Developing an Understanding of the Cost of Additive Manufacturing

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1 Introduction to Product Cost Estimation

Making good estimates of cost is very important for any successful and effective organisation. Normally, the goal of cost estimation is to enable the management of a business to make decisions by providing detailed information required to control current activities and plan future ones. In the context of the manufacturing business, cost estimation is used to control current processes, improve existing products, design future products and decide which new technology and equipment to adopt. It is, therefore, important for a multitude of decisions. The accuracy and consistency of cost estimation is critical as it determines the quality of this decision-making, and thus shapes the overall performance and effectiveness of an organisation. Overestimation of cost is bound to result in, among many other things, loss of sales and goodwill in the marketplace. Underestimation of cost is likely to result in financial shortfalls or losses. Because cost estimation is so important in manufacturing, a large body of research on costing methods, concepts and techniques have emerged (for an overview, see Niazi et al. 2006). This chapter explores which costing approaches are helpful to understand the costs incurred through the operation of Additive Manufacturing (AM) technology and how they can be used in practise. A number of textbooks exist on product cost estimation techniques used in the engineering domain to address a broad range of issues, spanning production cost estimation for standard components, cost analyses of complex products, cost optimization, rough and detailed costing methods supporting design, estimation of overhead costs and life cycle costing (see, for example, Ostwald 1992; Clark 1997; Brimson 1991). Available product cost estimation techniques can be assigned to individual categories, which provides an initial orientation. Figure 1 summarises a classification of cost estimation methods.

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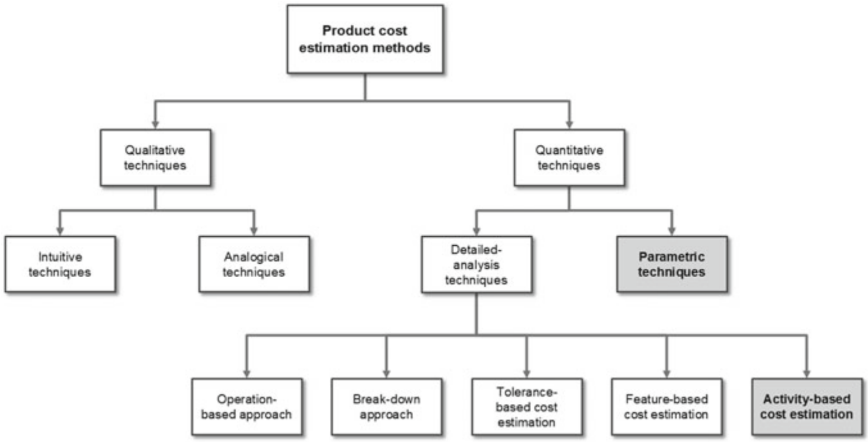

Fig. 1 Classification of product cost estimation techniques (adapted from Niazi et al. 2006)

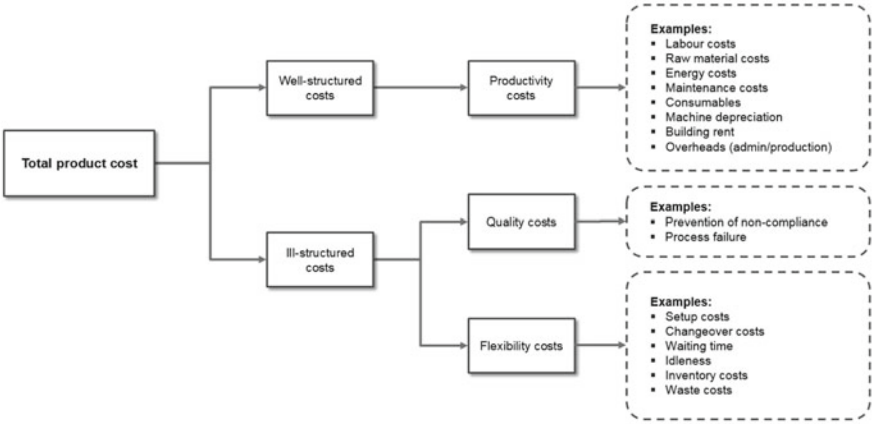

Fig. 2 Types of costs found in product cost estimation (adapted from Son 1991)

To identify which kinds of costs to include, and hence define the scope of a cost analysis, it is further helpful to classify costs by type. To support the analysis of the costs of advanced manufacturing technologies, a categorization relating to productivity, quality and flexibility has emerged. Additionally, when investigating costs in complex systems, it is useful to distinguish between well-structured costs and ill-structured costs (Son 1991). Well-structured costs are costs that are sufficiently well understood by accountants, for example, the costs of raw materials. Ill-structured costs, however, are costs that are not well understood due to limitations in knowledge or data or lacking accounting practise. Figure 2 summarises the general relationship between these categories and provides examples for each.

Having established the background and purpose of cost estimation, this chapter continues with a brief summary of existing AM cost estimation methods and models. This is followed by a section containing a step-by-step tutorial on how to build such cost models. The subsequent part discusses how such models can be applied to a common type of investigation known as breakeven analysis. This is followed by identification of problems with the simple cost models presented in this chapter and extensions that have been proposed to address these problems. Following this, it is briefly explained how to use specific cost estimates as a, particularly simple methodology to arrive at rough estimates of the cost of AM. The chapter ends with a series of conclusions.

2 Understanding the Characteristics of Additive Manufacturing Cost Models

Analyses of production costs come in two different flavours, namely, cost estimation techniques, which are referred to in this chapter as *cost estimators*, and *cost models*. The difference lies in their purpose. Cost estimators are specified to yield insight into the absolute cost performance within a manufacturing approach; they are judged on the basis of their accuracy and consistency. Cost models, on the other hand, are designed to represent cost relationships—their goal is, therefore, not only to produce valid cost estimates but to also reflect the relationships between various relevant aspects. For this reason, cost models are judged on their ability to capture important aspects in an appropriate way as well as on the accuracy and consistency of their results.

Investigations of the costs incurred by AM are of interest to a number of parties, including technology users, AM and prototyping service providers, software developers, AM technology vendors and the investment community. This chapter, however, will focus on AM cost models developed in the academic engineering literature for the simple reason that these models are published openly and described in a high level of detail. In the classification of cost estimation techniques presented in Fig. 1, most cost models proposed for AM fall into the categories of *parametric* costing techniques and *activity-based* costing techniques (Di Angelo and Di Stefano 2011). Parametric costing techniques express costs as a mathematical relationship between different variables that are obtained through statistical methods. As such, these techniques do not require a deep understanding of the investigated technology at hand and can be specified quite generally. In contrast, activity-based cost models rely on a detailed understanding of processes and products in terms of elementary operations, components and activities, allowing the attribution of particular cost elements. To form an activity-based cost model, these are summed up to obtain an overall product cost estimate. The seminal AM cost model was published in 1998 by Alexander et al. and falls under the category of activity-based costing.

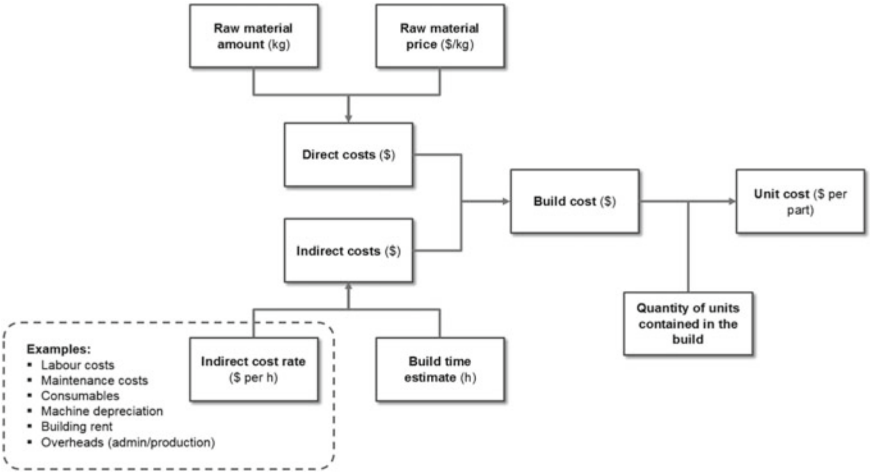

Fig. 3 Summary of an AM activity-based cost model

This model, and most that followed operates by first estimating the time required by different process steps, including the duration of the AM build process itself. A number of cost elements, normally of the well-structured kind (Fig. 2), can be assigned to the AM process through an indirect cost rate, which is measured in money terms per unit of time. Multiplied by the time estimate, this yields the total indirect cost associated with the build process. Indirect costs normally include machine maintenance, consumables, depreciation, labour and various overheads.

Next to indirect costs, there are also direct costs arising more immediately from the operation of the AM system. These normally include raw material costs and occasionally energy costs. In AM, direct costs are usually determined by the overall amount of material deposited over the course of the build process and are thus closely related to the geometries contained in the build. Therefore, AM cost models usually estimate direct costs on the basis of the volume of the product geometries contained in the build operation, including any sacrificial support structures. To obtain the activity-based cost model, direct and indirect costs are then added to produce an estimate of total cost, which can then be broken down to the unit cost of the individual part, or product, contained within a build. Figure 3 summarises this cost modelling approach in a flow chart.

The build cost and unit cost estimates resulting from such models are normally reliable and are used for a range of different purposes. For example, such models can be used in inter-process comparisons to evaluate the cost performance of different AM systems against each other or against the cost performance of conventional manufacturing technologies. Additionally, such models can be used to explore the cost effects of changes to product design, which would enter the model as a change in raw material, build time and quantity of parts included in the build volume. As discussed in the following sections of this chapter, AM cost models are also used to form opinions on how unit costs relate to the quantity of products manufactured. As indicated in Fig. 3, the available cost models are mostly limited to well-structured costs. For increased realism, some newer models include ill-structured aspects such as raw material degradation or material losses as well (see, for example, Baumers et al. 2017).

3 How to Build an Additive Manufacturing Cost Model

To construct a model of the activity-based costing type for AM, a number of steps are required, which are presented briefly in this section. The activity-based approach is very flexible so it is possible to adapt individual steps depending on the scope of the cost investigation and the type of AM technology analysed. This is important as the working principles and patterns of machine operation of different AM technology variants differ significantly (see, Gibson et al. 2010). Correspondingly, the costs associated with different AM technology types also exhibit substantial variation and respond differently to changes in individual variables, for example, production quantity.

Step 1: Definition of the scope of the costing model
Since AM processes are normally not implemented as stand alone systems in isolation, especially where they are adopted for manufacturing purposes, it is necessary to define the scope of the cost model as a first step. To provide an initial overview of the AM process, the generic AM process is instructive (Gibson et al. 2010). Figure 4 defines the typical scope of an AM cost model.
Three pre-processing steps are included in the cost model, namely, file conversion, file transfer and machine preparation. Further, it is assumed that two post-processing steps are included, namely, product removal and surface processing. It is assumed that these costs are measurable and can be expressed in the terms $C_{pre\text{-}processing}$ and $C_{post\text{-}processing}$, respectively.

Step 2: Build time estimation
The next step in the cost analysis is to estimate the build time required by the AM system to execute the investigated build operation. As many AM systems require significant time to warm up or cool down, during which no other activities can take place within the machine, such durations should be included in the build time

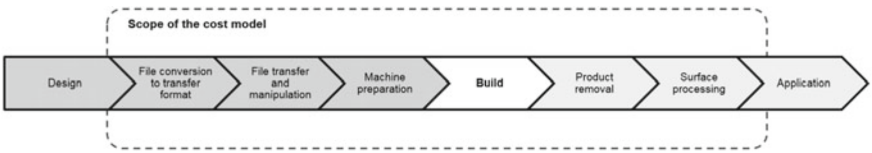

Fig. 4 Scope of the cost investigation in the generic AM process

estimator. However, as discussed in the literature, it must be expected that product geometry and build composition have a significant effect on build time (see, for example, Baumers et al. 2017). Hence, the accurate estimation of build time can be complex and highly specific to the system and the product geometries contained in the operation.

A simple build time estimator that performs well on some AM systems rests on the assumption that the processing speed per layer is constant. This simplification works well for AM systems processing full layers instantaneously, such as mask-based stereolithography, or if the build volumes are evenly filled with product geometries in three dimensions, such as in polymeric powder bed fusion systems operated at full capacity. Making this assumption, overall build time T_{build} can be approximated as follows:

$$T_{Build} = T_{setup} + T_{layer} l + T_{cool-down}, \tag{1}$$

where T_{setup} is the time required for machine initialization and warm up, T_{layer} is the processing time required per layer, l is the total number of layers in the build and $T_{cool\text{-}down}$ is the time required by the system to cool down following the end of the build process.

Step 3: Calculation of the indirect cost rate

Since the described model forms an activity-based costing approach, several cost elements and activities are attributed to overall costs through build time. This requires the calculation of an indirect cost rate $\dot{C}_{indirect}$ measured as a monetary cost incurred per unit of operating time ($/h). Since the elements of indirect cost are normally obtained on an annualised basis, these costs are broken down to an hourly rate by dividing the annual cost through the number of operating hours per year. It is important to note that this introduces an aspect of capacity utilisation over time, as it relies on the share of operating hours of overall time. In most models, the operating time is assumed to lie between 50 and 90% of total time. Since a diverse set of costs is included in indirect costs, it is instructive to discuss the three most important elements, which are given as follows:

1. Importantly, the indirect cost rate $\dot{C}_{indirect}$ reflects the purchase cost of the AM system and of ancillary systems, such as raw material handling or unpacking stations. As capital equipment, this cost does not arise as a lump sum but as a depreciation cost over time. In most studies, a straight line depreciation method is used with a depreciation period of 5–10 years. Additional costs included in machine costs are maintenance expenses and the costs of consumables such as protective gas, filters, seals and components with a replacement interval, as required by the investigated AM technology type.
2. $\dot{C}_{indirect}$ also includes the labour costs incurred by running the AM system, normally due to a specialised AM technician or machine operator. Interestingly, many AM cost models assume that a technician operates an AM system on a one-to-one basis, implying that the machine requires constant supervision and

technician activity. It should also be noted that labour costs include employer contributions. This means that labour costs are likely to exceed the actual technician's salary.

3. The indirect cost rate also reflects the overheads allocated to the operation of the AM system. Such overheads may result from production itself, for example, in the form of building space required to house the machine or other infrastructure costs. Additional overheads are administrative and relate to computer equipment, communications and software licences. Some cost models additionally include energy costs in the production overheads.

Step 4: Estimation of direct costs
Direct costs are the costs associated with physical inputs required for the operation of an AM system. As for all manufacturing technologies, the most important direct cost arises through the raw materials used in the process, including one or more build materials, and if required, sacrificial support materials. Since AM uses three-dimensional digital design files to control the process (normally in the *.stl format), it is usually possible to accurately estimate the total volume of the products and support structures contained in the build volume though specialised software. This information can then be combined with the price of the raw material, normally based on a quotation from a raw material vendor, to form a direct cost C_{direct} estimate. It should be noted that raw material refreshing forms a significant source of cost in some AM technology variants, therefore direct costs occasionally include a factor for material refresh or waste. Additionally, some models include energy costs as direct costs.

Step 5: Specifying the cost per build and unit cost
After obtaining the required data and computing the elements described in the above, it is possible to specify the cost model for the build C_{build}, including the pre-processing and post-processing costs.

$$C_{build} = C_{pre-processing} + \dot{C}_{indirect} T_{build} + C_{direct} + C_{post-processing} \quad (2)$$

If multiple parts are contained in the build volume, it will be important to break down C_{build} to the level of the individual part contained. Where the products contained within the build volume are different, it is possible to identify unit cost $C_{unit,i}$ associated with part i by multiplying C_{build} by its volume fraction, which is defined as the volume V of part i divided by the volume of all j parts contained in the build, such that

$$C_{unit,i} = C_{build} \frac{V_i}{\sum_j V_j} \quad (3)$$

If q units are contained in the build volume and all share the same geometry, meaning that they are instances of the same design, it is possible to further simplify the unit cost model C_{unit} by simply dividing C_{build} by q

$$C_{unit} = \frac{C_{build}}{q} \tag{4}$$

It has been noted above that cost estimates in AM tend to be very process- and geometry-specific. Additionally, it is clear that the estimated cost levels C_{unit} and C_{build} are determined by the scope of the cost analysis. To ensure the usefulness of the cost estimate and to allow an assessment in terms of accuracy, it is, therefore, important to provide additional information alongside the cost estimate. This should state clearly aspects such as build composition, machine type and setting, important operating parameters, build materials, degree of capacity utilisation over time and scope in terms of pre- and post-processing steps.

4 Using Cost Estimators in Breakeven Analyses

In many cases, it will be of interest to explore the relationship between unit cost and the quantity manufactured. While cost models of the above type can be used to describe such relationships, it is important to note that C_{build} is likely to change if q is varied. Moreover, as AM is a toolless process, it is normally considered realistic to allow for the insertion of additional, possibly unrelated, products in the analysed build volumes, further changing C_{build}. For this reason, establishing the relationship between quantity and unit cost, formally defined as a unit cost function $C_{unit}(q)$, is a complex task. Where build compositions are changed in non-systematic ways, for example, by mixing different components in build volumes, this is considered to be particularly challenging. Unsurprisingly, this has led to different conclusions about the unit cost behaviour of AM as production quantity expands. Some authors argue that there is a complex and hard-to-predict pattern resulting from a gradual filling up of the build volume, depending on build configuration and product geometries (Ruffo et al. 2006). Shown graphically for the technology variant polymeric powder bed fusion in Fig. 5, a complex, sawtooth unit cost pattern is observed as quantity expands. Other authors theorise that there is no clear relationship between unit cost and quantity and the unit cost function can be treated as a horizontal line (Hopkinson and Dickens 2003; Atzeni and Salmi 2012). This cost behaviour is also graphically summarised in Fig. 5.

Where the unit cost functions of different processes or systems are available, it is possible to perform *breakeven analyses*. The goal of such analyses is to identify points at which different unit cost functions intersect, thereby identifying quantities at which the unit costs of different processes are equal. These points form *cut-off* quantities that can, for example, inform process selection. In the example shown in Fig. 5, the two competing AM unit cost functions are compared to a unit cost function associated with injection moulding, allowing the identification of two alternative cut-off thresholds, below which the selection of the AM route would minimise cost and above which injection moulding would be the more cost-efficient pathway. Naturally, the use of such inter-process breakeven analyses assumes that the products

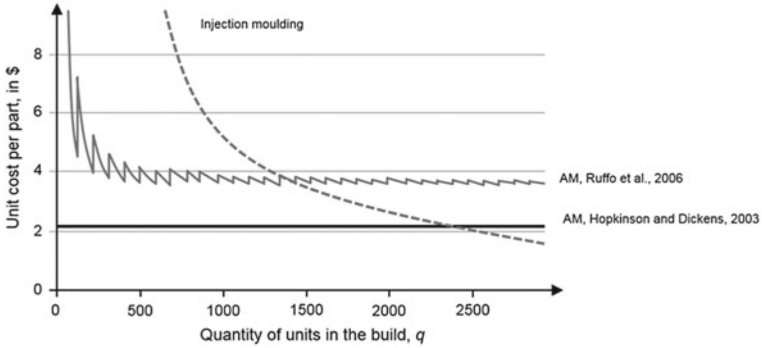

Fig. 5 Scope of the cost investigation in the generic AM process

created through the different processes are functionally equivalent, which forms a simplification. This is discussed, among other issues, in the following section.

5 Problems and Extensions

As stressed in this chapter, the construction of AM unit cost models requires a number of assumptions and simplifications. In many cases, it is justifiable or necessary to make these assumptions, either for practical reasons (such as lack of data) or because they do not diminish the accuracy of the model results. In other cases, it may be necessary to extend the basic cost model in order to maintain its usefulness and relevance. This section presents four problems that have emerged in the field of AM cost modelling and describes extensions to the basic model that aim to address these issues.

5.1 Efficient Capacity Utilisation

As discussed in the context of breakeven analyses, some AM cost models allow for significant unused build volume capacity in the estimation of unit costs. Especially considering AM's ability to fill empty capacity with other geometries, for example, by renting out unused build space, it may be questioned whether leaving capacity empty constitutes technically efficient technology usage. In principle, any manufacturing configuration that does not produce the maximum output from given set of inputs is considered technically inefficient, and hence cannot be seen as a part of a proper unit cost function (see, for example, Curwen and Else 2006). The ability to minimise cost by efficiently configuring, or *packing*, build volumes has led to the development of computer-based build volume packing tools, which are commonly part of software packages supporting the AM workflow and also machine control systems. To ensure efficiency in unit cost modelling, build volume packing has also been integrated within cost models in the AM literature (Baumers et al. 2013). However, as evident in the field of operations research, efficiency in manufacturing execution also entails a scheduling problem, which is traditionally discussed in the context of flexible manufacturing systems, such as Computer Numerically Controlled (CNC) machining. This implies that the build volume packing problem faced in AM cost estimation does not stand on its own and should be integrated with schedule optimization, leading to an even more complex cost estimation problem.

5.2 Additive Manufacturing as a Multi-step Process

It has been stressed in the above that AM cannot normally be implemented as a stand alone technology, especially in the commercial manufacturing setting. Despite forming part of early AM cost models (see, for example, Alexander et al. 1998), not all AM costing approaches consider this aspect. As indicated in the generic AM process shown in Fig. 4, the core AM process must normally integrate into a chain of surrounding process steps. For the cost modeller, the challenge thus becomes to appropriately define the boundaries of a cost investigation. Identifying appropriate process boundaries can be particularly challenging without sufficient technical knowledge of the product characteristics and of the AM technology under investigation. Due to substantially different capabilities, some AM technology variants will require entirely different pre- and post-processing operations and quality assurance processes (Gibson et al. 2010). To form an understanding of the overall setting in which AM technology is used, process mapping forms a suitable technique that will help define the scope of the cost model.

5.3 The Expected Cost Effect of Process Failure

Another commonly ignored aspect is that AM processes are prone to failure events of various sorts, which all have a detrimental effect on cost performance. Therefore, it may be important to include this aspect within cost modelling. Generally, it is possible to classify process failure into two broad types— outright build failure in which the process terminates prematurely, possibly destroying the parts contained in the build volume and product rejection due to a failure to comply with product specifications. Arguably, the more serious mode of process failure encountered is outright build failure. Here, an unforeseen event occurs at some point during machine operation that leads to the premature stoppage of the entire build process. Usually, after discovering that this has happened, the AM technicians will attempt to recover viable parts from the failed build volume and reschedule a replacement build for the parts that were not completed or damaged. This type of process failure is associated with significant costs for repeating the build and also disruption to the production schedule.

The second mode of process failure relates to the rejection of individual parts after completion of the build. This occurs, for example, if a foreign object or debris is present in the build volume and disturbs the deposition process or if there is an anomaly in the cooldown processes leading to excessive part deformation. In the AM workflow, the manufactured products are visually and dimensionally assessed by the AM operators to test for this type of failure. In case rejection occurs, the product will have to be built again. Since these events do not occur with certainty within a particular build, the nature of the cost model changes in a subtle way if the risk of failure is included. Rather than forming a deterministic cost model claiming to represent the absolute cost of the AM processes, the model becomes a probabilistic in a sense that it now reflects the *expected cost* of the AM process. Additionally, process failure may occur at different stages within the AM process, so individual elements of the process may be affected by a particular risk while other may not be affected—further increasing the challenge of the cost modelling effort. Due to the layer-by-layer operating principle of AM, the extent of the cost impact of build failure is likely related to the Z-height of the build configuration and, therefore, to degree of capacity utilisation. To minimise this risk, some professional operators of AM technology constrain the Z-height of their builds artificially, thereby addressing a complex risk management problem in practise. In terms of the overall magnitude of the expected cost of process failure, a recent study has shown that this risk may account for up to 38% of the total expected process cost of a polymeric powder bed fusion system (Baumers and Holweg 2016b).

6 The Cost Impact of Design Adaptation

In the engineering domain, it is generally assumed that the choices of material, design and manufacturing process are interdependent. This means that one aspect cannot normally be changed without assessing the knock-on effects on the other two aspects, as illustrated by Fig. 6. Therefore, where breakeven analyses are constructed on the basis of unit cost functions, as shown in Sect. 4, it may well be the case that inappropriate material/design/process combinations are compared, severely limiting the usefulness of the cost investigation.

To make inter-process cost investigations less vulnerable to this problem, some AM cost models compare different versions of products, tailored to the requirements of different processes (Atzeni and Salmi 2012; Baumers et al. 2017). While increasing the robustness of such cost comparisons, this extension adds the challenge of defining at least one additional product design and material specification, requiring substantial additional expertise regarding the product and alternative manufacturing processes.

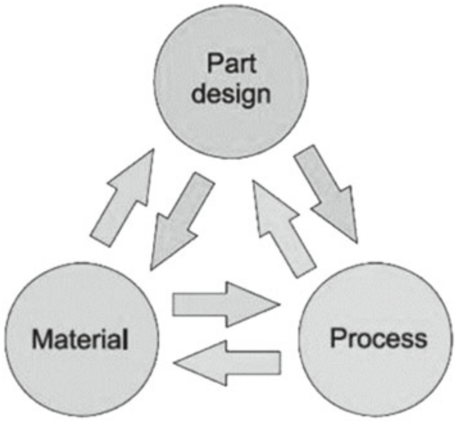

Fig. 6 Interdependence of design, material and process

7 Some Additional Considerations

It is clear that the ownership structure of the AM equipment as a capital asset will have a significant effect on the management decisions concerning it. However, as far as cost models of AM are concerned, the costs related to different ownership options, be it outright purchase, hire purchase or lease, will enter through the indirect cost rate. This makes the activity-based costing approach presented in this chapter quite robust and applicable to the business practises of most AM technology users and also technology vendors. Similarly, the AM technology user may enter into various arrangements with the technology vendor concerning machine repair, spare parts and maintenance. In practise, this can be organised as a flat annual fee or a usage-related fees. Again, the different configurations will enter into the indirect cost rate.

8 Using Specific Cost Estimates

This chapter has shown that basic and reasonably accurate AM cost models can be constructed with relative ease. However, simple models may rest on a number of assumptions and simplifications which may diminish their realism. To address some of these problems, a number of extensions have been proposed to increase the quality of the model at the expense of additional model complexity. Fortunately, in some cases, only a very rough approximation of cost is needed, for example, in preliminary analyses of product design or for initial assessments of business cases. In these contexts, specific cost indices, each encapsulating a snapshot of the cost performance of an AM technology in a particular setting, are useful. Such indices approximate the overall cost of an AM process per volume unit of material deposited, for example, in \$ per cm^3, and allow the calculation of a rough unit cost estimate if the geometric volume of the product under investigation is known. Table 1 summarises

Table 1 Specific cost indices obtained from the literature

Study	Technology variant	Material	Capacity utilisation	Support structures	Pre- and post-processing	Risk of build failure	Specific cost estimate[a] ($/cm^3)
Hopkinson and Dickens (2003)	Stereolithography	Unspecified epoxy polymer	Full build	Included	manual pre- and post-processing	Ignored	0.72
	Filament extrusion	Unspecified ABS	Full build	Included	manual pre- and post-processing	Ignored	0.60
	Laser sintering	Unspecified Nylon	Full build	Not applicable	manual pre- and post-processing	Ignored	0.37
Ruffo et al. (2006)	Laser sintering	Duraform PA (Nylon polymer)	Full build	Not required	manual pre- and post-processing	Ignored	0.36
Gibson et al. (2010)	Stereolithography	Unspecified polymer	Full build	Included	Ignored	Ignored	0.68
Grimm (2010)	Filament extrusion	ABSplus (polymer)	Single part	Included	Included	Ignored	0.70
	Material jetting	EX200 (polymer)	Single part	Included	Included	Ignored	1.88
	Film transfer imaging	FTI-GN (polymer)	Single part	Included	Included	Ignored	0.95
	Material jetting	VeroWhite (polymer)	Single part	Included	Included	Ignored	1.32
	Binder jetting	Zp150 (polymer composite)	Single part	Not required	Included	Ignored	0.48
	Sheet lamination	PVC	Single part	Included	Included	Ignored	1.75

(continued)

Table 1 (continued)

Study	Technology variant	Material	Capacity utilisation	Support structures	Pre- and post-processing	Risk of build failure	Specific cost estimate[a] ($/cm^3)
Atzeni and Salmi (2012)	Direct metal laser sintering	AlSi10 Mg	Full build	Included as a 10% waste factor	Pre- and post-processing, heat treatment	Ignored	11.70[b]
Baumers et al. (2013)	Direct metal laser sintering	Stainless steel 17-4PH	Full build	Included	Only wire erosion	Ignored	7.05
Baumers et al. (2014)	Material jetting	VeroClear	Full build	Included	Only build process	Ignored	2.30
Baumers et al. (2015)	Selective heat sintering	SHS Nylon composite	Full build	Not applicable	Only build process	Ignored	1.84
Piili et al. (2015)	Direct metal laser sintering	Stainless steel PH1	Full build	Not applicable	Only build process	Ignored	7.90
Baumers et al. (2016a)	Electron Beam melting	Ti6Al4 V	Full build	Included	Only build process	Ignored	7.63
Baumers and Holweg (2016b)	Laser sintering	PA2200 (Nylon)	Full build	Not applicable	Full process chain	Included	1.04

[a] As reported by Baumers et al. (forthcoming). Converted into US Dollars according to exchange rate on 01/01/2017 (1.2339 $/£)
[b] Data used for specific cost not cited explicitly; estimated from the data provided

specific cost indices extracted from the academic literature for a number of different AM systems, materials and process settings. As in the above, it must be stressed that the cost performance of an AM system depends on many different variables and parameters, so any unit cost estimate formed on the basis of specific unit cost indices must be seen as an initial and crude approximation.

9 Conclusions

After providing an overview of the background and purposes of manufacturing cost estimation, this chapter has provided a practical insight into AM cost modelling. It has shown how the elements of cost typically encountered in AM can be structured in a straightforward way. The chapter has also featured a number of recurring issues in the assessment of AM cost: the capacity utilizations problem, integration with other manufacturing processes, the cost impact of build failure and the requirement to explore the cost effect of design changes when considering different processes. While making it difficult to robustly appraise AM cost in many cases, these aspects are relevant due to the inherent openness of AM as a manufacturing technology. Dealing with this complexity is a price that those considering the adoption of AM technology for commercial purposes must be willing to pay. However, process cost modelling and the formulation of unit cost functions of the type discussed in this chapter is only the beginning of the journey towards an understanding of the full cost implications of AM as an industrial manufacturing technology. Nevertheless, some observers construe models of this kind as being reflective of the cost performance of AM in high volume industrial settings. This is not the case for two reasons. First, being largely based on a prototyping mind-set, AM system architectures and their operational processes (most importantly relating to quality assurance) are still evolving into manufacturing systems. New and currently emerging AM technologies and surrounding systems will need equally evolved cost models. Second, by concentrating on fixed, or *static*, technological relationships with respect to production quantity, the cost models discussed in this chapter ignore the *dynamic* sources of cost reductions central to competitiveness in many industries over time. Such sources of cost reduction are crucial in cost-driven industries, for example, in the automotive sector. New AM cost models will thus need to reflect production progress and efficiency gains manufacturing quantity increases over time. This is something the framework presented in this chapter is not capable of.

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External Resources: The activity of the Centre for Additive Manufacturing (CfAM) is focused on next generation multifunctional Additive Manufacturing (AM) technology that spans across both the fundamental and applied research. The focus of the Centre's activity is to work closely with businesses to tackle major research challenges, ensuring that the UK remains at the forefront of AM and its application in industry. The successful commercial exploitation of the Centre's research in order to meet industrial and national need for cutting edge, low carbon manufacturing technologies is a key priority. https://www.nottingham.ac.uk/research/groups/Cfam/.