resp. Engineer	3 years	76 minutes	Google Meet
Participant 5	Mnf. 3	Coordinator	8 years	41 minutes	Google Meet
Participant 6	Spl. 3	Manager	4 years	44 minutes	Google Meet
Participant 7	Mnf. 4	Manager	3 years	57 minutes	Google Meet

4. Results and Discussion

Additive manufacturing holds significant potential to exhibit greater environmental friendliness compared to conventional manufacturing processes, as it generates fewer harmful emissions into the environment. Our study's interviewees pointed out that the reduced emissions were closely linked to the streamlined nature of AM, involving less production phases that contribute to decreased exhaust activities. Manufacturer 4 noted that the decreased production phases also curtail emissions stemming due to logistic because of diminishing requirement for transporting various raw materials from different suppliers, as fewer types of materials are required for each outcome. Second manufacturer emphasized impurities are substantially reduced due to the reliance on electrical power for machine operation, eliminating the use of oil or coal and thus mitigating harmful pollution.

As supported by literature within our frame of reference [24, 25], AM yields to a significant decrement in wastes during the production of end products, ranging from 67% to even 93%. The empirical findings mirror these outcomes. Manufacturer 2 highlighted 71-85% of discarded outputs are possibly minimized, while the first one indicated a similar reduction, albeit ranging from around 87-92%, contingent upon the specific product being manufactured. This variance is attributed to the manufacturing process itself. The gradual AM method proves highly effective in comparison to traditional processes that involve material removal, leading to minimal waste material when additive manufacturing is employed.

Moreover, not only does additive manufacturing minimize waste generation in the production process, but it also exhibits high rates of material reuse and recycling. Literature discusses this phenomenon in the context of a Closed Loop Supply Chain (CLSC), wherein the forward and reverse supply chains between raw material suppliers, manufacturers, and end consumers are integrated into a network [26, 27]. However, our study's companies operate differently. In the context of manufacturing, none of the companies received or sent return flows from/to end consumers or raw material suppliers. Facilities employing additive manufacturing establish internal CLSCs. Instead of sending back waste or residual powder to suppliers, the powder is remixed with new powder for subsequent use. This approach creates an internal loop, virtually eliminating material waste in the manufacturing process. This internal recycling mechanism negates the necessity for the return transportation of raw materials to suppliers.

Unlike what literature describes in terms of return flows of leftover products or scrap from end consumers to raw material suppliers [28], these companies are part of a broader Closed Loop Supply Chain (CLSC) scheme. The raw material suppliers in our study engage in a form of recycling on a larger scale within this CLSC. They acquire residue components to manufacture fresh powder as resources into AM processes. Therefore, even though they don't receive return flows from manufacturers or end consumers, they do recycle waste material to create new powder. For instance, the second supplier reveals the composition consists of 90% residue and 10% waste elements, on the other hand, other suppliers primarily utilize scrap as their powder input. This indicates that raw material suppliers are, in essence, contributors to a CLSC by using scrap to produce powder, despite not participating in return flows from manufacturers or end consumers.

Regarding the IT segment connecting suppliers and manufacturers employing AM, it can be deduced that both the volume and frequency of transportation needs will decline, thereby reducing the emissions generated from transportation activities. The raw material powder used in additive manufacturing occupies less space in comparison with the unprocessed resource utilized in traditional production, as it is conveyed in mass. This assertion aligns with the experiences of the companies in our study, which deliver and receive powder in jars or buckets. Transporting raw material in powdered form reduces its bulkiness, requiring less volume than an equivalent quantity of unprocessed resources utilized in traditional production. This improved effectiveness in inbound transportation for raw material is attributed to the ability to transport powdered material.

Because additive manufacturing involves adding material to create a product rather than subtracting from it, the raw material is utilized more efficiently. As highlighted earlier, the reduction in raw material waste can range from around 75% to as much as 90%, indicating that additive manufacturing achieves superior material efficiency compared to conventional methods. This enhanced material efficiency has led all the factories in this research to concur that the production phases necessities significantly reduced resource, consequently diminishing the initial resource demand for manufacturers. The improved powder utilization and reusability have markedly reduced the number of resource transport to manufacturers. Less manufacturing phases potentially reduce the requirement for several raw material providers, as products can be crafted from a single type of raw material. This simplifies supply and demand coordination among various parties, ultimately boosting the efficiency of inbound transportation in terms of both volume and effectiveness.

Based on our empirical findings, it's evident that interviewees recognize the advantages of a decentralized manufacturing system, although the utilization of additive manufacturing hasn't been extensively expanded at this point. This stage of development is also reflected in the interviewees' perspectives on the future. Notably, two major companies represented by the interviewees envision a transition from factory to a consulting role. For talent acquisition, most interviewees shared their initial challenges when embarking on additive manufacturing. Through trial and error, employees gradually familiarized themselves with AM processes.

For companies operating within the realm of additive manufacturing, recruiting suitable personnel presents a challenge, primarily due to the technology's relatively nascent status as a production method. However, concerning inbound transportation, which predominantly falls within the purview of the logistics function and is thus distinct from the engineering aspect, the competences required to manage transportation between suppliers and manufacturers do not differ significantly. An aspect of societal impact tied to additive manufacturing is its influence on production location. When manufacturing is situated around the point of expenditure, a need arises for transporting filaments to potentially distant locales, especially when companies are aiming to establish a distributed manufacturing system. These locations might encompass rural regions and even offshore platforms.

A prominent challenge and bottleneck associated with additive manufacturing pertains to intellectual property. Given the emerging nature of additive manufacturing, certain aspects, such as intellectual property, lack comprehensive regulation. Consequently, several aspects about material designs within AM prove difficult for adjustment. This sentiment is corroborated by the first manufacturer. The objective of the factory is making certain materials globally attainable by electronically transmitting product designs to locations equipped with printers. However, the company faces limitations in achieving this due to unresolved sensitive intellectual property agreements. This risk underscores the potential for product copying if distribution occurs without proper authorization, thereby constraining the technology's deployment to specific facilities. Conversely, the other manufacturing companies featured in this study do not express significant concerns regarding advanced assets. Remaining participants at production aspect emphasize factories develop designs collaboratively, subsequently establishing appropriate non-disclosure agreements to safeguard intellectual property. This approach ensures confidentiality, even when production takes place at external facilities.

The additive manufacturing process facilitates the bulk transportation of powder, a characteristic evident in the practices of the companies under scrutiny. By delivering and receiving additive powder in compact containers like buckets or jars, the handling process becomes more manageable across various places and modes of transportation. Participants in this study highlight that material handling is notably simplified in comparison to traditional production. The packaging of products is highly accommodating to loading and unloading into transportation modes due to its container design, and there is less frequent need for inventory replenishment. Remarkably, interviewees emphasize that no intricate equipment or infrastructure is required for loading and unloading the additive raw material—a contrast to the usual demands of conventional manufacturing. With the packaging adaptability of additive powder, the handling process becomes more convenient and secure for workers involved in IT, as opposed to dealing with raw materials commonly used in conventional manufacturing. As a result, the material handling approach contributes to the well-being and health of employees participating in the loading and unloading procedures associated with inbound transportation.

5. Conclusion

The primary objective of the presented work is delving into the influence of AM on the sustainability of IT. A comprehensive exploration of this subject is undertaken, drawing insights from existing literature and interviews conducted with professionals closely associated with additive manufacturing. Through this investigation, we have unearthed a multitude of ways in which additive manufacturing impacts the sustainability of inbound transportation, all of which are succinctly outlined in our refined conceptual model.

Based on the amalgamation of insights garnered through existing work and interviewee perspectives, it is firmly deduced that AM exerts a substantial influence on the environmental aspect of inbound transportation. One inherent trait of additive manufacturing is its inherent efficiency in production, resulting in minimal waste generation. Unlike conventional manufacturing methods that involve material reduction to achieve desired shapes, additive manufacturing streamlines the process, thereby necessitating fewer raw materials as inputs. An additional advantage lies in the transportability of filament powder in bulk form. Consequently, the volume of raw materials to be transported is diminished, accompanied by a decreased frequency of transportation requirements. Infrequent transportation translates to reduced emissions associated with transporting additive manufacturing-related components. Furthermore, the recycling mechanism for materials is implemented within a broader framework. Unlike the conventional model of product returns to the manufacturer for recycling, additive manufacturing incorporates recycling through specialized recycling entities.

Based on the empirical findings, it becomes evident that the adoption of additive manufacturing does not invariably result in cost reduction when it supersedes conventional production methods. The scope of applicability for additive manufacturing remains limited to a specific range of products. Despite this, there are specific instances where additive manufacturing can yield cost savings, particularly in the domain of inbound transportation. The decreased frequency of transport required for input materials in additive manufacturing plays a role in this. Furthermore, the convenience of transporting raw materials in compact jars or buckets, coupled with their relatively light weight, contrasts with conventional manufacturing techniques that necessitate bulkier and non-powder inputs. Another economic advantage lies in the diminished necessity for manufacturers to maintain substantial raw material inventories. In conventional manufacturing setups, a considerable volume of production inputs is stockpiled, a practice that contrasts starkly with additive manufacturing processes where such extensive storage of inputs isn't required.

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References

[1] Guo, D., Li, M., Lyu, Z., Kang, K., Wu, W. Zhong, R.Y., & Huang, G.Q. (2021). Synchroperation in industry 4.0 manufacturing. *International Journal of Production Economics*, *238*, 108171. Retrieved August 8, 2023, from doi: 10.1016/j.ijpe.2021.108171

[2] Onu, P., & Mbohwa, C. (2021). Industry 4.0 opportunities in manufacturing SMEs: Sustainability outlook. *Materials Today: Proceedings*, *44*(1), pp. 1925-1930. Retrieved August 8, 2023, from doi: 10.1016/j.matpr.2020.12.095

[3] Bakirci, M. (2021). Reducing GPS impreciseness by odometer sensor reading to improve positioning accuracy. *International Journal of Automotive Science and Technology*, *5*(4), pp. 299-307. Retrieved August 8, 2023, from doi: 10.30939/ijastech.977039

[4] Wu, K.J., Liao, C.J., Tseng, M.L., & Chiu, A.S.F. (2015). Exploring decisive factors in green supply chain practices under uncertainty. *International Journal of Production Economics*, *159*, pp. 147-157. Retrieved August 8, 2023, from doi: 10.1016/j.ijpe.2014.09.030

[5] Guo, S., Agarwal, M., Cooper, C., Tian, Q., Gao, R.X., Guo, W., & Guo, Y.B. (2022). Machine learning for metal additive manufacturing: Towards a physics-informed data-driven paradigm. *Journal of Manufacturing Systems*, *62*, pp. 145-163. Retrieved August 8, 2023, from doi: 10.1016/j.jmsy.2021.11.003

[6] Xu, B., & Lin, B. (2015). Carbon dioxide emissions reduction in China's transport sector: A dynamic VAR (vector autoregression) approach. *Energy*, *83*, pp. 486-495. Retrieved August 8, 2023, from doi: 10.1016/j.energy.2015.02.052

[7] Khajavi, S.H., Partanen, J., Holmström, J., & Tuomi, J. (2015). Risk reduction in new product launch: A hybrid approach combining direct digital and tool-based manufacturing. *Computers in Industry*, *74*, pp. 29-42. Retrieved August 8, 2023, from doi: 10.1016/j.compind.2015.08.008

[8] Ren, L., Wang, Z., Ren, L., Han, Z., Liu, Q., & Song, Z. (2022). Graded biological materials and additive manufacturing technologies for producing bioinspired graded materials: An overview. *Composites Part B: Engineering*, *242*, 110086. Retrieved August 8, 2023, from doi: 10.1016/j.compositesb.2022.110086

[9] González-Henríquez, C.M., Sarabia-Vallejos, M.A., & Rodriguez-Hernandez, J. (2019). Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications. *Progress in Polymer Science*, *94*, pp. 57-116. Retrieved August 8, 2023, from doi: 10.1016/j.progpolymsci.2019.03.001

[10] Hegab, H., Khanna, N., Monib, N., & Salem, A. (2023). Design for sustainable additive manufacturing: A review. *Sustainable Materials and Technologies*, *35*, e00576. Retrieved August 8, 2023, from doi: 10.1016/j.susmat. 2023.e00576

[11] Naghshineh, B., & Carvalho, H. (2022). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, *247*, 108387. Retrieved August 8, 2023, from doi: 10.1016/j.ijpe.2021.108387

[12] Diercks, G., Larsen, H., & Steward, F. (2019). Transformative innovation policy: Addressing variety in an emerging policy paradigm. *Research Policy*, *48*(4), pp. 880-894. Retrieved August 8, 2023, from doi: 10.1016/j.respol.2018.10.028

[13] Harrison, R.P. Ruck, S. Rafiq, Q.A., & Medcalf, N. (2018). Decentralised manufacturing of cell and gene therapy products: Learning from other healthcare sectors. *Biotechnology Advances*, *36*(2), pp. 345-357. Retrieved August 8, 2023, from doi: 10.1016/j.biotechadv.2017.12.013

[14] Kendrick, B.A., Dhokia, V., & Newman, S.T. (2017). Strategies to realize decentralized manufacture through hybrid manufacturing platforms. *Robotics and Computer-Integrated Manufacturing*, *43*, pp. 68-78. Retrieved August 8, 2023, from doi: 10.1016/j.rcim.2015.11.007

[15] Hannibal, M., & Knight, G. (2018). Additive manufacturing and the global factory: Disruptive technologies and the location of international business. *International Business Review*, *27*(6), pp. 1116-1127. Retrieved August 8, 2023, from doi: 10.1016/j.ibusrev.2018.04.003

[16] Jong, S., Hoefnagels, R., Wetterlund, E., Pettersson, K., Faaij, A., & Junginger, M. (2017). Cost optimization of biofuel production – The impact of scale, integration, transport and supply chain configurations. *Applied Energy*, *195*, pp. 1055-1070. Retrieved August 8, 2023, from doi: 10.1016/j.apenergy.2017.03.109

[17] Smale, R., van Vliet, B., & Spaargaren, G. (2017). When social practices meet smart grids: Flexibility, grid management, and domestic consumption in The Netherlands. *Energy Research & Social Science*, *34*, pp. 132-140. Retrieved August 8, 2023, from doi: 10.1016/j.erss.2017.06.037

[18] Chen, B., Zhong, J., & Chen, Y. (2020). A hybrid approach for portfolio selection with higher-order moments: Empirical evidence from Shanghai Stock Exchange. *Expert Systems with Applications*, *145*, 113104. Retrieved August 8, 2023, from doi: 10.1016/j.eswa.2019.113104

[19] Haberly, D., MacDonald-Korth, D., Urban, M., & Wójcik, D. (2019). Asset management as a digital platform industry: a global financial network perspective. *Geoforum, 106*, pp. 167-181. Retrieved August 8, 2023, from doi: 10.1016/j.geoforum.2019.08.009

[20] Singh, S.R., & Khanna, P. (2021). Wire arc additive manufacturing (WAAM): A new process to shape engineering materials. *Materials Today: Proceedings*, *44*(1), pp. 118-128. Retrieved August 8, 2023, from doi: 10.1016/j.matpr.2020.08.030

[21] Pixner, F., Buzolin, R., Warchomicka, F., Pilz, A., & Enzinger, N. (2022). Wire-based electron beams additive manufacturing of tungsten. *International Journal of Refractory Metals and Hard Materials*, *108*, 105917. Retrieved August 8, 2023, from doi: 10.1016/j.ijrmhm.2022.105917

[22] Noy, I.Y., Shinar, D., & Horrey, W.J. (2018). Automated driving: Safety blind spots. *Safety Science*, *102*, pp. 68-78. Retrieved August 8, 2023, from doi: 10.1016/j.ssci.2017.07.018

[23] Zimmerer, K.S., Carney, J.A., & Vanek, S.J. (2015). Sustainable smallholder intensification in global change? Pivotal spatial interactions, gendered livelihoods, and agrobiodiversity. *Current Opinion in Environmental Sustainability*, *14*, pp. 49-60. Retrieved August 8, 2023, from doi: 10.1016/j.cosust.2015.03.004

[24] Valente, M., Sambucci, M., Chougan, M., & Ghaffar, S.H. (2023). Composite alkali-activated materials with waste tire rubber designed for additive manufacturing: an eco-sustainable and energy saving approach. *Journal of Materials Research and Technology*, *24*, pp. 3098-3117. Retrieved September 9, 2023, from doi: 10.1016/j.jmrt.2023.03.213

[25] Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, pp. 1573-1587. Retrieved September 9, 2023, from doi: 10.1016/j.jclepro.2016.04.150

[26] Son, D., Kim, S., & Jeong, B. (2021). Sustainable part consolidation model for customized products in closed-loop supply chain with additive manufacturing hub. *Additive Manufacturing*, *37*, 101643. Retrieved September 9, 2023, from doi: 10.1016/j.addma.2020.101643

[27] Verboeket, V., & Krikke, H. (2019). The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Computers in Industry*, *111*, pp. 91-107. Retrieved September 9, 2023, from doi: 10.1016/j.compind.2019.07.003

[28] Santander, P., Sanchez, F.A.C., Boudaoud, H., & Camargo, M. (2020) Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. *Resources, Conservation and Recycling*, *154*, 104531. Retrieved September 9, 2023, from doi: 10.1016/j.resconrec.2019.104531