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Hybrid-additive manufacturing cost model: A sustainable Through-Life Engineering support for Maintenance Repair Overhaul in the Aerospace

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Abstract

The drive for a more flexible Through-life Engineering servicing technology that can enhance both productivity and profitability for the operation of maintenance, repair, overhaul (MRO) in the aerospace implores harnessing the innovation of hybrid-additive manufacturing (HAM). Hybrid manufacturing system seeks to reduce cost by utilizing the tool-less production principle of additive manufacturing combine with the conventional subtractive manufacturing for product finishing or post-processing. HAM has many merits that make it an attractive option in manufacturing of high performance products as peculiar to MRO businesses. Therefore, this paper aims to establish a cost model derived from a “Time Driven Activity Based Costing” approach for the technological integration of Hybrid system to increase economic competitiveness of highly MRO services in the aerospace industry. Hence, a unique cost formulation method was investigated through analytical technique in cost engineering models for the purpose of manufacturing processes.

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1. Introduction

Maintenance, repair, and overhaul (MRO) is a technical process that involves either restoring or retaining any sort of mechanical, systems, electrical or electronic problems when they fail to fulfil their design purpose during the life cycle [1]. In order to ensure competitiveness in the rapidly changing global marketplace, more flexible processes are needed for potential cost savings. Hence, the quest of leveraging maintenance burden to extend product life cycle through an integrated service targeted to reduce or minimize the overall cost led to seeking innovative forms. Approaches are shifting from reduction of maintenance (e.g. design for zero failures – procedures to avoid failure), and better predictability (e.g. visualize future wear) to servicing products throughout their lifecycle [2]. High value manufacturing companies are increasingly offering through-life support for their products and assuring their respective performance over the projected period of time. The revenue being generated from the TES today within aerospace and defence sectors is over 55% and it is still growing. Industrial product service systems longing for how to reduce the maintenance costs and to maximize their net profit. Based on the existing literature and industry requirements, a fully integrated technological approach stands to generate significant levels of work improvement. As a result, manufacturers in the aerospace industries are

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investigating hybrid-additive manufacturing (HAM) technique as a means of repairing valuable components to reduce operating costs [3].

In this paper, the attributes of HAM process is explored. Since the support for the MRO is increasingly becoming a necessity for the airline operators, the need to adapt the evolving technology as a Through-life Engineering Services (TES) for sustainability and competitiveness increases with time. The cost drivers of HAM are to be identified and associated with further influence factors such as time and quality which are specifically important to the aerospace industry. In the knowledge of commercial HAM, machines combine the capability of additive manufacturing to create free form geometries with little material waste by means of well-established accuracy and repeatability of machining. The HAM system allows the part to remain fixture in one machine compartment by switching between adding and subtracting material throughout the build process and finishing the inaccessible internal geometries in a unique manner. The hybrid machines were designed to compensate for the inadequate accuracy and surface roughness and to mitigate material wastage which are the disadvantages of both additive and subtractive manufacturing techniques. In figure 1, the display is a breakdown of HAM showing a laser technique additive, CNC machining and the combination of both to form Hybrid system.

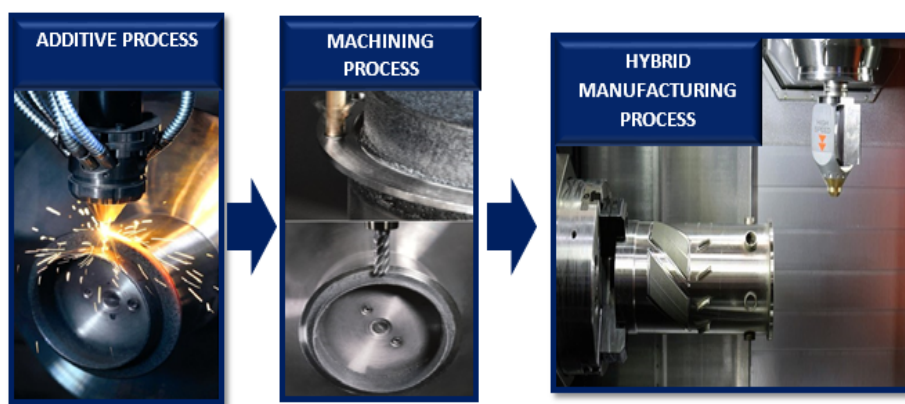


Fig. 1. Processes of Additive, Conventional and Hybrid System

2. Review knowledge

The literature review is conducted in the following categories respectively in order to fulfil the research aim, haven discussed the concept of Hybrid additive manufacturing. Therefore, Through-life Engineering services, as well as the concept of maintenance, repair, and overhaul (MRO) with respect to cost are investigated.

2.1. Through-Life Engineering Services

Through-life Engineering Services has to do with technical support needed to ensure feasible performance of a product in engineering system, from conception to design and from its projected operational life till end of life without the exception of its optimum whole life cost [4]. The tentacles of complex engineering systems where TES are often explored are as listed with application in aircraft engines and aerospace component services.

- Optimise component/system life
- Autonomous maintenance
- Cost engineering
- Managing degradation
- Application of advanced Information Technology
- Obsolescence management
- Uncertainty modelling and simulation

It is noted that the in-service phase of a product life cycle which creates the largest amount of cost and maintenance is a driver of in-service costs, which cannot be avoided due to a number of reasons such as consumables, wear, plug and play technology upgrades, and standardization of interfaces [5]. This aspect in cost engineering concept is explained better in “cost-knowledge-freedom” for the whole life cycle [6]. Figure 2 further illustrates how design knowledge, design freedom and cost committed cross path and linked to a hierarchy of process information for today and future design total production cost. Essence of Figure 2 is to provide graphical support for product-lifecycle; right from concept stage, through proper design, manufacture and operational life,

to product in-use and end of life disposal [6].

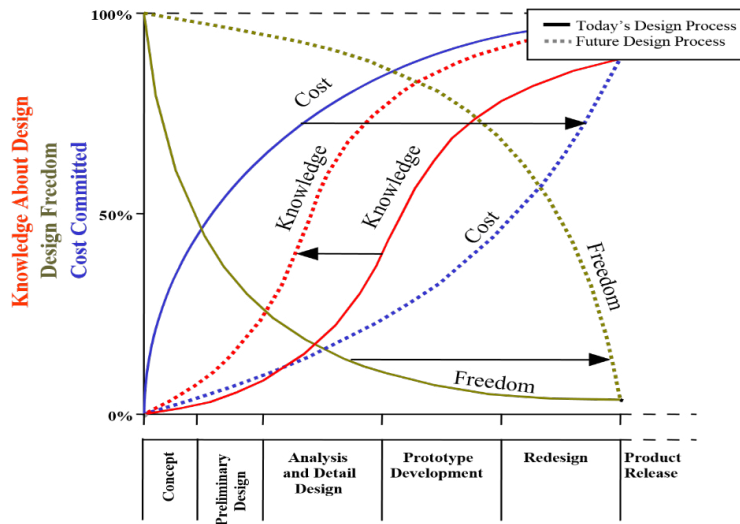


Fig. 2. The whole life cost estimation from design methods [Mavris et al., 2012].

2.2 Concept of MRO and Cost implication

There is limited literature related to modelling costs because the input variables in determining service life are stochastic [7]. Therefore modelling costs of performance-based service is a complex process and requires greater understanding of equipment usage. Maintenance, repair, and overhaul (MRO) providers ensure the airworthiness of aircrafts and their availability by maintaining all of its components which cause 10-20% of the airline's overall costs for operating an aircraft [8]. The field of MRO is noted as a high potential for economic benefits but more investigation is needed on technological and scientific optimization [1]. In another study, it was established that maintenance holds a key part of aircraft airworthiness criteria; thus, its main objective is to ensure a fully serviced, operational and safe aircraft [9].

The different types of aircraft repair are categorically illustrated according to [9]:

(1) Structural repairs: this takes place when an aircraft sustained structural damage (i.e., external skin, bulkheads, stringers, etc.). The damages to an aircraft structure are usually caused by ground service equipment, maintenance stands, bird strikes, or lightning strikes.

(2) Component repairs: this ranges from ideal part replacements till total overhaul. If a component fails to operate properly, it is removed from the aircraft and replaced by one that operates properly. The removed component is then repaired.

However, the major concern in the aerospace industry is high demand on the spare part supply chain specifically to be flexible, fast and efficient at the same time to be able to deliver the required part in time to the point of use. Similarly, the high value of aerospace parts involves the aspect of long product life cycle that comes with complex and expensive logistics. Since part availability and part quality are major requirements for spare part [6, 10]. To react to a short-term demand, improve reliability, and obtain cost savings, manufacturing flexibility index and production profile of conventional and digital manufacturing is under research to examine a process known as remanufacturing [11]. This remanufacturing technique is a process found fit within the understanding of HAM production method for sustaining MRO services.

3. Methodology

In a broad sense, a conceptual model as shown in the schematic diagram of Figure 3 is used to illustrate the arms of HAM strategies in the aerospace. The study motivation is how an integrated manufacturing system interweaves to deliver the benefit of cost reduction and production performance in a single production process.

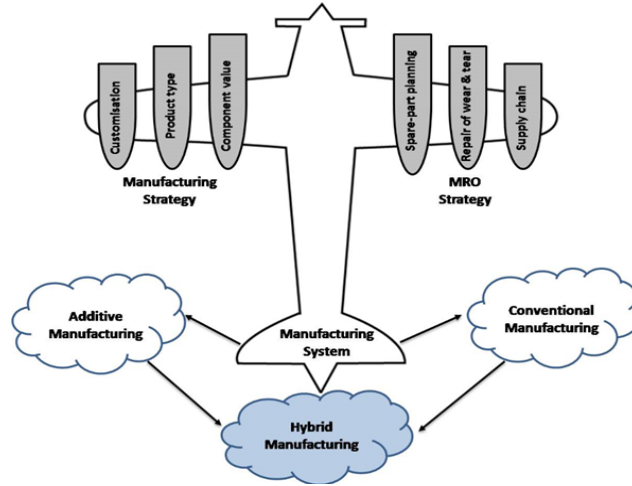


Fig. 3. Conceptual model of Hybrid manufacturing system

3.1. Cost Estimation Model

Development of the cost model consists of material and manufacturing cost (including setup and tool costs) mechanisms. A descriptive cost model for additive manufacturing was once proposed [12]. This technique was initially used for rapid prototyping (RP), but the authors provided for the development of technology that would allow the realisation of finished products in large scale. They compare the cost of three different kinds of additive manufacturing (stereolithography, fused deposition modelling and selective laser sintering) with one of the traditional molding process (injection moulding). The cost estimation model for RP process used more of a descriptive method to breakdown the AM cost into three major sections: machine costs, labour costs and material costs [12].

In manufacturing, the two main cost drivers are: direct and indirect costs, which are summarised in material, labour and overhead. In order to keep a firm running the minimum possible inputs to produce the maximum possible value for customers through competence tool is needed [3]. Noting that direct costs depend on the amount of material used and indirect costs depend on the time of construction as presented in Equation 1.

$$\text{Cost of a build} = \text{Direct costs} + \text{Indirect costs} \quad (1)$$

Where the direct costs represents the cost of the material used; and Indirect cost includes the labour, machine and overheads.

Considering cost calculation of single part in a build (assuming a contemporary production of different parts). Hence, the cost difference between AM and other processes is firstly examined through the cost of raw material to production to the final product. This can be represented by Equation 2.

$$\begin{aligned} C_{am} = & (MI_{r,am} + MI_{m,am}) + (P_{e,am} + P_{r,am} + P_{m,am}) \\ & + (FGI_{e,am} + FGI_{r,am} + FGI_{m,am}) + WT_{am} + RT_{am} + T_{am} \end{aligned} \quad (2)$$

Where, C_{am} is the cost of producing an additive manufactured product; MI is the cost of inventory for refining raw materials (r) and for manufacturing m for additive manufacturing (am); P is the cost of the process of material extraction (e), refining raw material (I), and manufacturing (m); FGI is the cost of finished goods inventory for material (I), refining raw materials (r), and manufacturing m for additive manufacturing (am); WT_{am} is the cost of wholesale trade for additive manufacturing (am); RT_{am} is the cost of retail trade for additive manufacturing (am); T_{am} is the transportation cost throughout the supply chain for an additive manufactured product (am).

When compared to the cost of traditional manufacturing, which is represented as equation 3:

$$\begin{aligned} C_{trad} = & (MI_{r,trad} + MI_{i,trad} + MI_{a,trad}) + (P_{e,trad} + P_{r,trad}) \\ & + (FGI_{e,trad} + FGI_{r,trad} + FGI_{i,trad}) + WT_{trad} + RT_{trad} + T_{trad} \end{aligned} \quad (3)$$

Where, C_{trad} is the cost of producing a product with traditional processes; MI is the cost of inventory for refining raw materials I and producing intermediate goods (i) and assembly (a); P is the cost of the process of material extraction I , refining raw material I , producing intermediate goods (i), and assembly (a); FGI is the cost of finished goods inventory for material (e), refining raw materials I , producing intermediate goods (i), and assembly (a); WT_{trad} is the cost of wholesale trade for traditional manufacturing

(*trad*); RT_{trad} is the cost of retail trade for traditional manufacturing (*trad*); T_{trad} is the transportation cost throughout the supply chain for traditional manufacturing product.

The total advantage of an additive manufacturing combined with the utility gain of traditional manufacturing methods can be represented by Equations 4-7.

$$TA_f = (F_{am,p} + F_{am,u} + F_{am,d}) - (F_{t,p} + F_{t,u} + F_{t,d}) \quad (4)$$

$$TA_l = (L_{am,p} + L_{am,u} + L_{am,d}) - (L_{t,p} + L_{t,u} + L_{t,d}) \quad (5)$$

$$TA_t = (T_{am,p} + T_{am,u} + T_{am,d}) - (T_{t,p} + T_{t,u} + T_{t,d}) \quad (6)$$

$$TA_u = U(P_{am}) - U(P_t) \quad (7)$$

TA is the total advantage of additive manufacturing compared to traditional methods in a facility (F), labour (L), time (T), and utility of the product (U); F is the facility needed using additive manufacturing process (*am*) or traditional methods (*t*) for production (P), utilization (U), and disposal (d) of the product; L is the labour hours per hour needed using additive manufacturing processes (*am*) or traditional methods (*t*); T is the time needed using additive manufacturing processes (*am*) or traditional methods (*t*); $U(P_{am})$ is the utility of a product manufactured using additive manufacturing including utility gained from increased abilities, enhancements, and use-life; $U(P_t)$ is the utility of traditional processes.

The formulation of the cost for a single build can be depicted by summing the activities costs (A_i) involved as expressed by Equation 8.

$$\text{Cost of a build} = \sum_i A_i \quad (8)$$

By estimating the summation of the integration of additive manufacturing and traditional manufacturing in a single process capacity to derive the activities such as quality control, surface treatment and support removal and limiting post processing activity. Hence, Equation 9 is the generic cost model derived from the combined integrated technique to benefit the MRO services which is a “Time Driven Activity Based costing” an approach adopted [7].

$$\sum_i C_{tot} A_i = C_{Setup}(A_i) + C_{TA}(TA_i) + C_{Postp}(A_i) \quad (9)$$

Where; $C_{tot}(A_i)$ is the total manufacturing costs, $C_{Setup}(A_i)$ is the machine set up costs, $C_{TA}(TA_i)$ is the cost for building up the part with combined effort of traditional and additive manufacturing methods, $C_{Postp}(P_i)$ is the cost for post-processing finishing technique.

3.2. Titanium Aerospace Bracket Case Study

To fully demonstrate the modelling strategies proposed with the flowchart for HAM, the authors focused on the cost analysis of a simple titanium aerospace bracket used in commercial aircraft. The existing component used to be manufactured using the conventional subtractive processes. It was constructed for Ti-64 (Titanium 6Al-4V). The bracket was modelled, based on available historical weight and calibrated complexity values of analogous components approximately 2.5 in x 2.1 in x 1 in, with a targeted weight of 40 grams.

The production is broken down into the following: Materials, Setup (Design & Machine), Machine Run Time, and Final Build Plate Removal using modified parametric framework. Where;

Materials Assumptions: The cost of Ti-64 of a ballpark - \$200; Bracket Weight – 1 kilogram; Scrap Rate – 10% (this accounted for both support structures and sintered powder particles siphoned out at the end)

Calculations: Total Bracket Material Cost - (1kg x 1.1) x \$200 = **\$220**.

Setup Assumptions: Setup Design Time - 1 hour; Setup Machine Time - 1 hour; Fully Burdened Operator - \$120,000

Calculation: Total Bracket Setup Cost - 2 hours x (120,000/2000hrs) = **\$120**

Machine Run Time Assumptions: Upfront Purchase Cost - \$750,000; Yearly Maintenance Contract Cost - \$10,000; Payback Period - 24 months; Hurdle Rate - 5% (this is the interest on the loan, the hurdle rate would be higher if we were looking for a profit as most service bureaus are); Asset Utilization - 80% is near full utilization for a typical HAM machine when accounting for maintenance and turnaround time.)

Bracket Fabrication Time: 40 hours (Maintaining the bracket is the only part on the build plate. There is variation time for fabrication between a few hours up to 130 hours.

Calculations: Monthly Machine Cost - $((750,000 \times (1 + (5\% \text{ hurdle} \times 2 \text{ years}))) + 20,000)/24 = \$35,208.33$ (This is a piece of a somewhat simplified NPV calculation that errors on the high side.). Obtainable Monthly Machine Time - $(25 \text{ days} \times 24 \text{ hours}) \times 80\% = 480 \text{ hours}$

Hourly Run Time Cost - $\$35,208.33/480 \text{ hours} = \$73.35$; Total per Bracket Run Time Cost - $40 \text{ hours} \times \$73.35 = \mathbf{\$2,934}$

Build Plate Removal Assumptions: Removal and Powder Recovery Time - 1 hour; Fully Burdened Operator - \$120,000 (2000 hours per year). Total Per Bracket Removal Costs - $1 \text{ hour} \times (120,000/2000\text{hrs}) = \mathbf{\$60}$

Some service bureaus account for this in their profit margin, but when running a printer of HAM internally, managers must understand and account for the potential fail rates in both cost and time projections.

Therefore, the check for optimal cost becomes feasible with optimal solution proposed for the sum of the direct and indirect cost $(\sum C_{in} + \sum C_d)$, which is less or equal to the total cost of building an object $(\sum A_i)$. Since the average total cost (C_{ATC}) which is equal to the sum of the average variable and fixed cost is a function of both the direct and indirect cost then Equation 10 holds thus,

$$\sum C_{ATC} \leq \sum A_i \quad (10)$$

Where Equation 10 point and leads to the optimisation of the total manufacturing costs as expressed in Equation 11 for the utility of both additive manufacturing and traditional manufacturing.

$$\min \sum C_{tot}(P_i) \quad (11)$$

On the other hand the solution becomes infeasible if the sum of the direct and indirect cost as well as the average variable and fixed costs exceeds the total cost of producing and building an object, thus, there is a need to carry out optimisation whose objective function will be to minimize the total direct and indirect cost.

Due to the novelty of HAM and high upfront investment costs required to buy the machines, the use cases is a cost-benefit driven process. The useful life should be dictated by the product iteration cycles and time to modernity or relative efficiency.

4. Conclusion

In this article, discussion is based on understanding how to properly allocate the activity-based costs associated with an integrated AM process and traditional (machining) process, where hybrid machines come into play for Through-Life servicing purpose under the capacity of maintenance repair overhaul business. This will enable manufacturer to identify the largest cost levers before manufacturing, so as to drive efficiency and targeted innovation for the technology users.

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