

"A System Approach for Modelling Additive Manufacturing Cost and Time"

1. Introduction

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. This project is part of the PhD in Systems Engineering titled "Modelling Applications of Additive Manufacturing in Defence Support Services" sponsored by Babcock International and carried out in Cranfield University.

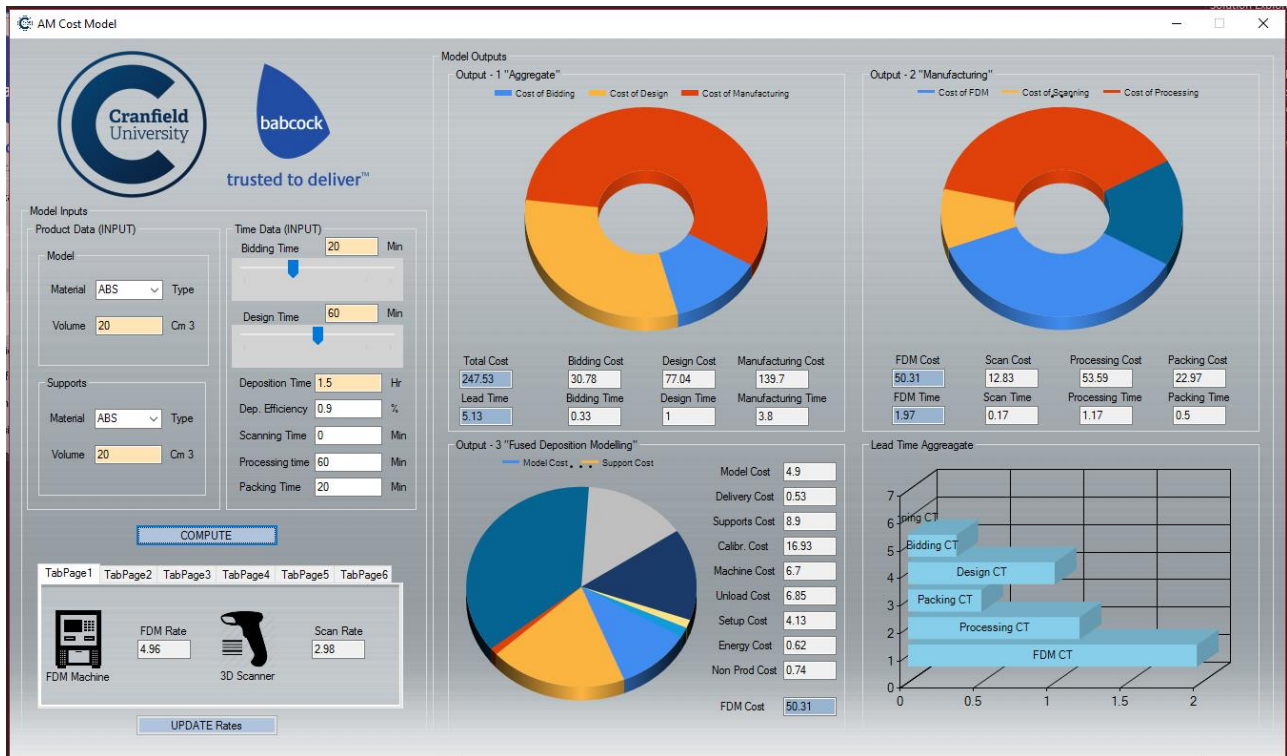


Figure 1 - Additive Manufacturing Cost Model

The Additive Manufacturing Cost Model is outlined in Figure 1 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.

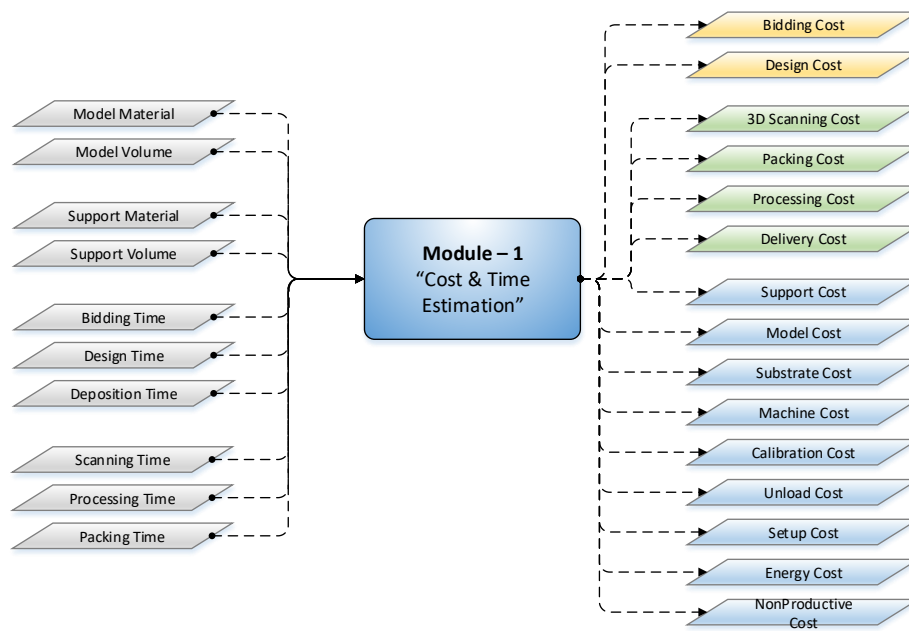


Figure 2 - Cost Model INPUTS/OUTPUTS

The User needs to provide 10 Inputs to the Model to retrieve a Cost Breakdown Structure of 15 cost elements, these are outlined in Figure 2. As follow the description of the System Approach followed to develop the Additive Manufacturing Cost Model.

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 costs, 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) 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 stages 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 on the buy-to-fly ratios. The cost model has been developed combining process mapping and “Activity Based Costing” (ABC).

2. Model Development

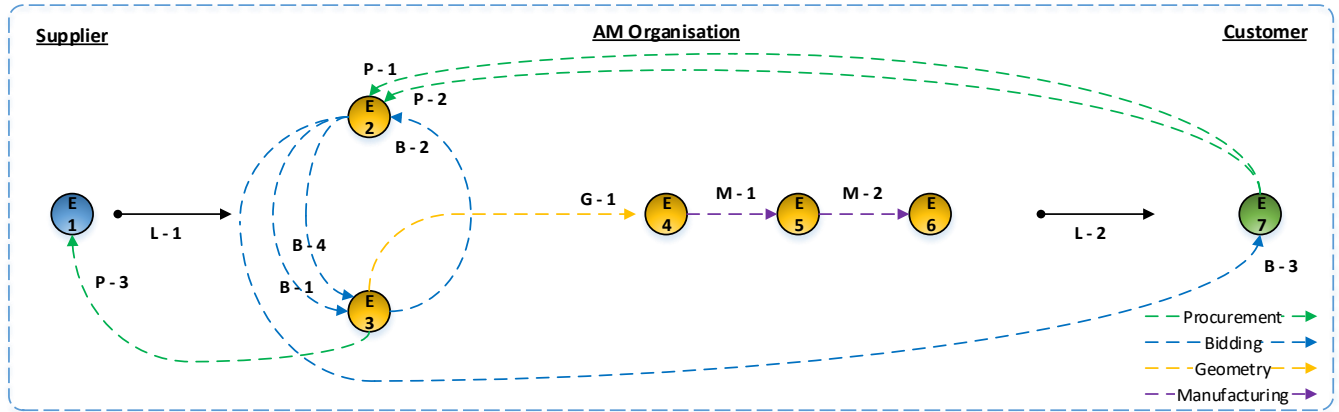


Figure 3 - System of Interest (Sol)

2.1 Define the System of Interest (Sol)

This section outlines the results of the definition of the “System of Interest” (Sol) which has been used for developing the model. The Sol is a critical visual model which outlines information related to the boundaries of the model, the system elements, links, sequences and triggering events. The Sol does not aim to represent exhaustively the complexity of the real world, it rather aims to provide a simplified version. The Sol which will feed the Modelling phase, is visualised in Figure 3. The Sol is made of 3 entities, the supplier of Raw Materials, the AM Organisation and the Customer.

Table 1 - 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 Sol 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 Sol 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 2.

Table 2 - 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)

2.2 Business Process Mapping

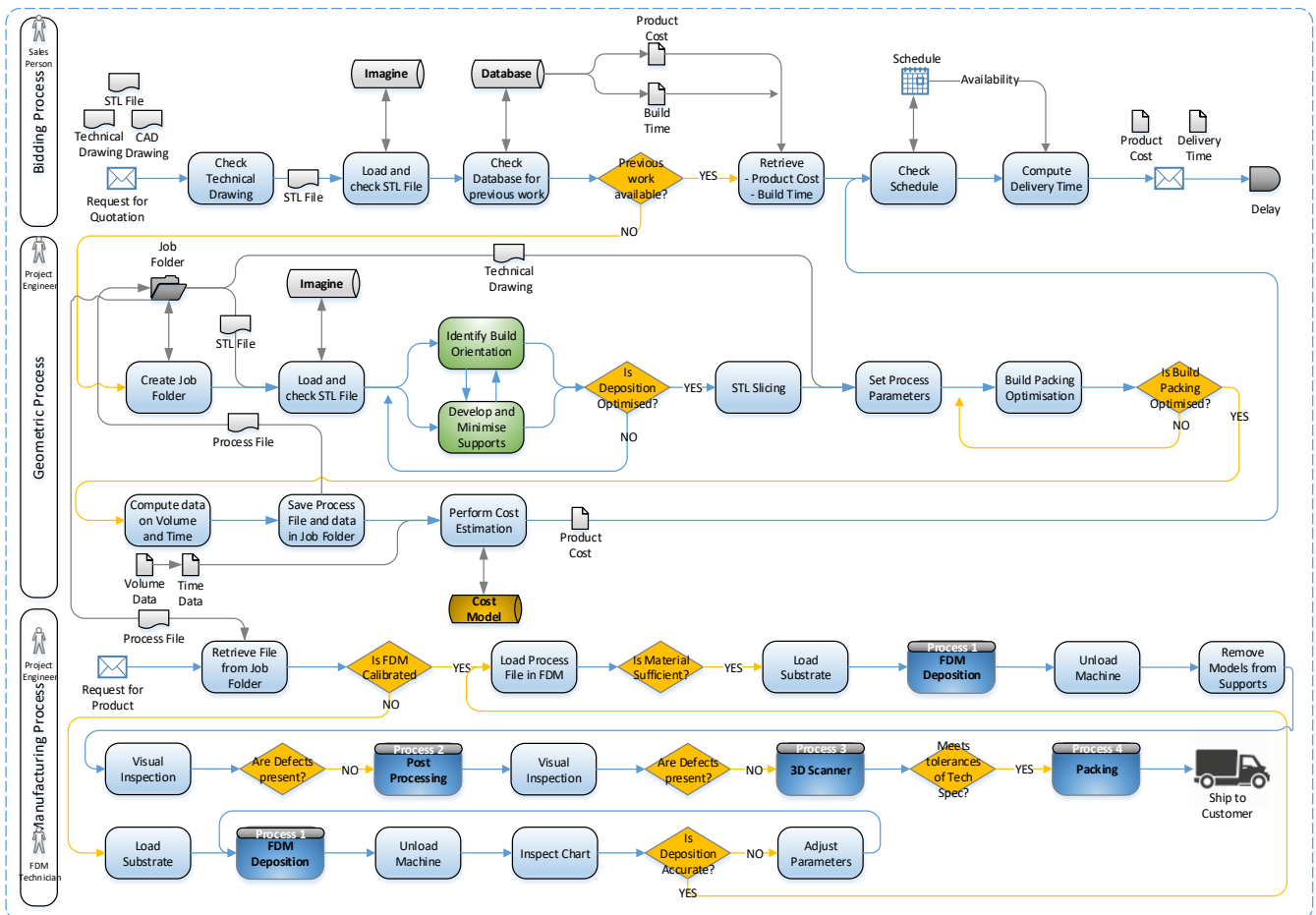


Figure 4 - Process Map

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 Figure 4. 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.

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.

Geometry preparation 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.

Manufacturing 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.

Scenarios Development

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).
 - Best Case Scenario: 30 minutes
 - Worst Case Scenario: 40 minutes

- 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.
 - Best Case Scenario: 60 minutes
 - Worst Case Scenario: 175 minutes

3.1 Cost Breakdown Structure (CBS)

This section aims to define and present the desired “Cost Breakdown Structure” (CBS) at a conceptual level. 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 Sol and BPM. The CBS outlined in Figure 5, presents 17 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 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.

This has been made to gather the highest level of detail possible focusing especially on the FDM system.

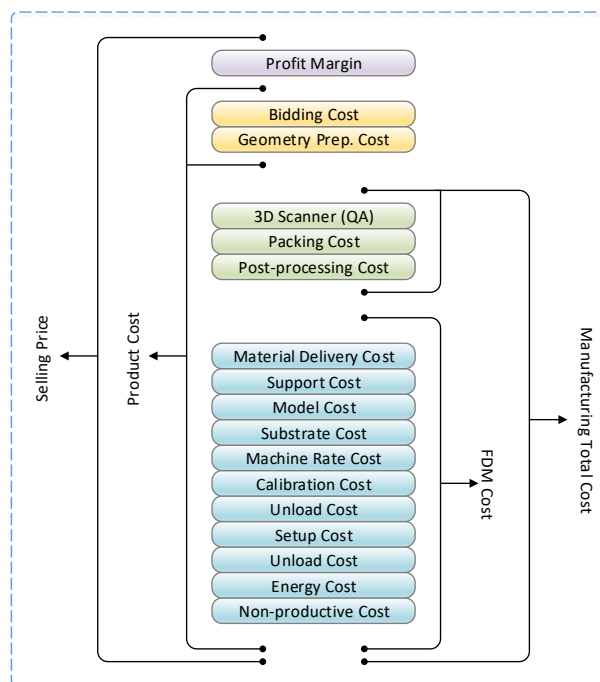


Figure 5 – Cost Breakdown Structure

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.

In order to obtain the desired CBS as a Model Output, resources consumed during the activities/processes have to be identified, the hourly rate of the initial investment in equipment, software and personnel have to be computed based on expected yearly utilisation, finally Cycle Times (CT) have to be identified.

3.2 Mathematical Modelling

Rates Calculation

Six 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:

- Capital Intensive Resources: Fused Deposition Modelling, Software and 3D Scanner
- Human Resources: Engineer, Technician and Sales representative

Capital Intensive Resources

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:

$$R_m = \frac{Inv_{Cost}}{T_u \cdot R_u} / (1 - O_v) \quad (1)$$

Where:

R_m = Rate of Machine

Inv_{Cost} = Investment Cost

T_u = Time of Utilisation

R_u = Rate of Utilisation

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:

$$R_s = \frac{Inv_{Cost}}{T_u \cdot R_u} \quad (2)$$

Where:

R_s = Rate of Software

Inv_{Cost} = Investment Cost

T_u = Time of Utilisation

R_u = Rate of Utilisation

Human Resources

The **rate of the human resources** is calculated as follow:

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

R_{sa} = Rate of Salary

$G_s = \text{Gross Salary}$

$C = \text{Contribution}$

$O_v = \text{Overheads}$

$A_{hr} = \text{Annual Hours}$

Bidding Process

The bidding process is modelled considering only the rate of the sales representative and the time to develop a technical offer and perform the cost estimation:

$$Bid_c = R_{sa} * Bid_{time} + Est_{time} * (R_{sa} + R_s) \quad (4)$$

Where:

$Bid_c = \text{Bidding Cost}$

$R_{sa} = \text{Rate of Salary}$

$Bid_{time} = \text{Bidding Time}$

$Est_{time} = \text{Estimation Time}$

$R_s = \text{Rate of Software}$

Geometry Preparation Process

The Geometry preparation process is modelled considering the rate of the designer, the rate of the software involved and the time to prepare a design for deposition:

$$Geo_c = Des_{time} * (R_{sa} + R_s) \quad (5)$$

Where:

$Geo_c = \text{Geometry Preparation Cost}$

$Des_{time} = \text{Design Time}$

$R_{sa} = \text{Rate of Salary}$

$R_s = \text{Rate of Software}$

Manufacturing Process

The FDM unit is modelled considering the cost of the deposition, the cost of the material and finally the cost of handling prior and after the deposition. As follow the list of the equations:

$$FDM_c = Dep_c + Mat_c + Han_c \quad (6)$$

Where:

$$FDM_c = FDM \text{ Cost}$$

$$Dep_c = Deposition \text{ Cost}$$

$$Mat_c = Material \text{ Cost}$$

$$Han_c = Handling \text{ Cost}$$

Deposition Cost

$$Dep_c = Cal_c + En_c + Non_c + Mac_c \quad (6.1)$$

Where:

$$Dep_c = Deposition \text{ Cost}$$

$$Cal_c = Calibration \text{ Cost}$$

$$En_c = Energy \text{ Cost}$$

$$Non_c = Non - productive \text{ Cost}$$

$$Mac_c = Machine \text{ Cost}$$

$$Cal_c = (time_v * R_m) + (time_v * R_{sa}) + (time_v * KW_{abs} * KW_{rate}) + Mat_{dep} \quad (6.1.1)$$

Where:

$$time_v = Time \text{ Variable}$$

$$R_m = Rate \text{ of Machine}$$

$$R_{sa} = Rate \text{ of Salary}$$

$$KW_{abs} = KW \text{ Absorbed}$$

$$KW_{rate} = KW \text{ Rate}$$

$$Mat_{dep} = Material \text{ Deposited}$$

$$En_c = Dep_{time} * KW_{abs} * KW_{rate} \quad (6.1.2)$$

Where:

$Dep_{time} = \text{Deposition Time}$

$KW_{abs} = \text{KW Absorbed}$

$KW_{rate} = \text{KW Rate}$

$$Non_c = Dep_{time} * (1 - FDM_{Eff}) * R_m \quad (6.1.3)$$

Where:

$Dep_{time} = \text{Deposition Time}$

$FDM_{Eff} = \text{FDM Efficiency}$

$R_m = \text{Rate of Machine}$

$$Mac_c = Dep_{time} * FDM_{Eff} * R_m \quad (6.1.4)$$

Where:

$Dep_{time} = \text{Deposition Time}$

$FDM_{Eff} = \text{FDM Efficiency}$

$R_m = \text{Rate of Machine}$

Material Cost

$$Mat_c = Sub_c + Mod_c + Sup_c + Del_c \quad (6.2)$$

Where:

$Sub_c = \text{Material Substrate Cost}$

$Mod_c = \text{Model Cost}$

$Sup_c = \text{Support Cost}$

$Del_c = \text{Delivery Cost}$

$$Mod_c = V_{dep} * \left(\frac{Cont_c + Del_c}{Cont_v} \right) \quad (6.2.1)$$

Where:

$Mod_c = \text{Model Cost}$

V_{dep} = Volume of Deposition

$Cont_c$ = Container Cost

Del_c = Delivery Cost

$Cont_v$ = Container Volume

$$Sup_c = V_{dep} * \left(\frac{Cont_c + Del_c}{Cont_v} \right) + Sub_c \quad (6.2.2)$$

Where:

Mod_c = Model Cost

V_{dep} = Volume of Deposition

$Cont_c$ = Container Cost

Del_c = Delivery Cost

$Cont_v$ = Container Volume

Sub_c = Substrate Cost

Handling Cost

$$Han_c = Unl_c + Set_c \quad (6.3)$$

Where:

Han_c = Handling Cost

Unl_c = Unload Cost

$Setup_c$ = Setup Cost

$$Set_c \text{ and } Unl_c = time_v * (R_m + R_{sa}) + (time_v * KW_{abs} * KW_{rate}) \quad (6.3.1)$$

Where:

$time_v$ = Time Variable

R_m = Rate of Machine

R_{sa} = Rate of Salary

KW_{abs} = KW Absorbed

KW_{rate} = KW Rate

The post-processing activity is carried out by hand by an operator. In order to model this cost, the salary and consumables rate is computed and multiplied by the time required for finishing the printed component.

$$Post_c = Fin_{time} * (R_{sa} + R_c) \quad (7)$$

Where:

$$Post_c = Post - processing Cost$$

$$Fin_{time} = Finishing Time$$

$$R_{sa} = Rate of Salary$$

$$R_c = Rate of Consumables$$

The Quality Assurance (QA) activity is carried out through the utilization of a 3D Scanner. The cost associated with this is modelled using the rate of the 3D Scanner and the technician multiplied by the scanning time.

$$QA_c = Scan_{time} * (R_{sa} + R_m) \quad (8)$$

Where:

$$QA_c = Quality Assurance Cost$$

$$Scan_{time} = Scanning Time$$

$$R_{sa} = Rate of Salary$$

$$R_m = Rate of Machine$$