CRANFIELD UNIVERSITY

JIANING GUO

FEATURE BASED COST AND CARBON EMISSION MODELLING FOR WIRE AND ARC ADDITIVE MANUFACTURING

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis
Academic Year: 2011 - 2012

Supervisors: Dr. Jörn Mehnen and Dr. Yuchun Xu
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The wire and arc additive manufacturing (WAAM) is a CNC and welding deposition based additive manufacturing method. This novel manufacturing technique has potential cost and environment advantage and was developed as an ideal alternative for industrial sustainable development.

The aim of this project is to develop a cost and carbon emission model primarily for the WAAM manufacturing cost (£) calculation and secondly for the WAAM carbon emission (KgCO2e) estimation, which can be used by the decision makers and design engineers in product design stage without detailed process information.

Literature review and an industry survey were carried out first to capture the overview of this research context and the essential data for cost modelling. Then the cost breakdown structure (CBS) and cost drivers were determined. Thereafter, a feature based cost model and detailed cost equations were developed. A specific Greenhouse Gases (GHG) emission model was also established which follows the specification of existing carbon footprint measurement standards.

As part of this project, an integrated software tool was developed by using MS Visual Basic language. The proposed cost and GHG emission model were implemented in this software. With the ability of directly capture geometry data from CAD files and fully automatic calculation, the software tool is efficient and convenient.

Three case studies were conducted to demonstrate the proposed cost model and software tool. The comparative cost analyses with other conventional manufacturing methods were also discussed in these case studies. Finally, the capacity and reliability of the cost software were validated by experts from industry and academia. The implementation of the research outcomes of this project can achieve accurate early cost estimation for WAAM conveniently. Moreover, it can clarify the cost and environment advantage of WAAM and assist to identify the most suitable situation for adopting WAAM from a cost and sustainable point of view.

Keywords: WAAM, cold metal transfer, cost estimation, GHG emission, CATIA automation.

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Guo Jianing

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
ALM	Additive Layer Manufacturing
API	Application Programming Interface
ADO	ActiveX Data Objects
B2B	Business to Business
CAD	Computer-aided design
CBR	Case-based Reasoning
CFP	Carbon Footprint
CMT	Cold Metal Transfer
CNC	Computer Numerical Control
DIS	Draft International Standard
DAO	Data Access Objects
FBC	Feature Based Costing
FEM	Finite Element Method
GHG	Greenhouse Gases
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
GWP	Global Warming Potential
ICE	Inventory of Carbon & Energy
IPCC	Intergovernmental Panel on Climate Change
PAS	Publically Available specification
PCE	Product Cost Engineering
PE	Parametric Estimating
RUAM	Ready to Use Additive Manufacturing
SLS	Selective Laser Sintering
SQL	Structures Query Language
UNFCCC	United Nations Framework Convention on Climate Change
VB	Visual Basic
WAAM	Wire and Arc Additive Manufacturing

1 Introduction

1.1 Background

Additive manufacturing (AM), also called additive layer manufacturing (ALM), can be defined as the process of joining materials to make products from CAD model data, usually layer upon layer, which is opposed to subtractive manufacturing methodologies, such as conventional machining. This technique started in the late 80's with Stereo lithography. Since then, many new methods have been invented and commercialised (Levy et al., 2003).

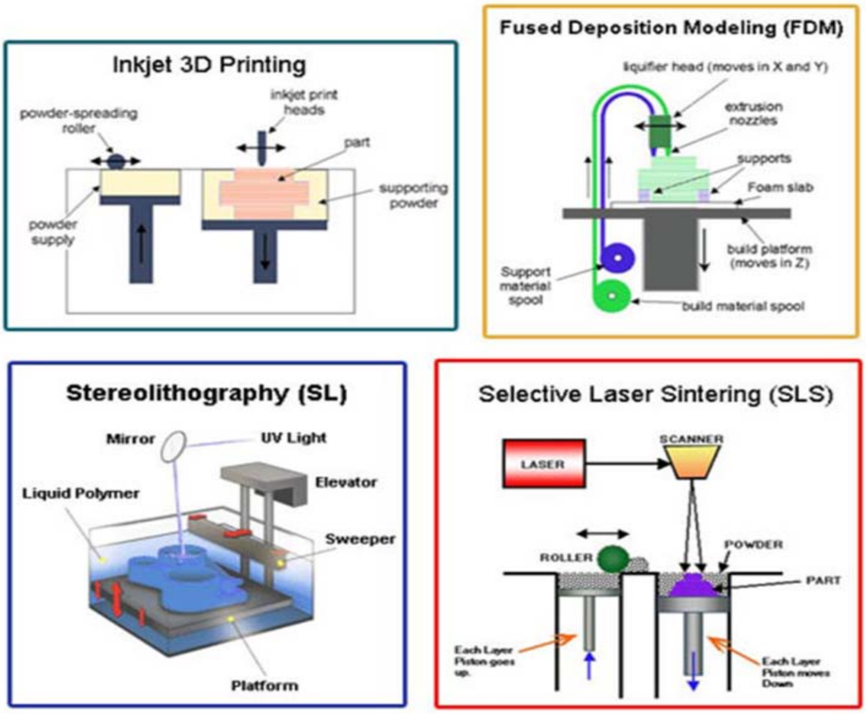


Figure 1.1: Several different AM techniques (Levy, 2003)

Due to the fierce competition in the changing markets today, ‘Time to market’ becomes a key point of success for companies and this is the original driving force behind the progress of additive manufacturing technique. From Wohlers (2010), the AM techniques have experienced more than two decades of research and development, now additive manufacturing progresses have had a significant impact on design and manufacturing. In the future, most of the manufacturing companies would produce half of their products by this process.

The aerospace industry is a vital sector embracing additive manufacturing, as this process can realise massive savings of expensive material, give design freedom and manufacture more complex components easily. According to Wilson (2010), the ALM technique can save $300 billion for the aircraft manufacturing industries alone. Other savings includes avoiding large amounts of investments that have to be made in conventional manufacturing for making aluminium or titanium billet, heat-treating, rolling, reheating, cutting up, etc. Nowadays, some important applications of ALM in the aerospace industry include ducts to cool down the wings of A380, thin walled structures in turbine blades, etc. (Nathan and Excell, 2010).

In the early stage of ALM progress, limited to the material (usually plastic) that is being used, the parts generated by ALM are usually not strong enough to be directly used as a final product. Therefore, ALM is also referred to as rapid prototyping technologies. However, between the scientific push and industrial pull, a project named: “Ready to Use Additive Manufacturing” (RUAM) was developed and takes the ALM technology one step further. RUAM is the name of an IMRC/EPSRC research project at Cranfield (finished December 2010) which implemented a novel ALM approach which combined welding deposition and conventional machining process together. It can fabricate metallic parts with precise net shape quality that can be used directly for the entire product life cycle. After several years of development, now this new ALM technique was named as Wire and Arc Additive Manufacturing (WAAM) which is currently attracting widespread attention from industry (Figure 1.2). From Mehnen et al., (2010), WAAM is a new, sustainable, cost and time efficient manufacturing process which makes use of well established and advanced cutting-edge technology. Parts are deposited layer by layer by means of metal wire welding process. The welding torch is guided by a 6 axis Robot, making the manufacturing process effective and flexible. These wire and arc welding based technologies provide a new approach to fabricate ready-to-use large (up to several metres) metal parts. By using new welding technologies such as cold metal transfer (CMT) or Inter pulse welding it is possible to obtain more than 10 times faster deposition rate than selective laser sintering (SLS) technologies. WAAM is also dedicated to integrating additive layer manufacturing and traditional machining into one single machine to provide accurate net shape with high produce efficiency. This technology shows a wide application prospect, especially in aerospace and automotive industry.

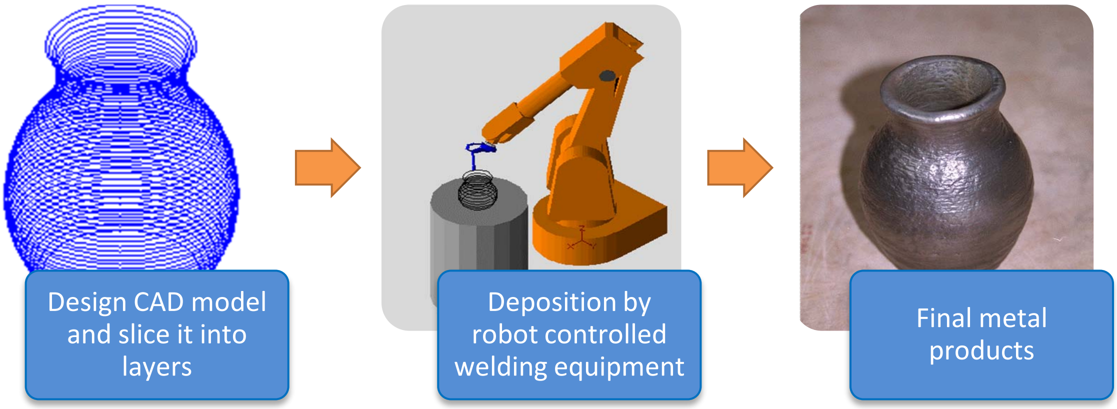


Figure 1.2: Basic WAAM process structure

1.2 Research Motivation

In the increasingly competitive global market, the cost, quality and novelty of products plays a critical role for a manufacturing company’s success. Customers always require higher quality with an ever-decreasing cost (Roy, 2003). Therefore, cost estimation and reduction are paramount for any manufacturing activity as it directly influences the strategic “go” or “no go” decisions made by a company (Shettigar, 2010). Meanwhile, with the improvement of public environmental awareness, the environmental impact of manufacturing process is becoming increasingly concerned. In Europe, some mechanisms such as carbon emission trading are also established by governments to control the climate change. The environmental impact now is becoming an important criterion for new manufacturing techniques. However, as a developing cutting edge manufacturing technology, it is noteworthy that little research has been done on WAAM cost and carbon emission assessment.

1.3 Problem Statement

Although theoretically the WAAM technique offers many benefits such as saving material, reducing fabrication time, etc. A reliable cost model is still demanded to quantitatively verify these advantages. However, due to the unique manufacturing process it involves, the existing cost model cannot be directly used for WAAM. The shortage of accurate product cost data leads to the customers do not confident enough to take WAAM as their alternatives, so the large scale application of WAAM is still limited. Meanwhile, the development of

WAAM technique itself also needs product cost data as a reference to identify its improvement direction. Although some researches about cost of WAAM were carried out in recent years, the requirement of WAAM cost modelling is still not be satisfied. Hence, developing an integrated cost model for WAAM which can be used to assess both manufacturing cost and environmental impact is necessary and valuable for the further development and application of WAAM.

1.4 Scope definition

The scope definition aims to define aspects of the project which may have been ambiguous, and to ensure delivering a quality solution in line with the original research requirement. The scope consideration is based on the time, resources and knowledge available for this project.

In Scope

This research project will focus in the following areas:

- product manufacturing cost of the WAAM components
- cradle-to-gate GHG emissions during WAAM process
- Integrated cost software tool development
- Case study

Out of Scope

These following points are not included in this research project:

- Indirect cost of WAAM components (e.g. administration cost, factory facilities cost, taxes, premium etc.)
- Quality inspection cost
- Full life cycle cost of the WAAM components
- Other pollutants to environment except GHG

1.5 Research Aim

The aim of this project is to develop a cost and carbon emission model primarily for the WAAM manufacturing cost (£) calculation and secondly for the WAAM carbon emission (KgCO2e) estimation, which can be used by the decision makers and design engineers in product design stage without detailed process information.

1.6 Thesis Structure

This thesis consists of eight chapters, the order and contents are explained as follows:

Chapter 1- Introduction: the context of this research was presented in this chapter. The aim of this research was determined through the problem statement. The overall structure of this thesis was also introduced at the end of this chapter.

Chapter 2- Literature Review: A critical literature review which covers the major areas of WAAM, cost and environmental impact was carried out by the author to assist in obtaining the fundamental knowledge related to the research subject. The research gaps was also discussed and identified after the literature review.

Chapter 3- Research Aim, Objectives and Methodology: The objectives for satisfying the overall research aim were determined and presented. A detailed illustration of the adopted research methodology was also included in this chapter.

Chapter 4- Cost Model Development: The author first identified the WAAM process map and the cost breakdown structure, and then determined the manufacturing features and the cost model framework. Finally detailed cost equations were developed and presented in this chapter.

Chapter 5- Carbon Emission Model Development: This chapter presented the adopted methodology, mapped out the carbon emission associated activities, identified system boundary, determined the data source and developed a specific GHG estimation procedure for WAAM.

Chapter 6- Integrated cost Software tool Development: The author explained the structure and function of the software. The key technologies for developing this integrated cost software tool were also presented in this chapter.

Chapter 7- Case Study and Cost Model Validation: This chapter presented how the integrated cost software works by apply it on three case studies. The cost comparison with other manufacturing methods was also discussed in these case studies. Then the applicability and accuracy of the integrated software tool was validated by expert judgements.

Chapter 8- Discussion and conclusions: The findings, contributions, limitations of this research project were discussed first, and then the overall conclusions of the research were made in this chapter.

2 Literature Review

2.1 Introduction

In order to gain the fundamental knowledge related to the research subject, and help to conduct this project successfully, a literature review which covers the major topics and areas of WAAM, cost and environmental impact was carried out in this chapter.

The literature review presented in this chapter was divided into several sections (Figure 2.1). The contexts of WAAM, cost engineering and environmental impact were studied respectively from section 2 to 4. Section5 discussed some existing research in this area. Moreover, the research gaps were analyzed and presented in the last section.

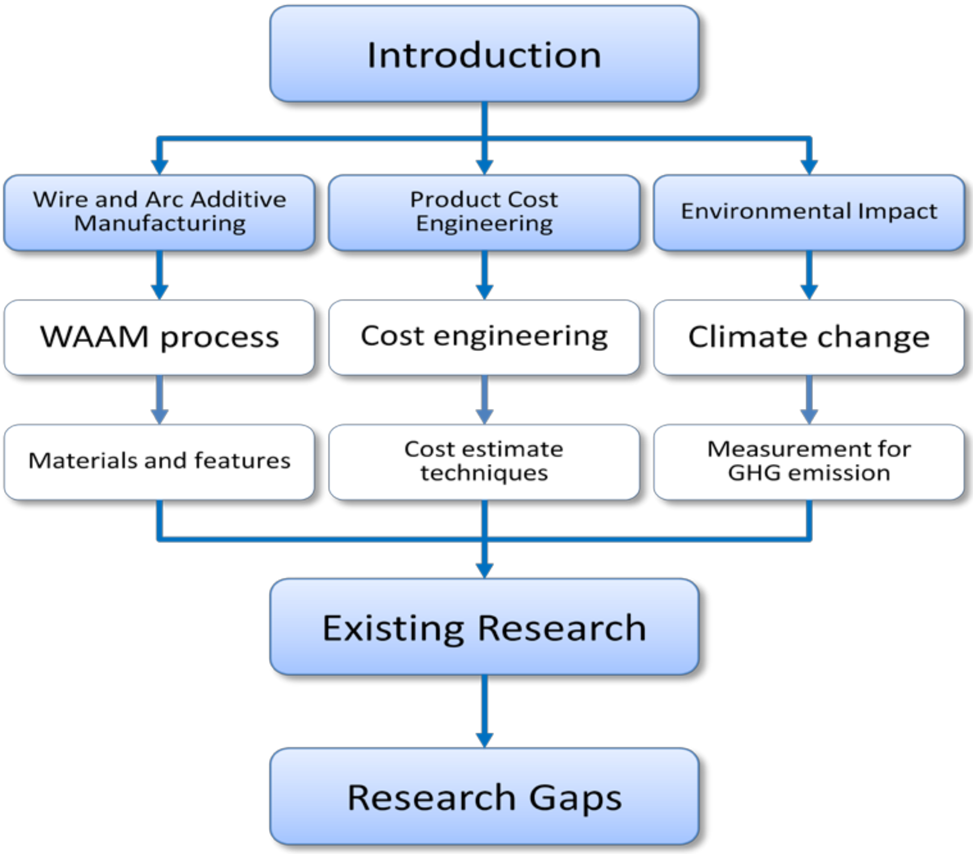


Figure 2.1: Literature review structure

2.2 Wire and Arc Additive Manufacturing

2.2.1 WAAM process

From Deherka (2010), the ready to use additive layer manufacturing can be classified into powder based or wire based on the way of feeding materials. Both of the processes consist of a heat source, a source for feeding material and a substrate which may be used as a part of the final component or not (Figure 2.2).

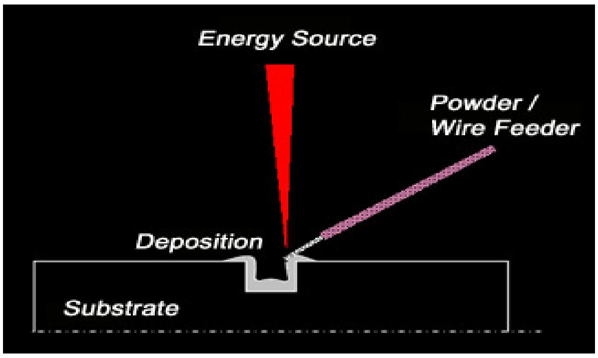


Figure 2.2: The basic principles of WAAM (Deherka, 2010)

The wire and arc additive layer manufacturing is gaining increasing popularity as the process allows to manufacture larger custom-made metal components with higher deposition rate (Ding, et al., 2011). As shown in Figure 2.3, in the WAAM process 3D metallic components are built by feeding wire metallic material and depositing beads of weld metal in a layer by layer way. The entire WAAM process is an innovative concept that opens a vast space of options for fabricating complex components efficiently. It is especially suitable for manufacturing or repairing parts in aerospace industry. (Mehnen, Ding, Lockett, Kazanas, 2010).

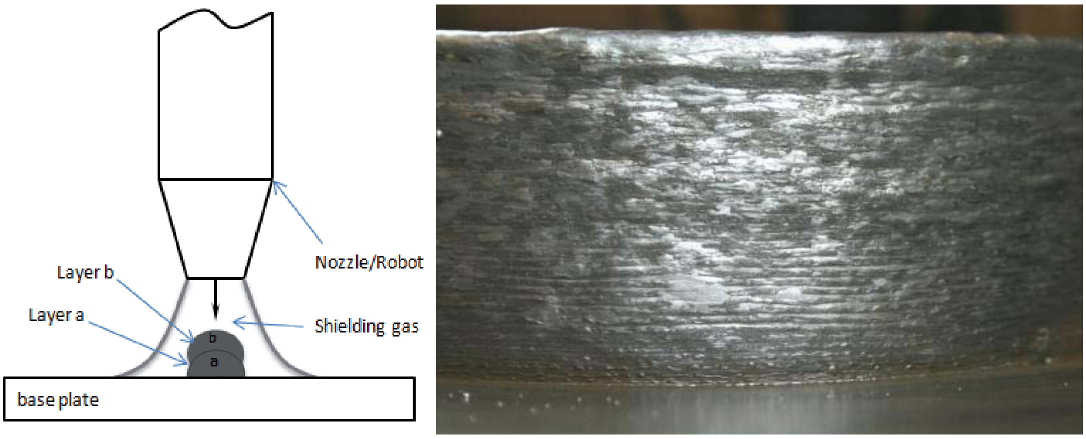


Figure 2.3: Layer deposition process of WAAM (Mehnen et al., 2010)

According to Mehnen (2008), compare to conventional metal rapid prototyping methods like laser powder welding the WAAM process can yield solid products with cast like features and obtain over 10 times faster deposition rate than SLS. Mehnen et al. (2010) also point out that by integrating welding deposition process with grinding process in one machine and using of new welding technologies such as CMT (Cold Metal Transfer) or Inter pulse Welding, the WAAM technique can be used to manufacturing high quality components with precisely defined surface geometries as well.

Figure 2.4: Products manufactured by WAAM

As a cutting-edge manufacturing technique, the WAAM provides a new, sustainable, cost and time efficient manufacturing process which utilizes full power of additive layer manufacture technique combined with the design-optimize and conventional machining process together. Each phase of the overall process can be linked optimally in order to achieve the best effect. The general structure of the overall WAAM design-manufacturing process is shown in Figure 2.5 (Mehnen, Ding, Lockett, Kazanas, 2010).

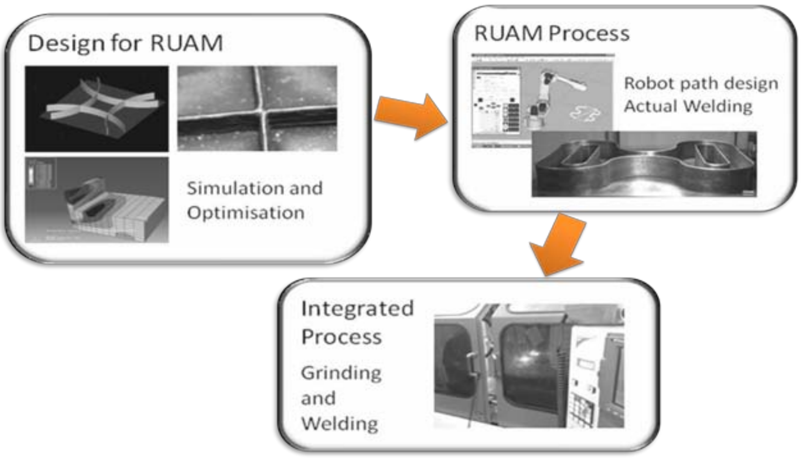


Figure 2.5: The WAAM design-manufacturing process (Mehnen et al., 2010)

In the design for WAAM phase, component is designed by CAD software, and then the temperature and stress properties during welding deposition will be analyzed by finite element method (FEM), the most appropriate welding tool paths will be identified and this helps to minimizing distortions of the WAAM products (Mehnen, Ding, Lockett, Kazanas, 2010).

A robot path generation program RUAMROB© was developed for the WAAM project. This soft ware tool consists of two main modules: a slicing module and a robot program generation module. From Ding et al., (2010), “By executing these two modules automatically, the program can slice the designed ALM parts and generate the ready-to-use path code for a Fanuc robot in one go. A user-friendly interface for RUAMROB© has also been developed to simplify the setting of parameters”.

In the actual deposition Process, the welding tracks are executed by a robotic system. A robot arm guides the welding torch along the optimized tool path. The specific welding techniques for depositing may vary depending on material and features of components (Williams, undated).

The integrated process aims to combine ALM and traditional machining such as grinding, milling and rolling into one machine to form continuous process. This integrated process helps to obtain final precise net shape with low cost and high efficiency (Mehnen et al., 2010) (Kashoob, 2011).

2.2.2 Materials and features

After more than ten years development, the WAAM technique has made a significant progress (Williams, undated). Modern welding and automation technologies provide opportunities that were not available in the past. Now WAAM can be used to deposit a variety of materials and features of real world workpieces that can be welded, such as steel, Ni alloys, and even highly reactive metallic e.g. Ti alloys in an out-of-chamber environment (Ding, et al., 2011).

The welding technique adopted by WAAM depends on the specific material and geometry feature to be manufactured. Standard wire based welding processes such as Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) are widely adopted as heat sources due to their low cost, high deposition rate and widespread Suitability for various kinds of metals as well

(Ding, et al., 2011). Other welding strategies adopted by WAAM include plasma and laser welding techniques (Williams, undated).

Martina (2010) adopted plasma wire deposition with WAAM to manufacture Ti-6Al-4V structures – a kind of advanced material widely used in aerospace industry. Furthermore, Leinonen (2011), using Cu97Si3 wire deposited on steel by CMT welding, this verified that mixed material component also can be well formed by WAAM.

Among all the welding techniques, the GMAW process has been successfully used with a variety of materials in WAAM such as titanium, stainless steel, and aluminium (Leinonen, 2011). Especially the CMT (a variant of GMAW) based WAAM process is believed to have most of the advantages such as wide range of thickness, uniform bead profile, low heat input, higher deposition rate with medium distortion and ease in integrating with a robotic system. Therefore, it is also very attractive for the aerospace industry applications (Deherka, 2010) (Singh, 2010).

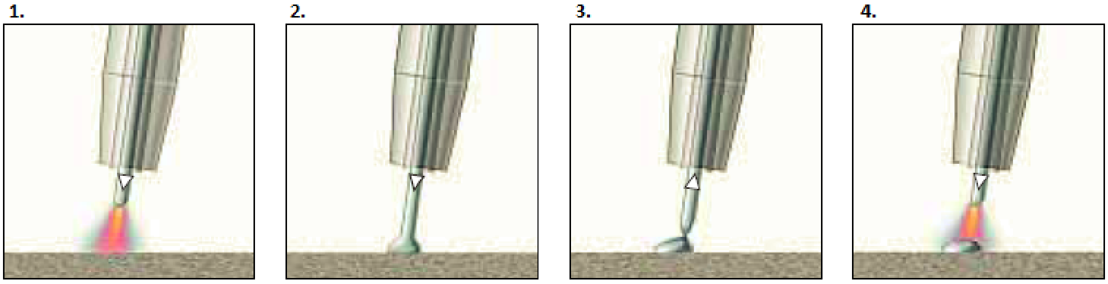


Figure 2.6: Process behaviour during a CMT weld cycle (Deherka, 2010)

In the cold metal transfer process, the motion of the wire is incorporated into the process control. The wire will be retracted when a short circuit is detected to aid droplet detachment, the power supply will be paused as well. Figure 2.6 illustrates the CMT process during a welding cycle (Leinonen, 2011). The feed-retract frequency is up to 70 times per second. The CMT process comes with a more stable arc than general GMAW methods, as the arc length can be mechanically adjusted by wire feeding system; and significantly less heat supply to the metals when weld bead is deposited. This helps to result in spatter free, energy saving and also less distortion for workpieces (Shettigar, 2010).

A systematic research about WAAM was carried out in Cranfield University welding research centre in recent years. Figure 2.7 shows various kinds of features manufactured by WAAM process in current status (Williams, undated).

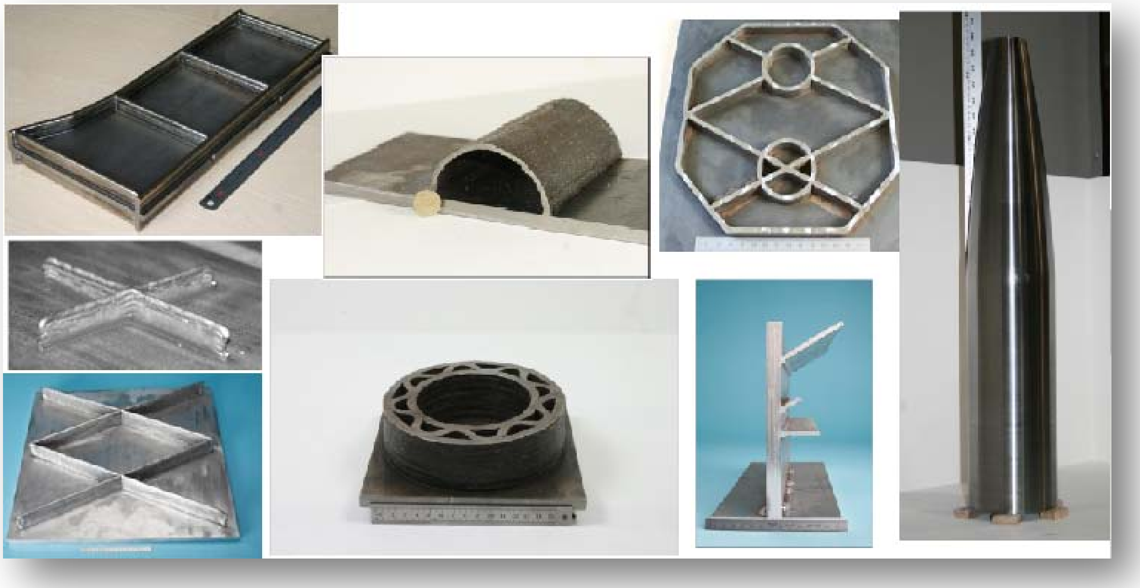


Figure 2.7: Different features deposited by WAAM

Deherka (2010) carried out research on building horizontal and inclined walls by using cold metal transfer (CMT) on carbon steel and aluminium. After modification the welding parameters developed for vertical wall, horizontal and 30°, 60°, 120°, 150 °inclined walls were successfully deposited. Ding et al. (2010) conducted a study on design and manufacturing wall crossing feature. A pattern of opposite angles connecting at the wall crossing vertices was developed to minimize sharp angles in the corners and peaks at the cross point. Crossing features can be satisfactorily produced with heights of up to height 100 mm and wall thicknesses of 4 mm. According to Williams (undated), materials and features which are possible to be produced by WAAM are listed in Table 2.1.

Table 2.1: WAAM materials and features

Materials		Features	
Titanium Alloys	Ti6Al4V	**Walls**	Vertical
Aluminum alloys	Al/Si		Inclined
	Al/Cu		Horizontal
	Al/Cu/Zn		Curved
Steel alloys	Low strength	**Intersections**	Linear
Copper Alloys	Cu/Si		Curved
---	---	**Enclosure**	Linear
---	---		Curved

2.3 Product Cost Engineering

2.3.1 Cost Engineering

According to Humphreys (2005), cost is regarding the amount of money expended or liability incurred with delivery of products and/or services. And from the perspective of total cost management, it should cover any expenditure of time, human, and physical resources.

From Asiedu (1998), the cost, quality and novelty of products can significantly influence the success of a company on the increasingly competitive global market. Furthermore, Roy (2003) pointed out that within today's highly competitive market place, customers require higher quality with an ever-decreasing cost. Therefore, cost reduction initiatives are essential for every company to survive and compete successfully. Cost estimation is perhaps the paramount factor in the outcome of a product or service for today's industries.

As shown in Figure 2.8, it is believed that over 70 percent of the total cost would be fixed in the conceptual design stage; although in that stage itself the incurred cost may have attributes less than 10 percent of the total cost (Roy, 2003). Hence, it is obvious that the concept to carry out precise cost analysis at a very early stage is important for the deduction of overall product cost.

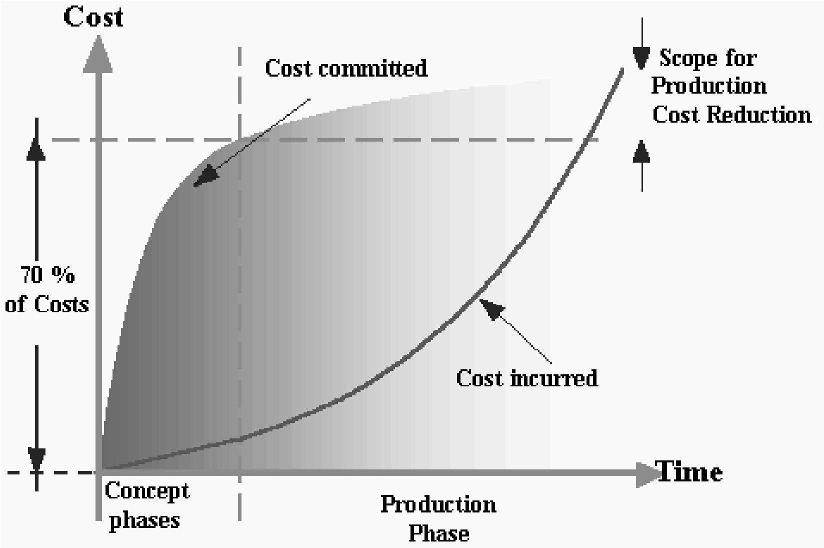


Figure 2.8: Cost Commitment Curve (Roy, 2003)

There exist a variety of cost categories depending on different classification perspectives. According to Curran, et al. (2004), the non-recurring or recurring cost, direct or indirect costs, and variable or fixed cost are common cost classifications which can facilitate the process of arranging a product’s costs into a cost breakdown structure.

Cost engineering can be defined as a scientific application which mainly studies the principles and techniques that are utilized to estimate or analyse the cost for delivery products or services (Stewart, et al., 1995). From Roy (2003), Cost engineering aims to identify and process the issues in cost estimation, control and management. It is mainly used to help cost estimator to analyse budget, and it also very important in supporting decision makers make strategic decisions during the development of a specific project.

Cost estimation can be seen as a predicting process to quantify the cost of a subject within a defined scope. Any estimated project cost is an opinion of probable cost and will not be an exact number. The accuracy depends on how well the project scope is defined and the time and effort is spend in estimate preparation (Humphreys, 2005). The final exact cost to a very large extent is influenced by the accuracy of the estimated cost, Figure 2.9 indicates the relation between the actual cost of a project and the estimated cost, too low or too high cost estimation will both lead to final cost increase. Only a realistic estimate can results in satisfied project costs (Asiedu, 1998).

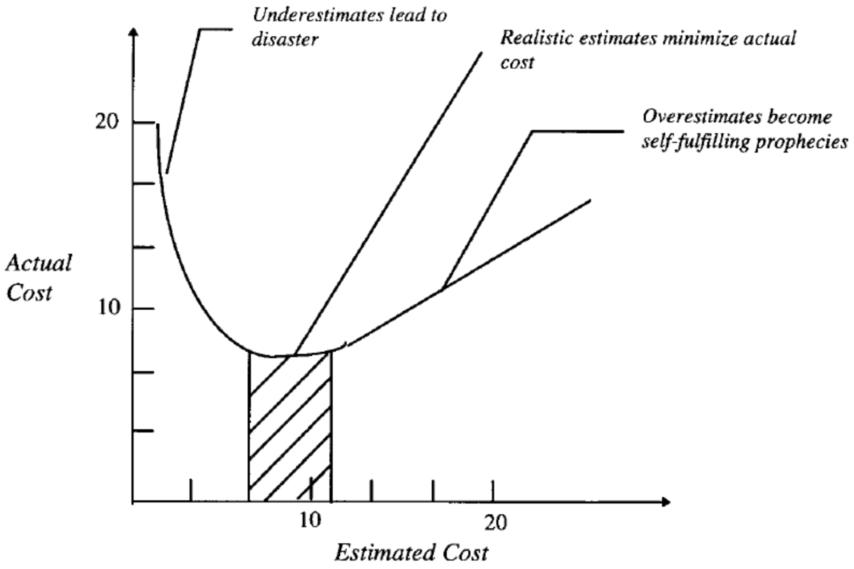


Figure 2.9: The Freiman curve (Asiedu, 1998)

2.3.2 Cost estimating techniques

According to Roy (2003), the cost estimating techniques can be classified into the following groups: traditional methods (first sight and detailed estimate), parametric estimating (PE), feature based costing (FBC), neural network based cost estimation and case-based reasoning (CBR). Shehab and Abdalla (2001) broadly categorized various cost estimation techniques as intuitive, parametric, generative, and variant-based approaches. Among all these cost estimation techniques the generative method is believed as the most accurate estimating approach by the same authors, while the variant-based methods such as knowledge, feature, operation, weight, etc. are suggested to be utilized in the design stage.

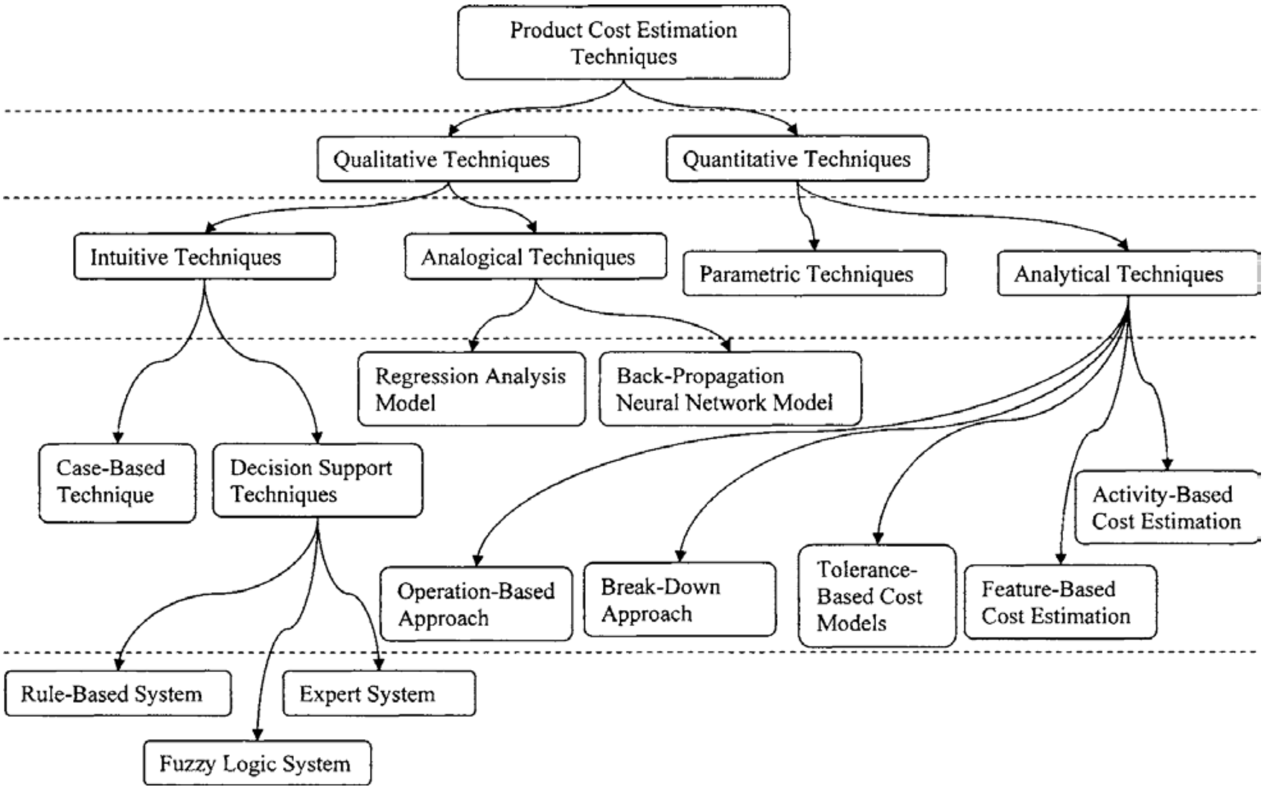
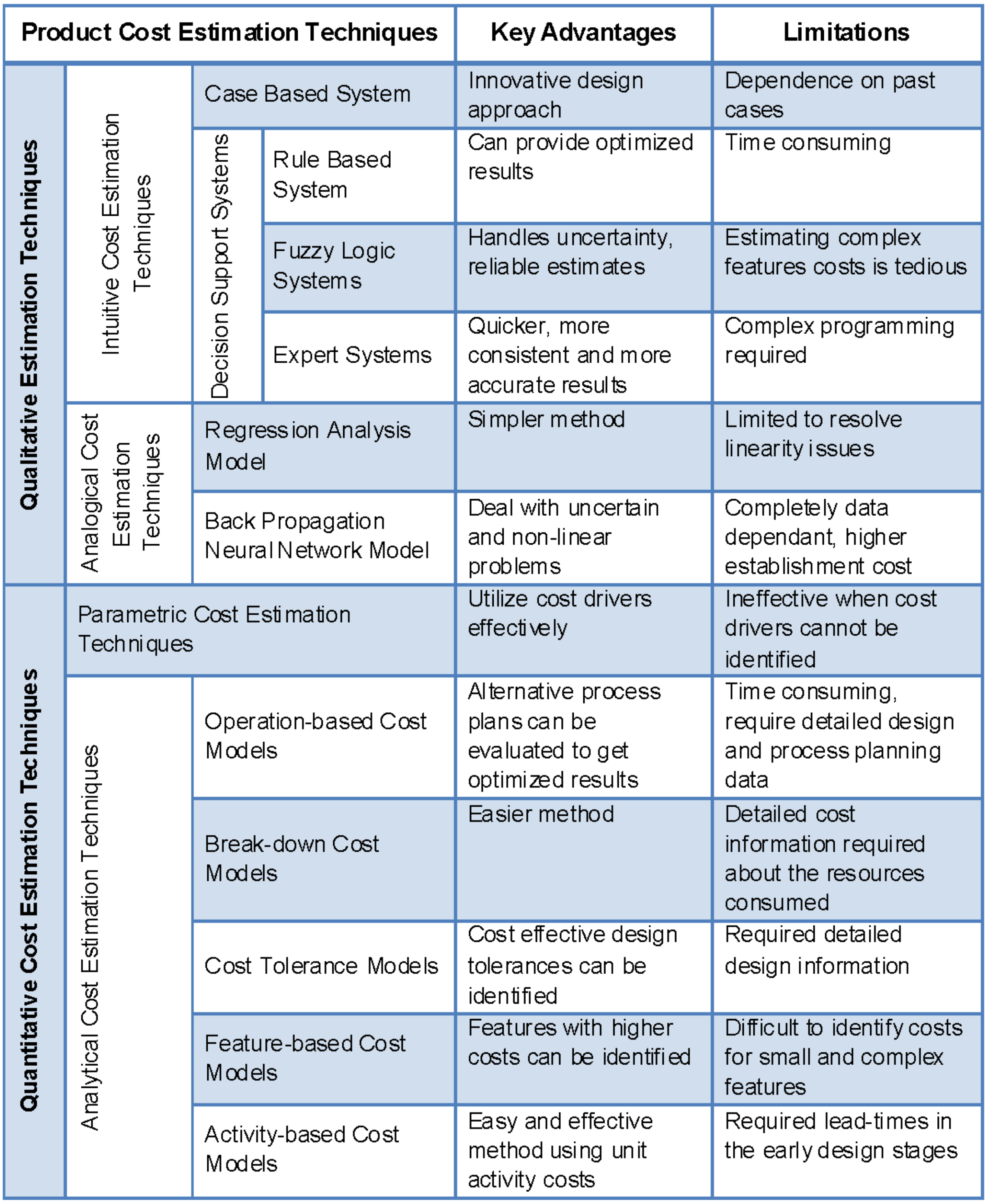


Figure 2.10: Classification of the PCE techniques (Niazi et al., 2006)

Niazi et al., (2006) reviewed the state of the art in product cost estimation area which covers various techniques and methodologies developed over the years and divided them into two major groups: qualitative and quantitative techniques. As defined by the same author, qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the previously manufactured products in order to identify the similarities. The identified similarities will help to estimate reliable cost for the new product by using the past design and manufacturing cost data. On the other hand, instead of simply depending on the experimental data, the quantitative cost estimation techniques are based on a detailed analysis of a product design, features, and fabrication processes, then calculate the cost by using an analytical function of certain product parameters or summing up the product elementary units of different consumed resources.

Furthermore, each group is hierarchically subdivided into various categories. The categories are illustrated in Figure 2.10. The advantages and limitations of each technique are also summarized by the same authors, which are shown in Table 2.2.

Table 2.2: The PCE techniques_ advantages and limitations (Niazi et al., 2006)



Product Cost Estimation Techniques				Key Advantages	Limitations
Qualitative Estimation Techniques	Intuitive Cost Estimation Techniques	Case Based System		Innovative design approach	Dependence on past cases
		Decision Support Systems	Rule Based System	Can provide optimized results	Time consuming
			Fuzzy Logic Systems	Handles uncertainty, reliable estimates	Estimating complex features costs is tedious
			Expert Systems	Quicker, more consistent and more accurate results	Complex programming required
	Analogical Cost Estimation Techniques	Regression Analysis Model		Simpler method	Limited to resolve linearity issues
		Back Propagation Neural Network Model		Deal with uncertain and non-linear problems	Completely data dependant, higher establishment cost
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified
	Analytical Cost Estimation Techniques	Operation-based Cost Models		Alternative process plans can be evaluated to get optimized results	Time consuming, require detailed design and process planning data
		Break-down Cost Models		Easier method	Detailed cost information required about the resources consumed
		Cost Tolerance Models		Cost effective design tolerances can be identified	Required detailed design information
		Feature-based Cost Models		Features with higher costs can be identified	Difficult to identify costs for small and complex features
		Activity-based Cost Models		Easy and effective method using unit activity costs	Required lead-times in the early design stages

2.3.3 Cost estimating process

A 12 step cost estimating process was proposed in *2008 NASA Cost Estimating Handbook*. This is a detailed introduction of how to conduct the entire cost estimation for products or services.

Figure 2.11 illustrates the whole process of NASA 12 step cost estimation methodology. There are three main parts in this process. The first part is project definition, step 1 to 3 were included in this part. The project requirements, inputs, expectations, resources and schedules will be clarified first. Then all elements of the project involved in cost estimation will be determined through WBS. After that, establish a project baseline document which can fully define the project. When part 1 was finished, the project will be thoroughly defined and understood by the estimators. The second part is cost methodology development, step 4 to 7 were contained in this part. First the ground rules and assumptions were established to define the cost estimation scope. Then determine the most suitable cost estimating methodology and specific cost model. Finally collect and normalize all the required data associated with cost estimating. Through part 2, the cost methodology which can guide the development of the cost estimation will be determined. The last part is actual cost estimation and documentation, step 8 to 12 consist this part. The accurate cost estimation was conducted first, and then the cost risk assessment was incorporated. Thereafter, the results were documented and presented. Finally, the cost estimation results may be updated on a regular basis. Through this 12 step methodology, the entire cost estimation project can be confidently conducted.

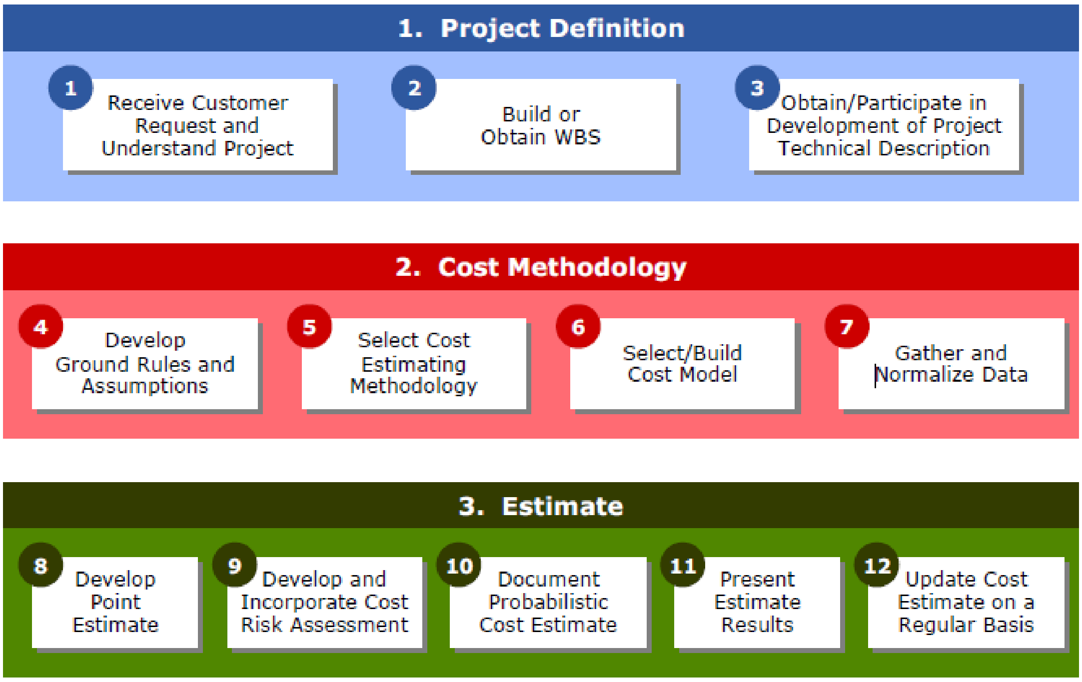


Figure 2.11: Cost estimation process (2008 NASA Cost Estimating Handbook)

2.4 Environmental impact

2.4.1 Global warming

Over the 20th century, the global average temperature has increased by approximately 0.6 °C, this phenomenon of climate change is well known as “global warming”. A common view is that the current global warming rate will continue or even accelerate (Root, 2003).

The major anthropogenic factor of global warming is the increasing emission of greenhouse gases (GHG) by human activities. These greenhouse gases can absorb the heat from the earth’s surface and stop it from passing straight out into space, which leads to the planet warming. Figure 2.12 indicates the amount of greenhouse gas emissions by each sector in the year 2000, it can be seen that the industrial processes is the second contribution (Khangura, 2010).

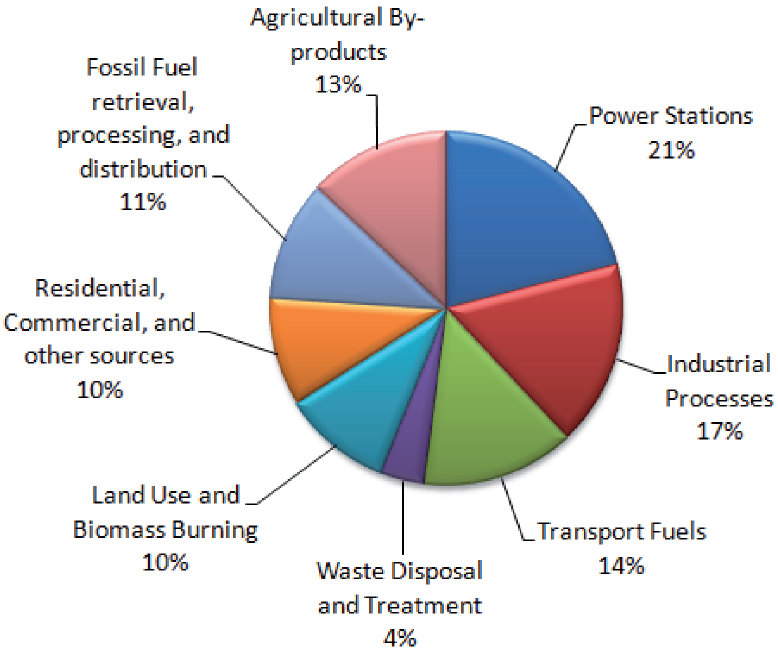


Figure 2.12: Global GHG emission by sector (Khangura, 2010)

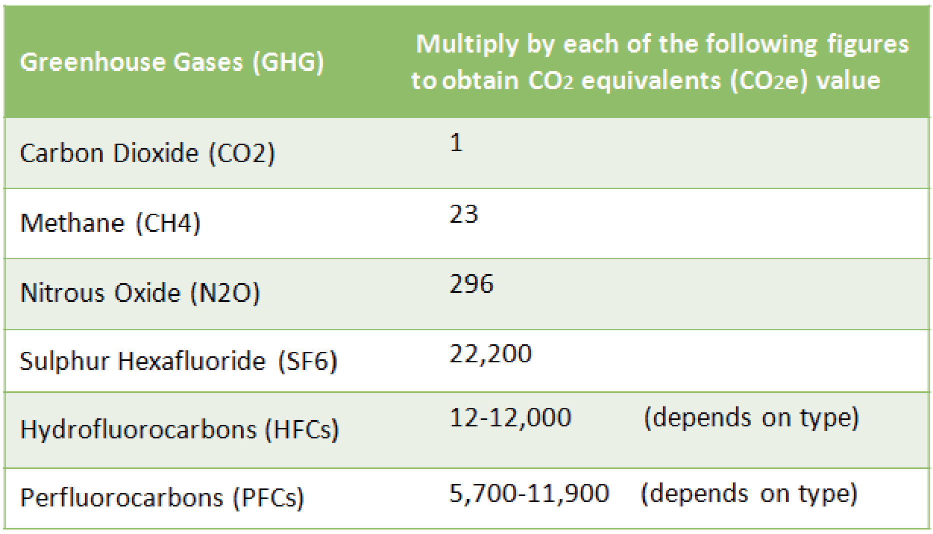
Global warming now is an issue that should be dealt with at a global level and each individual country is asked to take their responsibility for GHG control. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was produced. The objective of the treaty is to “stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. In addition, a protocol of

UNFCCC named Kyoto Protocol is signed in 1997 and officially enforced in 2005. In this protocol, 37 industrialised countries commit to reduce their greenhouse gas emissions by 5.2% on average for the period 2008-2012, relative to the base year 1990. Some mechanisms such as carbon emission trading was also established which aim to assist countries to achieve the targets set by the agreement.

2.4.2 Measurement for GHG emission

The unit used to measure GHG emission is tons of carbon dioxide, Other GHGs are converted to this measurement according to their global warming potential (GWP). From the intergovernmental panel on climate change assessment report (IPCC, 2001), the conversion rate of each GHG into CO_2 unit is shown in Table 2.3. Meanwhile, a term ‘carbon footprint’ is used to describe the amount of GHG emissions caused by a particular activity or entity.

Table 2.3: Greenhouse gas conversion rates (IPCC, 2001)



Greenhouse Gases (GHG)	Multiply by each of the following figures to obtain CO_2 equivalents (CO_2e) value
Carbon Dioxide (CO2)	1
Methane (CH4)	23
Nitrous Oxide (N2O)	296
Sulphur Hexafluoride (SF6)	22,200
Hydrofluorocarbons (HFCs)	12-12,000 (depends on type)
Perfluorocarbons (PFCs)	5,700-11,900 (depends on type)

The international standard organization published an ISO standard ISO14064 in 2006, which provides an integrated set of tools for programs aimed at measuring, quantifying and reducing greenhouse gas emissions. From this standard, the GHG inventory is formed of 3 components: the GHG sources - a physical process to release GHG into the atmosphere; the GHG sinks - a process or unit which removes GHG from the atmosphere; the GHG reservoirs - a physical unit which is able to store GHG from GHG sinks and/or from the source. According to Khangura (2010), The ISO 14064 provides a high level outline for businesses and the government to fulfil the Kyoto Protocol. However, a more detailed method is required to actually perform this task.

A publically available specification (PAS) for assessing product life cycle GHG emissions: PAS 2050 was formulated by BSI British Standards and co-sponsored by the Carbon Trust and the Department for Environment, Food and Rural Affairs (DECC & DEFRA, 2012). More than a high level outline, this specification focuses on providing an actual method to carry out a lifecycle assessment on specific goods or service. Meanwhile, a support document '*Guide to PAS: 2050 - How to assess the carbon footprint of goods and services*' is published by BSI which aims to help businesses to implement the PAS2050's methodology by offering specific and practical guidance. As shown in Figure 2.13, the guidance breaks down the carbon foot print assessment process into five steps (British Standards Institution, 2011).

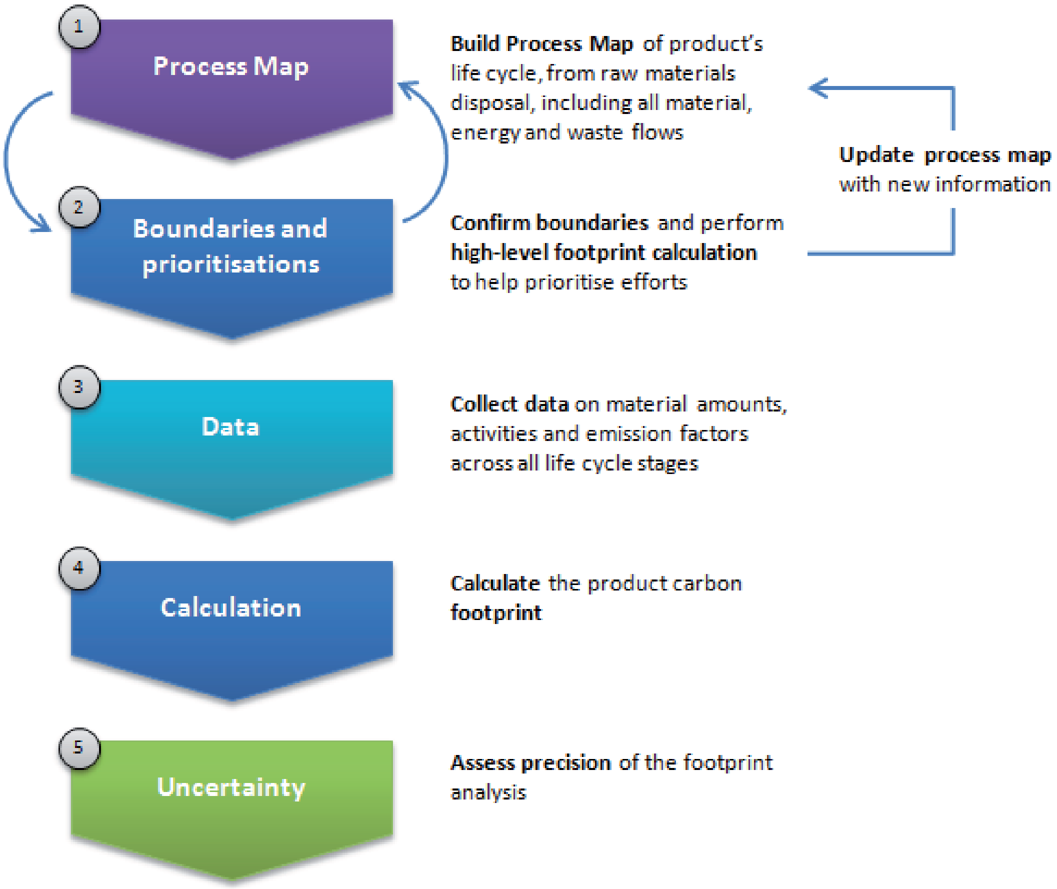


Figure 2.13: Five steps to calculating the carbon footprint (Guide to PAS 2050, 2008)

Based on the ISO 14064 and PAS2050, the international standard organization also intends to publish a more specific standard – ISO14067. This new International Standard will detail the principles, requirements and guidelines for the quantification and communication of the carbon footprint of goods and services (CFPs). In this standard the GHG emissions and removals of a product are based on a life-cycle assessment, meanwhile, requirements and guidelines for the quantification and communication of a partial carbon footprint of products (partial CFP) are also provided. The DIS (draft international standard) version was published on 6th January 2012. However, the final version is still not available.

2.5 Existing research

A number of journals and articles regarding feature based cost estimating can be found while literature which focused on cost estimation of ALM techniques is limited in number. Some of them are listed and reviewed below.

Ou-Yang and Lin (1997) proposed a feature based model to estimate the manufacturing cost of the machining products. The geometrical shape and product precision are specified for its features. This feature based model tool aims to provide designers who are not familiar with various manufacturing process as an initial estimate of the manufacturing costs associated with their design during the design stage. The limitation of this model is that it is designed only for traditional manufacturing techniques.

Jung (2002) developed a feature based cost estimation model for various machining processes. By classifying various machining activities into 4 basic categories, this model is able to accurately and rapidly handle cost estimate for infinite shapes combined with these features. In this model, machining features are classified into turning, face milling, end milling, drilling/reaming operations, and then further subdivided into a number of activities. Each specific activity’s operation time can be calculated then summed up to estimate the total cost.

Tipaji, et al. (2008) developed a cost estimation model which is based on the weld features of MIG welded joints. The model can estimate the cost of forty two different joints. The calculated results by this cost model had been compared with an expert welder’s quotation and got validated. The MIG welding technique is also presently used by WAAM technology.

Chayouki, et al. (2009) designed a software tool “COSTWELD” by using Visual Basic. This is a feature based cost estimation tool for weld assemblies. Two concepts of features: preparation feature and welding feature are presented in this model. By editing the independent feature and cost database, the cost model is flexible enough to incorporate new process and adjust the equations for different application.

Karunakaran, et al. (2010) presented a hybrid layered manufacturing process named ArcHLM, which is a new type of ALM technology developed by IIT Bombay. A manufacturing time and cost case study was carried out as well, from this study, it is believed that the ArcHLM technology is both time efficient and cheaper than conventional CNC machining.

Allen (2006) published a report which compared the costs of AM and machining in aerospace industry. The Buy-to-Fly ratio (compare the size of the original billet to that of the finished part) is used as a key factor to compare the economy of both techniques. The develop trend of AM technology is also predicted in this report. As a conclusion, the author believes that AM technique is commercially viable for components with a buy-to-fly ratio of about 12:1. In the future, with the increasing deposition rate, the specific cost of AM will drop and a buy-to-fly ratio of about 3 is economical enough to be manufactured by AM.

Khangura (2010) studied the cost and environmental aspects of RUAM. An integrated process in assessing the carbon footprint and cost for RUAM is developed by this author. After carrying out a case study, the author believes RUAM has the potential to provide a huge cost saving with minimum wastage and carbon emission as well. The shortcoming of this model is it inclined to be more high level and not precise enough.

Shettigar (2010) developed a feature based cost model for RUAM. According to this author, it is the first time to adopt feature based method on WAAM cost estimation. Meanwhile, A Visual Basic Software programme called RUAM Cost Weld has been coded by the same author. A detailed case study including a benchmark simple structure and a complex large real-world structure was carried out to validate the software. The economy of WAAM was also discussed by comparing it with traditional manufacturing techniques. Although it is a significant progress on WAAM cost estimate, but there are still some limitations. Firstly, this model can only handle a few features and materials; secondly, the data input and sum of the results are time consuming, especially when analysing complex components; finally, the accuracy could be further improved by considering more process details.

2.6 Research gap analysis

It can be seen from the literature review that the cost estimation methodologies are well developed and now widely used for various product cost analysis. Many of them can be applied at early design phase. However, cost model for additive manufacturing process is limited in number. A few existing cost models are limited by applicability, efficiency and accuracy. Until now, little research effort has been done in WAAM cost modelling area which aims to develop an accurate systematic cost estimation procedure supported by mathematic equations and then utilize it to carry out WAAM cost assessment. Such a dedicated cost and carbon emission model for WAAM is still not available.

To the best knowledge of the author, a comprehensive cost and carbon emission assessment tool for WAAM process which concentrates on providing accurate and efficient cost estimation in product design stage is not available. Hence it is essential to overcome this knowledge gap by developing a dedicated WAAM cost and carbon emission model and then implementing it in a practical software tool.

2.7 Summary

A detailed literature review which covers the major topics and areas of WAAM, cost and environmental impact was presented in this chapter. The manufacturing process of WAAM, the categories of material and features can be manufactured by WAAM were explored first, then the cost engineering concepts, various cost estimating techniques, the global warming context, and existing GHG emission quantification standards were reviewed.

In this chapter, the author also discussed the existing research regarding this topic. It was identified that the cost modelling research for additive manufacturing is limited in number. Little research has been done on the WAAM cost and carbon emission assessment. There is no integrated cost software tool that could be utilised to assess every type of WAAM products accurately and conveniently.

3 Research Aim, Objectives and Methodology

3.1 Introduction

It is vital to adopt an appropriate research methodology for a specific research. In this chapter, the research aim and objectives were determined based on the identified research gap first. Then the author gave a detailed introduction on the adopted research methodology, including the stage division and the output of each stage.

3.2 Research Aim and Objectives

The aim of this project is to develop a cost and carbon emission model primarily for the WAAM manufacturing cost (£) calculation and secondly for the WAAM carbon emission (KgCO2e) estimation, which can be used by the decision makers and design engineers in product design stage without detailed process information.

The research objectives are listed as follows:

1. **Create the overview of WAAM, environmental impact and cost estimation theories.**

Study the technology of WAAM, recognise the specific process and activities of WAAM; identify various cost estimation theories; explore relevant provisions and standards for environmental impact; investigate existing research on WAAM cost estimation. Find out the research gap and form the initial cost model concept.

2. **Determine the process map, CBS and cost driver, develop the WAAM cost framework and detailed cost equations.**

Investigate the WAAM manufacturing process. Establish the cost breakdown structure and identify the cost drivers. Define the manufacturing feature for WAAM. Construct a feature based cost model framework. Develop detailed cost equations according to the proposed cost framework.

3. **Develop GHG emission model for WAAM**

Investigate the existing GHG emission estimation standards, identify the GHG emission associated activities of WAAM, and develop specific WAAM carbon emission procedure.

4. **Develop an integrated software tool to implement the proposed cost and GHG emission model**

Study Visual Basic programming language and MS Access database techniques. Explore the techniques for automatically capture geometry, weight and material data from CAD files. Determine the structure and data flow of the software. Develop the cooperative database for process parameters and unit prices regarding WAAM. Design the graphic user interface. Implement the proposed cost and GHG emission model in this software tool.

5. **Apply this integrated software tool on cost estimation and comparative cost analysis.**

Using the proposed cost software tool to carry out actual cost and GHG emission estimation, and compare the cost of other alternative manufacturing techniques such as casting and milling.

6. **Validate this integrated cost model through case study and expert judgement.**

After the actual application in case studies, discuss the accuracy and applicability of the proposed model and software tool, validate them by expert judgements.

3.3 Research Methodology

The different steps to go through to achieve the research aim are presented in Figure 3.1. The structure of research methodology of this project consists of four major phases. They are literature review, data collection and analysis, cost model development, cost model validation. The actions and outputs of each phase are also presented in this section.

1. **Literature review**

This stage aims to obtain a fundamental understanding of this subject and its related fields, discuss the knowledge gap, and form an original Cost & CO_2

emission model concept. Objectives 1 was conducted at this stage, which includes the study of the technology and process of WAAM, identify the specific process stages and activities; understanding the increasing attention in environmental impacts, study relevant carbon emission quantification provisions and standards; explore various cost estimation theories then determine a suitable one for WAAM. The deliverable in this stage is a project brief introduction document and literature review report.

2. Data Collection and Analysis

This phase is mainly to gather and analyse the necessary data for the cost and CO_2 emission model. These data covers cost information of material, equipment, labour and energy, the WAAM process parameters and carbon emission associated data. They were obtained from literature, industry survey, expert knowledge and public database. By collecting and analysing these data, the WAAM process map, CBS and cost drivers can be determined. A comprehensive database for estimating WAAM cost and GHG emission also was developed. The output of this phase is the process map, CBS, data collection from and database.

3. Cost Model Development

The main aim in this phase is to develop a cost and carbon emission model for WAAM, then implement the proposed model in an integrated software tool. Objectives 2 to 4 were conducted in this stage. The cost model framework, detailed cost equations, GHG emission estimation procedure, CAD model identification techniques were studied respectively, then they were programmed into an integrated cost software tool, which comes with a CAD data automatically access program module to improve the data input efficiency; a precise cost & CO_2 calculate program module to ensure the accuracy of the results; an independent database to support data expansibility and maintainability; a user friendly interface to input settings and display results. The deliverable of this phase is the cost model software.

4. Cost model validation

Finally, a validation process for the developed cost model was carried out through case study and expert judgement. Some real-world components were used for the cost model validation. The defect identified through case studies, the suggestions and recommendations from experts were used to refine the proposed model. Conclusion and recommendation of this subject was made in this stage. The deliverable of this stage is the thesis and validated cost software tool.

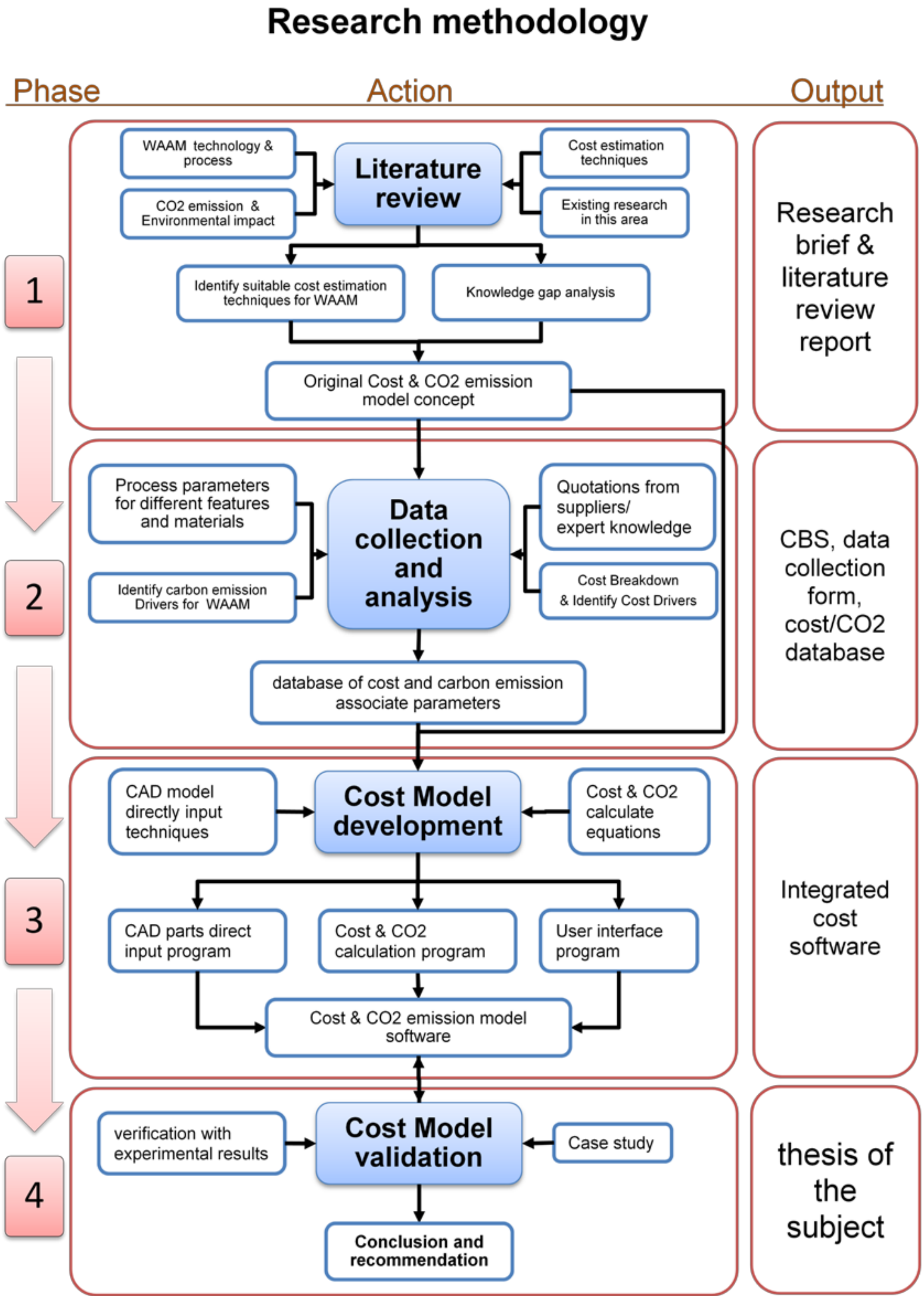


Figure 3.1: Research methodology

4 Cost Model Development

4.1 Introduction

The importance of developing a reliable cost model during early design stage is widely recognized. This project tends to adopt quantitative cost estimation techniques e.g. some type of analytical methods for WAAM cost modelling. Considering the actual state of the art of WAAM, a tool path based or feature based cost model is possible choice.

A robot path generation program named RUAMROB has been developed at Cranfield University (Ding, et al., 2010). With this software, the accurate total working time can be obtained, which is essential for cost calculation. However, due to the immaturity of RUAMROB, many shortcomings can be found such as cannot process tool path for complex components, the welding parameters are not included, etc. Therefore, it is reasonable to develop a tool path based cost calculate software in the condition that tool path software is robust enough. Even we can integrate them together at that time. However, at present other approach should be considered for developing the cost model.

A fabrication of geometrical features by WAAM research project is ongoing in Cranfield University. The process parameters were investigated through large amount of experiments, then the parameters for manufacturing each geometrical feature were analysed and optimised (Panagiotis, 2012). Hence it provides a feasible way to approach cost for WAAM by using a feature based model. The total manufacturing cost can be calculated by determining the costs of each feature first and then sum up all these features' cost together. This is an accurate and reliable method. Moreover, compared with tool path based approach the feature-based cost estimation methodology is more suitable to be used in product design stage and identify cost consuming features easily.

4.2 The WAAM process map

As previously presented in chapter 1, this project concentrates on the manufacturing cost of WAAM products. The cost of design, optimization and quality inspection were considered out of scope. Moreover, the indirect cost such as administration cost and factory plant cost were excluded as well. The WAAM process map for cost modelling in this project was shown in Figure 4.1.

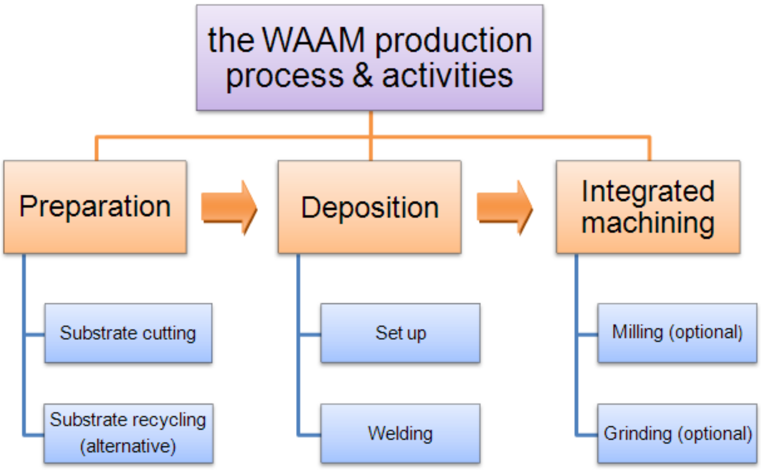


Figure 4.1: The WAAM process map for cost modelling

4.3 Cost breakdown structure development and cost drivers identification

4.3.1 Cost breakdown structure (CBS) development

According to the determined WAAM process map, the overall cost of the WAAM production can be subdivided into many cost elements. Figure 4.2 is the cost breakdown structure for WAAM.

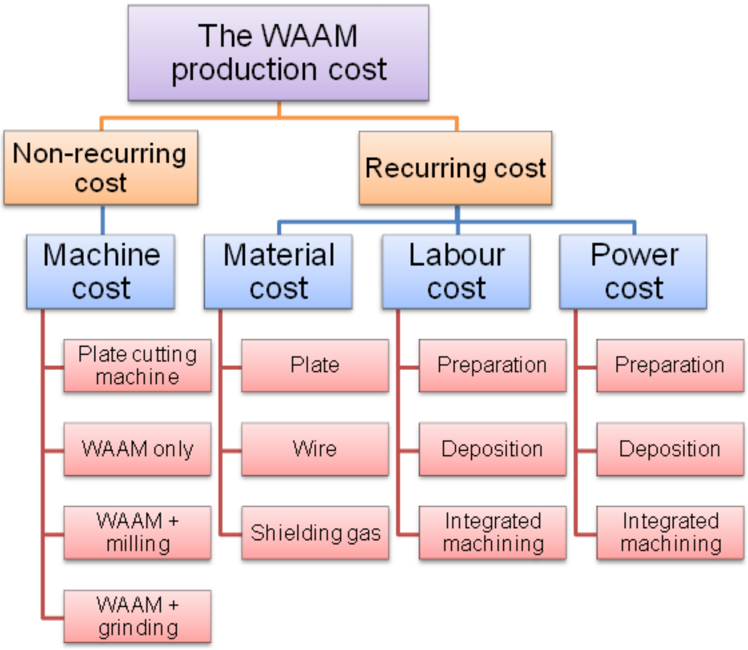


Figure 4.2: The WAAM cost breakdown structure

4.3.2 Cost drivers identification

The cost drivers can be identified from the WAAM process map and cost breakdown structure. In this project, the cost drives were classified into two categories: the geometric cost drivers and non-geometric cost drivers, which were listed in Figure 4.3.

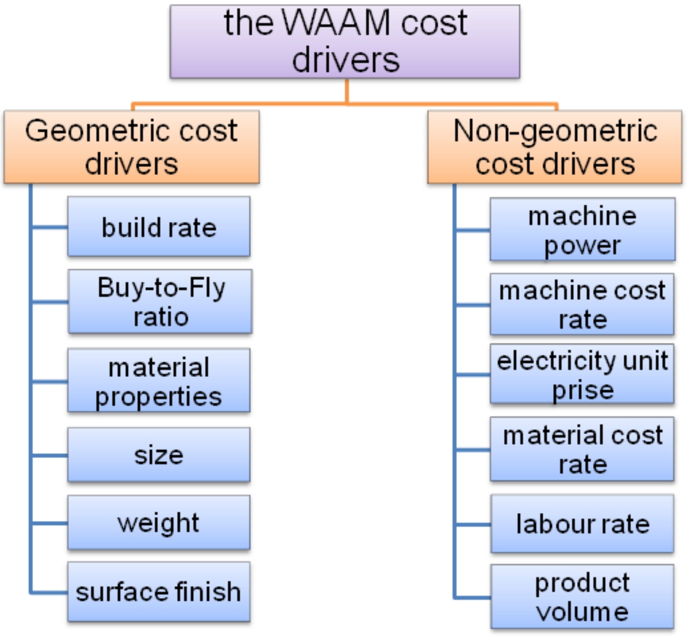


Figure 4.3: The WAAM cost drivers

The term “buy-to-fly ratio” here is usually used in aerospace industry to compare the size of the original billet to that of the finished part (Allen, 2006). It will determine how much material you need to purchase in order to manufacture the final product. One point should be clarified is that the buy-to-fly ratio depends on the manufacturing method. For machining due to large amount of material will be removed from the original billet the buy-to-fly ratio is usually high, while for WAAM the material of final product is converted from welding wire with very high efficiency, hence the buy-to-fly ratio of WAAM can be treated as the ratio between the initial deposited weight and the net shape weight.

4.4 Feature based cost model framework

4.4.1 Feature based cost model concept

The manufacturing cost of a component can be estimated by utilizing the production process and the process parameters it required. But usually it is hard to obtain detailed process data during design stage. To overcome this issue, a factor that can be identified by the cost estimator in the product design stage and will influence the final production cost is required (Ou-Yang et al., 1997). From the fabrication of geometrical features by WAAM research project which is ongoing in Cranfield University, it can be found that the process parameters vary with the manufactured features, and for a certain feature, the process parameters are similar. That means the manufacturing cost of a specific WAAM component can be calculated by utilizing the features it contains. This is the initial concept for WAAM cost modelling in this project.

In this feature based cost model, various WAAM products were treated as a combination of different basic features, the total production cost consists of cost for manufacture each feature, material cost, set up cost, substrate cost and integrated machining cost. In which the integrated machining cost was considered as an optional cost depends on the surface finish requirement; the substrate preparation cost includes two alternative process cost: substrate cutting or recycling cost; the set up cost will be uniformly distributed to the amount of products in case of batch production. Meanwhile, a factor “complex index” was adopted to describe the complexity of the WAAM product, which primarily affects the setup time.

4.4.2 Feature based cost assessment process

To compute the WAAM production cost through the proposed approach, a five-step cost assessment process was established as following:

Step 1: identify the process parameters such as build rate and buy-to-fly ratio which is corresponding to the manufacturing features.

Step 2: calculate the deposited mass of each feature. The mass deposited to form a near net shape can be computed as:

$$\mathbf{M_d} = \mathbf{M_n} \times \mathbf{B} \tag{1}$$

Where:

$\mathbf{M_d}$ = the mass deposited to form a near net shape for one feature

$\mathbf{M_n}$ = the net shape mass (designed mass in CAD model) of one feature

$\mathbf{B}$ = buy-to-fly ratio, a term used to describe the ratio of material deposited to material that eventually goes to the net shape product.

Step 3: calculate the required build time of each feature. The overall build time for each feature can be computed as:

$$\mathbf{T_b = M_d / R_b} \qquad (2)$$

Where:

$\mathbf{T_b}$ = the required build time of one feature

$\mathbf{M_d}$ = the mass deposited to form a near net shape of one feature

$\mathbf{R_b}$ = build rate (Kg/h) of one feature

Step 4: calculate the welding deposition cost of each feature. This can be compute through the following equation:

$$\mathbf{C_{fi} = T_b \times R_m} \qquad (3)$$

Where:

$\mathbf{C_{fi}}$ = welding deposition cost of feature i

$\mathbf{T_b}$ = the required build time of one feature

$\mathbf{R_m}$ = welding deposition cost rate (£/h), which includes the machine cost rate, labour rate, power cost rate and shielding gas cost rate

Step 5: calculate the total cost for manufacture one WAAM component. This can be compute through the following equation:

$$\mathbf{TC} = \sum_{\mathbf{i}} \mathbf{C_{fi}} + \mathbf{C_s} + \mathbf{C_b} + \mathbf{C_{machining}} + \mathbf{C_{Material}} \qquad (4)$$

Where:

$\mathbf{TC}$ = the total cost for manufacture one WAAM component

$\mathbf{C_{fi}}$ = welding deposition cost of feature i (see eq. 3)

$\mathbf{C_s}$ = set up cost

$\mathbf{C_b}$ = substrate cost

$\mathbf{C_{machining}}$ = integrated machining cost

$\mathbf{C_{Material}}$ = material cost

4.5 Identify the WAAM features

Many different definitions of feature can be found in different context. The similarity among these definitions is that features represent the engineering meaning of the geometry of a part or assembly (Shah, 1991). From manufacturing cost assessment point of view, the feature should be a geometric form that having an appearance associated with manufacturing activities (Jung, 2002). According to this proposal, the feature in this project is mainly a geometric from which can represent specific cost associated manufacturing parameters. Jung (2002) also categorised a four-class manufacturing features for metal cutting parts. However, it is not suitable for additive manufacturing application. Due to the nature of additive manufacturing itself, the features manufactured by WAAM are wall-like categories which were shown in Figure4.4 (Kazanas, 2011).

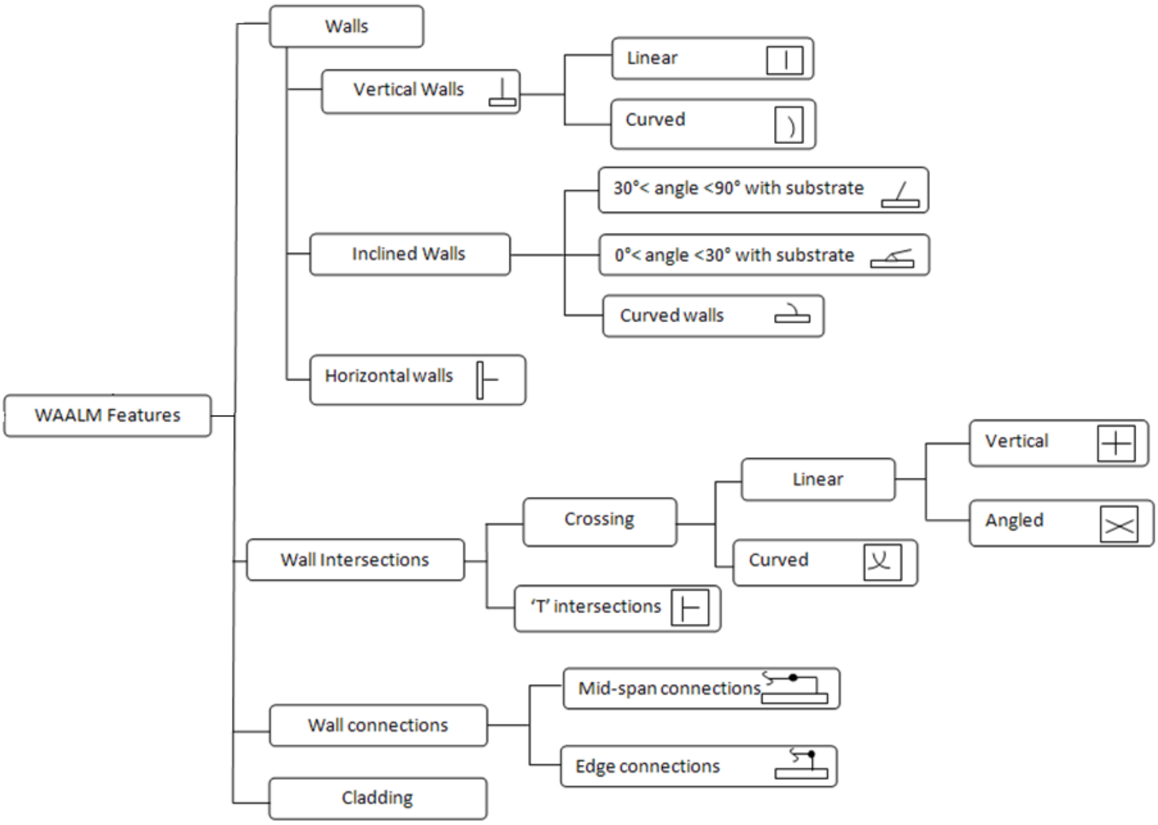


Figure 4.4: The WAAM feature taxonomy (Kazanas, 2011)

Considering the state of the art of WAAM, currently not all these features listed above have been fully studied. In order to find out which feature should be included in this project and their relationship and priority in affecting WAAM cost (main feature and sub feature, etc.), a questionnaire was designed to capture relevant knowledge from the Cranfield university welding research centre.

Table 4.1: The WAAM features in this cost model

The WAAM features in this cost model			
Main-features	**Sub-features**	**material**	**Wall thickness**
Vertical wall	With intersections	Aluminium	thickness⩽8mm
30° -90° Inclined wall	No intersection	Titanium	Thickness>8mm
0° -30° Inclined wall	---	Steel	---
curved Inclined wall	---	---	---
Horizontal wall	---	---	---

From the interview and questionnaire with WAAM staff and experts, the features included in this project were determined and listed in Table 4.1, where a specific WAAM feature = main feature + sub feature + material + wall thickness. As shown in Figure 4.5, the main feature depends on the angle $\theta$of wall deposition direction to horizontal plane. The sub feature here is the connection form between features which could influence the buy-to-fly ratio. The wall thickness can affects the alloy efficiency and build rate. Therefore these aspects were considered in the manufacturing feature definition. The different type of material was taken into account as well.

Figure 4.5: Definition of wall deposition angle θ

Figure 4.6 shows various kinds of vertical walls, the pattern of horizontal section may vary, as long as the deposition direction (see from vertical section) is vertical to the horizontal plane, it should be treated as vertical wall. Figure 4.7 indicates the aspects of real horizontal and inclined walls, please note due to the substrate is not always horizontal, so the angle between substrate and wall deposition direction is not always as same as deposition angle. Therefore the deposition angle should always be used as the only principle to judge the category of main feature.

Figure 4.6: Various kinds of vertical walls

Figure 4.7: Inclined wall and horizontal wall

As indicated in Table 4.2, detailed manufacturing parameters have been encapsulated in the manufacturing features. Therefore, without the requirement of knowing various manufacturing parameters, as long as the cost estimator can identify the features contained in one particular product, the manufacturing cost of this product can be calculated out.

Table 4.2: Manufacturing Parameters Encapsulated in Features

Manufacturing Parameters Encapsulated in Features	
1	Wire feed speed (WFS)
2	Torch travel speed (TS)
3	Wire diameter
4	Welding process
5	Amperage
6	Voltage
7	Alloy efficiency
8	Shielding gas type
9	Shielding gas consumption rate

4.6 Cost model equations development

4.6.1 Build rate

The overall build rate is affected by the welding deposition rate and non-deposition time (e.g. torch travel from one end point to next start point, part rotate time in case of double side deposition, extra cooling down time for special parts, etc.). However, the industry survey indicated that compare with the deposition speed (typically 3mm/s), the torch travel speed without welding (typically 200mm/s) and the part rotate speed (typically 300degree/s) are so fast and can be ignored, while the extra cooling down time for special parts is out of scope in this research. Hence the build rate can be treated as same as the deposition rate.

$$\mathbf{R_b} = \frac{\boldsymbol{\pi} \times \mathbf{D_w^2} \times \mathbf{v_F} \times \boldsymbol{\rho}}{\mathbf{4}} \tag{5}$$

Where:

$\mathbf{R_b}$ = build rate of one feature

$\mathbf{D_w}$ = welding wire diameter of one feature

$\mathbf{v_F}$ = wire feeding speed of one feature (WFS)

$\boldsymbol{\rho}$ = welding wire density

4.6.2 Buy-to-Fly ratio

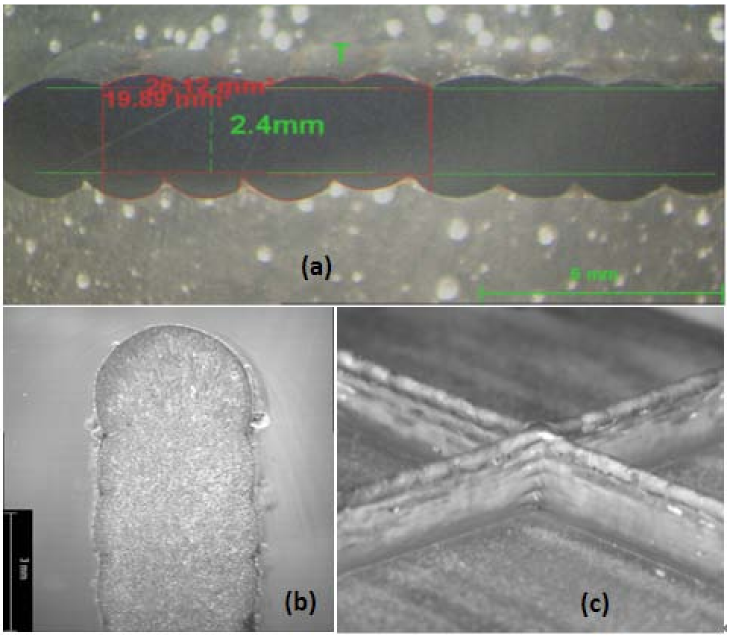


Figure 4.8 Factors influencing the buy-to-fly ratio

Figure 4.8 indicates the factors influencing the buy-to-fly ratio. In which (a) is a vertical section shows the surface waviness caused by the overlapping of weld beads. The "alloy efficiency" is a term used to measure the influence of the surface waviness (Shettigar, 2010). In the case of (a), the alloy efficiency =effective area/ overall area. However, picture (a) is only the condition of single track per layer, for thick wall (>8mm), a multi-track deposition strategy will be adopted. In this condition all tracks in the middle do not affect the wall waviness so the alloy efficiency will become higher than single track. This can be computed by the following equation:

$$\mathbf{E_a = \frac{S_e}{S_t} = 1 - \frac{S_w}{S_t} = 1 - \frac{1 - E_{a1}}{1 + (1 - x)(n - 1)}} \tag{6}$$

Where:

$\mathbf{E_a}$ = alloy efficiency (any tracks) of one feature

$\mathbf{E_{a1}}$ = alloy efficiency (single track) of one feature

$\mathbf{S_e}$ = effective section area

$\mathbf{S_w}$ = waviness section area

$\mathbf{S_t}$ = total section area

$\mathbf{x}$ = overlap rate (between tracks)

$\mathbf{n}$ = total number of tracks per layer

Picture (b) in figure 4.8 indicates the top layer fillet effect caused by the surface tension of the weld beads. This top layer fillet need to be trimmed off by finish machining, therefore the additional fillet volume need to be deposited first. After an interview with the WAAM expert, the fillet is proposed to have a semicircle section, where the diameter equals to the track width (or wall width for single track). Then the fillet volume can be calculated by the following formula:

$$\mathbf{V_{f1}} = \frac{1}{2} \times \boldsymbol{\pi} \times \left(\frac{\mathbf{W_t}}{2}\right)^2 \times \frac{\mathbf{V_n}}{\mathbf{H_n} \times \mathbf{W_n}} \tag{7}$$

Where:

$\mathbf{V_{f1}}$ = single track top layer fillet volume

$\mathbf{W_t}$ = track width

$\mathbf{V_n}$ = feature net shape volume

$\mathbf{H_n}$ = feature net shape height (or equivalent height for non-vertical wall)

$\mathbf{W_n}$ = feature net shape wall width

$$\mathbf{V_f} = \mathbf{V_{f1}} \times [\mathbf{1} + (\mathbf{1} - \mathbf{x})(\mathbf{n} - \mathbf{1})] \tag{8}$$

Where:

$\mathbf{V_f}$ = top layer fillet volume for any tracks

$\mathbf{V_{f1}}$ = single track top layer fillet volume (see eq. 7)

$\mathbf{x}$ = overlap rate (between tracks)

$\mathbf{n}$ = total number of tracks per layer

Another influence factor is the intersection among features which is shown in picture (c) of figure 4.8. At the intersected points when welding deposition the deposited shape tends to form stress raising sharp corners and overlap peaks, to overcome this issue several different deposition strategies such as use a pattern of opposite angles connecting at their vertices were investigated (Mehnen, et al., 2010). These build strategies also lead to additional material deposited at the intersection point. From the questionnaire information, the additional volume at intersection can be computed from the following equation:

$$\mathbf{V_i = W_n^2 \times H_n \times N} \tag{9}$$

Where:

$\mathbf{V_i}$ = additional volume at intersection of one feature

$\mathbf{W_n}$ = feature net shape wall width

$\mathbf{H_n}$ = feature net shape height (or equivalent height for non-vertical wall)

$\mathbf{N}$ = the number of “equivalent intersection” of one feature

There are two kinds of intersections: the cross intersection and the “T” shape intersection. From the industry survey, the additional volume of cross intersections is approximately double of that of “T” shape intersections. In this research project, a term “equivalent intersection” is used to convert these two types of intersections. One “T” shape intersection equals to one equivalent intersection, and one cross intersection equals to two equivalent intersections. For instance, if two vertical walls form one cross intersection, then each vertical wall will be treated as to have two equivalent intersections.

Finally, the deposited mass can be calculated by using equation (1), (6), (7), (8), (9) together.

$$\mathbf{M_d = M_n \times B = \rho \times \frac{V_n + V_f + V_i}{E_a}} \tag{10}$$

4.6.3 Welding Deposition cost rate

The welding deposition cost rate includes machine cost rate, labour rate, power cost rate and shielding gas cost rate.

The machine cost includes machine depreciation and machine overhead cost, where the depreciation rate is calculated based on the straight line depreciation method. The machine overhead is assumed as 30% of machine cost which consists of routine maintenance cost, unexpected breakdowns and services cost, and factory space used cost (Shehab, Abdalla, 2002).

$$\mathbf{C_M = 1.3 \times \frac{C_m}{t_1 \times t_2 \times t_3 \times t_4 \times E_m}} \tag{11}$$

Where:

$\mathbf{C_M}$ = machine cost rate

$\mathbf{C_m}$ = machine cost

$\mathbf{t_1}$ = working weeks per year

$\mathbf{t_2}$ = working days per week

$\mathbf{t_3}$ = working hours per day

$\mathbf{t_4}$ = amortisation period

$\mathbf{E_m}$ = machine utilization

In WAAM production, the welding deposition process is fully automated, therefore the manual labour is not required during most of the deposition time. A technician can easily handle a factory comprising of three RUAM machine without much difficulty (Shettigar, 2010). From this point of view, the labour cost rate during welding deposition process is 1/3 of standard labour rate ($\mathbf{C_L}$). While for a UK based manufacturing company using high tech equipment and a skilled worker, a labour rate of £55/h is proposed after interview with aerospace industry.

The power cost rate consists of robot power and welding machine power. The robot power is nearly constant for various WAAM products, while the welding machine power varies with the change of features. Hence, the voltage and current settings of the welding machine is used for welding machine power cost calculation.

$$\mathbf{C_P = \left(P_R + \frac{V_W \times A_W}{E_W \times 1000} \right) \times C_{power}} \tag{12}$$

Where:

$\mathbf{C_P}$ = power cost rate

$\mathbf{C_{power}}$ = power unit price (£/Kwh)

$\mathbf{P_R}$ = average robot power consumption

$\mathbf{V_W}$ = voltage settings of the welding machine

$\mathbf{A_W}$ = current settings of the welding machine

$\mathbf{E_W}$ = welding machine efficiency

The shielding gas (argon and helium) cost rate can be computed by the following equation:

$$\mathbf{C_G} = \frac{\mathbf{R_G} \times \mathbf{C_g} \times \mathbf{P_{atm}}}{\mathbf{V_G} \times \mathbf{P_G}} \tag{13}$$

Where:

$\mathbf{C_G}$ = shielding gas cost rate

$\mathbf{R_G}$ = shielding gas flow rate

$\mathbf{P_G}$ = shielding gas pressure

$\mathbf{P_{atm}}$ = standard atmosphere pressure

$\mathbf{V_G}$ = gas cylinder volume

$\mathbf{C_g}$ = cost per cylinder

However, for CO2 gas cylinder equation (13) is not suitable due to CO2 has liquefaction property under high pressure. From the weld gas supplier, 1kg liquid CO2 in gas cylinder will convert to 509L CO2 gas under standard atmosphere pressure. This figure is used for CO2 cost rate calculation in this project.

The shielding gas type and consumption rates (flow rate) are different for different materials. The detailed shielding gas type and flow rate for different material are listed in Table 4.3 (Shettigar, 2010).

Table 4.3: The shielding gas requirements for different materials

Material	Gas specification	Consumption rate mm^3/min
Titanium	Argon 50%+Helium 50%	37000
Steel	Argon 80%+$C0_2$ 20%	15000
Aluminium	Argon 99.98%	16000

Finally, the manufacturing cost rate can be calculated by the following equation:

$$\mathbf{R_m = C_M + \frac{C_L}{3} + C_P + C_G} \tag{14}$$

4.6.4 Substrate cost

There are two types of substrates, for common WAAM products the substrate can be recycled after deposition, while for some hybrid WAAM products the substrate are non-recyclable and will become a part of the final product. According to the industry survey, the substrate cutting and recycling process are highly automated and very effective. Hence the primary substrate cost is the cost of material. Therefore, only the material cost of substrate was considered in this cost model. For substrate-recycled WAAM products, the substrate cost is zero. While for the hybrid WAAM products, sometimes not all the material will finally goes to the product. For instance, the substrate may thicker than it in the final product to prevent thermo distortion, or the substrate area may larger to provide extra room for fixture. A term “substrate efficiency” in this cost model is used to correct the substrate mass.

$$\mathbf{C_b = \frac{M_b}{E_s} \times C_{material}} \tag{15}$$

Where:

$\mathbf{C_b}$ = substrate cost (only for non-recyclable substrate)

$\mathbf{M_b}$ = substrate mass in the final product

$\mathbf{E_s}$ = substrate efficiency (<1)

$\mathbf{C_{material}}$ = material cost rate

4.6.5 Setup cost

From interview with WAAM experts, the setup for WAAM consists of the following works: program the WAAM machine, load material and adjust the fixtures. However, the overall setup time depends on the complexity of the product.

After discussed with WAAM expert, the “complex index” is used to describe the geometrical complexity of a product. From simple to complex, the WAAM products are divided into four complexity levels: low (complex index = 0.5), medium (complex index = 1), high (complex index = 2), very high (complex index = 4). Each complex level has a specific setup time correction factor which is used to correct the setup time. The average setup time of medium-complex WAAM product is 1 hour, and this will be used as a benchmark, the setup time of other complex level can be calculated by using the benchmark multiply the correction factor.

The definition of complex level is:

- Low: only one independent feature.*
- Medium: several independent features, no intersections. *
- High: several features with intersections between each other.*
- Very high: products need to be deposited on both side of the substrate (a turntable is required to fix the substrate).

* If the product has a large size (>1.5 meter long), the complex index will increase to next higher level.

In the setup phase, the welding machine does not actually welding, the motion system also in static status. This means the power consumption is negligible during setup. The following equation is used to calculate the setup cost:

$$\mathbf{C_s = (C_M + C_L) \times T_s \times C_{sf}} \qquad (16)$$

Where:

$\mathbf{C_s}$ = setup cost

$\mathbf{C_M}$ = machine cost rate

$\mathbf{C_L}$ = labour rate

$\mathbf{T_s}$ = setup time for medium complex WAAM parts

$\mathbf{C_{sf}}$ = setup time correction factor depends on complex index

4.6.6 Integrated machining cost

The aim of integrated machining is to remove the surface roughness to obtain precise net shape. Due to the machining process is integrated into the WAAM system it does not need a separate setup process, and no additional material cost occur as well. So in this condition, the machine cost, tool replacement cost, labour cost and energy cost were considered to composing the total integrated machining cost. In which the tool replacement cost can be represented as machine cost rate multiply a factor (Dewhurst, et al., 1988). Finally, the following equation is used to calculate the integrated machining cost:

$$\mathbf{C_{machining}} = \left(\frac{\mathbf{C_M}}{\mathbf{1-n}} + \frac{\mathbf{C_L}}{\mathbf{3}} + \mathbf{P_m} \times \mathbf{C_{power}}\right) \times \frac{\mathbf{M_G - M_N}}{\mathbf{R_{material}} \times \boldsymbol{\rho}} \qquad (17)$$

Where:

$\mathbf{C_{machining}}$ = integrated machining cost

n = Taylor tool life index (depends on tool material)

$\mathbf{C_M}$ = machine cost rate

$\mathbf{C_L}$ = labour rate

$\mathbf{P_m}$ = average machining power consumption

$\mathbf{C_{power}}$ = power unit price (£/Kwh)

$\mathbf{M_G}$ = product gross mass

$\mathbf{M_N}$ = product net mass

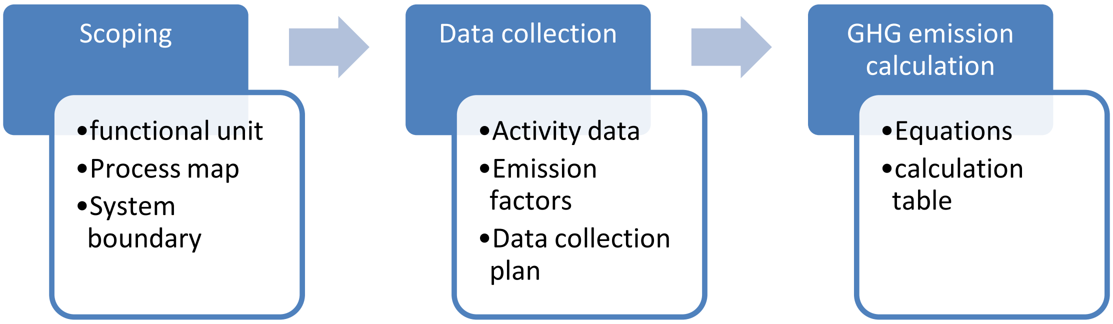
$\boldsymbol{\rho}$ = density of the material

$\mathbf{R_{material}}$ = material removal rate for medium complex WAAM parts ($^{\mathrm{m}^3}/_{\mathrm{h}}$)

5 Carbon Emission Model Development

5.1 Introduction

'Carbon footprint' is a term used to describe the amount of greenhouse gas (GHG) emissions caused by a particular activity or entity, and thus a way for organisations and individuals to assess their contribution to climate change (BSI, 2011). In 2011, PAS 2050 was updated to improve and refine the standard – based on initial experiences and international developments of product carbon emission measurement. A key aim of the update was to align the PAS 2050 methodology and its use with other internationally recognized carbon footprint methods such as the GHG Protocol Product Standard and ISO 14067, *Carbon Footprint of Products*. The PAS2050 provides an actual method to carry out a lifecycle assessment on specific goods or service and it also compatible with the coming ISO 14067. Therefore, this project follows the specification of PAS2050 standard. A three step GHG estimation methodology was illustrated in Figure 5.1.



Scoping
- functional unit
- Process map
- System boundary

Data collection
- Activity data
- Emission factors
- Data collection plan

GHG emission calculation
- Equations
- calculation table

Figure 5.1: Methodology for WAAM carbon emission assessment

5.2 The WAAM carbon emission assessment

5.2.1 Scoping

For accessing the carbon footprint, the product must be defined in terms of a 'functional unit'. The functional unit defines the function of the product that will be assessed and the quantity of product to which all of the data collected will relate (BSI, 2011). For WAAM products the functional unit in this research project is one piece of component manufactured by the WAAM process. Due to the current status of WAAM itself, the yield rate (rate of finished product) is not taken into account (no relevant data available).

Once the functional unit has been defined, the next step is to map out the life cycle of the product to be assessed. According to the BAS2050, the WAAM products belong to B2B (business to business) products class; its cradle-to-gate life cycle stages were shown in Figure 5.2. Then the detailed WAAM process map regarding GHG estimation can be found in Figure 5.3.

Figure 5.2: Process map stages for business-to-business goods (PAS2050)

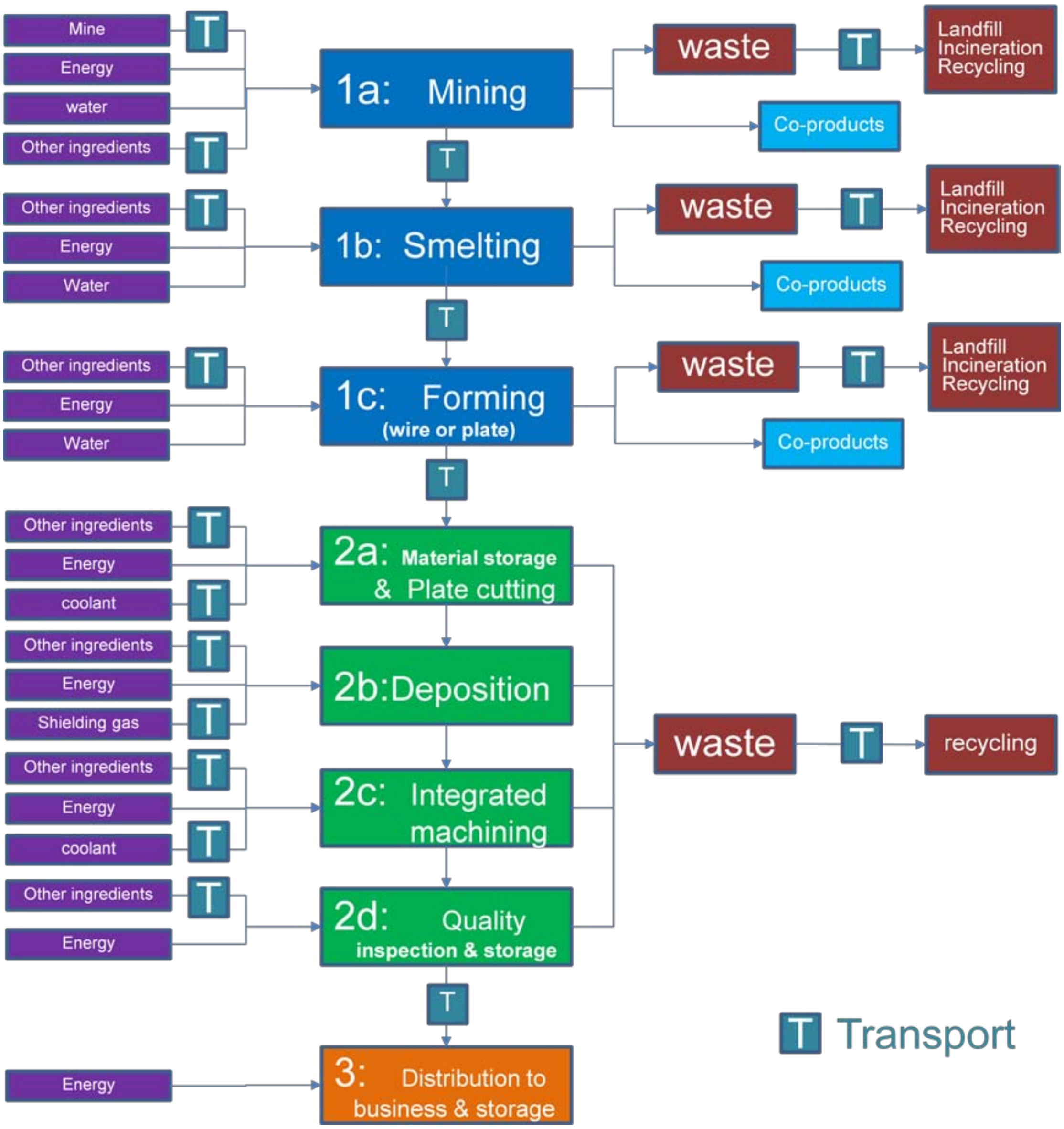


Figure 5.3: The WAAM process map for GHG assessment

The life cycle process map can be used to help identify which parts of the overall system will, and will not, be included in the assessment. According to PAS 2050, a carbon footprint must include all emissions of the 63 GHGs listed in the specification. Meanwhile, it is vital that at least 95 percent of the total mass and at least 95 percent of the total anticipated impact of the final product is being assessed.

The PAS 2050 allows for two standard types of assessment (Figure 5.4):

1. **Cradle to gate** – which takes into account all life cycle stages from raw material extraction up to the point at which it leaves the organization undertaking the assessment.

2. **Cradle to grave** – which takes into account all life cycle stages from raw material extraction right up to disposal at end of life.

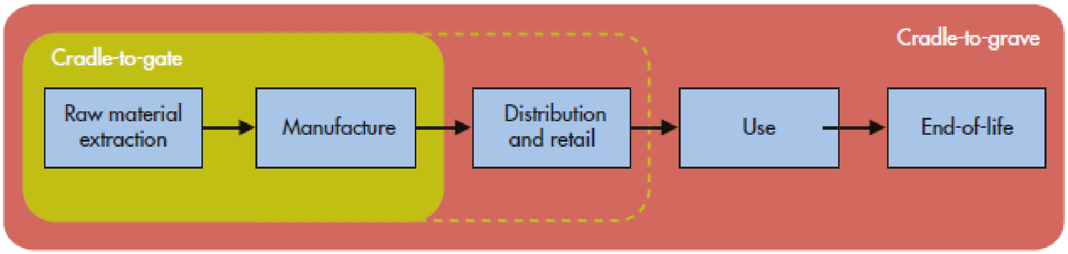


Figure 5.4: Different types of carbon emission assessment (PAS2050)

The WAAM process is developed to manufacture industrial components which can be classified to B2B product, so the "cradle-to-gate" assessment is reasonable, thus the use and the end of life stages can be excluded. Moreover, the WAAM process is a developing novel technique, and not yet is widely used in industry, so there is no proper GHG emission data associated with "distribution and retail" activity. The WAAM process also could play as an intermediate stage of overall production process in practical applications. So the distribution and retail stage was determined to be excluded in this project as well.

Besides raw material, energy and shielding gas, The WAAM process needs coolant for milling and grinding, as well as some other ingredients such as lubricant and cleaning agent. The coolant is recycled, other ingredients' consumption are anticipated to be immaterial for the total carbon footprint (less than 1 percent). So in this project, these factors were considered to be excluded.

The storage of raw material and product may come with GHG emission, especially for those needs cryopreservation. The WAAM substrate cutting do causes a certain amount of GHG emission as well. However, from industry survey it can be found that the WAAM products and raw material are all metal and do not require extra energy and coolant. Meanwhile, compare with the overall WAAM process the GHG emission during substrate cutting is also negligible. In addition, the quality inspection in current WAAM process varies with the experiment requirement and may change in future commercial production. Hence all these factors listed above were considered to be out of scope.

Other boundary consideration is to streamline the raw material stage. The production of raw material belongs to external supply chain and the supplier usually may vary. While an in-depth investigation for the detailed material production process is not feasible in this project, but the inventory of carbon for one specific material is generally stable and easy to access from associated database. So only the mass of consumed raw material and its transportation will be considered in this project.

Finally, the included activities and process for GHG emission assessment in this project was listed in Figure5.5.

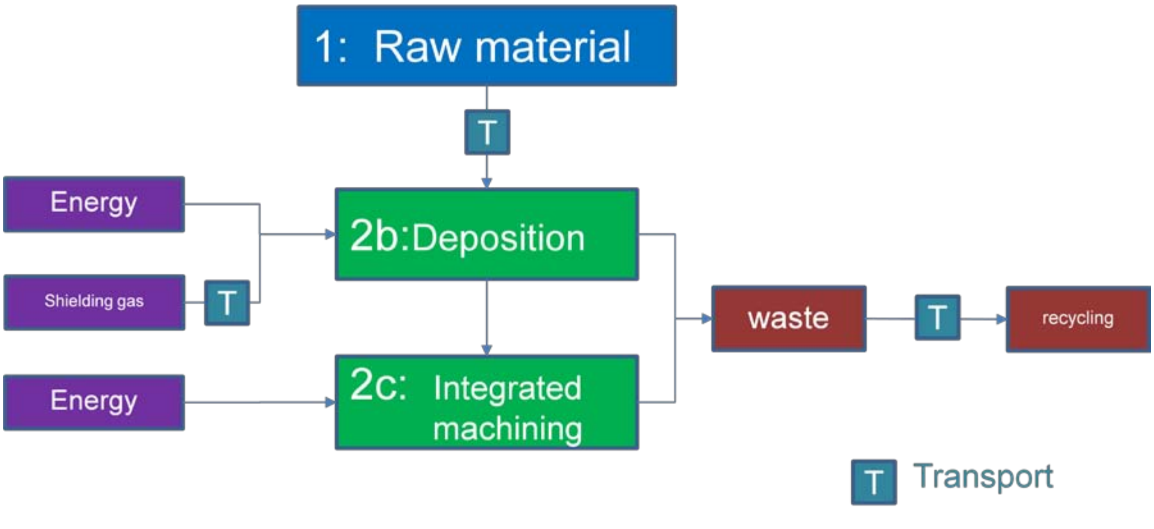


Figure 5.5: List of all included activities and processes for GHG emission assessment (system boundary)

5.2.2 Data collection

From the PAS 2050, two categories of data need to be collected for carrying out GHG emission assessment. They are:

Activity data: referring to quantities of inputs and outputs for a process, typically described for a unit of production for a specified year of production

Emission factors: values that convert activity data quantities into GHG emissions, usually expressed in units of ‘kg CO_2e’.

For these two categories of data, there are two types of data sources:

Primary sources – first-hand information, specific to the activity in question. Collected internally or from the supply chain

Secondary sources – average, or typical, information about a general activity concentration from a published study or other source.

In accordance with the principles of ‘relevance’ and ‘accuracy’, primary data are generally preferred. In addition, at least 10 per cent of the total cradle-to-gate emissions must have been calculated from primary data.

A data collection plan is essential in this stage. It should cover all of the data which are required for the carbon footprint assessment in this project. Meanwhile, the data collection plan should outline top targets for primary data collection, and highlight areas where secondary data will be sought instead when the primary data collection may not be feasible (PAS2050, 2011). Table 5.1 is the GHG emission data collection plan in this project.

Table 5.1: Data collection plan for the WAAM GHG emission assessment:

Data required	Anticipated source
Mass of the product	Primary data
Buy-to-fly ratio	Primary data
Build rate	Primary data
machine power	Primary data
Material removal rate during machining	Primary data / secondary data
Gas cylinder volume / weight	Primary data / secondary data
Shielding gas flow rate	Primary data

Material transportation distance & method	Primary data / secondary data
Waste (metal chips) transportation distance & method	Primary data / secondary data
All emission factors	Secondary data

5.2.3 GHG Footprint calculation

From PAS2050, a general formula for GHG emission calculation is Carbon footprint = activity data (kg/litres/kWh/tkm, etc.) × emission factor (kg CO2e per kg/litre/kWh/tkm, etc.). According to the defined scope in chapter 5.2.1, the GHG emission of WAAM consists of four sectors: raw material, electricity, transportation and waste disposal. The GHG emission of each sector can be calculated out through the above equation, and then the overall carbon footprint of WAAM products can be computed by sum each sector up.

The emission factor of raw material, purchased electricity, freight transportation and waste disposal can be obtained from two data sources. One is the *Inventory of Carbon & Energy (ICE)* database (Hammond et al., 2008), which is a project carried out by the University of Bath and gives details about the carbon emissions for various building materials. The other is *Greenhouse gas conversion factors for company reporting* 2012 guidelines (DECC and DEFRA, 2012), which is a public available guideline from the Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (DEFRA). Table 5.2 indicates the emission factor for various activity data of WAAM.

Table 5.2: Carbon emission factors of WAAM

item	Emission factors	Data source
Aluminium wire	11.2 (KgCO2e/Kg)	ICE
Aluminium plate	11.5 (KgCO2e/Kg)	ICE
Steel wire	2.83 (KgCO2e/Kg)	ICE
Steel plate	3.19 (KgCO2e/Kg)	ICE
Titanium	1.07 (KgCO2e/£)	DEFRA
Shielding gas	1.06 (KgCO2e/£)	DEFRA
Electricity	0.4939 (KgCO2e/kWh)	DEFRA
Freight transportation	0.641 (KgCO2/TonneKm)	DEFRA
Waste disposal	21 (KgCO2e/Tonne)	DEFRA

6 Integrated Cost and Carbon Emission Software Tool

6.1 Introduction

The proposed cost and carbon emission model were built by using Visual Basic 6.0 with Microsoft Access database support. This cost and carbon emission software tool is user friendly and easy to operate. Due to the design of an independent backend database, it can incorporate furthermore data easily; all the data such as process parameters and material unit price can be conveniently edited or added in the future. In order to minimise the operation time, this software comes with a CAD data automatically access program module which can improve the parameter input efficiency significantly. Hence the user does not have to manually input all the geometry data of the part to be estimated, only by simply clicking several button, the cost and carbon emission results will be calculated out in seconds. This is a significant aspect of this software tool which can eliminate time consuming manual labour and obtain a very quick and precise cost result.

6.2 Software structure and flow chart

- **Cost & carbon emission software structure**

In order to make the cost software more efficiently and user friendly, four modules are designed for this program. The relationship among these modules and the overall structure of the software are indicated in Figure 6.1.

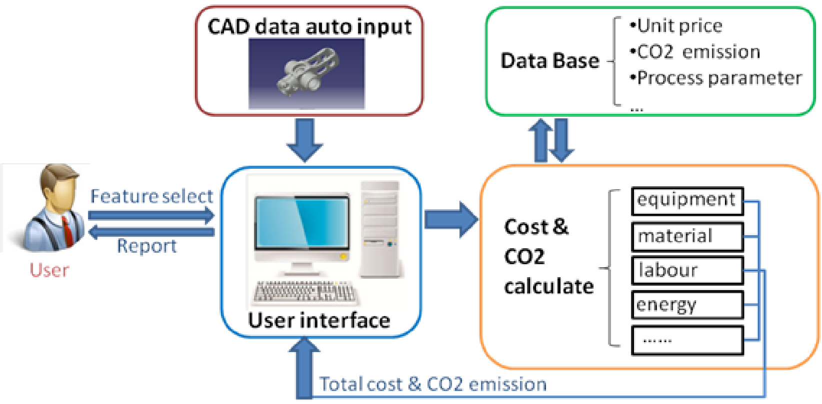


Figure 6.1: The structure of cost software

- **Cost & carbon emission software flow chart**

The software has a welcome page on which the user can select either edit database or calculate cost. When "edit database" function is selected, a data form page with four tabs will appear on where the database can be edited, added or deleted. "Calculate cost" function will take the user to a CAD model select page first, then the software will open selected CAD file by using CATIA and capture relevant data, all these data will be listed on a data confirmation page where they will get verified. After this, the final cost and carbon emission result will be calculated out and listed on the result report page. The software also provides a function to save the result as an independent Microsoft Excel file. Figure 6.2 shows the software flow chart.

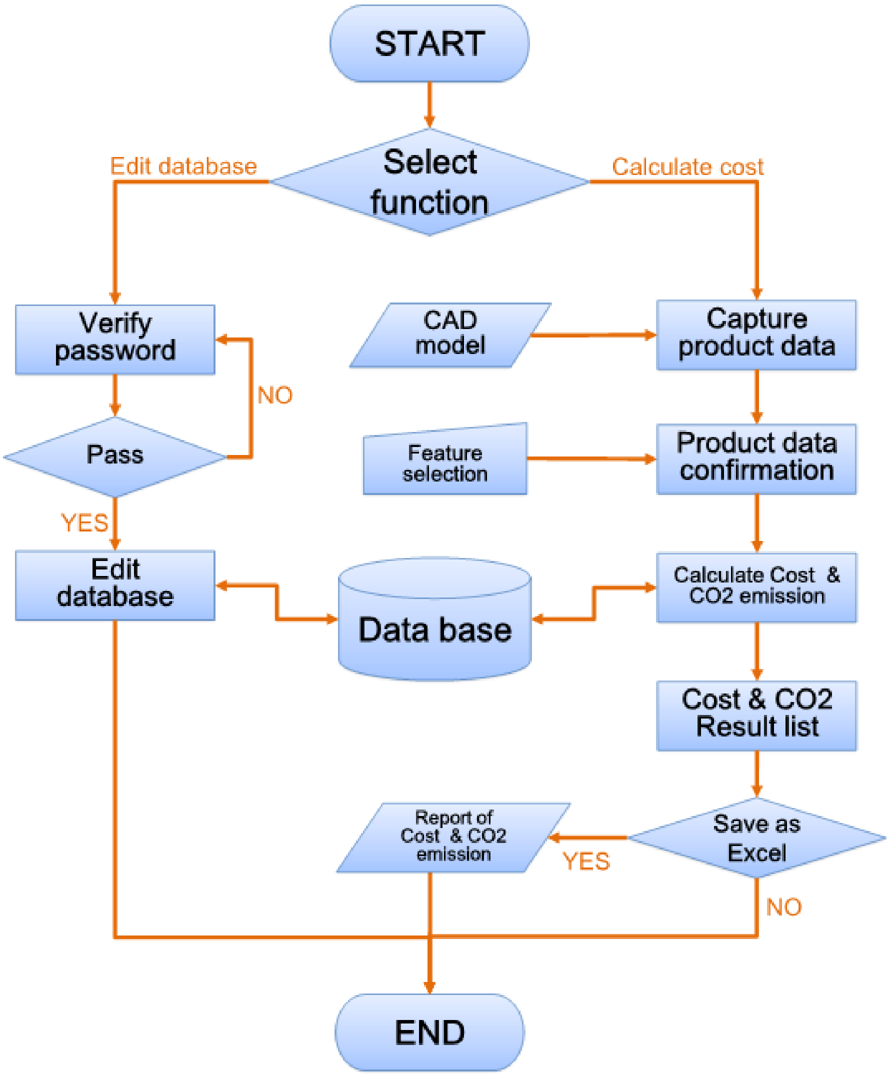


Figure 6.2: Software flow chart

6.3 Software Development

6.3.1 Automatically identify CAD models

The CAD techniques were initially carried out in 1960s, after years of development now it can cover the range from 2D vector-based drafting to 3D solid and surface modelling. A huge number of commercial CAD software are available to meet the requirement in different companies, such as AUTO CAD, UG, CATIA, PRO-E, Solid Works, etc. Among which CATIA is a multi-platform CAD/CAM/CAE software suite developed by the French company Dassault Systemes. Due to the robust functions it provides, at present CATIA has become the dominated CAD software in aerospace and automotive industries. Hence in this project, the cost software is designed to be compatible with CAD models generated by CATIA.

Most CATIA part CAD model is a native format “.CATpart” which is associated with CATIA only. Therefore it is hard to open this formatted file directly by other software. However, by means of CATIA automation technique, this task can be achieved. The automation technology is built on top of the Microsoft COM (Component Object Model), which is essentially a technology to enables software communicates with each other.

As illustrated in Figure 6.3, in the automated application of CATIA, all the data are encapsulated into objects and organised in a parent-child hierarchical structure. Meanwhile, CATIA V5 provides a series of application programming interfaces (API) which are source code-based specification intended to be used as an interface by software components to communicate with each other. The properties and contents of the encapsulated objects can be accessed by external programs via API. For instance, In Visual BASIC development environment, the codes listed below can be used to open a CATIA application.

```
Dim CATIA As Object
  Set CATIA = GetObject(, "CATIA.Application")
  Set CATIA = CreateObject("CATIA.Application")
  CATIA.Visible = True
Dim oPartdocument As PartDocument
   Set oPartdocument = CATIA.Documents.Open(strFilepath)
```

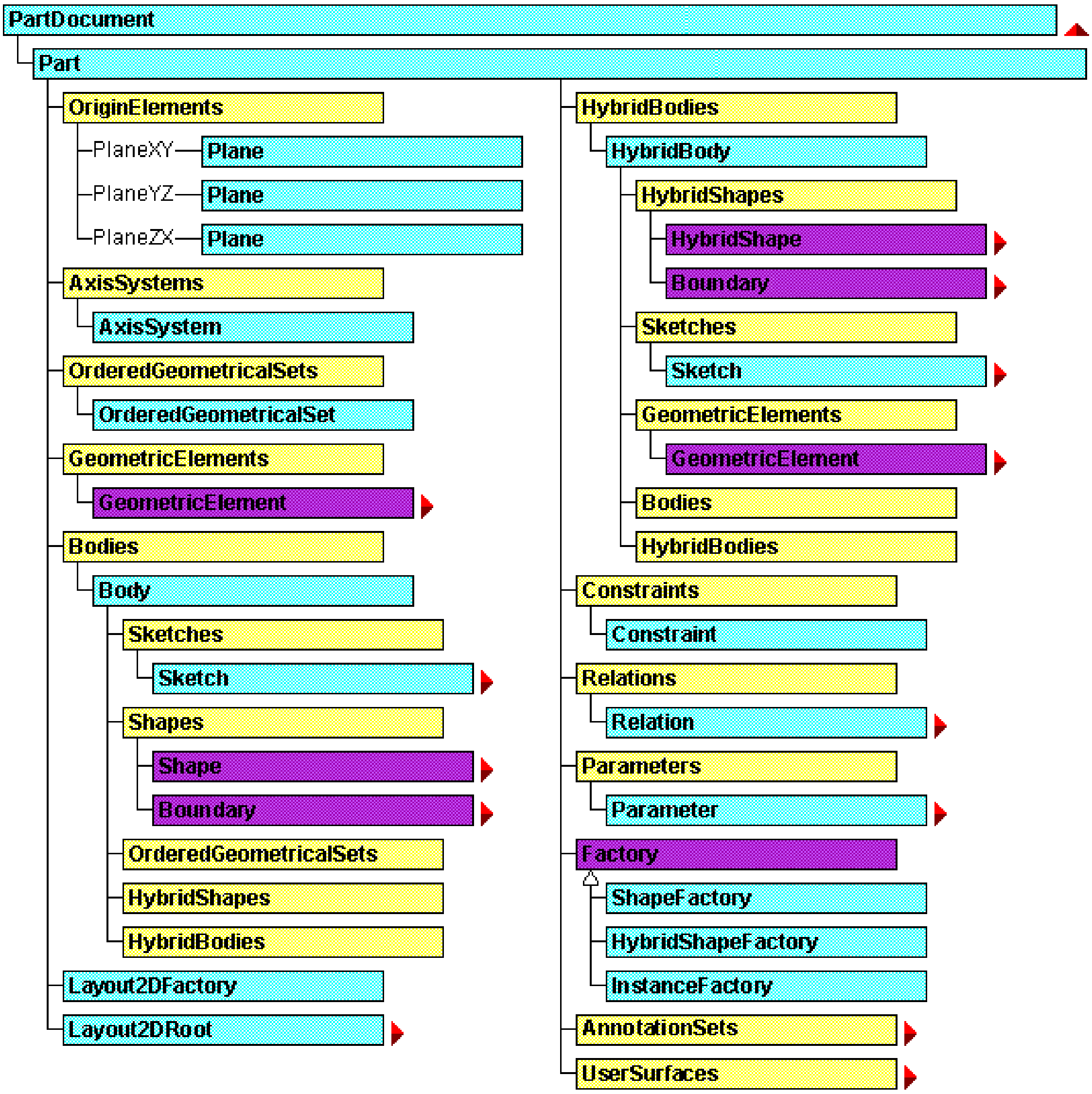


Figure 6.3: The Infrastructure of CATIA Part Document Automation Objects (CATIA V5 automation)

CATIA provides various methods to create solid CAD models. This means even for the same geometry shape, there are still many different modelling approaches. Therefore it is very hard to identify the CAD model regardless its modelling approach. In this project considering the geometry of WAAM product are most wall-like, the most feasible and convenient modelling approach in CATIA is to use the “Sketch-based features” tool (Figure 6.4). Hence the program is designed to identify and capture data from CATIA CAD parts which was consists of sketch-based features: Pad, Rib and Shaft. The integrated cost software utilises CATIA API to open selected WAAM CAD model and exchange data. The geometry properties such as volume, thickness and equivalent height of each feature of the selected WAAM CAD model will be obtained automatically, the material property such as material name and density can be directly captured as well. For each “sketch-based feature”, the user do not need to name it in advance, the software will only capture and list them with their original name, then the user need to manually identify and assign a proper WAAM manufacturing feature to it The software will also take a thumbnail of the CAD model to help the user confirming the correctness of the WAAM part to be calculated.

Figure 6.4: Sketch-based features in CATIA

During the CAD model identification process, the user only need to select the CAD model file at the beginning and assign proper WAAM manufacturing feature to each section after the CAD model was automatically captured. This cost software is compatible with CATIA V5 R18 or higher version, the measure unit of CATIA software should be set to metric. Other criteria for the CAD model to fulfil were it must be a .CATPart file, only one “part body” is permitted in one file, each WAAM feature should be drawn respectively by using the CATIA "sketch-based features" tool, only "pad" "rib" "shaft" will be processed by this program, the CAD model may contains "dress-up features" such as chamfer and fillet but it will be ignored, the wall thickness and height must be marked out in the sketch of each feature by using the "length constraint" tool, material property should be added in the CATIA CAD model in advance as well. Otherwise the software may capture wrong data from the CAD model. However, the user still has an opportunity to check and edit these data when they were shown on the "data verification page" later.

6.3.2 Data base design

In order to improve the maintainability of the cost associated data, an independent database was designed as a part of the cost software. The Microsoft access database program is adopted in this project due to its flexible and easy to use property. The cost data were stored in an independent .mdb formatted file and can be edited through cost software or Microsoft Access.

There are four tables in the database file namely: “welding deposition data”, “unit price information”, “machine information”, “GHG emission information”. The user can edit, add or delete records of each table, but the table name and data fields were not allowed to change, otherwise the software will fail to connect the database.

Table 6.1: The name and contents of database table

Table name	Contents
welding deposition data	Welding process parameters, integrated machining material removal rate
unit price information	Material expenses, labour rate, electricity price
machine information	Machine specification , price, depreciation period
GHG emission information	GHG emission factor and activity data for material, energy, transportation and waste disposal

Visual basic provides several methods such as data control, data access objects (DAO), ActiveX data objects (ADO), etc. to manage external database. Compared to the other two data access methods, the ADO is a more powerful data control in Visual Basic environment, as ADO is ActiveX-based, it can work in different platforms (different computer systems) and different programming languages. Besides, it can access many different kinds of data such as data displayed in the Internet browsers, email text and even graphics other than the usual relational and non relational database information. Therefore, ADO data access method was adopted in this cost program. The VB codes below were used to connect external MS database:

```
Dim Conn as ADODB.Connection
Dim Rs as ADODB.Recordset
Dim ConnStr as string
ConnStr = "Provider=Microsoft.Jet.OLEDB.4.0;Data Source=" & MDBfilePath & ";Persist
        Security Info=True;Jet OLEDB:Database Password=" & strPassword
Conn.Open ConnStr
Conn.CursorLocation = adUseClient
Rs.Open "……"
```

After connected to the external database, several ADO Recordset will be created and then by using the SQL (Structures Query Language) query keywords such as "SELECT * FROM TableName WHERE FieldName = X…", the specific information in certain tables of the database can be accessed or edited by the cost software.

6.3.3 Graphic user interface

In order to make the cost software more effective and convenient to use, a user friendly graphic interface was developed. This user interface consists of several graphic windows. Figure 6.5 shows the function of these windows and their relationship. With help of this clear and easy-to-use user interface, the cost and GHG emission estimation procedure can be conducted conveniently.

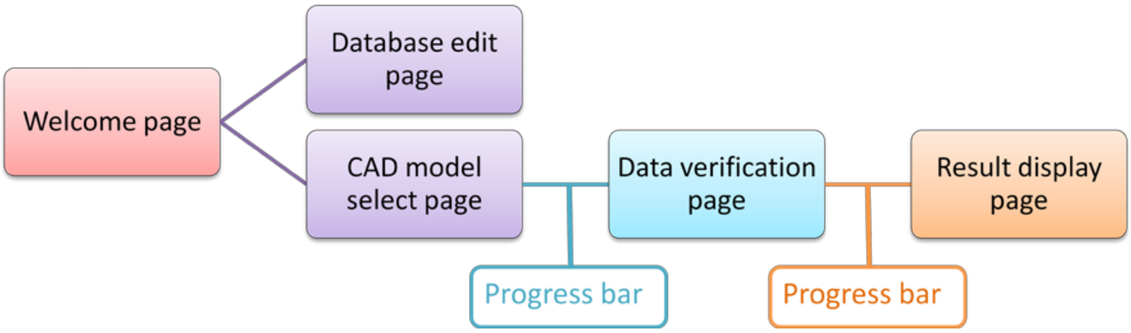
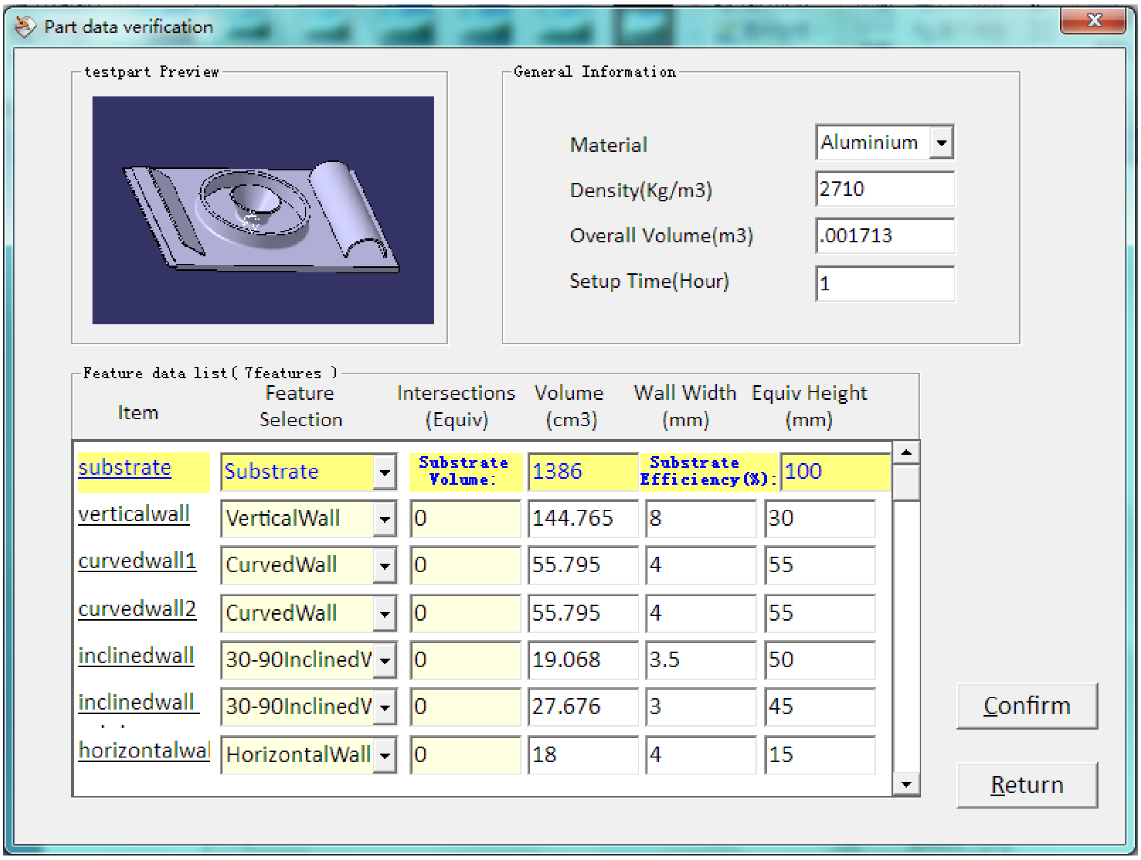


Figure 6.5: Graphic user interface windows of the cost software

When the cost software startup, a welcome page will appear, the user can select edit databse or caculate cost. When edit database was selected, the user will be lead to a database edit page. To protect the data security, the data table will not be displayed unless a validated password was inputted. There were four tabs on the database edit page, each tab dedicates to display one data form. The user can edit, add or delete data record by click corresponding command buttons on each tab conveniently.

The cost software use a step-by-step guide interface to execute cost and carbon emission assessment. When the user selected “calculate cost” function on the welcome page, the CAD model select page will appear where the user can not only select CAD model through a common dialog window, but also can input the batch size, complexity and integrated machining method of a product. Meanwhile, the user can set new database name and password for the cost software if they were changed. Then, the software will capture CAD model data through CATIA automatically, a progress bar is designed to show the realtime progress during accessing. After this, all captured data will be displayed on the data verification page. There were two functions on this page, firstly the user can check any automatically captured data, if necessary they can manually trim it; secondly the user need to determine main feature and sub feature for each item on this page as well. When this step was finished, the cost software will start to calculate cost and carbon emissions. There is another progress bar to display the calculation progress as well. Finally, the result display page will appear to show the results. The results consists of 3 sectors: material consumption, cost detail, GHG emission. If necessary, all these results can be saved into a Microsoft Excel formatted file.



Material: Aluminium

Density(Kg/m3): 2710

Overall Volume(m3): .001713

Setup Time(Hour): 1

Item	Feature Selection	Intersections (Equiv)	Volume (cm3)	Wall Width (mm)	Equiv Height (mm)
substrate	Substrate	Substrate Volume:	1386	Substrate Efficiency(%):	100
verticalwall	VerticalWall	0	144.765	8	30
curvedwall1	CurvedWall	0	55.795	4	55
curvedwall2	CurvedWall	0	55.795	4	55
inclinedwall	30-90InclinedV	0	19.068	3.5	50
inclinedwall	30-90InclinedV	0	27.676	3	45
horizontalwal	HorizontalWall	0	18	4	15

Figure 6.6: Screenshot of the cost software (data verification page)

7 Case Study and Model Validation

7.1 Case study to demonstrate the application of the integrated cost software tool

A simple geometry part is chosen for demonstrating the use and functions of the cost software tool. The material of this part is mild carbon steel. Traditional manufacturing method for this part is CNC milling, the buy-to-fly ratio of milling is 4. While for the WAAM process, this part has a hybrid structure which consists of two crossed vertical wall and a rectangle substrate, it can be formed by depositing the "+" shape on a rectangle plate directly. The 3D CAD model and 2D drawing of this part are shown in Figure 7.1 and Figure 7.2 respectively.

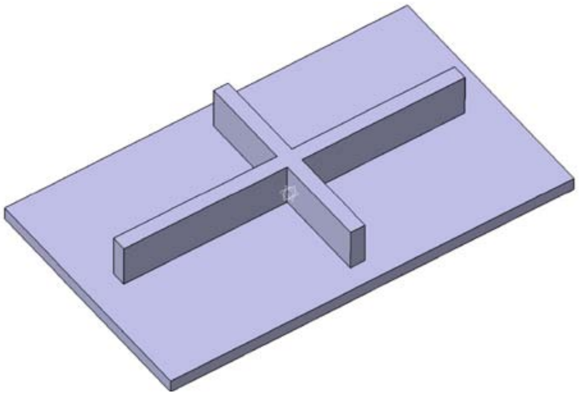


Figure 7.1: 3D CAD model of the first case study part

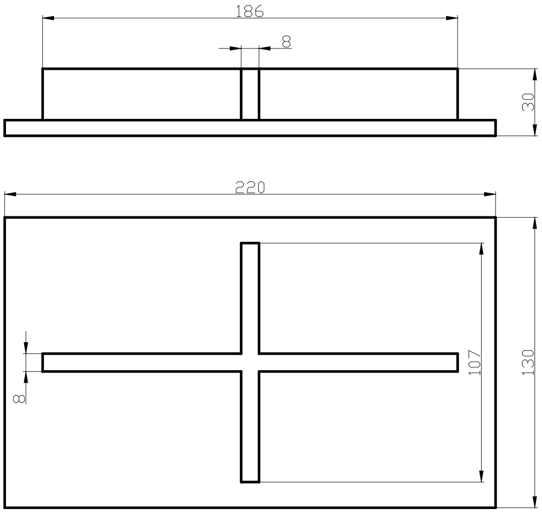


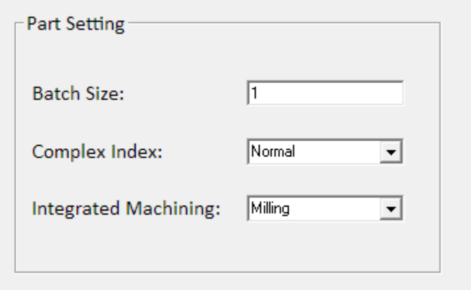
Figure 7.2: 2D drawing with measurements

To estimate the product cost, a precondition is to ensure all the required data were stored in the database correctly. On the welcome page of the cost software, the “edit database” option can be used to verify this. The data used for this case study were listed in Table 7.1.

Table 7.1: Process and unit price data for first case study part

Process parameters		Unit prices	
Wire diameter	1.2mm	**Labour rate**	55 £/hour
Wire feed speed	6.13m/min	**electricity**	0.07 £/kwh
Alloy efficiency	86.49%	**Welding wire**	5 £/kg
Voltage	11.86V	**Metal plate**	4.5 £/kg
Current	92.61A	**Shielding gas**	18.78 £/cylinder
Gas flow rate	15000ml/min	**WAAM machine**	£47000
Welding machine efficiency	90%	**Milling machine**	£65000
Milling material removal rate	164.48mm3/s	---	

On the software welcome page, once the user selected the “calculate cost” function, the software will show a step-by-step guide to execute the cost estimation. Firstly, the CAD model select page will display, the software will automatically capture the geometrical data and material property of the part after its CAD model is chosen. Meanwhile, there is a “part setting” option, the product batch size, part complex index and integrated machining method can be inputted here. Figure 7.3 shows the settings in this case study (single production with integrated CNC milling).


Part Setting

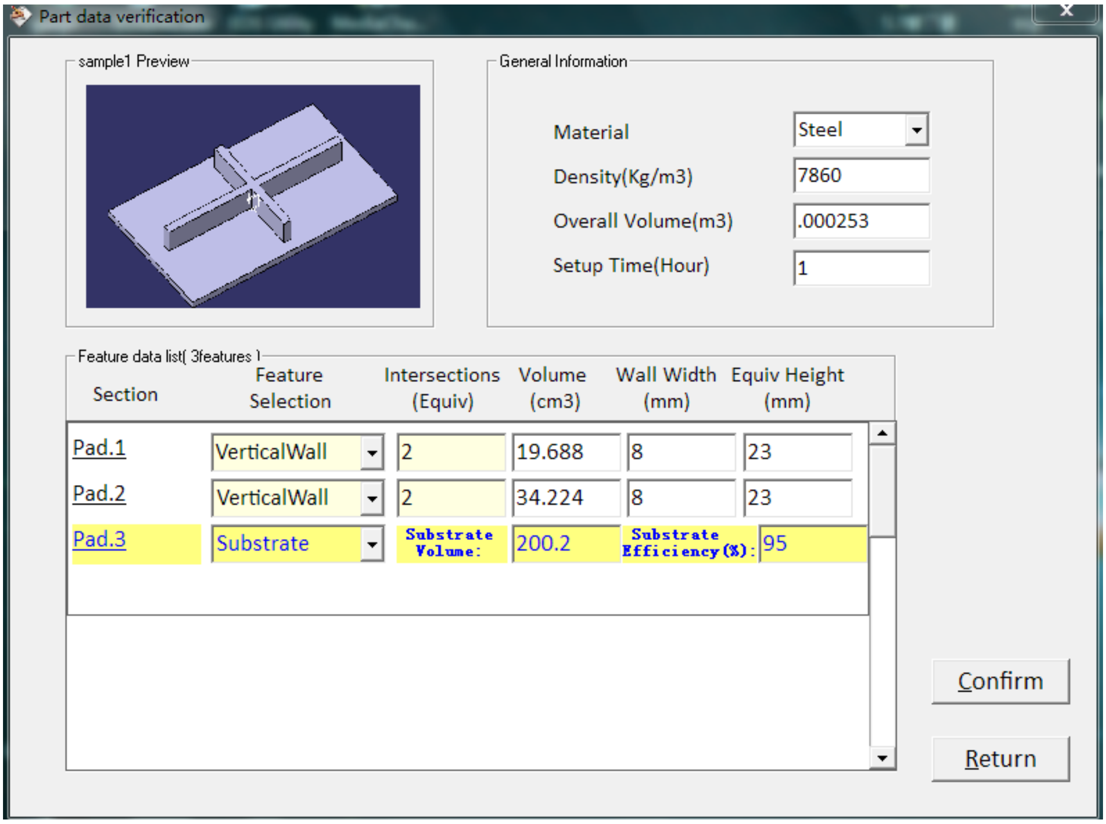
Batch Size: 1

Complex Index: Normal

Integrated Machining: Milling

Figure 7.3: Part setting for first case study

Secondly, the cost software will show data verification page after capturing data from CAD model. The user have to manually select feature type and sub feature (intesections) number for each section of the part. Besides this, most data have been automatically captured and no manual input is required, while all the items listed in this page also can be trimed by the user if desired. The verified data in this case study was shown in Figure 7.4.



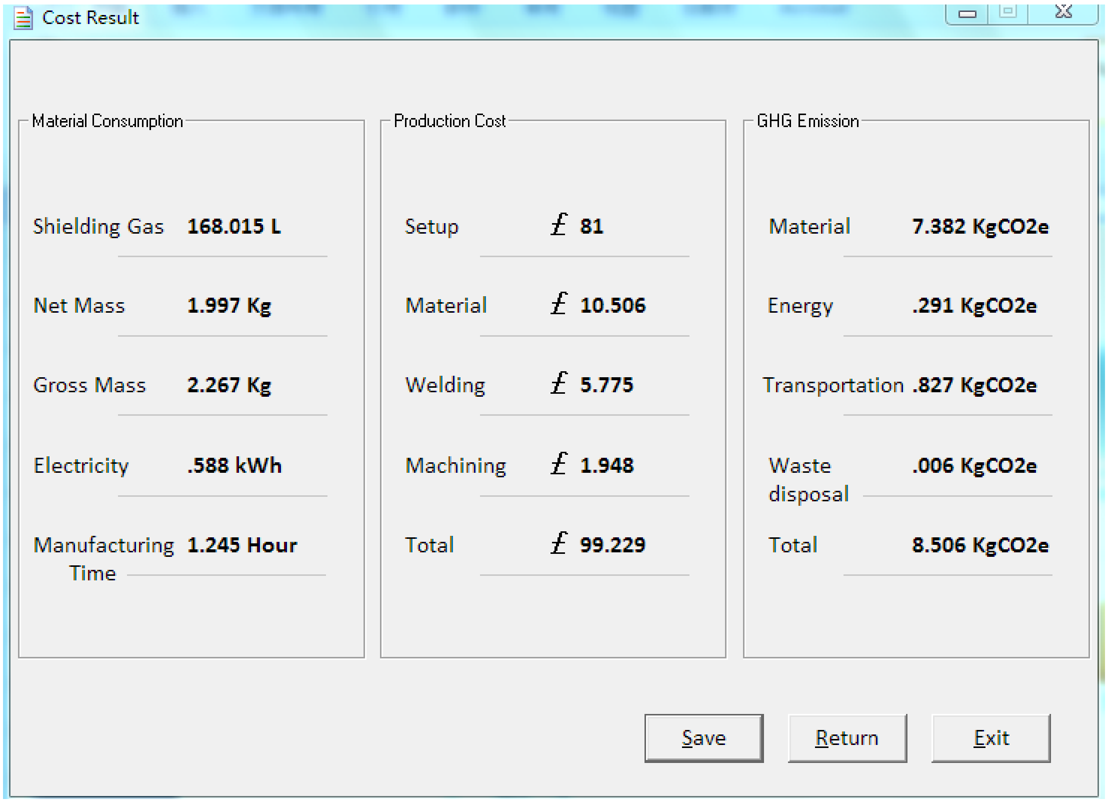
Material: Steel
Density(Kg/m3): 7860
Overall Volume(m3): .000253
Setup Time(Hour): 1

Feature data list(3features)

Section	Feature Selection	Intersections (Equiv)	Volume (cm3)	Wall Width (mm)	Equiv Height (mm)
Pad.1	VerticalWall	2	19.688	8	23
Pad.2	VerticalWall	2	34.224	8	23
Pad.3	Substrate	Substrate Volume:	200.2	Substrate Efficiency(%):	95

Figure 7.4: Features and geometry data for first case study

Finally, after the part features and geometry data were confirmed, by press the “confirm” button, the software will calculate out the cost and GHG emission results in seconds, and then display them on the result display page, where the result consists of 3 parts: material consumption, cost detail and GHG emission. Meanwhile,the result disply page has a “save” option to save all these results as an independent Microsoft Excel formatted report. The result of this case study can be found in Figure 7.5.



Material Consumption

Shielding Gas	168.015 L
Net Mass	1.997 Kg
Gross Mass	2.267 Kg
Electricity	.588 kWh
Manufacturing Time	1.245 Hour

Production Cost

Setup	£ 81
Material	£ 10.506
Welding	£ 5.775
Machining	£ 1.948
Total	£ 99.229

GHG Emission

Material	7.382 KgCO2e
Energy	.291 KgCO2e
Transportation	.827 KgCO2e
Waste disposal	.006 KgCO2e
Total	8.506 KgCO2e

Figure 7.5: Cost and GHG emission result of the first case study

Through this case study, the simplicity and the ease of use of this software was indicated. Only by a three-step-option with little manual labour, the cost and GHG emission can be estimated conveniently.

The result calculated by this cost software was validated with the WAAM experts. It was proved to be matching with the empirical material consumption and cost results. This validates the accuracy and reliability of this software tool.

It also can be found from the result that the buy-to-fly ratio of this part under WAAM process is only 1.14, compared with 4 by milling, more than 60% raw material can be saved. And from the environmental influence point of view, since 85% GHG emission of this part comes from raw material consumption, therefore a massive reduction of GHG emission can be obtained by using WAAM. This indicates the potential advantage of the WAAM process: low consumption, low cost, high efficiency and more sustainable. Further case study in these aspects will be carried out later through two real-world components.

7.2 Case study of real-world components

7.2.1 Real-world Case 1, an aluminium part from automotive industry

Figure 7.6 and 7.7 indicates a more complex structure which is chosen for real-world case study 1. This is an aluminium part comes from automotive industry. A significant feature is its buy-to-fly ratio. It can reach to 12 when manufactured by conventional machining process. This means over 90% of raw material have to be cutting off during machining. However, it is very common for typical complex aerospace and automotive industry components.

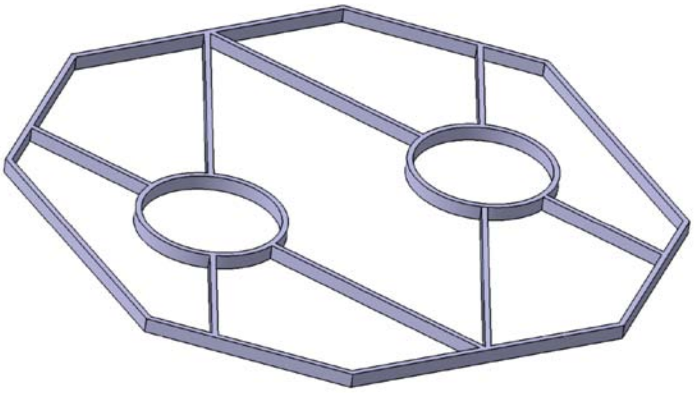


Figure 7.6: 3D model for real-world case study 1

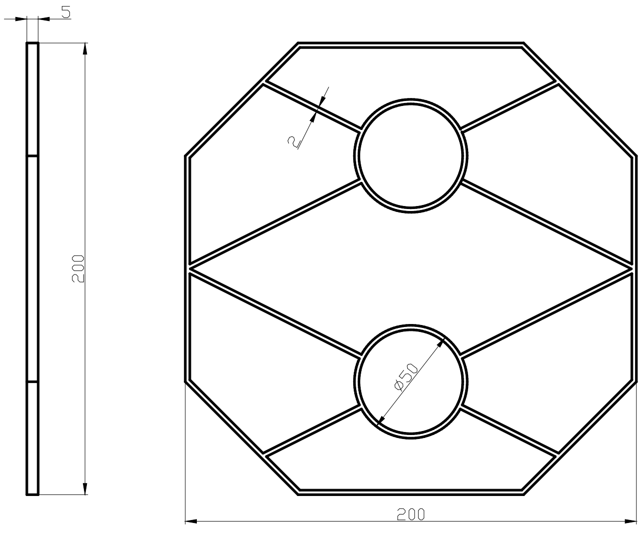


Figure 7.7: 2D drawing with dimensions of real-world case study 1

The data used for estimating WAAM cost were listed in Table 7.2, the process is welding deposition plus integrated milling, and the product batch size is set to 4 parts per batch. The cost and GHG emission result estimated by the cost software tool was shown in Table 7.3. The total cost is £32.992, manufacturing time is 0.469h (includes 0.25h setup time). The overall GHG emission is 1.399KgCO2e.

Table 7.2: Process and unit price data for real-world case study1

Process parameters		Unit prices	
Wire diameter	1.2mm	**Labour rate**	55 £/hour
Wire feed speed	2m/min	**electricity**	0.07 £/kwh
Alloy efficiency	65%	**Welding wire**	80 £/kg
Voltage	13V	**Shielding gas**	13.2£/cylinder
Current	43A	**WAAM machine**	£47000
Gas flow rate	16000ml/min	**Milling machine**	£65000
Welding machine efficiency	90%	**Welding deposition rate**	37.7 mm3/s
Milling material removal rate	262.5mm3/s	---	

Table 7.3: Cost and GHG emission result of real-world case study 1

WAAM Cost and carbon emission calculation results					
Shielding gas (L)	195.701	Setup cost (£)	20.25	GHG from material (KgCO2e)	1.089
Net mass (kg)	0.041	Material cost (£)	5.998	GHG from electricity (KgCO2e)	0.186
Gross mass (kg)	0.075	Welding deposition cost (£)	6.22	GHG from transportation (KgCO2e)	0.123
Electricity consumption (kWh)	0.377	Integrated machining cost (£)	0.524	GHG from waste disposal (KgCO2e)	0.001
Manufacturing time (hour)	0.469	Total cost (£)	32.992	Total GHG emission (KgCO2e)	1.399

Traditional manufacturing method for this part is milling or casting. The casting process also can reduce raw material consumption, and may have cost advantage in case of large batch production. However, the casting process relies on tooling (mould, pattern, core box, etc.), while the tooling design and manufacturing is both time and cost consuming. Obviously it is not suitable for small batch production. Sometimes the design should be revised frequently and lead-time is critical, the casting process also shows its disadvantage in this condition. The milling process is relatively flexible hence they can overcome this issue and more suitable for small batch production. However, the material utilization and machining time should be unsatisfactory especially for high buy-to-fly ratio components. The product cost comparison among WAAM, casting and milling was analysed below.

Chougule (2006) developed a casting cost estimation model which is meant for design engineers who may have limited casting process knowledge to estimate cost in early design stage accurately. This cost model focus on manufacturing cost and the total casting cost was divided to 5 elements: tooling, material, labour, energy and overheads. The casting cost calculated by this model was listed in Table 7.4.

Table 7.4: Casting cost detail of real-world case study 1

Tooling cost*	£840
Material cost	£3.518
Labour cost	£5
Energy cost	£0.006
Overhead cost	£0.005

* should be amortized over the number of castings produced.

Figure 7.8 is the graph of cost per product vs. the number of components produced by WAAM and casting process. It can be found that WAAM has significant cost advantage in case of single or small batch production, while the casting cost drops rapidly with the increasing of the production quantities. The cost becomes equal when production quantity is 40, then casting holds the edge. Finally the casting cost is only 1/3 of WAAM when order quantity is over 2000.

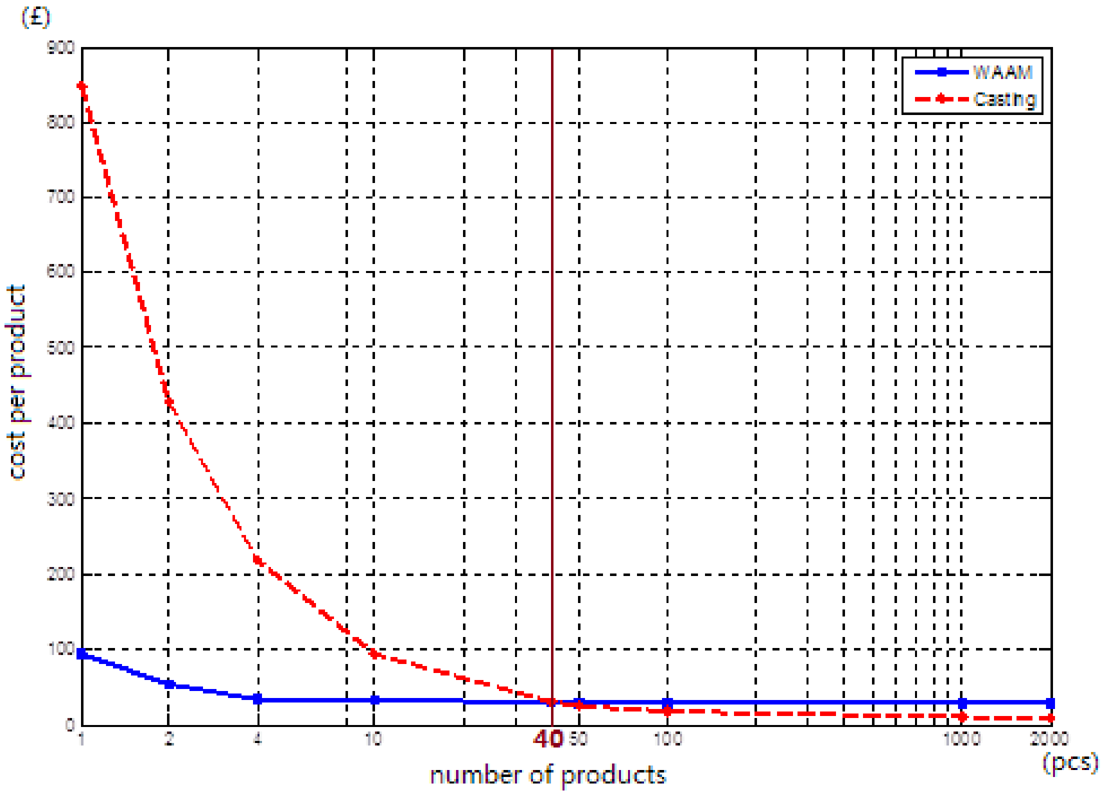


Figure 7.8: Cost curves for WAAM and Casting of real-world case study 1

Dewhurst et al. (1988) developed an early cost estimating procedure in product design stage for machining and injection moulding process. The machining cost (including machine, labour, tool cost) can be determined without full knowledge of the manufacturing processing plans. This procedure was utilized to calculate manufacturing cost by milling here. For the purpose of comparing the cost between WAAM and milling, the material cost and setup cost were added to form the entire manufacturing cost of milling. The setup time in this case is assumed to be as same as it of the WAAM process. Table 7.5 shows the data used to calculate milling cost.

Table 7.5: Data for estimating milling cost in real-world case study 1

Aluminium billet	50 £/kg
Gross mass	0.474 kg
Net shape mass	0.041 kg
Material removal rate	640 mm3/s
Setup time	0.25 hour
Machine cost rate	15 £/hour
Labour rate	55 £/hour
Average electricity consumption	3 kW

The cost for manufacturing this part by milling is £44.29; the overall manufacturing time is 0.319hour (includes 0.25h setup time). Other cost details were listed in Table 7.6. The manufacturing time by milling is lower than WAAM (0.469h) as illustrated in Figure 7.9. This is due to aluminium can reach a high cutting speed when milling, its material removal rate in this case is 640 mm^3/s. While limited by the 2mm thin wall thickness when WAAM, the welding deposition rate is only 37.7mm^3/s in this case. So even though the mass of removed material in milling is much more than the deposited mass in WAAM (0.451Kg to 0.075Kg), the overall manufacturing time by milling is still shorter than WAAM. Hence, it can be found that to reach higher welding deposition rate is vital for the improvement of WAAM efficiency.

Table 7.6: Cost comparison between WAAM and milling for real-world case study 1

	WAAM	**Milling**
Material cost	**£ 5.998**	**£ 23.7**
Setup cost	**£ 20.25**	**£ 17.5**
processing cost	**£ 6.744**	**£ 3.09**
Energy consumption	**0.377 kWh**	**0.208 kWh**
Total cost	**£ 32.992**	**£ 44.29**
manufacturing time	**0.469 hour**	**0.319 hour**

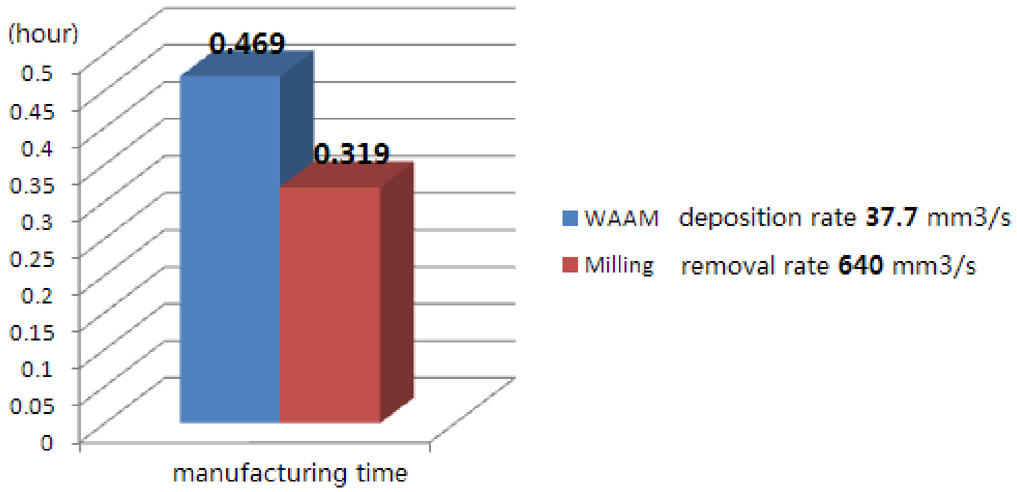


Figure 7.9: Comparative manufacturing time between WAAM and Milling in real-world case study 1

Figure 7.10 compares the product cost between WAAM and milling. The overall cost by WAAM is 74.5% of the cost by milling. While the processing cost and setup cost of WAAM are higher than milling due to its longer manufacturing time (WAAM in this case has very low welding deposition rate) and higher machine depreciation (robot guided CMT welding plus integrated CNC milling). However, the material cost had a massive reduction by WAAM than by milling, only 1/4 raw material is required by WAAM. Generally speaking, by adopting the WAAM technology, the product cost can drop down significantly, and large amount of raw material will be saved which is good for the sustainable development.

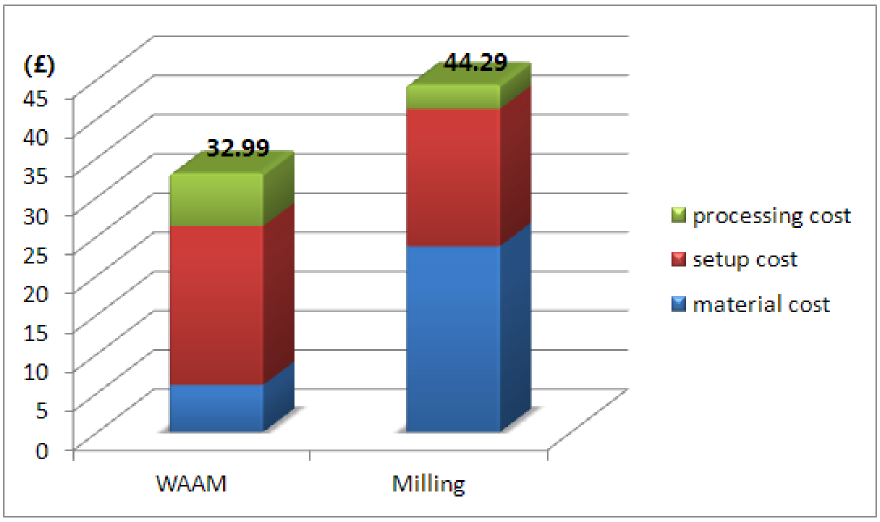


Figure 7.10: Cost by WAAM and by Milling of real-world case study 1

7.2.2 Real-world Case 2, a titanium part from aerospace industry

The part selected for real-world case study 2 is a complex double side hollow component which is typical in aircraft frame products. The machining buy –to-fly ratio is 5. The geometry of this part is shown in Figures 7.11 and 7.12.

The material of this part is titanium alloy Ti-6Al-4V. Due to its light weight and excellent mechanical properties, this kind of titanium alloy is getting increasingly applied in aircraft frame structure. However, the price of titanium alloy is expensive, and the machining rate for Ti-6Al-4V is much lower than aluminium and steel due to its poor cutting performance. This means when manufacturing high buy-to-fly ratio titanium parts by machining, the manufacturing time may becomes very long and the raw material cost can also gets huge. The specific product cost of WAAM and milling under this condition will be analysed in the following case study.

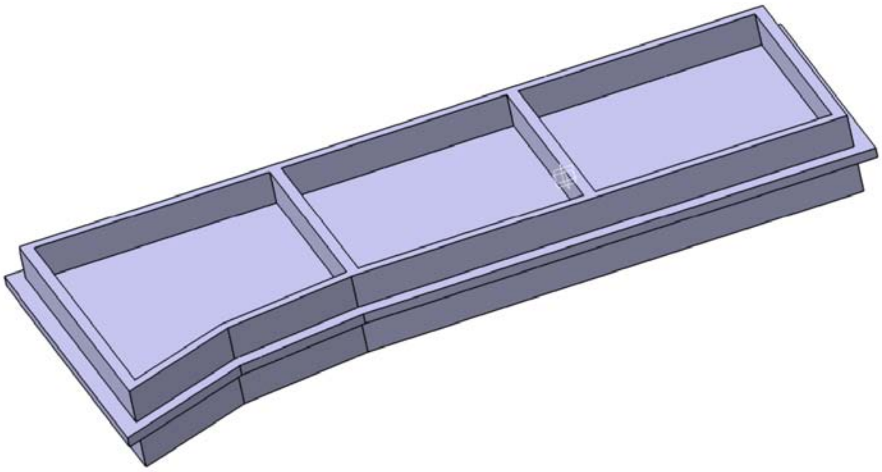


Figure 7.11: 3D model for real-world case study 2

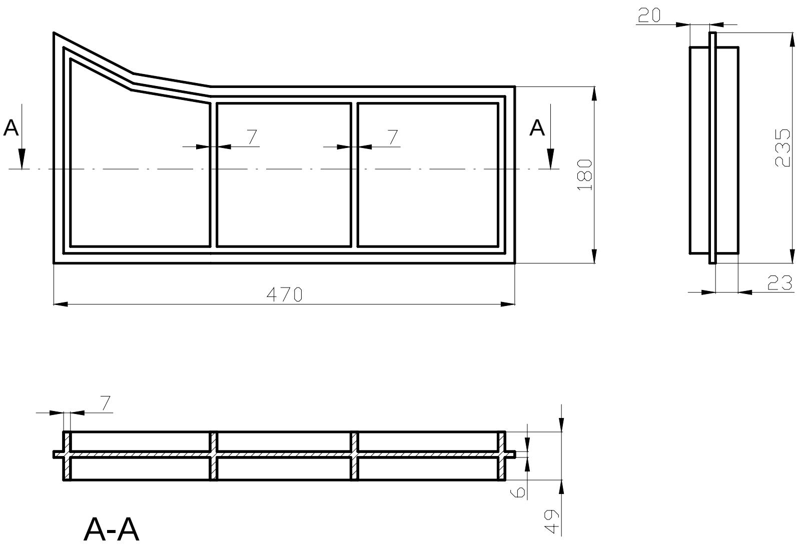
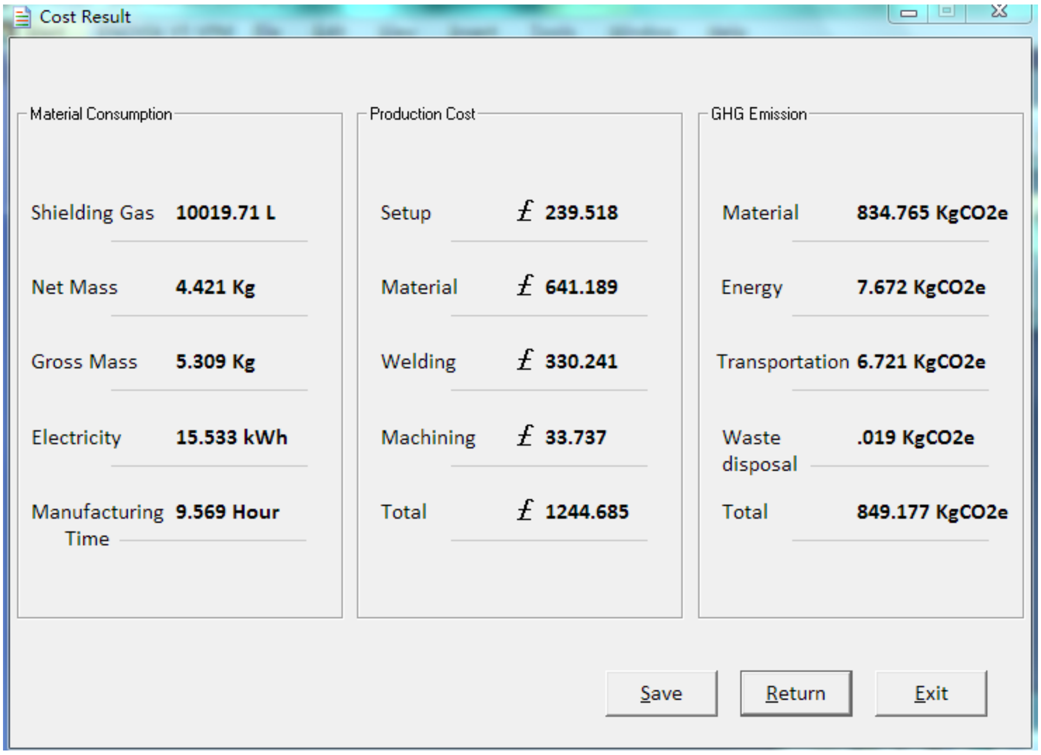


Figure 7.12: Drawing with dimensions of real-world case study 2

The data used for estimating WAAM cost in this case study were listed in Table 7.7. A double sided deposition strategy is applied which requires more setup time, the setup time for this part is 3 hours for single production. The process is welding deposition plus integrated milling. The cost and GHG emission result computed by the cost software tool is shown in Figure 7.13. The total cost is £1244.69, manufacturing time is 9.569h (includes 3h setup time). The overall GHG emission is 849.18KgCO2e.

Table 7.7: Process and unit price data for real-world case study2

Process parameters		**Unit prices**	
Wire diameter	1.2mm	**Labour rate**	55 £/hour
Wire feed speed	1.6m/min	**electricity**	0.07 £/kwh
Alloy efficiency	89.36%	**Titanium wire**	170 £/kg
Voltage	10V	**Titanium billet**	70 £/kg
Current	100A	**Shielding gas**	154£/cylinder
Gas flow rate	30000ml/min	**WAAM machine**	£42000
Welding machine efficiency	80%	**Milling machine**	£65000
Milling material removal rate	55.14mm3/s	**Welding deposition rate**	30.16 mm3/s



Material Consumption

Shielding Gas 10019.71 L
Net Mass 4.421 Kg
Gross Mass 5.309 Kg
Electricity 15.533 kWh
Manufacturing Time 9.569 Hour

Production Cost

Setup £ 239.518
Material £ 641.189
Welding £ 330.241
Machining £ 33.737
Total £ 1244.685

GHG Emission

Material 834.765 KgCO2e
Energy 7.672 KgCO2e
Transportation 6.721 KgCO2e
Waste disposal .019 KgCO2e
Total 849.177 KgCO2e

Figure 7.13: Cost and GHG emission result of real-world case study 2

The estimated single production milling cost data of this part were listed in Table 7.8. The total cost for milling is £2180.083, manufacturing time is 11.76h (includes 3h setup time). The overall GHG emission is 1669.33KgCO2e. Detailed cost results compared to WAAM were listed in Table 7.9.

Table 7.8: Data for estimating milling cost in real-world case study 2

Titanium billet	70 £/kg
Gross mass	22 kg
Net shape mass	4.421 kg
Material removal rate	110 mm3/s
Setup time	3 hour
Machine cost rate	15 £/hour
Labour rate	55 £/hour
Average electricity consumption	3 kW

Table 7.9: Cost comparison between WAAM and milling for real-world case study 2

	WAAM	Milling
Material cost	**£ 641.189**	**£ 1540**
Setup cost	**£ 239.518**	**£ 210**
processing cost	**£ 363.978**	**£ 430.083**
Energy consumption	**15.533 kWh**	**26.287 kWh**
Total cost	**£ 1244.69**	**£ 2180.083**
manufacturing time	**9.569 hour**	**11.76 hour**
GHG emission	**849.177 kgCO2e**	**1669.33 kgCO2e**

Further cost comparison was illustrated in Figure 7.14. The overall cost by WAAM is only 57% of the cost by milling. Both the processing cost and the material cost are lower than milling, this is because the shorter manufacturing time and much lower raw material consumption of WAAM. From the case study, it can be obviously found that the WAAM technique will become attractive over traditional machining methods in case of the component has low machining rate, high material price and high buy-to-fly ratio.

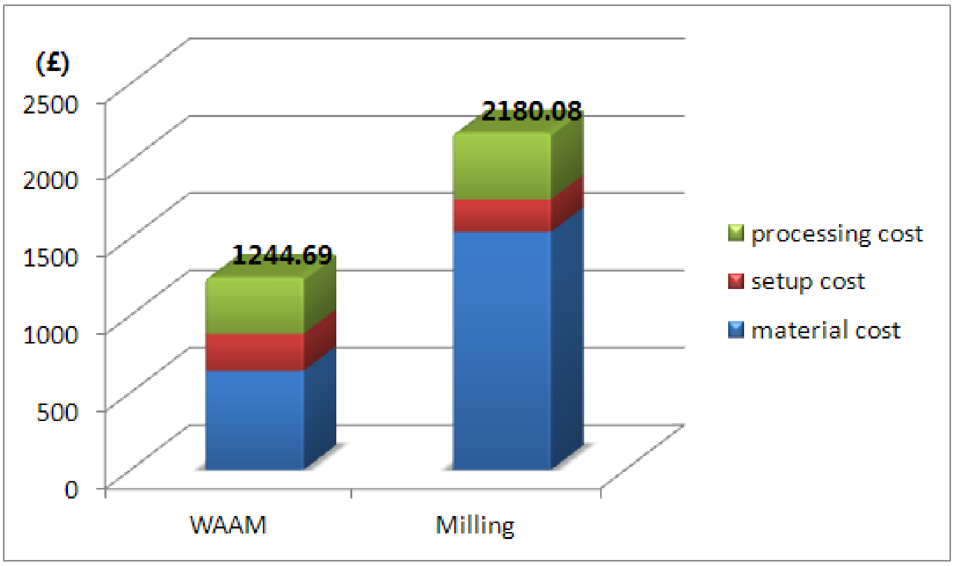


Figure 7.14: Cost by WAAM and by Milling of real-world case study 2

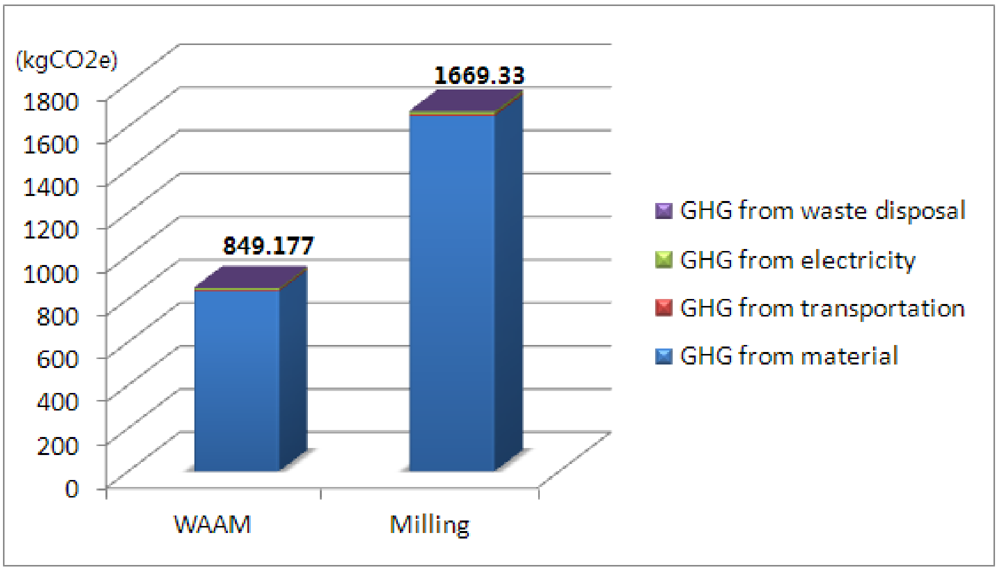


Figure 7.15: GHG comparison between WAAM and Milling

The GHG emission was compared in Figure 7.15, it can be seen that the primary GHG emission comes from raw material. The other factors are relatively negligible. As the WAAM technique can significantly reduce raw material consumption, so the amount of GHG emission also can be significantly reduced by WAAM. In this case study, the GHG emission amount by WAAM is 55.7% of it by milling. Therefore, the WAAM technique is more environmental friendly and can well meet the requirement of industrial sustainable development.

7.3 Interactive session and experts judgements

The initial capacity and reliability of this integrated cost software tool were demonstrated through case study 1 and validated with WAAM experts. Then after two real-world components case study, further validation exercises were conducted through an interactive session. The attendees of the interactive session including welding and machining experts involved in the ongoing WAAM research project, college experts works in cost and manufacturing areas, postgraduate researchers from manufacturing and decision engineering department, other industry expert, etc. Figure 7.16 indicates the background of the validation session attendees.

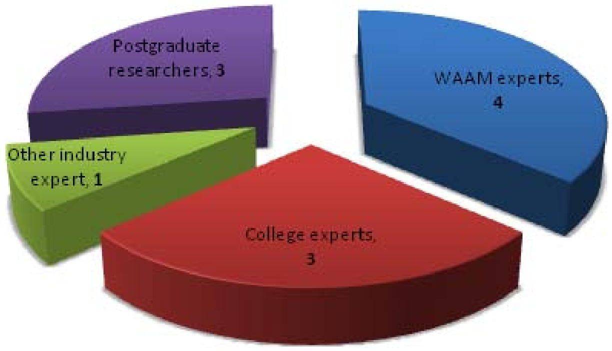


Figure 7.16: The background of the validation session attendees

At the validation session, the author presented his entire work first, including the context of the project, the cost model framework, detailed equations, integrated software tool and case studies. Then the author demonstrated the operation of the software tool. Thereafter, they both went through discussion and interaction. Meanwhile, a validation questionnaire is distributed to the experts to collect their feedback and judgement for the capacity and reliability of the proposed model. The questions includes: Q1, the adequacy and rigor of the cost framework; Q2, the rationality of the cost equations; Q3, the function of the software tool; Q4, the convenience and efficiency of the software tool; Q5, the accuracy of the cost and carbon emission results. The experts were required to assign a score from 0 to 5 for these questions, where 5 means very satisfied and 0 means not satisfied at all. For each question, if the score is over 3, it indicates the corresponding factor is validated. Figure 7.17 shows the validation result, the entire validation questionnaire was presented in appendix C.

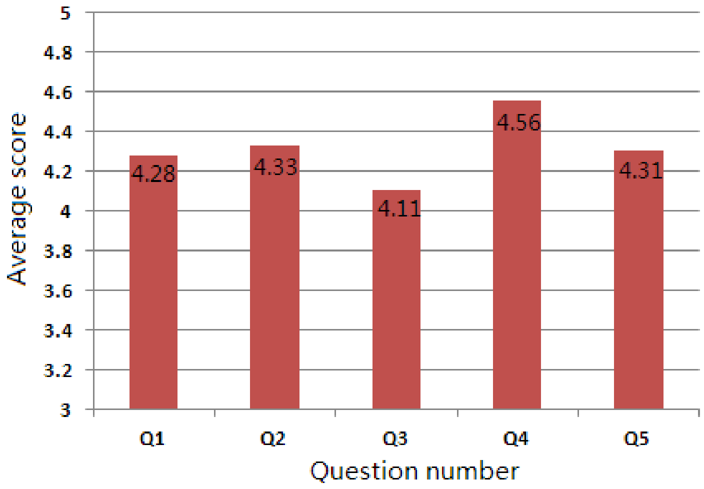


Figure 7.17: Cost model validation result

Through case studies and expert judgement, the validation of this project was successfully conducted. The validation result indicated the capacity and reliability of the integrated cost software tool. It is applicable for the estimation of WAAM cost and GHG emission and the results match the experimental data. Several suggestions and recommendations were also given by the experts, such as revise the comparison with other alternative manufacturing methods, the cost details need to be clarified, further fill the database with process parameters for more features, etc.. Finally, most of them have been implemented by the author.

8 Discussion and Conclusions

8.1 Discussion of research findings

The main research findings from literature review, industry survey, model development, software design and case study will be discussed in this section.

8.1.1 Literature review

The state of the art of The WAAM technique and its key features were studied. The WAAM is a CNC and welding deposition based additive manufacturing technique. It has potential cost and environment advantage as an ideal alternative for industrial sustainable development. The specific welding technique and process parameters vary with the manufactured features. Various product cost estimation theories were analysed, the value of carrying out precise cost estimation during product design stage was recognised. The variant-based methods which belong to analytical cost estimation techniques are suitable for early cost estimation purpose. The anthropogenic global warming is a serious impact to environmental, while the industrial processes are one of the major contributions. Therefore, it is essential to implements GHG emission assessment for specific manufacturing process. Existing GHG emission measurement methodologies proposed in PAS2050 can be applied for WAAM. Literatures regarding cost estimating for conventional manufacturing techniques can be easily found while little researcher focused on cost estimation for WAAM techniques.

The literature review assisted the author to obtain the essential knowledge related to the research subject. The research gap and initial WAAM cost modelling approach were also identified from the literature review.

8.1.2 Industry survey

In order to obtain information of the WAAM process and collect feedback on the initial feature based cost model framework, an industry survey was carried out through questionnaire and expert interview. The WAAM process map, cost breakdown structure and cost drivers were established according to literature and then verified by the WAAM experts. A five-step cost model framework was also developed based on the CBS and cost drivers. It was used to guide the development of the detailed cost equations latter. The WAAM process detail and parameters, equipments, consumptions were explored and recorded for the database development. Meanwhile, the geometrical features that can be manufactured by WAAM were identified. A setup time estimation approach was also developed with the WAAM expert and therefore solved the issue of determining the setup time in the product design stage.

8.1.3 Model development

A systematic definition for the WAAM manufacturing features was determined; the WAAM manufacturing features were defined as a combination of main feature (geometrical feature), sub-feature (intersections among main features), wall thickness and material. The process parameters encapsulated in manufacturing features were also determined for the development of cost database. Then a set of detailed cost equations were developed to bridge the user available data and the cost framework. The methodology for GHG emission assessment was selected from relevant standard. According to the proposed GHG estimation approach, the cradle-to-gate process map of WAAM products was identified. Then the activities included in the GHG estimation system were filtered and streamlined according to the system boundary definition guideline of the standard. The final WAAM GHG estimation boundary includes GHG from material and energy consumption, transportation, waste disposal. All the required activity data and GHG emission factor data were collected for the actual calculation as well.

8.1.4 Software tool design

The proposed WAAM cost and GHG emission model were implemented in an integrated software tool. It was built by using Visual Basic 6.0 with Microsoft Access database support. The design of an independent backend database makes all the data such as process parameters and material unit prices can be conveniently edited or added. In order to minimise the operation time, this software comes with a CAD data automatically access program module which can improve the parameter input efficiency significantly. Moreover, this software tool has multifunction such as edit backend database and save result as independent spreadsheet for the user's convenience. A significant aspect of this software tool is that it can eliminate time consuming manual labour and obtain a very quick and precise cost result.

8.1.5 Case study and validation

The integrated cost software tool was applied in the case study to calculate cost and GHG emission for 3 different WAAM components. The first case is a sample WAAM structure which is chosen for demonstrating the use and functions of the cost software tool. The result indicated the simplicity and the ease of use of this software. The cost and GHG emission can be estimated in minutes with little manual labour. The result was also proved by the WAAM experts to be matching with the empirical material consumption and cost results. Furthermore, two real-world components from automotive and aerospace industry were used in the following two case studies. The accuracy and applicability for the cost estimation of real-world WAAM products were further validated through an interactive validating section. The cost and GHG emission results of WAAM were compared with other manufacturing methods as well. The comparison revealed that WAAM has significant cost advantage to casting in case of single or small batch production, while casting still holds the edge in large batch production. WAAM should become attractive over milling in case of the component has low machining rate, high material price and high buy-to-fly ratio. Moreover, the WAAM technique can significantly reduce raw material consumption and the GHG emission amount. Therefore, WAAM is more environmental friendly and can well meet the requirement of industrial sustainable development.

8.2 Research contributions

Based on the findings discussed in chapter 8.1, the research contributions of this project were summarized as follows:

The proposed feature based cost model framework is a novel approach for the WAAM cost assessment. It provides a feasible way for the design engineers and decision makers to assess the manufacturing cost in product design stage without demand of detailed process data. A series of WAAM cost equations were developed which considered more process details than former ones, so more accurate cost estimation can be achieved.

The study of WAAM GHG estimating system boundary clarified the GHG emission related activities of WAAM. A specific GHG quantification procedure for WAAM which is accordance with the guideline of PAS 2050 was established. Detailed WAAM GHG emission data can be calculated out through this procedure.

The proposed cost and carbon emission model were implemented in an integrated software tool. The geometry data of the WAAM parts is automatically captured from CAD model. The backend database can be easily updated to make the software handling more features in future. Due to its high efficiency and easy operation, only by a three-step-option with little manual labour, the cost and GHG emission can be estimated conveniently.

The cost and GHG emission results were compared with other competitive manufacturing methods. The most suitable situation for adopting WAAM was indicated.

8.3 Research limitations

This research project also has several limitations. They are discussed in the following paragraphs.

The WAAM technique is not yet widely applied in practice. The quality inspection procedure for WAAM products is not standardised. Therefore, no quality inspection cost was considered in this cost model.

To obtain the precise net shape, most WAAM products need finish machining process. However, limited by the research time, the major effort was used on welding deposition cost equation development. A simplified cost approach was chosen for integrated machining, the cost result may deviates from the actual value in some extreme conditions.

The cost of substrate in this project only takes material cost into account. Although this is approved by WAAM experts the actual substrate cost do contain energy, labour and machine cost. Therefore, the substrate cost calculation method in this project is not accurate enough.

The cost model and software tool were designed to handle all the features defined in section 4.5. But only the data of process parameters for vertical wall with different material and wall thickness were sufficient in the database. More data for other geometry features are required for the database.

In order to reduce manual input, the cost software was designed with the ability of capturing CAD model data automatically. However, there are several limitations in this aspect. For instance, the CAD model must fulfil certain criteria first, and the feature identification for the CAD subcomponents had to be conducted manually.

8.4 Future work

According to the research limitations and the expected development of WAAM technique, the future work could be performed on the following aspects:

Update the process parameters for more features and materials. Add machine deprecation, unit price data for different region and companies.

Revise the integrated machining cost calculation method. Take the influence of the part’s size and geometry complexity to the material removal rate into account.

Investigate the quality inspection activities of WAAM. Develop a cost estimating method for WAAM quality inspection process.

Add a function of cost comparison between different WAAM features or manufacturing strategy to further assist the design engineer optimising product design from cost reduction point of view.

Integrate the cost estimation software tool to a comprehensive design-manufacturing software system. Where the product design, process planning, tool path programming and cost estimation can be carried out cooperatively.

8.5 Conclusions

In this project, a feature based cost estimation model and specific GHG emission model were developed for the wire and arc additive manufacturing process. The overview of the research context, CBS, cost drivers and the essential data for cost modelling were obtained from Literature review and industry survey. The proposed cost and GHG model were implemented in an integrated software tool. With the ability to directly capture geometry data from CAD file, the cost software is efficient and convenient. Three case studies were carried out in this research project to demonstrate the integrated cost software tool. The cost comparisons with other conventional manufacturing methods were also discussed in case study. The calculated cost results in case study were examined by experts. The experts' judgement confirmed the accuracy and applicability of this integrated cost software tool. The implementation of the research outcomes of this project can achieve accurate early cost estimation for WAAM conveniently. Moreover, it can clarify the cost and environment advantage of WAAM and assist to identify the most suitable situation for adopting WAAM form cost and sustainable point of view. Other conclusion regarding the comparative cost analysis are WAAM should become attractive over conventional machining in case of the component has low machining rate, high material price and high buy-to-fly ratio. The WAAM technique can significantly reduce raw material consumption and the GHG emission amount.

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APPENDICES

Appendix A Industry Survey Questionnaire

INDUSTRY SURVEY QUESTIONNAIRE ON COST ASSESSMENT FOR WIRE AND ARC ADDITIVE MANUFACTURING

Introduction: The purpose of this questionnaire is to collect feedback on a feature based cost model framework (attached in this questionnaire) and obtain information on the WAAM process. This work is part of an MSc by Research study entitled “Feature Based Cost and Carbon Emission Modelling for Wire and Arc Additive Manufacturing” undertaken at Cranfield University.

Disclaimer: Your response will be treated in the strictest confidence. Respondents’ names will not be disclosed nor identified in the research report. Please be assured that the information provided will only be used for academic and research purposes and will not be passed to a third party.

Contact Details
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School of Applied Sciences
Cranfield University, Cranfield
Email: jianing.guo@cranfield.ac.uk

Interviewee Details: (or attach your business card)

Name:
Job Title:
Organisation:
Email:
Years of Experience

Thanks for taking part in this research. This questionnaire consists of three parts, part one is cost model framework review and part two is WAAM process information collection, while part three is questions about complex index of the WAAM products. The questionnaire can be finished no more than half an hour.

Before you answer the questions, please read the appendix first. In which the WAAM process map, cost breakdown structure and the cost model framework was presented.

Part 1, cost model framework review

Q.1 How adequate do you think the WAAM process map, cost breakdown structure (CBS) and cost driver can represent the actual WAAM process activities and cost elements? Please assign a score from 0 to 5, where 5 means very adequate and 0 means not adequate at all.

Your answer:

Suggestions for the improvement of the WAAM process map, CBS and cost driver:

Q.2 How rigorous is the cost model framework? Please assign a score from 0 to 5, where 5 means very rigorous and 0 means not rigorous at all.

Your answer:

Comments on making this framework more rigorous:

Q.3 Do you think the cost model framework considered all the necessary cost items? If not, please provide items should be taken into account.

Your answer:

Part 2, the WAAM process information collection

Q.4 Considering the current research status, how many features do you think have sufficient experimental data for cost assessment? Please select from the list below. (You can also refer to appendix 1: the WAAM Feature Taxonomy).

A vertical wall (liner), **B** vertical wall (curved), **C** inclined wall (30° to 90°), **D** inclined wall (0° to 30°), **E** inclined wall (curved), **F** horizontal wall, **G** vertical wall intersections, **H** angled wall intersections, **I** curved wall intersections, **J** 'T' intersections, **K** mid-span wall connections, **L** edge wall connections, **M** cladding

Your answer:

Q.5 Do you think the wall thickness should be taken as sub-feature for the feature based cost model?

Your answer: YES/NO* *(please delete as appropriate)

If yes, please provide the dipartition of wall thickness range step (e.g. 1mm per step):

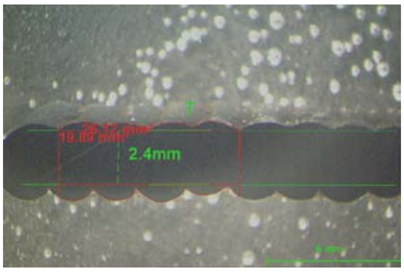
If no, please give the reason you considered:

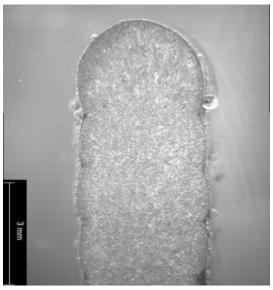
Q.6 How many activities are included in the WAAM set up process? Please list:

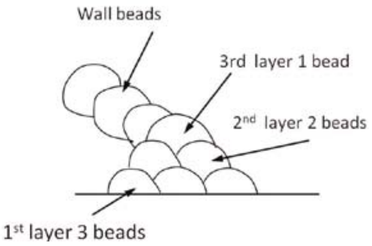
Q.7 Before deposition, a substrate should be cut. What method is used for substrate cutting? What factors do you think should be considered for substrate cutting cost assessment?

Q.8 If the substrate needs to be recycled for next deposition, what method is used for substrate recycling? What factors do you think should be considered for recycling cost assessment?

Q.9 "Alloy Efficiency" is a term used to describe the ratio between net shape weight (after removing surface roughness by machining) and gross weight (initial deposited weight). From literature, it is affected by the surface roughness, top layer edge fillet, support layer for inclined wall (see pictures below). Is there any other factor (especially for wall intersections and wall connections) do you think should be considered for estimating alloy efficiency?







Your answer:

Q.10 Apart from wire feed speed (WFS), the tool path strategy also influences the build rate. This influence is primarily comes from non-deposition time (e.g. torch moves from one layer end point to next layer start point without welding deposition). Please give the ratio between actual deposition time and gross build time of each feature (for Continuous welding track this ratio is 1, otherwise it will less than 1).

Your answer:

Q.11 During deposition, what is the relationship among layer width, layer height and total layer numbers?

Q.12 Please provide the proper wall thickness that can be manufactured by WAAM. If this value varies with material or feature, please list them respectively.

Minimum wall thickness: _____maximum wall thickness:

Q.13 Individual parts with a small area but large mass (i.e. tall) are difficult to build by WAAM due to heating of the component. Please provide the height/area ratio suitable for WAAM. If this value varies with material or feature, please list them respectively

Maximum height/area ratio:

Q.14 How many WAAM machines were developed currently? Please list their constitution, capability and price respectively.

Part 3, Complex index of the WAAM products

The "complex index" is used to describe the geometrical complexity of a product. From simple to complex, the WAAM products are divided into four complex levels: low, medium, high, very high. This complex index is used to assess the setup time before welding deposition and the material removal rate of post machining. Each complex level will corresponding to a correction factor, the general setup time and material removal rate of medium-complex WAAM product will be used as a benchmark, the setup time and material removal rate of other complex level can be calculated by using the benchmark multiply the correction factor.

The definition of complex level:

- **Low: only one independent feature.***
- **Medium: several independent features, no intersections and connections. ***
- **High: several features with intersections and/or connections between each other.***
- **Very high: products need to be deposited on both side of the substrate (a turntable is required to fix the substrate).**

*** If the product has a large size (>1.5 meter long), the complex index will increase to next higher level.**

Q.15 How reasonable do you think the definition of complex level is? Please assign a score from 0 to 5, where 5 means very reasonable and 0 means not reasonable at all.

Your answer:

Suggestions for the improvement of the complex level definition:

Q.16 Please give the general setup time and material removal rate of medium-complex WAAM products

Setup time before welding deposition:

Material removal rate of post machining:

Q.17 Please fill the following form to give the correction factor of each complex level

Complex level	**Set up time correction factor**	**Material removal rate correction factor**
Very high		
high		
medium	1	1
low		

This is the end of questionnaire, thanks again for your participation.

Appendix B Software user Manual

- Instruction

This integrated cost software tool was designed to implement the featured based cost and carbon emission model. With the input of CAD model of a specific WAAM component, the software tool can automatically compute out the detailed material consumption, manufacturing time, manufacturing cost and GHG emission. No other process parameters were required when using this software tool (they have been stored in the backend database in advance). This user manual aims to give a detailed instruction on the function and operation of this integrated cost software tool

- Before you start

This software tool consists of 3 files: a main program, a database and a cost report template. The user should keep these three files in same path. It is highly recommended to put these files in an independent folder in your hard disk. Please note some temporary files will be generated during processing, therefore if the main program file path is read only, e.g. stored on a CD, the software will not work correctly. To run this software you also need CATIA V5 R18 (or higher version) and Microsoft Office 2007(or higher version) installed in your computer.

The CAD model can be identified by this software tool do need to be drawn under some agreed order first (this means not any CATIA CAD model can be correctly identified). The rules for drawing the CAD model are it must be a .CATPart formatted file, only one part body is permitted in one file, each WAAM feature should be drawn respectively by using the CATIA "sketch-based features" tool, only "pad" "rib" "shaft" will be processed by this program, the CAD model can contain "dress-up features" such as chamfer or fillet but it will be ignored when processing, the wall thickness and height must be marked out in the sketch of each feature by using the "length constraint" tool, material property should be added in the CATIA CAD model in advance as well. Otherwise the software may capture wrong data from the CAD model. However, the user still has an opportunity to check and edit these data when the software shows the "CAD model data verification page".

- Calculate cost

The main program of this software is an .exe file, double chick the icon to start the program. A welcome page will display when program started (see Figure1). This page provides two options: calculate cost or edit database, click the “calculate cost” will lead you to carry out cost calculation function.

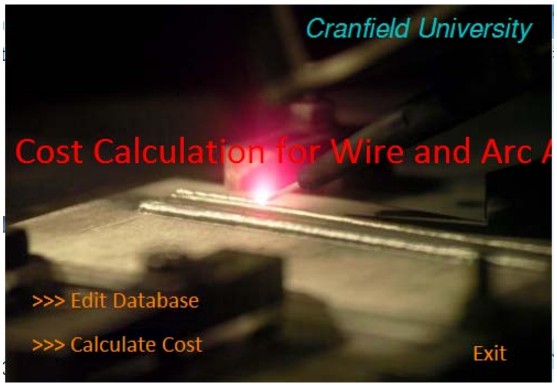
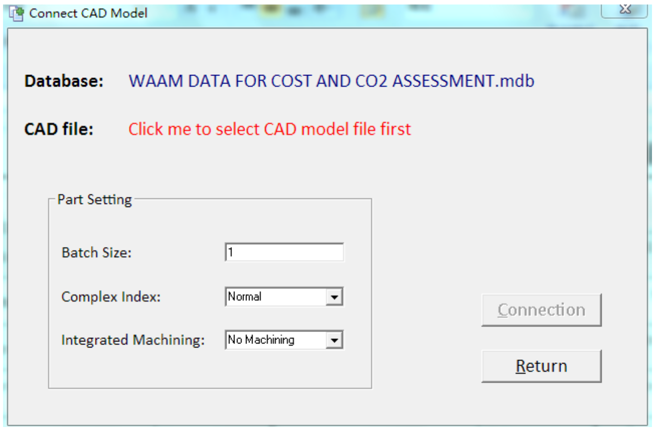


Figure 1: Welcome page

The user needs a three step operation to finish the product cost calculation. The first step is to select the CAD file on the “CAD model select page” which is shown in Figure 2.



Database: WAAM DATA FOR COST AND CO2 ASSESSMENT.mdb

CAD file: Click me to select CAD model file first

Part Setting

Batch Size: 1

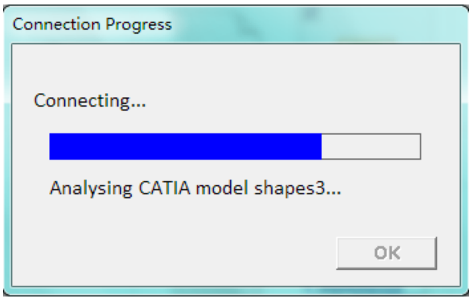
Complex Index: Normal

Integrated Machining: No Machining

Figure 2: CAD model select page

On this page, click the “click me to select CAD model file first”, then you can select CAD file through a dialogue window. After that, you need to input the product batch size, select complex index and finish machining method form the drop-down list. When finish this, click “connection”. If you want to return to welcome page, click “Return”.

The backend database name is also listed on this page, if the database file name or password were changed you can click the database name on this page to input new file name and password.

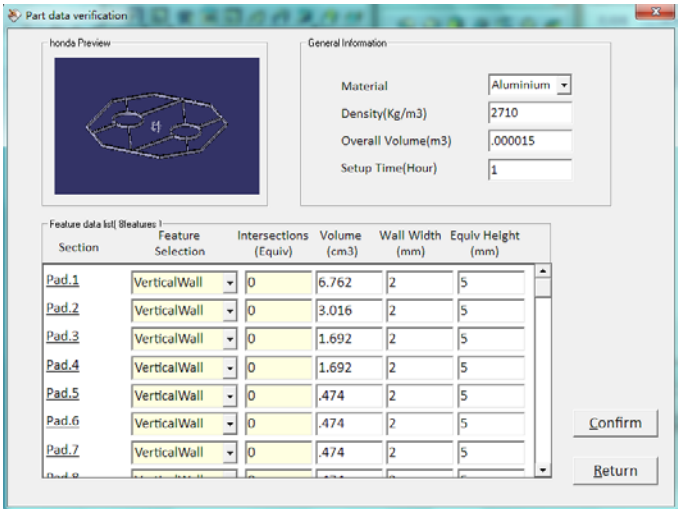


Connecting...

Analysing CATIA model shapes3...

Figure 3: CAD file connection progress bar

The “connection” button is only enabled when CAD file was selected. After click this button, a progress bar will show to indicate the data connection progress (Figure 3). Then the captured data will be listed on “CAD model data verification page”, where you need to carry out the second step operation.

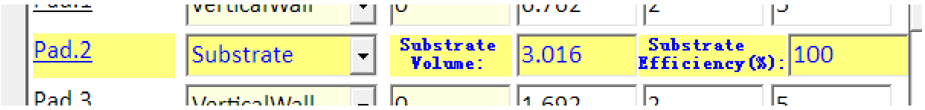


Material: Aluminium
Density(Kg/m3): 2710
Overall Volume(m3): .000015
Setup Time(Hour): 1

Section	Feature Selection	Intersections (Equiv)	Volume (cm3)	Wall Width (mm)	Equiv Height (mm)
Pad.1	VerticalWall	0	6.762	2	5
Pad.2	VerticalWall	0	3.016	2	5
Pad.3	VerticalWall	0	1.692	2	5
Pad.4	VerticalWall	0	1.692	2	5
Pad.5	VerticalWall	0	.474	2	5
Pad.6	VerticalWall	0	.474	2	5
Pad.7	VerticalWall	0	.474	2	5

Figure 4: CAD model data verification page

Figure 4 shows the CAD model dada verification page; you need to select the main feature and sub-feature (light yellow area) manually for each section of the component. The features displayed in the drop-down list depend on the feature types stored in the backend database. For some hybrid products you may assign "substrate" as a feature, in this condition the data display for the substrate section will change (Figure 5), and you need to input the utilization rate of the substrate additionally.

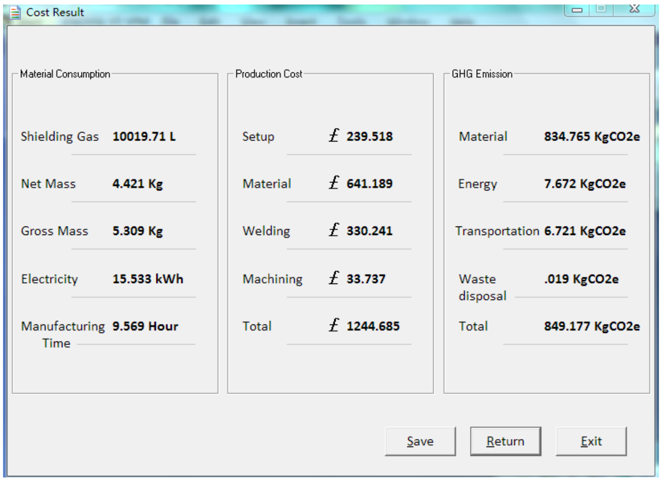


Pad.2	Substrate	Substrate Volume:	3.016	Substrate Efficiency(%):	100

Figure 5: Data input box for substrate features (yellow area)

Other data listed on this page were automatically captured from the CAD file; you do not need to change them in most conditions. However, if the CAD model is not fully match the drawing rules then some data may go wrong. If this happens, you can manually check and trim them. When all data were confirmed, click "confirm" to finish this operation.

When "confirm" button was clicked, the software will automatically execute the final step: calculate and display the results. If the required data for calculation is incomplete a message box will show to notice you to check them. Meanwhile, a progress bar will indicate the calculation progress as well. Figure 6 is the result display page where all the results are listed on. You can click "save" button to save this result as a MS Excel formatted file, or click "return" to execute another calculation, or click "exit" to quit this program.



Material Consumption

Shielding Gas	10019.71 L
Net Mass	4.421 Kg
Gross Mass	5.309 Kg
Electricity	15.533 kWh
Manufacturing Time	9.569 Hour

Production Cost

Setup	£ 239.518
Material	£ 641.189
Welding	£ 330.241
Machining	£ 33.737
Total	£ 1244.685

GHG Emission

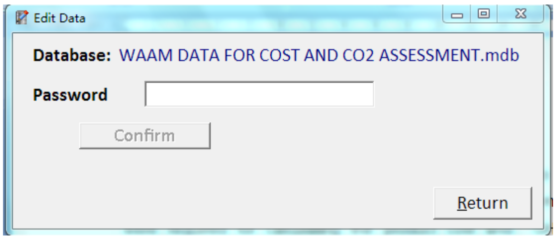
Material	834.765 KgCO2e
Energy	7.672 KgCO2e
Transportation	6.721 KgCO2e
Waste disposal	.019 KgCO2e
Total	849.177 KgCO2e

Figure 6: Result display page

- Edit database

This WAAM cost software tool use a backend database to store the process parameters, unit prices, machine information and GHG emission data which were required for calculating the product cost and GHG emission. The database is an independent MS Access formatted file. You can directly open and edit it by using MS Access software. Please aware that the name of the data form and data record were not allowed to change. You do can change the database name and password, whilst once you did this you have to change them in the cost software as well.

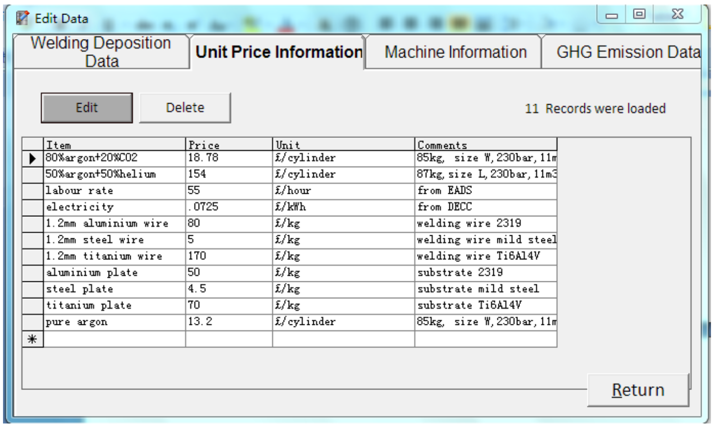
As an alternative, you can edit these data by using the "edit data" function provided by the cost software tool itself. To execute this operation, you need to choose "edit data" function from the welcome page, and then the software will lead you to the database edit page. You have to input the database password first before you can check and edit the database (Figure 7).



Database: WAAM DATA FOR COST AND CO2 ASSESSMENT.mdb

Figure 7: Password input box

The confirm button will be enabled when you inputted the password, and then the data will be displayed in 4 tabs, each tab corresponds to a data form of the database. Figure 8 shows the database display page.



11 Records were loaded

Item	Price	Unit	Comments
80%argon+20%CO2	18.78	£/cylinder	85kg, size W,230bar,11m
50%argon+50%helium	154	£/cylinder	87kg,size L,230bar,11m3
labour rate	55	£/hour	from EADS
electricity	.0725	£/kWh	from DECC
1.2mm aluminium wire	80	£/kg	welding wire 2319
1.2mm steel wire	5	£/kg	welding wire mild steel
1.2mm titanium wire	170	£/kg	welding wire Ti6Al4V
aluminium plate	50	£/kg	substrate 2319
steel plate	4.5	£/kg	substrate mild steel
titanium plate	70	£/kg	substrate Ti6Al4V
pure argon	13.2	£/cylinder	85kg, size W,230bar,11m

Figure 8: Database display page

On this page, you can click the “edit” button to enable the data edit function. Once the “edit” button becomes dark, it indicates the data is editable; you can directly edit the data from the data table. If you want to delete a whole record, use the black arrow on the left of the table to select the row you want to delete, and then click “delete”. In order to prevent disoperation, the software will show a message box to make sure you want to delete the record. If you want to add a new record you can just add it at the end of the table where you will find a blank row indicated by a “*” sign. You can change the data form to be edited by switch the tabs. When edit data is completed, click “return” button, then you will return to the welcome page.

Appendix C Questionnaire for cost model validation

QUESTIONNAIRE ON COST MODELLING FOR WIRE AND ARC ADDITIVE MANUFACTURING

Introduction: The purpose of this questionnaire is to collect feedback for a feature based cost model and software tool design project. The result will be used to evaluate and validate the research achievement.

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Interviewee Details: (or attach your business card)

Name:
Job Title:
Organisation:
Email:
Years of Experience

Disclaimer: Your response will be treated in the strictest confidence. Respondents' names will not be disclosed nor identified in the research report. Please be assured that the information provided will only be used for academic and research purposes and will not be passed to a third party.

Thanks for taking part in this research. This questionnaire consists of 5 questions which are lists on the next page.

- Please assign a score from **0** to **5** to the questions listed below, where 5 means **very satisfied** and 0 means **not satisfied at all**.

Q.1 How adequate and rigorous do you think the cost model framework can represent the actual WAAM product cost?

Your answer:

Q.2 How reasonable do you think the cost model equations are?

Your answer:

Q.3 To what extent do you think the cost software is functional enough for WAAM cost and GHG emission calculation?

Your answer:

Q.4 How convenient and efficient do you think the cost software is?

Your answer:

Q.5 How accurate do you think the cost and GHG emission result of the case study is?

Your answer:

- If any score of these questions above is **under 3**, please list the reason and give your suggestion for improvement.

This is the end of questionnaire, thanks again for your participation.

Appendix D List of collected data for cost estimation

GHG emission data:

ID	Item	Figure	Unit	Comments	DataSource
1	electricity	0.49	KgCO2e/kWh	emission factor	DEFRA
2	freight transportation	0.64	KgCO2e/TonneKm	emission factor	DEFRA
3	waste disposal	21.00	KgCO2e/Tonne	emission factor	DEFRA
4	shielding gas	1.06	KgCO2e/£	emission factor	DEFRA
5	aluminium wire	11.20	KgCO2e/Kg	emission factor	ICE
6	aluminium plate	11.50	KgCO2e/Kg	emission factor	ICE
7	steel wire	2.83	KgCO2e/Kg	emission factor	ICE
8	steel plate	3.19	KgCO2e/Kg	emission factor	ICE
9	titanium wire	1.07	KgCO2e/£	emission factor	DEFRA
10	titanium plate	1.07	KgCO2e/£	emission factor	DEFRA
11	metal material transportation distance	500.00	Km	activity data	testdata
12	shielding gas transportation distance	100.00	Km	activity data	testdata
13	waste transportation distance	100.00	Km	activity data	testdata

Machine information:

ID	Category	Model	Cost (GBP)	AveragePowerConsumption(kW)	DepreciationYear	MachineUtilization(%)	Comments
1	CMT machine		20000		5	70	
2	TIG machine		15000		5	70	
3	wire feeder		2000		5	70	
4	robot	FANUC ARCMate120iB	25000	1	5	70	
5	milling machine		65000	3	5	70	test data

6	grinding machine		100000	3	5	70	test data
7	CMT+ROBOT WAAM		47000	1	5	70	for aluminum and steel
8	TIG+ROBOT WAAM		42000	1	5	70	for titanium

Unit price information:

ID	Item	Price	Unit	Comments
1	labour rate	55	£/hour	from EADS
2	electricity	0.0725	£/kWh	from DECC
3	1.2mm aluminium wire	80	£/kg	welding wire 2319
4	1.2mm steel wire	5	£/kg	welding wire mild steel
5	1.2mm titanium wire	170	£/kg	welding wire Ti6Al4V
6	aluminium plate	50	£/kg	substrate 2319
7	steel plate	4.5	£/kg	substrate mild steel
8	titanium plate	70	£/kg	substrate Ti6Al4V
9	pure argon	13.2	£/cylinder	85kg, size W,230bar,11m3
12	80%argon+20%CO2	18.78	£/cylinder	85kg, size W,230bar,11m3
13	50%argon+50%helium	154	£/cylinder	87kg,size L,230bar,11m3

Welding deposition data:

ID	Feature	Material	WallThickness(mm)	WireDiameter(mm)	WireFeedSpeed(m/min)	AlloyEfficiency(%)	Voltage (V)	Current (A)
1	Vertical Wall	aluminium	2.00	1.20	2.00	65.00	13.00	43.00
2	Vertical Wall	aluminium	3.00	1.20	3.00	78.00	13.00	45.00
3	Vertical Wall	aluminium	4.00	1.20	3.70	90.00	12.00	60.00
4	Vertical Wall	aluminium	5.00	1.20	4.00	90.00	12.50	75.00

5	Vertical Wall	aluminium	6.00	1.20	4.20	88.00	12.50	79.00
6	Vertical Wall	aluminium	7.00	1.20	4.70	91.00	13.50	87.00
7	Vertical Wall	aluminium	8.00	1.20	4.80	92.00	13.90	90.00
8	Vertical Wall	steel	2.00	1.20	2.01	93.72	9.85	56.07
9	Vertical Wall	steel	3.00	1.20	3.84	94.67	11.33	75.78
10	Vertical Wall	steel	4.00	1.20	8.43	93.25	14.11	112.27
11	Vertical Wall	steel	5.00	1.20	3.84	93.68	11.33	75.78
12	Vertical Wall	steel	6.00	1.20	10.78	92.12	14.86	144.38
13	Vertical Wall	steel	7.00	1.20	13.01	92.78	18.33	177.13
14	Vertical Wall	steel	8.00	1.20	6.13	86.49	11.86	92.61
15	Vertical Wall	titanium	3.00	1.20	3.00	89.19	61.64	12.15
16	Vertical Wall	titanium	4.00	1.20	6.00	89.36	109.87	13.63
17	Vertical Wall	titanium	5.00	1.20	8.00	87.93	120.78	14.23
18	Vertical Wall	titanium	6.00	1.20	8.00	87.93	120.78	14.23
19	Vertical Wall	titanium	7.00	1.20	1.60	89.36	10.00	100.00
20	Vertical Wall	titanium	8.00	1.20	8.00	87.93	120.78	14.23