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A techno-economic analytical approach of laser-based additive manufacturing processes for aerospace application

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Abstract

Additive manufacturing (AM) of laser-based technological solution is developing at an exponential rate and is stepping towards industrialisation. The value and possibilities it bring to modern design and manufacturing tasks specifically for metallic products cannot be undermined. Amongst its significant benefits are; manufacturability, materials, part quality, production and economics. In spite of the benefits, uncertainties within the processes and high investment costs deter firms from implementing and adopting this technology. As such, getting to know about the technical and economic analysis model is necessary for sustainability and competitiveness of manufacturers. Consequently, while many papers in the literature provide cost estimation models for additively manufactured parts, there does not exist a thorough indicator towards decision making. Hence, a concurrent decision tool using techno-economic analysis that helps justify the implementation of laser additive manufacturing systems, and realisation performance efficiencies is explored in this study.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: Decision making; Laser additive manufacturing; Techno-economic

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1. Introduction

As marketplace competition drives industrial innovation to increase product value and decrease production costs, emerging technologies foster a new era through Industry 4.0. Additive manufacturing (AM) is regarded as a novel technical innovation enabling manufacturing sustainability and innovative solutions. One attractive aspect of this technology drive has been towards current design and materials challenges in the manufacturing of components for the aerospace industry. Additive manufacturing production often known as Rapid Prototyping is defined by the American Society of Testing and Materials (ASTM) F2792 and ISO 17296 as "the process of joining materials to make objects usually layer by layer from three-dimensional model data, different from subtractive manufacturing technologies [1, 2]. These additive technologies are the initiator of digital manufacturing advancement that are developed through computer-aided engineering that provides the competitiveness of modern component production [3]. The operation of AM processes have introduced a vast array of new opportunities for increasing efficiency, lowering costs, and improving quality throughout the advanced manufacturing sector [4]. Typically the processes of AM are broken into seven categories, and the comparative advantages and disadvantages of these technologies have been described extensively [2, 3]. Without holding monopoly of AM, three out of the seven categories of these manufacturing systems are laser-based, which are; directed energy deposition, powder bed fusion and vat-polymerisation [3]. Two out of the three mentioned processes have the capability of manufacturing metallic components. The most significant and predominant among the processes for metal AM are: Selective Laser Melting/Sintering (SLM/S; for melting powdered material or fusing powder), Laser Engineering Net Shaping (LENS) and Laminated Object Manufacturing (LOM; for sheet materials) [5]. The revenue potential of these processes has led to a boom in research and development (R&D) efforts from academia, industry and especially Original Equipment Manufacturers (OEMs). The materials R&D has been highly reported for aluminium, stainless steel, expressly titanium and its alloys [6, 7]. Such area of study is manufacturing of small and medium-sized Ti-6Al-4V parts for aerospace industry [5]. In record also are comparisons between additive manufacturing and traditional production as well as new developments in the field [8]. While many papers in the literature provide cost estimation models for additively manufactured parts, [9, 10]. Companies such as Arcam, EOS, SLM Solutions, ExOne, Sciaky, Optomec, and Concept Laser lead the global metals industry, each providing unique process capabilities [5]. Hence, commercial companies must decide which process and corresponding machine manufacturer best meets their individual needs. This study explored the use of technical, economic and techno-economic criteria tailored to provide decision-makers with opportunities of a different course of action with respect to their overall aim of selecting a production process. The goal of this study is to develop a decision tree analysis to help engineers rapidly understand the techno-economic impacts of manufacturing decisions when deciding additive processes.

2. Literature review

Techno-economic analysis (TEA) is a tool that can help justify the large-scale implementation of cohesive manufacturing systems, and realisation of potential cost and performance efficiencies [11]. In this sense, "techno" analysis implies that the selection of processes should be guided based on current technological capabilities and limitations, while "economic" analysis implies that engineers and other decision makers must be cognisant of the costs of producing a given component in addition to other performance metrics (e.g., material utilisation and process time).

- Techno-economic analysis: An approach for evaluating the economic feasibility of a known technical structure.
- Economic feasibility: A measure of the economic attractiveness of a technology, typically determined by comparing the costs and the benefits of a technology for a certain stakeholder.

2.1. Additive manufacturing and lasers technologies

Technology and innovation such as additive manufacturing (AM) technologies are pre-competitive platforms or breaking point for demonstration of concept with possible commercial viability either of a new or improved products, processes, or services [4]. As manufacturing is regarded as the process of converting a raw material into a finished product, AM involves several processes that create three-dimensional (3D) parts and structures of layers compacted [4]. There are eight steps involved in the generic process of AM from Computer Aided Design (CAD) to application as depicted in Fig. 1.

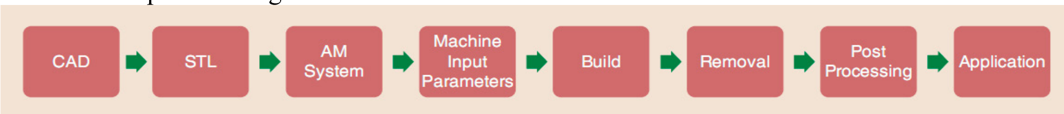

Fig. 1. The general AM process steps (Gibson, Rosen, & Stucker, 2010)

Additive manufacturing is realised on three levels, according to [3]:

- The first one is the production of models;
- The second one is the production of prototypes;
- The third one is the production of details that meet requirements construction documentation and are set in complex technical systems for the whole period of exploitation

The major classifications of AM are namely: Laser based additive manufacturing and Non-laser based additive manufacturing. Further knowledge on the laser based technologies commercially available are; Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC), Laser Metal Deposition (LMD), Laser Engineered Net Shaping (LENS) [12]. The laser power used for these processes spans from some Watt to several Kilowatt and applications differ from design prototypes to structural components. Laser based AM processes share the same manufacturing principle, although each process might have its own range of usable materials, procedures, and applicable situations [13]. Basically, LASER is, "Light Amplification by Stimulated Emission of Radiation" that provides a high intensity and a highly collimated beam of energy that can be quickly moved in a controlled manner with the help of directional mirrors or lenses, Fig 2a is a depiction [11]. The principle behind this manufacturing systems lies in the use of a laser beam to provide thermal energy for the melting and consolidating of the additive materials [13]. In metal based processes, the ISO 17296-1 standard suggests the following classification tree for metal processing AM as found in Fig 2b below, as in (Fig. 2).

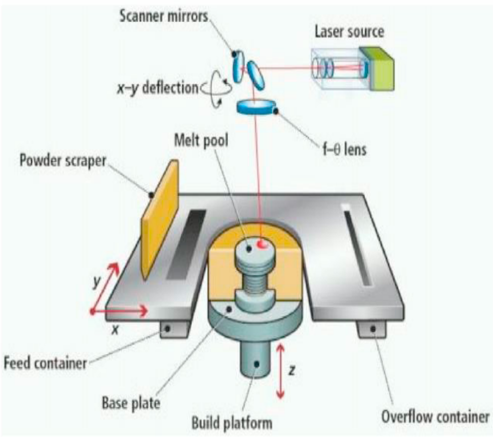

Fig. 2a. Exemplary sketch of Laser Beam Melting process (Yasa at al., 2011)

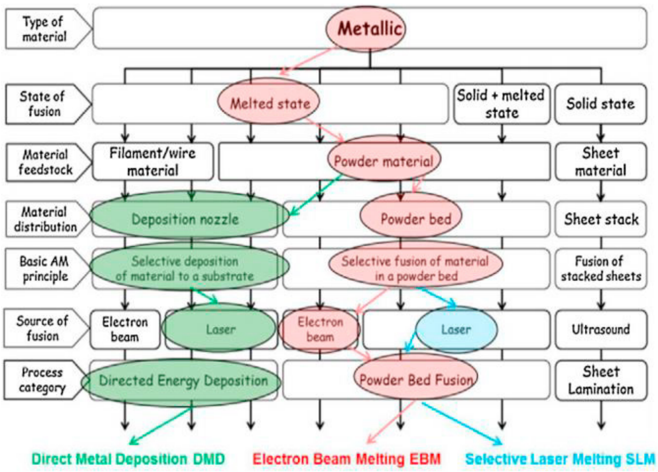

Fig. 2b. Morphological box for representation of metal based laser AM processes (Schmdt et al., 2017)

2.2 Technology adoption and innovation diffusion theory in manufacturing

As a potentially disruptive technology for several industries, due to its capabilities to reduce costs and generate value addition, a number of advantages arising from the adoption of AM have been identified [14]. An influential model devised by a scholar into the theory of diffusion of innovations (DOI) has become a key analytical tool overtime in marketing, organisation and innovation studies as presented by Everett M. Rogers [15]. According to

Rogers postulation, innovation diffusion rate is also affected by other aspects, such as the type of innovation-decision (by individual or organisation), and the nature of the social system in which the innovation is diffusing. However, a noted attribute in this submission is not only if a technology is adopted but the extent of its implementation. Oliveria & Martins [16] described a framework consisting of three elements that influenced the technological innovation adoption by users enterprises. As in Fig. 3, this could be used for studying the adoption of different types of Information technology innovations, to establish that there is a solid theoretical base and consistent empirical support for technology diffusion as the case of laser enabled additive manufacturing.

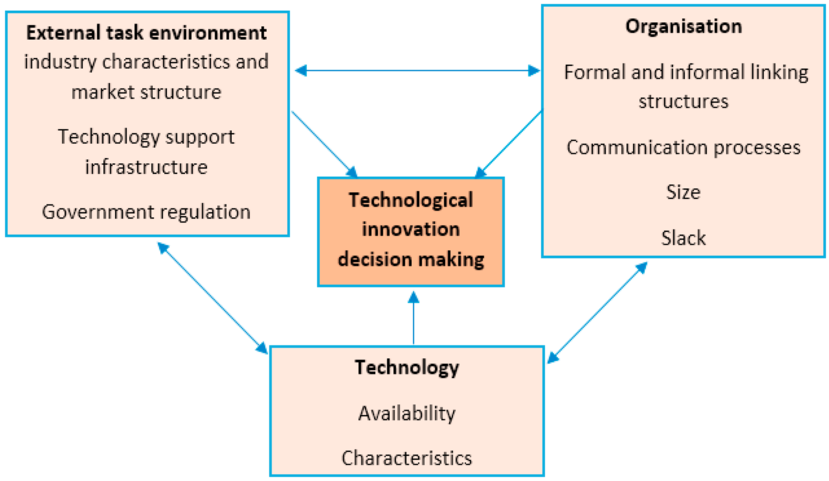

Fig. 3. A framework for Technology, Organisation and Environment (Oliveira & Martins, 2011).

3. Propositions on techno-economic feasibility analysis

The technological drivers' enabler are understood relatively well. In general, four types of technological drivers have been identified: the potential for precise replications of existing products [3], the potential for performance increase by improving product function and reducing weight [8], the potential for customising products for specific applications or individual customer needs [7], and the potential for functional integration, reducing the need for assembly [2]. Building on these characteristics, an often discussed development is the sharing of additive manufacturing resources between companies or via production hubs to enhance asset appropriation, which is enabled by the universal character of AM technologies and the lack of switching costs [4]. At the same time, AM enables the shift from globally spread (centralised, large scale) production to more local production models [2].

3.1 Economic deterministic

To make an investment decision, the forecasted profit from an investment must be assessed relative to some quantitative profitability measurements with regards to the investment needed to generate that profit [15]. As in the case of laser based additive manufacturing, production cost may give an indication that a particular AM technique is viable, most organisations are also concerned about capital costs, such as machine and process knowledge, and the risk and returns associated with investing in new manufacturing technologies. Calculating metrics such as net present value (NPV), internal rate of return (IRR), and payback period (PBP) provides insight into the real return on investment after the adoption of new processes. Metrics like NPV provide organisations with the ability to understand how investments into manufacturing technology will increase future value, measured in terms of current value. It is useful for non-linear price escalation of capital costs, which is common in aerospace [3]. The economic model which considers the time value of money is the discounted cash-flow rate of return (DCFROR). NPV is used to assess the economic viability of projects within the design space, which can then be use to comprehensively compare the process alternatives. This method is especially recommended when uncertainties are present and thus risk is a challenge [17].

3.2 Scenario development analysis

Given the large variability in goals, there is no strict format to follow by using Techno-economic analysis (TEA), it is only a framework for developing an economic assessment. Each TEA needs to be tailored to the goals of the assessment and the requirements of the applications that are being compared [18].

Techno-economic knowledge exploits future forecasting, technology design and investment theories for the purposes of evaluating the economic feasibility of complex technical systems such as laser-based additive manufacturing [3]. The future and proliferation of additive manufacturing laser enabled metallic process is unknown; however, it might be advantageous to project and estimate its future adoptions using the widely accepted model of technology diffusion as presented by Mansfield, [19].

$$p(t) = \frac{1}{1+e^{\alpha-\beta t}} \tag{1}$$

Where

p (t) = the proportion of potential users who have adopted the new technology by time t

α = Location parameter

β = Shape parameter ($\beta > 0$)

In order to examine additive manufacturing, trends in adoption rate with respect to the number of domestic unit sales of its product can be fitted using least squares criterion to an exponential curve that represents S-curve of technology diffusion as in the equation above. It is assumed that the proportion of potential units sold by time *t* follows a similar path as the proportion of potential users who have adopted the new technology by time *t*.

4. Indicators for decision analysis

Decision makers need criteria identification, Hirooka [20] asserted that the combination of engineering and economics approach is critical for any technology to transform from research to industry. This means that a comprehensive techno-economic analysis to investigate the economic potential of different scenarios as an essential step for proceeding with the sustainability agenda of the aviation industry.

4.1 Criteria identification

The first step is to identify the criteria that best reflect the company's strategic goals, situation, typical project characteristics, environment and other factors that may have an impact on such project or be a result of it (Fig. 4)

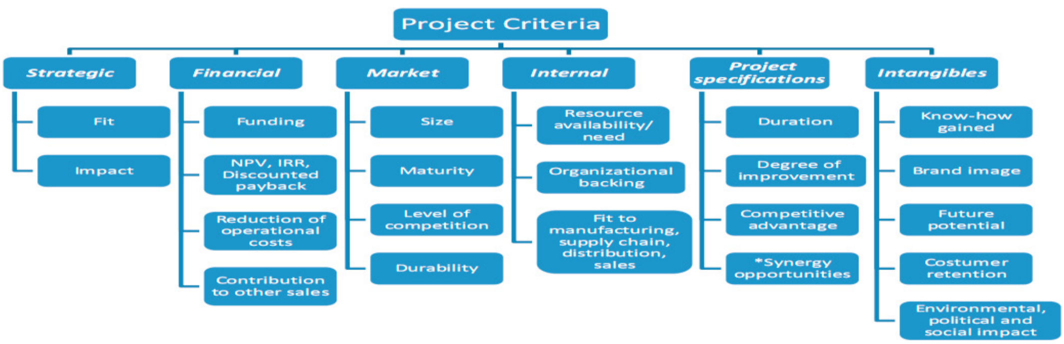

Fig. 4. List of possible criteria taxonomy (Henriksen et al., 1999)

4.2 *Methodology Application*

The approach in this research has been exploratory, using project selection methodology tool [21]. This methodology consists of the following main steps:

1. Setting the evaluation process: criteria identification, construction of descriptors of performance and reference levels, criteria value functions and criteria weighting;
2. Structuring the evaluation: project type filter, criteria selection, project data collection and triage filter;
3. Project evaluation: partial scores and overall scores;
4. Risk analysis;
5. Resource allocation;
6. Decision and conclusions.

Phillips & Bana Costa [22] explained this stated social approach and its combination with multi-criteria decision analysis. The methodology describes the main activities in the implementation process and supports a taxonomy of implementers. Hence, a single case was selected for this study in order to get an in-depth opinion of the technology in review.

4.2.1 Company background

Company A is a leading supplier and builder of aircraft components for some certain commercial planes mostly Airbus in South Africa. Amongst the industry targets is to dramatically cut aircraft component production costs through new technology through a dubbed additive manufacturing initiative out-sourced to a Council of Research Institute. By exploring the application of Titanium powder-based additive layer manufacturing for fabrication of large and complex aerospace components. In order to stimulate a wider understanding of new technology and demonstrate technology readiness levels by focusing on 'clever products' and 'clever processes'.

A monkey-structured survey was developed, using questionnaires to collect information from experts and engineers within the company. In order to capture their accumulated process knowledge which is a popular approach [23]. Guidance for identifying the most suitable survey area, identifies four most critical constituencies as: linkage with aerospace organisational importance; feasibility of execution; organisation buy-in; organisation benefit. Although, most of the information derived from experts and engineers is vague and incomputable and therefore there is a need to translate it into numerical values for mathematical quantification [24].

However, the lack of established technology standards created a significant barrier to entry into the target market; therefore the company looks to other markets. Though the company has achieved significant success the challenge for case company is that in order to maintain the business benefits of the technology, it needs to prove its production capability.

5. Results and discussion

An insight on the importance of the techno-economic criteria during policy-making can be obtained from the proposed study. In order to generate a compromise solution, this study provided a means by which decision makers can arrive at a conclusion that is scientifically based.

For example case, the challenge of changing culture and building a reputation as a production company are likely to be less influential in a Company coming from a background in traditional machining and established in an aerospace supply chain. In such a case, the challenges with understanding laser enabled additive manufacture constraints and changing a traditional production culture would likely have greater influence on implementation success (Fig. 5) have the details.

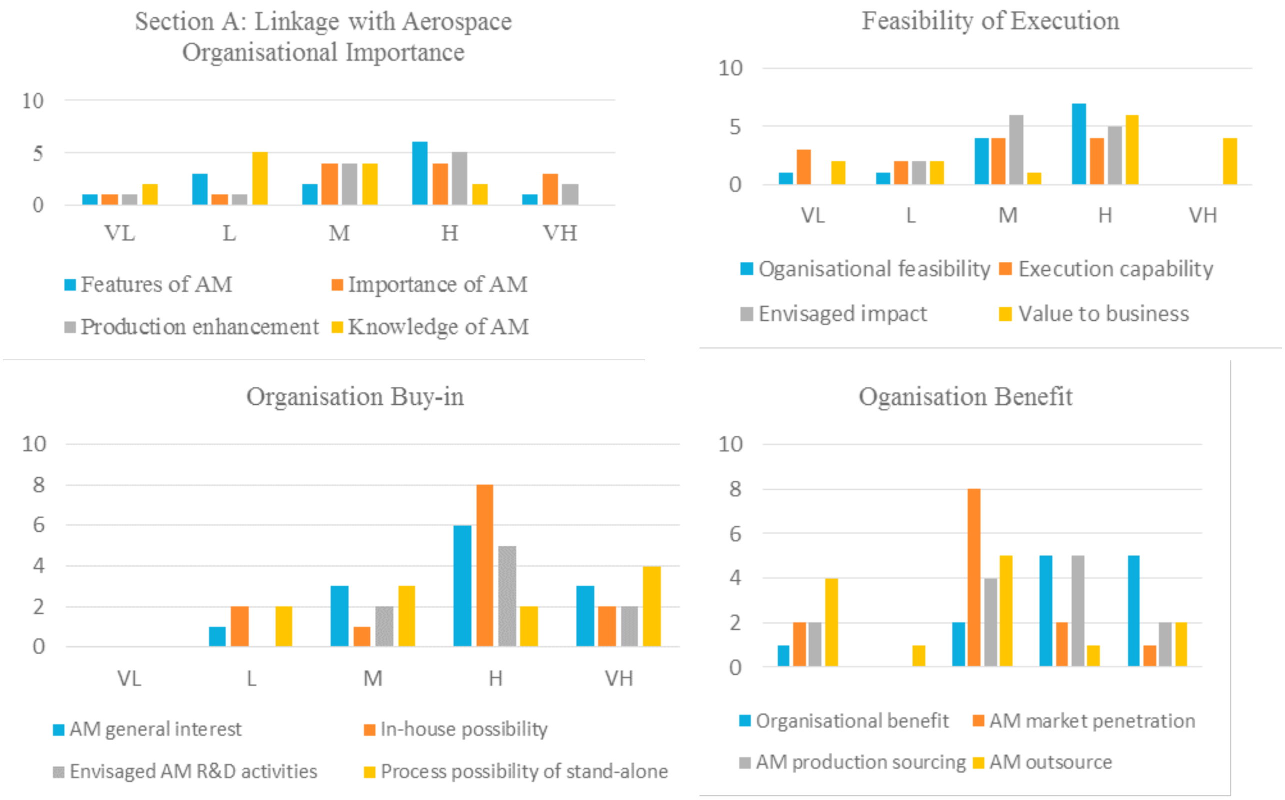

Fig. 5. The result of the case survey

Though there is unlikely to be one correct approach to implementing AM processes, this study has provided an insight through techno-economic analysis to assist managers in implementing this potentially disruptive technology class.

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Appendix A. A Survey Monkey for viability check of Additive Manufacturing processes.
Research questionnaire

Dear Participant,

You are here with invited to participate in an academic research project. The current stage of our research requires real-life data from relevant manufacturing industries. This stems from the drive to evaluate the viability of laser based additive manufacturing by developing a framework to support competitiveness and sustainability in the manufacturing industry of South Africa. Your responses will be treated with the highest confidentiality and it will be used solely for the purpose of research. Data representation in publications will also ensure anonymity and confidentiality.

We truly appreciate your willingness to participate in this important research project and the valuable time you are willing to commit in completing this research questionnaire.

Kind regards

Researchers.

Descriptions	**Symbols**
Very low	VL
Low	L
Medium	M
High	H
Very high	VH

Section A: Linkage with Aerospace Organizational Importance

Questions	VL	L	M	H	VH
How would you rate the features of additive manufacturing with respect to your organisation production					
How would you rate the importance of additive manufacturing for production activities with respect to your organisation?					
How would you rate if additive manufacturing product's innovation can enhance your production output?					
How would you rate the knowledge of additive manufacturing within your organisation?					

Section B: Feasibility of Execution

Questions	VL	L	M	H	VH
How would you rate if additive manufacturing technology is feasible for your organisation production?					
How would you rate if additive manufacturing is capable of executing existing production process?					
How would you rate if additive manufacturing could be envisaged to impact your organisation?					
How would you rate if additive manufacturing could add value to your organisation business?					

Section C: Organization Buy-in

Questions	VL	L	M	H	VH
How would you rate your general interest and satisfaction with additive manufacturing processes					
How would you rate if additive manufacturing technology could hold specific in-house production unit in your organisation?					
How would you rate if additive manufacturing technology could have standby research and development (R&D) activities within your organisation on the long-run?					
How would you rate if additive manufacturing could be a stand-alone process for production in your organisation?					

Section C: Organization Benefit

Questions	VL	L	M	H	VH
How would you rate your organisation could benefit from additive manufacturing technology?					

How would you rate market penetration of additive manufacturing products for your organisation?					
How would you rate if additive manufacturing production process could be in-source for your organisation?					
How would you rate if additive manufacturing production process could be outsource for your organisation?					

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