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Overview of sustainability studies of CNC machining and LAM of stainless steel

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Abstract

Laser additive manufacturing (LAM), known also as 3D printing, is a powder bed fusion (PBF) type of additive manufacturing (AM) technology used to fabricate metal parts out of metal powder. The development of the technology from building prototype parts to functional parts has increased remarkably in 2000s. LAM of metals is promising technology that offers new opportunities to manufacturing and to resource efficiency. However, there is only few published articles about its sustainability.

Aim in this study was to create supply chain model of LAM and CNC machining and create a methodology to carry out a life cycle inventory (LCI) data collection for these techniques. The methodology of the study was literature review and scenario modeling. The acquisition of raw material, production phase and transportations were used as basis of comparison. The modelled scenarios were fictitious and created for industries, like aviation and healthcare that often require swift delivery as well as customized parts.

The results of this study showed that the use of LAM offers a possibility to reduce downtime in supply chains of spare parts and reduce part inventory more effectively than CNC machining. Also the gap between customers and business is possible to be shortened with LAM thus offering a possibility to reduce emissions due to less transportation. The results also indicated weight reduction possibility with LAM due to optimized part geometry which allow lesser amount of metallic powder to be used in making parts.

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1. Introduction

The increase of added value to products as a result of improved productivity and efficiency due to existing and emerging manufacturing methods cannot be overemphasized (Manyika et al., 2012). These methods potentially offer benefits for both high quality products and process efficiencies. Laser additive manufacturing (LAM) is one of the methods, which has been identified to offer such benefits (Yoon et al., 2014).

LAM is able to make parts using the exact amount of powder needed for final part and almost all surplus powder may be reusable. This method is able to produce parts closer to end users as well as eliminate any additional transportation of preformed as raw material to manufacturing centers as starting material for conventional processes. CNC machining for instance may require voluminous metal bars or plates as startup from which only small amounts remain as final part. The acquisition of right size of initial material in conventional processes may often result in delays in operations. Manufacturing companies may not have needed startup material in their stock-keeping-unit as using over dimensioned stock often increases production cost and even result in material wastage. This is because starting production as close as possible of the exact stock is preferred as both price and material efficiency can be achieved. The possibility to build parts with negligible amount of waste and with a better supply chain flow are core to application of LAM.

Life cycle thinking can be seen as a concept to attain the objective of sustainability. Life cycle thinking means widening the traditional view from manufacturing processes to include various aspects related to the product over its entire life cycle. Life cycle management (LCM) is a voluntary framework to implement life cycle thinking and the objective of sustainability into the industry. To have sufficient effect LCM needs to be involved in all the levels of the organization such as management, distribution, sales and marketing, production, procurement, and product development. (Remmen et al. 2007). This paper discusses the possible sustainability benefits of LAM in the procurement, production and distribution.

Nomenclature

AM	Additive manufacturing
PBF	Powder bed fusion
CNC	Computer numeric control
CO2PE!	Cooperative effort on process emissions in manufacturing
DED	Direct energy deposition
EOS	Electrical optical systems
ECUs	Energy consuming units
JIT	Just in time
LAM	Laser additive manufacturing
LCI	Life cycle inventory
LCM	Life cycle management
SEC	Specific energy consumption
UPLCI	Unit process life cycle inventory

Huang et al. (2012) have shown in their study that additive manufacturing can be promising in three main areas of operations. The study indicated as possible improvements achievable with AM (Huang et al., 2012).

1. the ability to create individualized parts that can function effectively for better healthcare and quality of life,

2. the capability to reduce environmental impacts of manufacturing, and the potential to simplify supply chain that may offer maximal efficiency and
3. alertness in responding to demand with satisfaction.

Sreenivasan et al. (2010) points out in more detail that the specific points of product life cycle where environmental benefits, such as greenhouse gas emission reduction, might occur are the reduced need to mine and process raw material ores due to increased material efficiency, ability to design more energy efficient products via enchanted cooling methods, the decreased fuel-consumption due to lighter vehicles in transport-related products.

World Economic Forum (2013) and European Commission (2013) have estimated that the supply chains with LAM might shorten as parts are possible to be built closer to customers with improved intermediate connections. The studies indicate that instead of the traditional supply models that often required several stock-keeping units, modern model of doing business such as just-in-time (JIT) are feasible with LAM. This is thought of as possible as the gap between customers and manufacturer get shortened with decentralization and as well as reduced led time. World Economic Forum (2013) claims that the use of LAM might improve sustainable gains in terms of material efficiency and might also result in better transportation systems as improved packaging are used during shipment. LAM is believed to reduce costs as well as fuel consumptions in airlines that use new engines parts made with this technique as a results of the lightweight of components made possible either as hollow or net shaped structure (World Economic Forum, 2013; EC, 2013).

The use of life cycle assessment oriented methods may highlight the potential and accuracy to measure product and process efficiencies in discrete manufacturing like LAM. A method that exist as a guide for systematic life cycle inventorying analysis for discrete manufacturing is CO2PE! UPLCI Initiative. This method has been previously been applied for LAM by Kellens et al. (2012) and is explained in more detail in part 3 of this paper. Duflou et al. (2012) identified in their study that there are large discrepancies on the energy demand of discrete part manufacturing processes obtained by different assessment methods. This paper gives an example on how to conduct an "In-Depth approach" to metal LAM process to facilitate the acquisition of process specific data.

1.1. Supply chain in LAM

Perumal (2006) have shown in their study that the main characteristics of an excellent supply chain are a delivery of high quality products to customer responses, efficient converting of inputs into outputs and improvement of asset utilization e.g. leveraging inventory and working capital (Perumal, 2006). These elements can affect the merit of spare parts supply chains managing as the focus must also be on the reduction of operating cost without altering wishes of customer. There may be challenges that might oppose the achievement of such objective like unavailability of parts or delay of production. One challenge that has remain persistent over time is the unpredictability of demand, especially for new product launches for which the data on parts failure rates may be unreachable which may lead to delays in production. A high inventory is usually the only option for companies to overcome this challenge. A lot of additional burden may be imposed on companies as unused parts may have to be substituted, recycled or even landfilled as a result of wrong specifications. Another problem could be the need to support both old customers and new customers. This responsibility can in large extent require management to keep large unit stocking in order to meet the pre-and after sale request or changes. Thus greater workforce, larger amount of parts and tools may be needed to be managed simultaneously which foretell increased responsibility of management.

A solution to these and other similar problems are not far-fetched. As having an all-inclusive system that can work properly to eliminate or reduce these shortfalls in operations of firms is a sure yardstick to reduce some of the inefficiencies in companies. AM might be one solutions to overcome such problems in manufacturing companies. Some professionals believe also that AM will totally transform manufacturing supply chains.

The analyses of sustainable developments are tied to manufacturing and transportation operation (Nyman and Sarlin, 2013). However, the value chain in manufacturing companies in recent times are becoming increasingly long and complicated making it more vulnerable than ever before. As a result its supply chain have changed to occur over long and broadened scope with an increasingly complex relations (Mentzer et al., 2001).

1.2. Sustainability in LAM

Gunasekaran and Spalanzani (2012) have shown that sustainability benefits of LAM can be seen from the possibility to improve swiftness in operation and raw material efficiency. Sustainability and customized products are increasingly becoming fundamental basis for competition in engineering industries. The reduction of many of the ancillary process aid and the numerous preparation steps often needed in comparable conventional processes in fabricating products are the benefits of LAM. LAM can also improve material efficiency considerably. Conventional manufacturing often requires specific form of startup material from which parts are removed as waste in order to get final parts. The amount of stock needed and also need for transportation might be reduced when using LAM. (Nyamekye, 2014).

A collaborated study between EOS, Filton branch England and Airbus Group innovations compared the lifecycle of two critical technologies rapid investment casting and LAM of stainless steel bracket for Airbus A380 (EOS, 2014). The goal of their study was to evaluate rapid investment casting and PBF for a standard Airbus structural part, including detailed aspects of the overall lifecycle. The study which was adapted from streamlined lifecycle assessment of Airbus and ISO 14040 series requirements data aimed to serve as basis for further preliminary closed loop analysis into other aerospace parts, processes, and end-of-life strategies. Figure 1 shows the two designs of brackets used for the study.

Fig. 1. Prototype of an optimized Airbus A380 bracket manufactured with AM (front) and investment casting (back) (EOS, 2014).

As it can be seen from the Figure 1, considerable amount of material could be assumed to be saved as a result of the net-like design of the AM part. The study also propose that designing complex geometry, as shown in the front model for dynamic applications, might reduce emissions as weight of parts are reduced. A further potential of increasing functionality of components whiles decreasing cost of operation in aviation industry were also highlighted.

Yoon et al. (2014) have similarly compared in their study polymeric additive manufacturing (AM) methods, and traditional processes like injection molding and machining (e.g. milling and drilling). Their study was limited to energy consumption in producing plastic parts. The result of their study showed that specific energy consumption (SEC) during AM process was about a 100-fold compared to the conventional methods. Despite the high SEC of AM the study indicates that the use of material is more efficient in AM than in machining and injection molding. (Yoon et al., 2014).

2. Aim and purpose of this study

Aim of this study was to 1) determine the benefit of LAM on sustainability gains in terms of supply chain and 2) offer a methodology to conduct LCI analysis of the LAM and CNC machining. The supply chain benefits were studied by building possible supply chain scenarios for CNC machining and LAM. The building of these scenarios serve a base for a more in-depth analysis. The purpose of the building of the framework for practical test was to identify and characterize the different machine units and phases of each of the manufacturing processes to be able to ascertain their potential impact to efficiency.

Purpose of this study was to examine, how value chain in LAM from the raw material acquisition to the end user could be improved based on imaginary case study. The motivation was also to characterize LCI of LAM.

The purpose of the study was to find out what factors affect the sustainability of LAM and what elements can be measured in LCI as determinates of sustainability.

3. Methodology

The methodology used in this study were supply chain scenarios based on assumptions and experimental tests. Case models were created to examine the movement of raw material until final parts delivering to end users. A further analysis with practical test was carried out for LCI study.

In view of the supply chain, models were designed to include the transportation links among some key performers. The stages considered for the supply chain modelling started with transportation of raw material through to the end user without any pre or post activities.

In performing the LCI studies, it was necessary to limit the collection to one of the stages in the value chain of both processes. The production phase of both methods were selected as it involved actual fabrication of part. The procedure used to collect energy and raw material consumptions were carefully selected to agree with the standardized unit process LCI methodology, CO_2PE! Initiative!. This method was followed as a guide to perform the energy and material measurements. Figure 2 presents the steps included in the CO2PE! UPLCI Initiate.

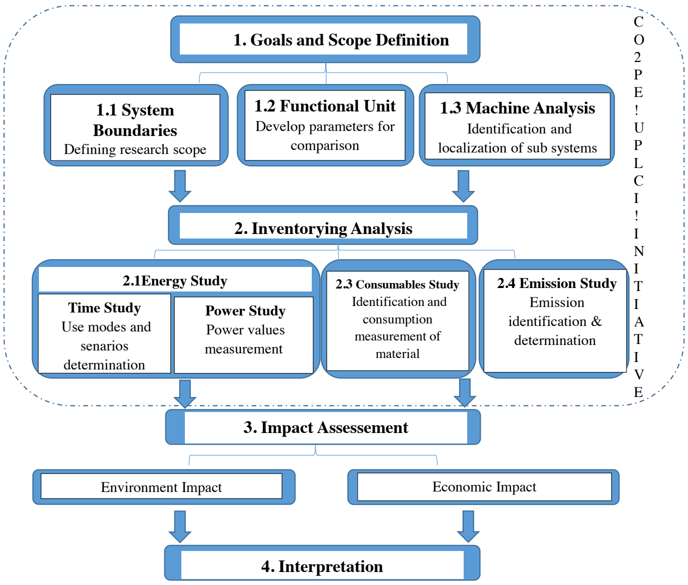

Fig. 2. Representation of systematic methodology for LCI study redrawn from (Kellens et al., 2012).

4. Experimental set-up

4.1. Data and assumptions for supply chain

The comparison of the supply chains for the two manufacturing processes were established by considering their configurations. Three assumptions were made in relation to these scenarios:

- It was assumed that supply chain starts from the steel bar for traditional process and powder for LAM process leaving out the ore extraction and atomization process.
- It was also assumed that customers will have a possibility to order parts from manufacturing companies directly. This implies that customers are not building parts even though it is feasible for large scale companies to acquire building unit.
- Lastly, it was assumed that raw material in both scenarios may be acquired locally from place of production. Transportation of raw material to production sites will be local.

4.2. Data and procedure used for LCI

The prerequisite for performing the LCI were to define the scope and goal of the study as well as parameters to be studied, functional units, system boundaries and phases to be included in the study.

In this study some assumption were made in order to ease the amount of data coverage. There could be several parameters and levels of manufacturing as well as functional units to be measured during an LCI analysis in a manufacturing process. As such simplifying or describing limitations of the study is important. The experimental part of this study was limited to production phase of both examined processes within a very narrow confinement. In order to characterize LCI of both LAM and CNC machining, numerical values were needed to quantify amount of energy and raw material used and the waste generated during the production phases. According to the methodology data could be measured, calculated or estimated based on experimental or literature studies. This study used measurements to investigate the material and energy consumption for the LCI studies.

5. Results and discussion

5.1. Supply chains

Conventional manufacturing: Figure 3 shows the hypothetical supply chain model created based part acquisition using the conventional (CNC machining) method.

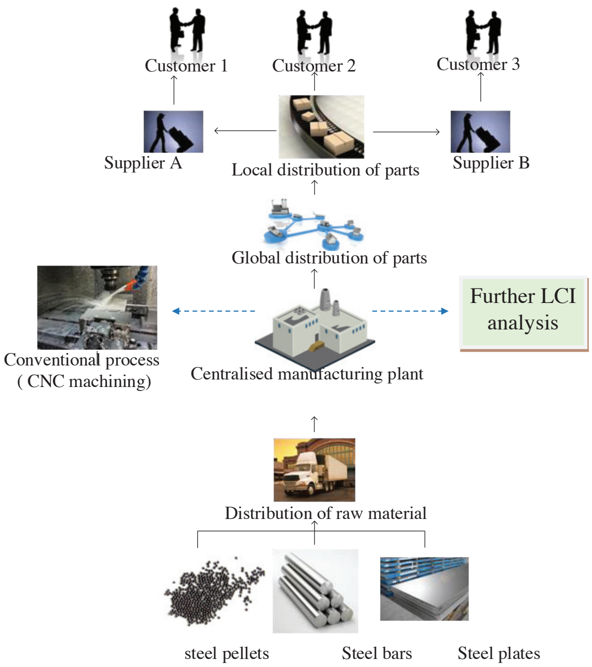

Fig. 3. Supply chain for conventionally manufactured part.

As it can be seen from Figure 3, the conventional model includes several intermediate steps in delivering products to end users. Aside these transitional steps, there could still be further delays as a results of the numerous process stages that may be needed in the fabrication stage. These may be as result of tools and fixtures installations or trail test in the case of machining. The process flow from bottom to up (see Figure 3) shows steel preforms are conveyed to manufacturing centre where machining of final parts are carried out.

The inclusion of local suppliers that may require stocking of parts was included with the aim to offer quick responds to orders and meet deadline of customer. This expatiate the supply chains and may also cover larger floor space as warehousing. As more often than not, a stocking of finished parts are kept both at the factory floors and in centralized distribution station where end users may order parts directly from or through local distributors. These form of logistics of finished parts often subject customers and companies to further labour and financial burden as extra cost and activities may be incurred.

LAM: The supply chain model of LAM depicts procurement phases between companies and end users. The mode of business may be direct or indirect using the service of middlemen. Figure 4 is an illustration of the supply chain of laser additive manufacturing for a stainless steel part.

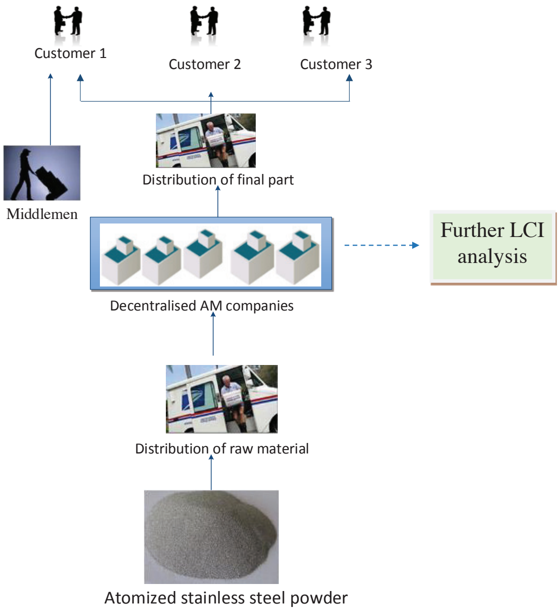

Fig. 4. Supply chain for laser additive manufactured part.

As it can be noticed from Figure 4, smaller space may be needed for production in LAM workshops and may create job opportunities as it supports decentralization. LAM has the advantage of producing parts closer to the market and has the potential to transform the supply chain to be more dynamic in manufacturing sectors. This presumes that the labor trading consideration for outsourcing may be reduced or eliminated. This may reduce lead time, cost and reduce rate of supply chain management risks significantly.

Land use with storage in LAM might be minimum as there is no need for stocking for either preforms (bar, pellets or plate) or finished products as required in conventional manufacturing methods such as CNC machining. In contrast, products can be built on demand in LAM.

The utilization of currier service in LAM shows that special schedules are not needed for distribution as raw material in the form of powder and finished parts are easily handled through normal post.

A significant reduction of lead time, cost and risk to the supply chain is thus achievable with LAM. These enhancements are not only feasible in manufacturing activities because of the replacement of carriage and inventory but also with the efficiency during the in-process chain in building parts on production level.

New designs from customers or size specifications can be incorporated into already stored data on a computer and printed layer by layer with just few steps without a need of a human presence in the production stage.

Companies may be offered the possibility to circular economy as generated chips from competitive process like CNC machining may be re-used in other AM processes, like direct energy deposition (DED) with only mechanical grinding to crush chips into desired grain sizes (Salminen, 2015). By so doing, SEC to produce metallic power from virgin material may also be reduced which highlights sustainable gain (Soukka, 2015).

5.2 Life cycle inventory

The outcome of the application of the systematic methodology CO2PE! UPLCI Initiative in this study are as presented in this session.

System boundary: In performing the LCI for the study, the scope in which research was carried out were defined as shown in Figure 5.

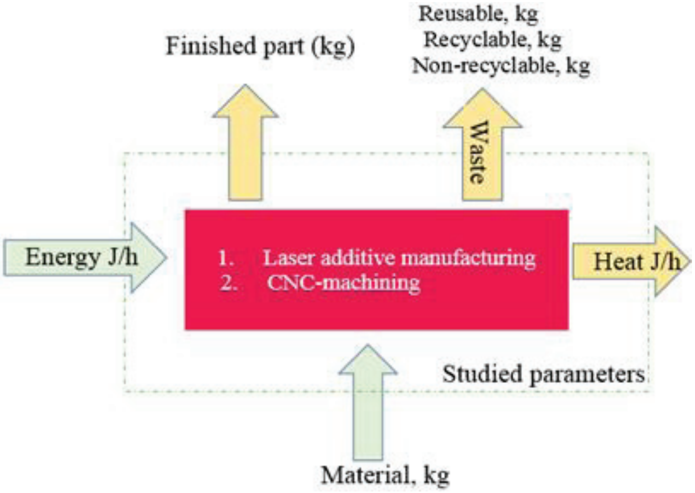

Fig. 5. Representation of system boundary.

As it is can be seen from Figure 5 the system boundary used in this study considered the amount of input and output energy and materials within manufacturing process.

Machine analysis studies: In order to carry out the LCI analysis it was important to define the machine tools and levels of the process to be studied. A primary selection of machine tools and levels to be investigated was necessary prior to the analysis. This step of the systematic LCI method allowed effective identification of energy and resource consuming units and their possible subsystems. The machine levels selected for CNC machining and LAM in this study are as shown in Figures 6a and 6b respectively.

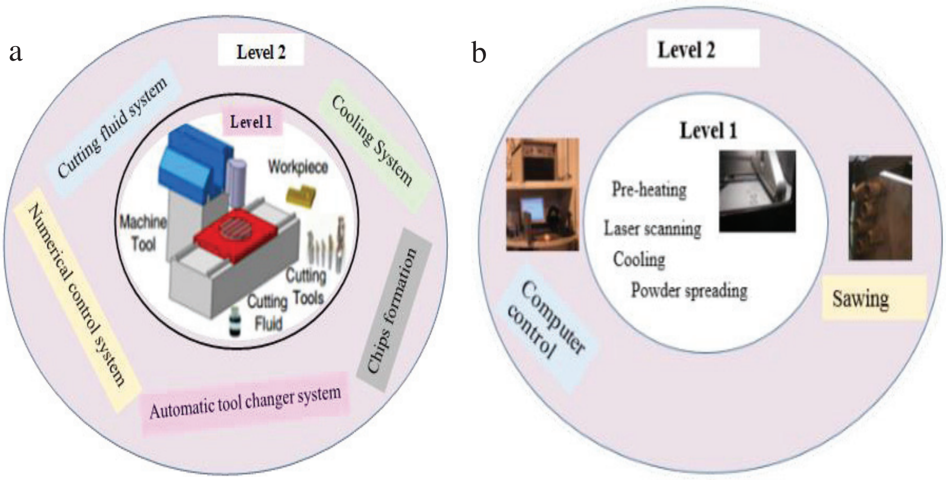

Fig. 6. Representation of a) CNC machining b) LAM levels analysed.

As it can be noticed from the Figures 6a and 6b, two levels of production in CNC machining and LAM were included in this study. The power values of energy driven elements were considered for energy consuming units (ECUs). Components such as such automatic tool changer, spindle motors, rotating tools and cutting fluid motor were considered for CNC machining. The ECUs in LAM on the other hand included heating units, laser and its cooling unit, servo, scanners and lightening system. Material inputs and outputs in various levels shown in Figure 6a and 6b were used to analyse material consumption in this study. The second level elements were studied as they complemented the finishing of production. Defining and selecting these elements was necessary as indicated in the methodology. Machine systems outside of these levels were not considered during LCI study. For instance energy consumed in lighting the production centre or conveying parts to machining centre were not considered as ECUs.

Geometry of work pieces: In this study practical tests were carried out with varying designs which included measure of degree of manufacturing flexibility and weight reductions. A modified research machine representing EOS EOSINT M-series was for LAM parts and a PUMA 2500Y multi axis lathe for CNC machined parts. Three test samples were designed as sample A, B and C for the experimental study. Samples A and C were designed to be produced with LAM only whereas sample B was planned to be produced with both CNC machining and LAM. Dimensions of the work pieces were 20 x 40 x 35 mm and an internal hole with a diameter of 24 mm. The models A and C were used as one of the criteria to affirm complexity and flexibility in LAM while sample A, B and C offered bases to compare resource and energy consumption for both processes. Geometry of test pieces used in the practical studies are as shown in Figure 7.

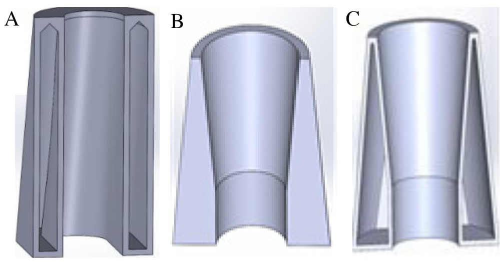

Fig. 7. Solid and cross sectional views of samples A, B and C used in this study.

As it can be seen from Figure 7, the models were designed to have solid and hollow walls. It was for instance only practicable to produce models B with CNC machining as the method was limited by the sharp edges in sample A and also the hollow wall in sample A and C. The internal geometry of sample A had sharp corners, hollow wall and a chamfered outside geometry. In order to have hollow walls in final parts of samples A and C there were 2 mm passage holes incorporated into design to remove excess powder after building. These features were included into designs in order to increase complexity of final products.

6. Conclusions and further studies

Aim of this study was to 1) perform comparative study of the supply chain configurations of LAM and CNC machining and 2) offer a methodology to conduct LCI analysis of the LAM and CNC machining.

This study has outlined how supply chains in LAM are improved with a modelled scenario based on marginal assumptions. The benefit might be true in practical cases as procurement management were improved with these models. Further studies however are needed to ensure the exactness of this benefit of agile supply model.

It was noticed that factors such as materials consumption, manufacturing steps, length of supply chain as well as swiftness of production affect the sustainability of a process. The production phase of LAM was identified to give a better sustainable gains in terms of material efficiency. However this cannot be said to be the only phase of sustainable gains as other phases were not included in the LCI study. In this study materials were measured as main determinates of efficiency.

In future, it would be imperative to examine the supply chain and LCI of LAM based on a practical use case. It may also be beneficial to broaden the scope of boundary to have a wider view of the material and energy efficiency offered by LAM by conducting a full life cycle assessment. It will be a notable undertaking to study the degree to which these parameters affect sustainability in LAM in further studies.

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