Proceedings Paper:
Busachi, A., Erkoyuncu, J., Colegrove, P. et al. (2018) A system approach for modelling additive manufacturing in defence acquisition programs. In: Teti, R. and D'Addona, D.M., (eds.) Procedia CIRP. 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17, 19-21 Jul 2017, Gulf of Naples, Italy. Elsevier, pp. 209-214. ISSN: 2212-8271.

https://doi.org/10.1016/j.procir.2017.12.201

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 67 (2018) 209 – 214

www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17

A system approach for modelling additive manufacturing in defence acquisition programs

Alessandro Busachi[a,*], John Erkoyuncu[a], Paul Colegrove[c], Richard Drake[b], Chris Watts[b], Filomeno Martina[c] Nikolaos Tapoglou[d], Helen Lockett[a]

[a]*Cranfield University, Colleg Road, Cranfield, MK430AL, United Kingdom*
[b]*Babcock International, Ashton House, Bristol, BS32HQ, United Kingdom*
[c]*Welding Engineering and Laser Processing Centre, Cranfield University,* Colleg Road, Cranfield, MK430AL*, United Kingdom*
[d]*University of Sheffield,Western Bank, Sheffield, S102TN, United Kingdom*

* Corresponding author. Tel.:+447790779432; *E-mail address:* a.busachi@cranfield.ac.uk

Abstract

Defence Contractors and NATO – Ministry of Defences (MoDs) are currently exploiting Additive Manufacturing (AM) Technology to improve availability of defence platforms and support soldiers deployed in remote Area of Operations (AO). Additive Manufacturing is considered a disruptive technology when employed in a military context to reduce the reliance on supply chains and improve the responsiveness to Operation Tempo (OT). This papers aims at presenting a novel system approach to model the end-to-end process of delivering a product printed with AM and estimate accurately the time and costs of AM. Understanding better the time and costs of AM will allow the MoDs and Defence Contractors to perform comparison with current practices and support their decision making in AM technology acquisition.

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Defence Acquisition; Additive Manufacturing; Systems Engineering

1. Introduction

AM has been extensively investigated in the military environment due to its ability to provide rapid, delocalized and flexible manufacturing of plastic and metal components. Deploying AM in AO's provides major advantages to the NATO – MoD's. Nevertheless, it is important to estimate the time and cost of AM to quantify the Key Performance Indicators (KPI) and make a comparison with current practices. This will allow key decision makers to adopt a data driven approach when considering AM in their technology acquisition programs. This paper presents both a novel system approach and an exhaustive AM Cost Model for estimation.

2. Literature Review

Hopkinson and Dicknes (2003) developed a cost model to provide direct comparison between "Additive Manufacturing" (AM) and injection moulding. The AM process has been broken down into machine cots, labour cost and material cost. The cost model developed is based on expert judgement, extended and educated assumption and fed by a wide range of data. Ruffo et al. (2006) advances the cost modelling on AM with the development of a cost model which considers the high impact of investment and overheads of modern manufacturing processes. The cost model considers activities associated with AM and divides them into direct and indirect costs. These activities have been translated into hourly rates (£/hour) providing evidence of the application of "Activity Based Costing" (ABC) technique. The developed "Cost Breakdown Structure" (CBS) included labour, material, machine absorption and production/administrative overheads. Moreover, the authors were able to model the costs associated with the alteration of the orientation of the part within the build chamber. Lindemann et al. (2012) Provided a further development into cost modelling for AM introducing a more consistent way of applying "Activity Based Costing" (ABC)

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2017.12.201

and “Event Driven Process Chains” (EDPC) for costing AM. The cost model has been developed to estimate the life-cycle costs of AM including the costs occurring from the conceptualisation of the design till the disposal of the product. Lindemann’s approach is based on process analysis, cost drivers analysis and product life-cycle analysis. The cost model implements “Time Driven Activity Based Costing” (TDABC) as a computation technique. According to Lindemann et al. (2012) geometrical complexity is a strong influencing factors on the product cost estimate as this has an impact on the cycle time of the machine. Moreover, the need for more accurate deposition time estimation is required. Zhai and Lockett (2012) developed an early stage cost model to compare the costs of “Wire + Arc Additive Manufacturing” (WAAM) technology and CNC. As WAAM technology is featured with high deposition rates, medium design freedom, it is applied to large aerospace structural components and the focus of their cost model is to provide an accurate product cost estimation but mostly outline a comparison

3. Methodology

In Fig.1 the followed methodology is presented. The methodology is made of 7 phases.

As follow a description of the phases:

Phase – 1 “Literature Review” A literature review has been carried out on Additive Manufacturing costing. To do this an analysis of publications on SCOPUS and Sciencedirect databases has been done with the keywords “Additive Manufacturing” and “Cost Modelling” and “Cost Estimation”. A total of 4 relevant publications have been identified.

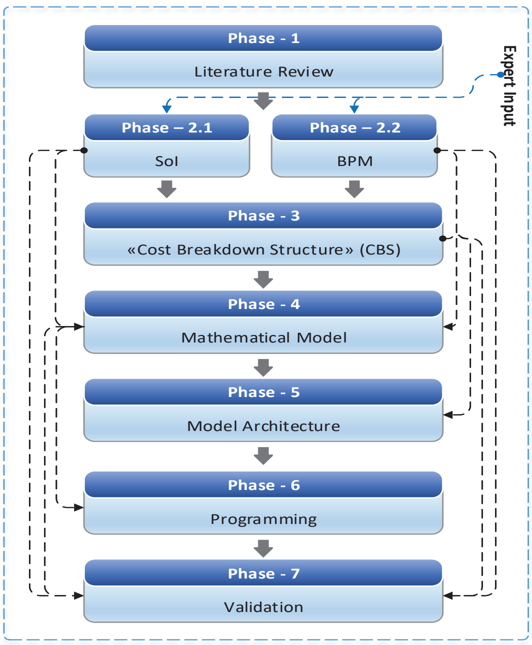

Fig. 1. Methodology.

Phase – 2.1 “System of Interest” (SoI): this represents a conceptual modelling activity which seeks to define the boundaries of the investigated system (the AM organisation), its elements, sequences, links, triggering events and dynamics.

Phase – 2.2 “Business Process Mapping” (BPM): this is the sequential conceptual modelling activity which provides a further level of information on the AM organisation and how it delivers value through its processes.

Phase – 3 “Cost Breakdown Structure” (CBS): fed by the SoI and BPM, this phase looks at defining at a conceptual level the CBS. The CBS represents also the desired Model output which needs to be as detailed as possible on the FDM system.

Phase – 4 “Mathematical Model”: fed by the SoI, BPM and CBS, this phase aims at developing the equations which represents the occurrence of costs during the process of delivering value within the AM organisation. This phase is based on the work of Zhai and Lockett (2012).

Phase – 5 “Model Architecture”: this phase aims at studying and defining the logic of the cost model, how the code should be written, what are the inputs/outputs, how to display them to make them significant and how to keep the model flexible in order to make it functional and adaptable to various organisations.

Phase – 7 “Validation”: this phase aims at validating the cost model in both ways, through the validation of the process to develop it and through case studies with real organisation in order to compare the results and verify the accuracy and reliability of the model.

Table 1 – List of Experts

Years of Experience	Position	Organisation
20	Managing Director	R&D Company
7	Project Engineer	R&D Company
20	Head of Manufacturing	R&D Company
15	Senior Lecturer	Academia

In order to develop the SoI and BPM, relevant experts have been identified and presented in Table 1and four unstructured interviews have been carried out to elicit and capture expert judgement.

4. System of Interest (SoI)

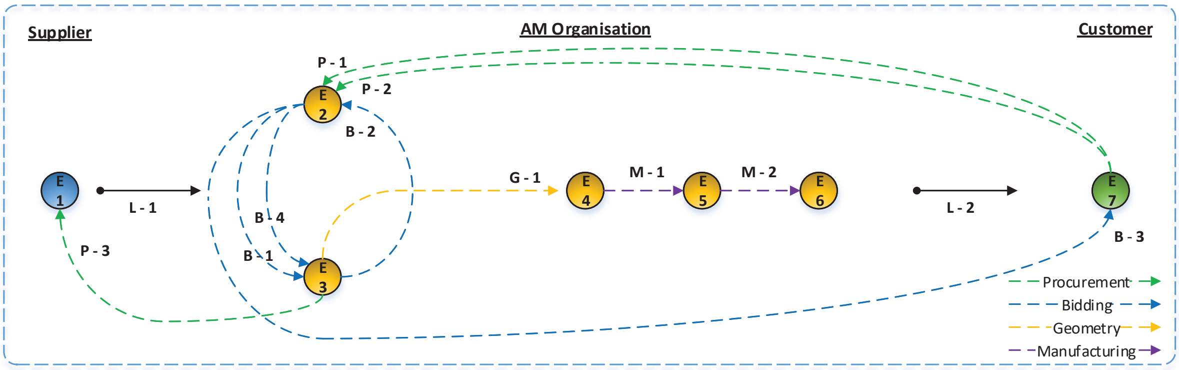

Fig. 2. System of Interest (SoI).

This section outlines the results of the definition of the "System of Interest" (SoI) which has been used for developing the model. The SoI is a critical visual model which outlines information related to the boundaries of the model, the system elements, links, sequences and triggering events. The SoI does not aim to represent exhaustively the complexity of the real world, it rather aims to provide a simplified version.

The SoI which will feed the Modelling phase, is visualised in Fig. The SoI is made of 3 entities, the supplier of Raw Materials, the AM Organisation and the Customer.

Table 2 - System Elements

System Elements (SE)	
E – 1	Raw Material supplier
E – 2	AM Organisation – Commercial
E – 3	AM Organisation – Technical
E – 4	AM Organisation -- FDM
E – 5	AM Organisation – Post Processing
E – 6	AM Organisation – 3D Scanner
E – 7	Customer

The core of the SoI is the AM Organisation which is comprehensive of a commercial element (E-2) in charge of sales activities and setting Selling Price and Delivery Date, a technical element (E-3) responsible to process geometries and perform estimates on Cost and Lead Time, a Fused Deposition Modelling (FDM) element (E-4) responsible to convert the 3D CAD Files into a physical product, post-processing element (E-5) which converts the near-net shape product into a net shape one and finally a 3D Scanner (E-6) which performs Quality Assurance tests. On the sides of the SoI the supplier (E-1) of Raw Material and the customer (E7) are located.

The aim of the system is to create and deliver value to the customer (E-7). The value creation is obtained through the interaction of E1/E2/E3/E4/E5/E6/E7 which are interconnected through links outlined in Table 3.

Table 3 - Links between Elements

Links between Elements	
P – 1	Procurement – (E-7) sends Request for Quotation to (E-2)
P – 2	Procurement – (E-7) places order to (E-2)
P – 3	Procurement – (E-3) requests Raw Material from supplier (E-1)
B – 1	Bidding – (E-2) requests (E-3) for technical review of RfQ and estimates on Cost and Lead Time
B – 2	Bidding – (E-3) provides estimates on Cost and Lead Time to (E-2)
B – 3	Bidding – (E-2) develops Delivery Date and Price and quotes to (E-7)
B – 4	Bidding – (E-2) places order internally and requests (E-3) to perform geometric work
G – 1	Geometric – (E-3) performs geometric work and develops Control Files for FDM machine
M – 1	Manufacturing – FDM machine receives Control Files and prints the product
M – 2	Manufacturing – AM product is post processed and sent to Quality Assurance (3D Scanner)
L – 1	Inbound Logistics – From Supplier (E-1) to AM Organisation
L – 2	Outbound Logistics – From AM Organisation to Customer (E-7)

In order to obtain a further level of information regarding the value creation process of the AM Organisation, a process analysis has been carried out and presented in the form of a Process Map outlined in Fig. . The process analysis outlined that the AM Organisation is made of 3 interconnected processes: 1) Bidding Process, 2) Geometric Process and 3) Manufacturing Process. The Process Map has been developed in order to atomize the business processes into the necessary sequential activities. Moreover, this type of documents provides an extensive number of information such as INPUTS/OUTPUTS, responsibility of activities, necessary resources, decisions and scenarios.

5. Business Process Map

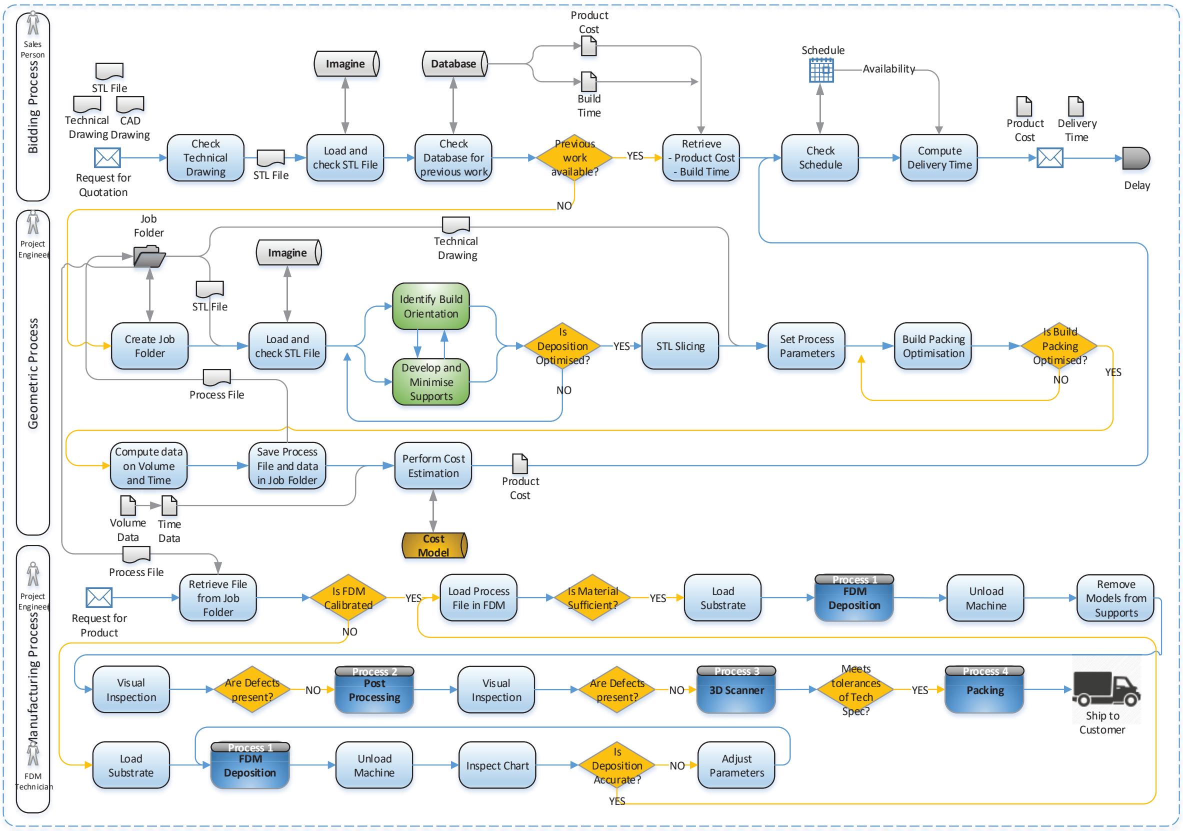

Fig. 3. Process map.

5.1. Bidding process

This process is featured by seven sequential activities and is triggered by the "Request for Quotation" (RFQ). A Sales persona and an Engineer with FDM experience is responsible to carry out all the activities. The Engineer is supported by an "Additive Manufacturing" (AM) software which is able to read STL files which contains the data on the geometry. The aim of the process is to provide customers with two key decision variables: lead time and product price. Based on these two variables the customer will draw its decision on placing an order or select another supplier. If a geometry has been processed before by the engineer, the data on product cost and price are already available on a database. If the geometry has not been processed before the engineer has to go through the geometry preparation process in order to complete the bidding process.

5.2. Bidding process

This process is made of nine sequential activities and is triggered by the need to retrieve data on product volume and time of deposition. The process has two aims, prepare an STL to control an FDM deposition and obtain an early estimate on product cost. Key activities are: build orientation identification, development and minimization of supports and finally cost estimation. These activities do not have standard cycle times and vary significantly.

5.3. Bidding process

This process is made of three main sub-processes and eleven activities. The sub-processes are FDM process, post-processing and 3D scanning. The deposition process is triggered by the arrival of the order by the customer. It has to be outlined that the FDM machine has to be calibrated each build.

Through the interviews with experts, it was possible to develop two scenarios that occur within an AM Organisation and outline the worst case and best case for each of them.

Scenario 1 – "previous experience is available": an STL file has been already processed and is stored and available for printing. Cost and cycle times have been already computed therefore the Sales person has only to compute the delivery time through the interrogation of the schedule of the machine. Has to be outlined that prices might have to be adjusted to changes in the macro environment (i.e. material cost increment).

Scenario 2 – "previous experience is not available": the engineer has not processed the STL file before; therefore, he has to complete the geometry preparation process. Cycle times may vary dramatically based on project complexity.

6. Additive Manufacturing Cost Model

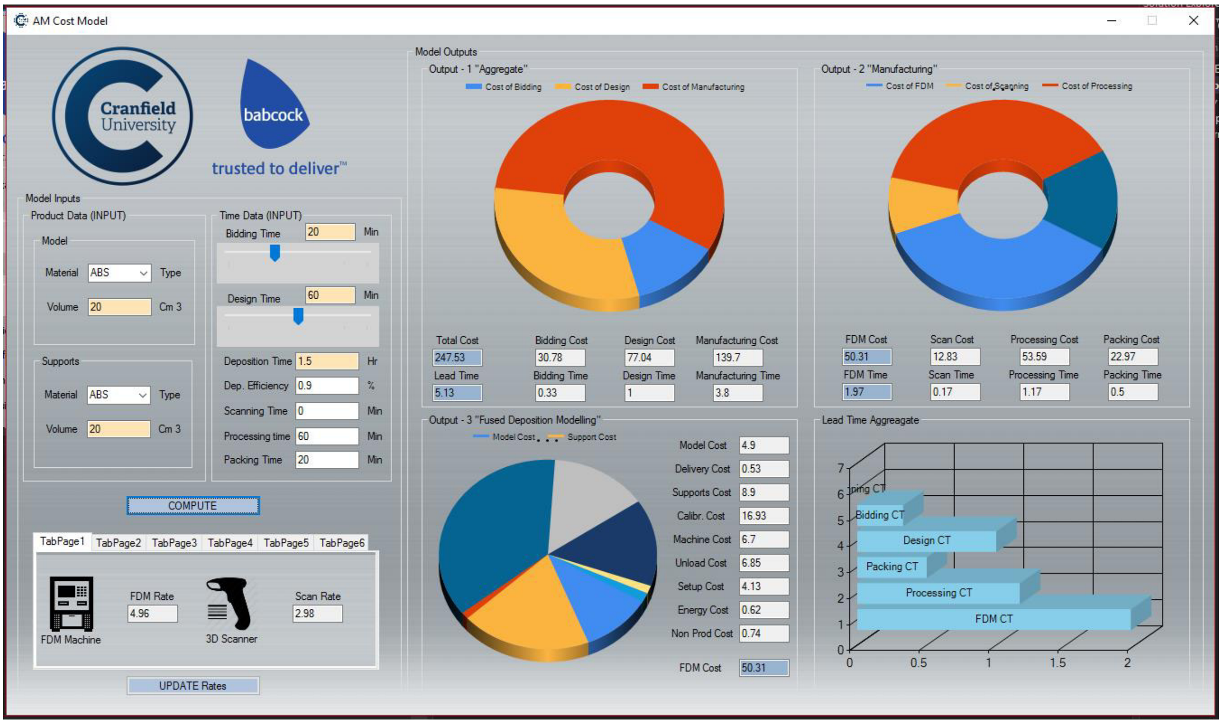

Fig. 4. Additive manufacturing cost model.

The Additive Manufacturing Cost Model is outlined in Fig. and can perform an accurate and detailed estimation of the process to deliver a plastic component printed with Fused Deposition Modelling (FDM). The Cost Model considers mainly three processes to deliver the component: 1) Bidding Process, 2) Design Process and 3) Manufacturing Process.

The CBS is the Model Output which has to be as detailed and comprehensive as possible. The CBS has been developed through logical inferences and analysis of the combined SoI and BPM. The CBS is made of the cost of bidding, the cost of preparing the geometry for AM and the cost to manufacture it. While the cost of bidding and the cost of preparing the geometry have been included at a high level, the cost of manufacturing has been atomised.

6.1. Rates Calculation

Three main rates have to be computed as these are consumed in the Bidding, Geometry preparation and Manufacturing process. These are divided into two main categories:

The rate of the machines (FDM and 3D Scanner) is calculated as follows and considers the initial investment, the time of utilisation, the utilisation rate and the overheads for factory space, consumables and maintenance:

$$\boldsymbol{R_m} = \frac{\boldsymbol{Inv_{Cost}}}{\boldsymbol{T_u * R_u}} \,/\, (\boldsymbol{1 - O_v}) \qquad (1)$$

Where:
$\boldsymbol{R_m}$ = *Rate of Machine*
$\boldsymbol{Inv_{Cost}}$ = *Investment Cost*
$\boldsymbol{T_u}$ = *Time of Utilisation*
$\boldsymbol{R_u}$ = *Rate of Utilisation*
$\boldsymbol{O_v}$ = *Overheads*

The rate of the software employed for processing the geometry and converting a 3D CAD File into an STL which can control the machine is calculated considering the initial investment, the time of utilisation and the utilisation rate:

$$\boldsymbol{R_s} = \frac{\boldsymbol{Inv_{Cost}}}{\boldsymbol{T_u * R_u}} \qquad (2)$$

Where:
$\boldsymbol{R_s}$ = *Rate of Sofware*
$\boldsymbol{Inv_{Cost}}$ = *Investment Cost*
$\boldsymbol{T_u}$ = *Time of Utilisation*
$\boldsymbol{R_u}$ = *Rate of Utilisation*

The rate of the human resources is calculated as follow:

$$\boldsymbol{R_{sa}} = \frac{\boldsymbol{G_s * C}}{\boldsymbol{A_{hr}}} * \boldsymbol{O_v} \qquad (3)$$

Where:
$\boldsymbol{R_{sa}}$ = *Rate of Salary*
$\boldsymbol{G_s}$ = *Gross Salary*
$\boldsymbol{C}$ = *Contribution*
$\boldsymbol{O_v}$ = *Overheads*
$\boldsymbol{A_{hr}}$ = *Annual Hours*

7. Discussion

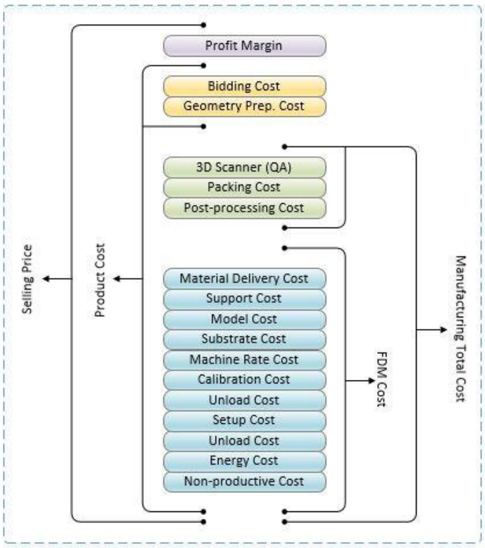

Fig. 5. Cost breakdown structure (CBS).

This applied research project aims at developing a Cost Model to estimate the time and costs of the end-to-end process to deliver a component printed through Additive Manufacturing. The CBS is the Model Output which has to be as detailed and comprehensive as possible. The CBS has been developed through logical inferences and analysis of the combined SoI and BPM. The CBS outlined in Fig. , presents 15 cost elements which occur within an AM Organisation which added together represent the Total Cost of the end-to-end process of delivering value to customer. The cost to manufacture is made of the Fused Deposition Modelling (FDM) cost for printing the part, the Post-processing cost to obtain a finished part, the 3D scanner used for Quality Assurance to measure the physical tolerances of the part and finally the packing of the part for delivering it to the customer. The Cost Model is also able to estimate the cost and time of the bidding process and geometry preparation process. The User needs to provide 10 Inputs to the Model to retrieve a Cost Breakdown Structure of 15 cost elements in Fig. .

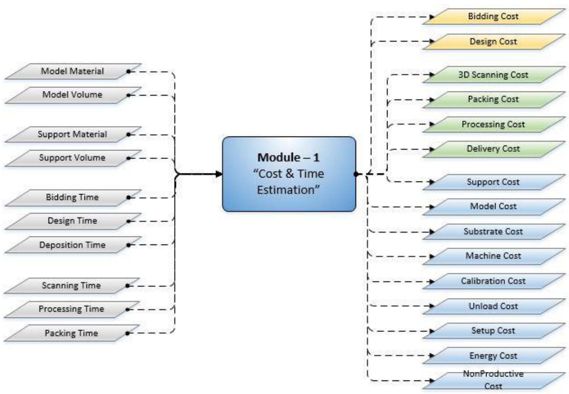

Fig. 6. Cost model inputs/outputs.

8. Conclusion and Future Work

The current Cost Model represents a good starting point for estimating the time and cost of delivering an AM printed component nevertheless the model is featured with some limitations. Firstly, the geometry complexity of the design has an impact on the time of deposition due to increased movement of the deposition nozzle to deposit the features. Moreover, the orientation of the part has an impact on the time of deposition due to the related support volume. Furthermore, an equation would be required to estimate the time of deposition having as input the volume of material. Additionally, build failures may occur resulting in loosing time and cost. This should be included nevertheless there is a lack of data of failure rates. During a deposition the wire might deplete and an operator should replace it. Nevertheless, this is dependent on the part volume and the level of the canister and a standard case is difficult to define. It is reporter by users that higher degree of utilization of the build chamber have a positive impact on the time of deposition as the deposition efficiency increases. Activities related to the 3D Scanner should be modelled as these might consume time. Moreover, the processing time of the acquired data through the 3D Scanner might be higher than the actual acquisition. Finally, the 3D Scanner might not be used in all cases therefore this should be an option in the model.

9. Acknowledgement

The Authors would like to thank Dr Richard Drake, Dr Chris Watts, Steve Wilding of Babcock International, KW Special Projects for their valuable contribution. This research is performed within the EPSRC Centre for Innovative Manufacturing in Through-Life Engineering Services, grant number EP/1033246/1.

10. References

[1] Hopkinson, N., Dicknes, P. Analysis of rapid manufacturing—using layer manufacturing processes for production. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217, 2003; pp. 31–39.

[2] Lindemann, C., Jahnke, U., Moi, M., Koch, R. Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing. Solid Freeform Fabrication Symposium. 2012.

[3] Ruffo, M., Tuck, C., Hague, R. Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes. Proceedings of the Institution of Mechanical Engineers, Journal of Engineering Manufacture. 2006.