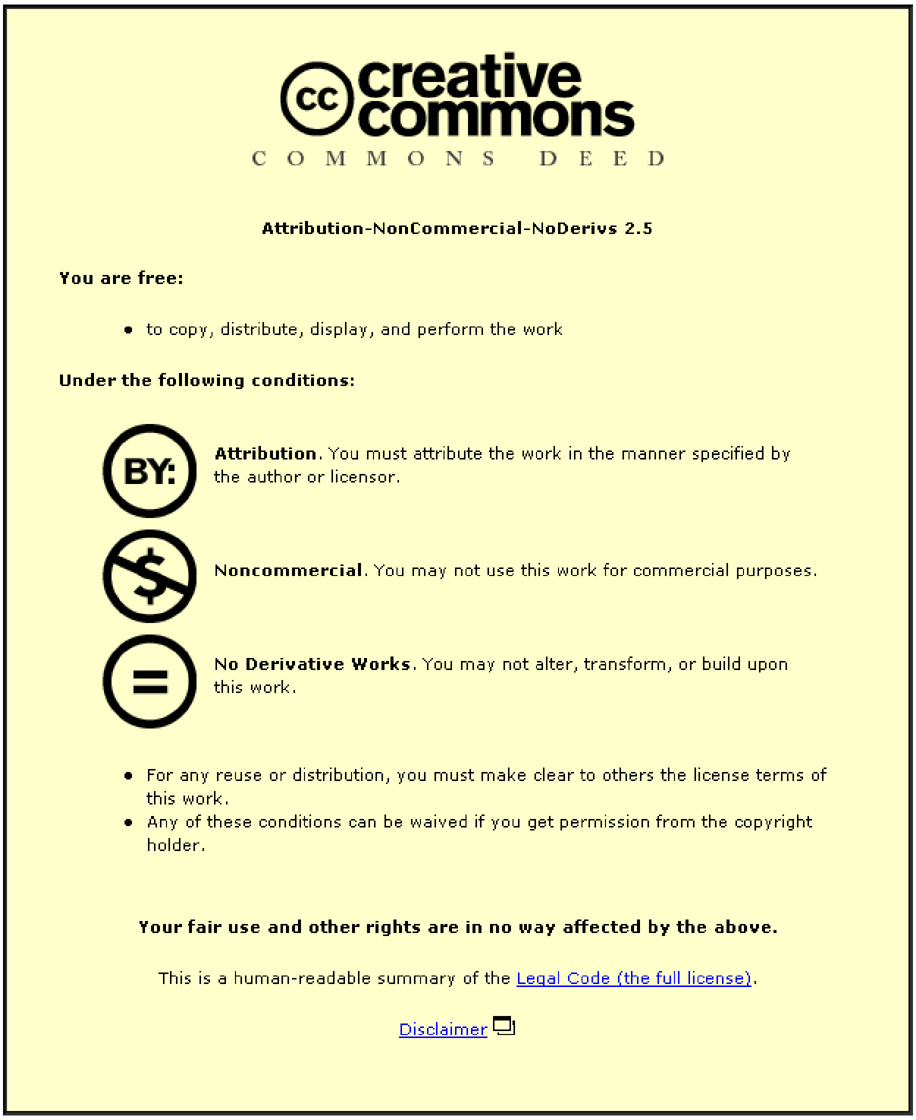

Loughborough University

Design School

Optimising Additive Manufacturing for Fine Art Sculpture and Digital Restoration of Archaeological Artefacts

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A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy

Declaration

I declare that this thesis is an original piece of work, created by the author, and has not been submitted for any other award.

Abstract

Additive manufacturing (AM) has shown itself to be beneficial in many application areas, including product design and manufacture, medical models and prosthetics, architectural modelling and artistic endeavours. For some of these applications, coupling AM with reverse engineering (RE) enables the utilisation of data from existing 3D shapes. This thesis describes the application of AM and RE within sculpture manufacture, in order to optimise the process chains for sculpture reproduction and relic conservation and restoration. This area poses particular problems since the original artefacts can often be fragile and inaccessible, and the finishing required on the AM replicas is both complex and varied. Several case studies within both literature and practical projects are presented, which cover essential knowledge of producing large scale sculptures from an original models as well as a wide range of artefact shapes and downstream finishing techniques. The combination of digital technologies and traditional art requires interdisciplinary knowledge across engineering and fine art. Also, definitions and requirements (e.g. ‘accuracy’), can be applied as both engineering and artistic terms when specifications and trade-offs are being considered. The thesis discusses the feasibility for using these technologies across domains, and explores the potential for developing new market opportunities for AM. It presents and analyses a number of case study projects undertaken by the author with a view to developing cost and time models for various processes used. These models have then been used to develop a series of "process maps", which enable users of AM in this area to decide upon the optimum process route to follow, under various circumstances. The maps were validated and user feedback obtained through the execution of two further sculpture manufacturing projects. The thesis finishes with conclusions about the feasibility of the approach, its constraints, the pros and cons of adopting AM in this area and recommendations for future research.

Acknowledgements

First and foremost, I would like to show my deepest gratitude to my supervisor, Dr Ian Campbell, a respectable, responsible and resourceful scholar, who has provided me with valuable guidance in every stage of the writing of this thesis. Without his professional instruction, impressive kindness and patience, I could not have completed my thesis. His keen and vigorous academic observation enlightens me not only in this thesis but also in my future research.

I would also like to thank my co-supervisor Dr Ian Graham who has helped me to develop the fundamental and essential academic competence. I shall extend my thanks to Dr Richard Bibb and Mr Dylan Lee for all their kindness and help. My sincere appreciation also goes to the leadership in the Palace Museum Beijing (i.e. Forbidden City), the Summer Palace, Central Academy of Fine Arts (CAFA) and Beijing University, who participated this study with great cooperation.

Last but not least, I would like to thank my parents and Alex Hui for their encouragement and support.

Acronyms/Abbreviations/Glossary of terms (list in alphabetical order)

Abbreviation	**Glossary of terms (Explanation)**
AM	Additive Manufacturing
CAD/CAM	Computer Aid Design / Computer Aid Manufacturing
FDM	Fused Deposition Modelling
FE	Forward Engineering: Generation of feature instance by executing and transformations from design idea. (M. Antkiewicz, K. Czarnecki, M. Stephan, 2009)
FreeForm	FreeForm is a computer software package that enables haptic sculpture and shaping of complex organic shapes.
Haptic	From Greek meaning to touch. Haptic refers to touch as optic refers to sight. Haptic devices make it possible to touch and manipulate virtual objects.
LOM	Laminated Object Manufacturing
MMJ	Multi Jet Modelling
Poly-jet	An AM process that creates highly detailed parts using an inkjet printing-style process of building up successive layers.
RE	Reverse Engineering: Retrieval of existing objects via digital technologies' application by detecting feature instances (M. Antkiewicz, K. Czarnecki, M. Stephan, 2009)
RQ	Research Question
SLA	Stereo-Lithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
3D Scanning	3-Dimensional Scanning
3DP	Three Dimensional Printing
UK	United Kingdom
US	United States (of America)

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1. Chapter One: Introduction

1.1. Background/Research context

Throughout the development of Additive Manufacturing (AM), applications have arisen in many areas. Technology specific to particular applications often benefits from rapid improvements as user take-up accelerates. However, the capability and adoption of AM in finely detailed complex surface creation remains limited, especially in fine art sculpture. This is demonstrated by the relative lack of published work in this area when compared to engineering and medical applications. Although capabilities are theoretically adequate, there is a gap between knowledge and practice. Artists desire an easier and more precise way to produce their art works, in order to leave time for the important creative and conceptual activities. Consequently, engineers are needed to optimise digital technology and process chains to support this market, and provide acceptable solutions to the sculptors. This shall result in the simplifying of complicated manufacturing processes and a reduction in reliance upon lengthy, repetitive and tedious manual production work. The desire to see engineering principles brought to bear in an artistic area was the motivation behind this research

1.2. Research audience

This research will benefit specialists working in the fields of sculpture and archaeological restoration by optimising and recommending manufacturing process chains for a range of different activities, while also helping collaboration between sculptors, engineers and clients. Also, covering both technological and traditional art techniques could broaden designers' minds and open new directions for fine art creation. Moreover, the progress of this research develops a relatively new research area for AM and covers significant issues as well as potential benefits for enhancing the capability of AM. As such, it is also aimed at future researchers in the field of applying AM to sculpture manufacturing.

1.3. The need for the research

The research context is one where the sculpture industry has yet to benefit significantly from AM, especially when viewed alongside the many success stories in other fields. Theoretically, complex surface creation is one of the strengths of AM, and it is clear that complementary needs and opportunities exist. So the question must be asked "what are the problems of applying AM in the world of fine art, and how should AM be optimised for sculpture reproduction"?

The general requirements of fine art sculpture in terms of aesthetics, manufacture and artistic integrity need to be understood clearly. Also, the conjunctive areas of 3D digital art and fine art sculpture must be identified. Furthermore, the potential benefits of AM to fine art sculpture and the extent to which 3D technologies might be accepted in the field of fine art are key elements for this research. More practical challenges include the optimal combination of reverse engineering (RE) and digital data manipulation and optimisation in computer aided design/computer aided manufacturing (CAD/CAM) systems. In summary:

- Definitions of fine art sculpture are needed in order to clarify the natural boundaries to and classifications of 3D Digital Art, and to usefully constrain the research.
- The ranges of materials, tools and manufacturing processes need to be compiled for both conventional sculpture and 3D digital art.
- Dissemination methods common in historical and contemporary sculpture need to be understood.

1.4. Aims and objectives

Starting from the research need described above, an initial series of outcomes (termed aims and objectives) were developed for this research. These were revisited throughout the "literature review" stage of the research and finally decided upon as follows:

Research Aims:

- To better understand the process chain of digital manufacturing technology in the reproduction of sculpture artworks
- To reduce the tedious work associated with current practice in the traditional sculpture industry

Research Objectives:

1. Provide definitions of Fine Art Sculpture and apply them to usefully constrain the research.
2. Clarify the natural boundaries to, or classifications for, 3D digital art.
3. Specify how historical & contemporary practice in sculpture is disseminated.
4. Find out what materials/tools are used for traditional sculpture and 3D digital art.
5. Find out what manufacturing processes are used for both traditional sculpture and 3D digital art.
6. Develop a method for comparing the different processes that are available.
7. Develop a tool to assist practitioners in this area to decide which processes to use.

1.5. Research questions and research methodology

1.5.1. Research questions

Through an analysis of the literature review and by taking into consideration the aims and objectives, the following research questions were identified as being central to the research.

A. What are the general requirements of Fine art sculpture in both terms of aesthetics and manufacturing integrity?

B. What are the conjunctive areas of 3D digital art and fine art sculpture?

C. What is the benefit of using AM for fine art sculpture? (In terms of measurable outcomes for validating the research)

D. To what extent will 3D technology be accepted by practitioners in the fine art field and what are the barriers to acceptance?

E. How can the optimal combination of Forward Engineering (FE), Reverse Engineering (RE) and traditional techniques be determined? (As specifically applied to fine art)

F. How can the capability of digital technology best be promoted within fine art field?

The relationship between the research questions and the objectives is shown in Table 1-1.

Table 1-1 Matrix of the link between research objectives and questions

	A	B	C	D	E	F
1	🟩		🟩			🟩
2		🟩		🟩		
3	🟩					🟩
4		🟩		🟩		
5			🟩	🟩		
6	🟩				🟩	🟩
7			🟩		🟩	

1.5.2. Overview of research methodology

Complimentary research methods were followed to satisfy the objectives and research questions through the collection of information from multiple sources. For example, resources were compiled in other languages and from other disciplines, translated and summarised as appropriate. Besides the literature review, interviews and surveys were employed alongside action research to obtain comprehensive information and to provide a degree of "triangulation" (i.e. using more than one method to answer a particular research question). The various research methods used are described briefly below.

- **Interviews**

The use of interviews for research has been proposed due to their flexibility, enabling multi-sensory channels, such as verbal, non-verbal, and visual. The order of the interview can be controlled as well as giving space for spontaneity. In addition, responses to complex and deep issues can be stressed by the interviewer to obtain complete answers (L. Cohen, etc. 2011). As a powerful implement for researchers, the interview does not only mark a move away from seeing human subjects as simply manipulable and data as somehow external to individuals, and can also contribute to generating knowledge between humans through conversations (S. Kvale, 2007).

This is the most efficient and flexible way to get basic knowledge and latest progress from experts. General questions were prepared to ask people who work in relevant areas and branches questions that could develop in different directions during the interviews. Thus, more specific problems and fresh ideas could be much more easily found out with solid objects or image shown as examples, which was also good for analysing the conjunctive area of art work production and AM.

For example, the interview with Roger Moss, who was the first interviewee in the Digital Art field, was designed to be based on a questionnaire but extended with some branch questions according to the responses, to generate more knowledge and get a better understanding.

- **Questionnaires**

The questionnaire is a widely used and useful instrument for collecting survey information, providing structure, often with numerical data, being able to be administered without the presence of the researcher, and often being comparatively straightforward to analyse (N. Wilson and S. McLean, 2003).

Different questionnaires were designed for different people with the aim of letting them share their experience easily and more effectively. Obtaining knowledge of artistic sculpture from expert sculptors and arts school students was necessary in order to gain a better understanding of acceptable standards of art works. However, collecting information from designers or engineers who work in AM field had the aim of evaluating the barriers to and feasibility of applying this technology to complex surface, multi-materials 3D modelling. (The samples of questionnaire are attached in appendices).

- **Action research**

As a systematic study, action research could be seen as a small-scale intervention in the functioning of real work and a close examination of the effects of such an intervention (L. Cohen, etc. 2011), which combines action and reflection with intention of improving practice (D. Ebbutt, 1983). The combination of action and research forms a disciplined inquiry, in which the intention is made to understand, improve and reform practice (L. Stenhouse, J. Rudduck, 1985). In short, action research is designed to bridge the gap between research and practice (B. Somekh, 2006).

This was a significant method for this research, as so far, there are actually few successful examples of adopting AM technology into the reproduction of traditional sculpture. The research needed to be undertaken through action combined with observation.

- **Trials**

Trials were designed for working with different background specialists to evaluate the process of producing the same / similar 3D art works by both conventional and innovative digital methods. Then, comparison of the results was undertaken to obtain a better understanding of the problems and feasibility, in terms of time efficiency, work standards, total cost and technical accessibility.

- **Case studies**

A case study can be seen a specific instance that is frequently designed to illustrate a more general principle (J. Nisbett and J. Watt, 1984), and it is ‘the study of an instance in action’ (C. Adelman, et al. 1976). Case studies can establish cause and effect, indeed one of their strengths is that they observe effects in real contexts, recognising that context is a powerful determinant of both causes and effects. As Nisbett and Watt (1984: 78) remark, "the whole is more than the sum of its parts".

On one hand, the purpose of some of the case studies found through the literature review were to find development / progress and existing problems of current research in relevant areas. On the other hand, some hidden barriers and potential opportunities needed to be explored with experiments / projects undertaken in a real situation and coupled with observation and analysis.

- **Role playing**

Role playing is defined as participation in simulated social situations that are intended to throw light upon the role/rule contexts governing ‘real life’ social episodes (V. Hamilton, 1976), a summary can be seen in Table 1-2.

Table 1-2 Dimensions of role-play methods (Source adapted from V. Hamilton, 1976)

	Form	Content
Set	Imaginary vs. Performed	Person: self vs. other
Action	Scripted vs. Improvised	Role: subject vs. another role
Dependent variables	Verbal vs. Behavioural	Context: scenario other actors audience

Put myself into sculptors as well as engineers' positions to gain essential knowledge for evaluation of feasibilities, especially to investigate communication difficulties.

- **Scenario development & evaluation**

Record the entire process chain of AM method adopted for artistic sculpture production and get feedback from authors / experts to evaluate and analysis the results.

A comparison summary of research methods is shown in table 1-3.

Table 1-3 Summary of Research Methods

Research Method	**Advantages**	**Disadvantages**
Literature Review	Plenty of information Cover any areas Get anytime, anywhere Keep up to date by alert	Un-relevant information Too much to manage Accessibility of paper
Interview	Efficient Minimise misunderstanding Reliability	Expert availability Personal views
Questionnaire	Sufficient feedbacks Feel ease to answer Accessibility (cross country)	Time scope Feedback quality Reliability
Action Research	Combine knowledge and practice Relevance Communication in teamwork	Accessibility Time scope
Trial	User centred	Accessibility Reflect limit problems
Case Studies	Get information from readily available experience Wide range Accessibility	Non-directly relevant Different specific problems
Role Playing	Directly relevant Better understandings	Accessibility Interdisciplinary knowledge
Scenario Development & Evaluation	Authority knowledge Comprehensive analysis	Risk of failed experiments Experts' knowledge

1.5.3. Research methods used for specific research questions

Table 1-4 Research methods used for specific research questions

RQ	Methodology	Reason for the Choice
RQ 1	Review of literature/work of others Interview sculptors	Literature review to obtain plenty of resource and general understanding Interview to avoid misunderstanding and missed information
RQ 2	Review of literature/work of others Interview (for scoping issues and developing detailed questions)/ questionnaire in both fields	Literature review to obtain basic knowledge from various resource Interview and questionnaire for getting specific information and different views
RQ 3	Review of literature/work of others Action research with author doing some design work Trials with other designers/sculptors doing some design work (both using conventional and AM methods)	Literature review to obtain information of existing relevant research and progress Action research and trials for investigation of feasibilities and experiment results in practice
RQ 4	Review of literature/work of others Action research with author doing some design work Trials with other designers/sculptors doing some design work (both using conventional and AM methods)	Literature review to obtain general problems, needs, and opportunities. Action research and trials for comparison with conventional and AM methods
RQ 5	Case studies Role playing	Case studies for analysis current situations, existing research and progress Role playing for understanding and investigation of real situations in practice
RQ 6	Scenario development and evaluation (by author and “experts”)	This research method for developing and evaluating new process chains

1.6. Outline of thesis structure

A general introduction of this research is provided in the first chapter, which includes essential information of research background, needs, aims and objectives, research audience, research questions and methodology. Additive manufacturing is introduced as the key technology for this research and for investigating the research opportunities. Review of Fine Art Sculpture follows the review of AM to show the knowledge of research requirements and tasks. The review of AM and Fine Art Sculpture together indicate understanding of research aims, objectives and research questions. Finishing techniques are reviewed as a significant part in manufacturing process chain for both AM methods and traditional methods in sculpture industry. Primary research with interviews and questionnaires are detailed in parallel with literature research as a foundation for further research, then, practical case studies are explained as the main research method – action research – follows the primary research and literature research. The results and discussions of practical projects are presented straight away in the next chapter. Analysis of all research information is explained to show the results, and process chain maps are designed as visual information and outcomes of the research. Finally, conclusions and recommendations for further research are written in the last chapter. The thesis structure is also shown below in Figure 1-1 as a flow chart:

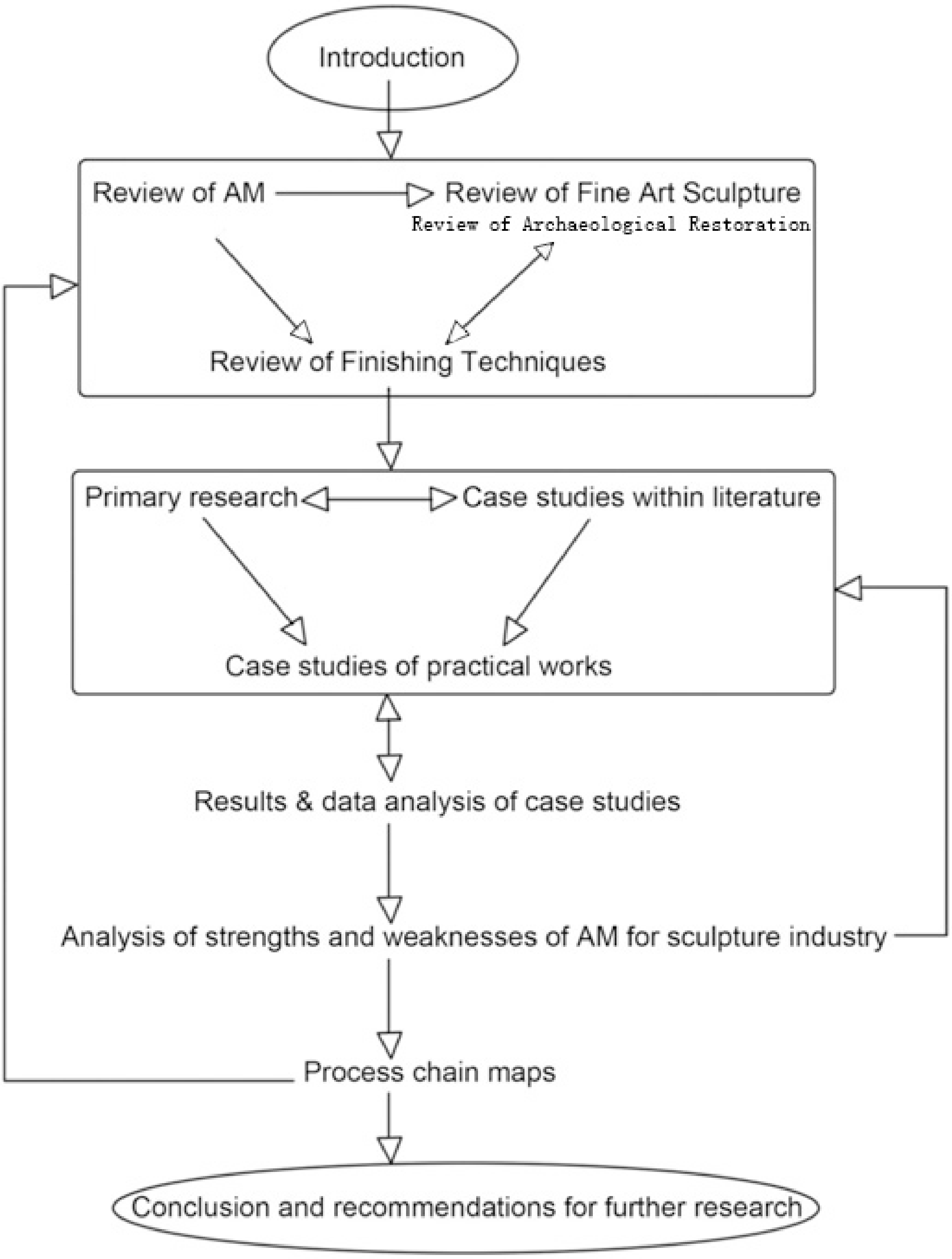

Figure 1-1 Flow chart of the thesis structure

2. Chapter Two: Additive Manufacturing

2.1. Definition of additive manufacturing

Additive Manufacturing (AM) generally refers to techniques that produce 3D shaped parts by gradual creation or addition of solid material, which fundamentally differentiates them from forming and material removal manufacturing techniques (J. Kruth, et al, 1998). AM processes have come through an evolution since the first "Rapid Prototyping" (RP) technologies, and AM is therefore the preferred term for this range of technologies capable of producing physical models directly from CAD data in a relatively short timescale.

An internationally recognised definition of AM is the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2013). The term additive manufacturing describes technologies which can be used anywhere throughout the product life cycle from pre-production to full scale production and even for tooling applications or post production customisation.

The collective description for AM technologies is that by using an automatic process, they produce three dimensional objects directly from digital models by the successive addition of material, without the use of a specialised tooling. AM is also known as: Additive Fabrication, Solid Freeform Fabrication (SFF), Layered Manufacturing, and 3D Printing. Sometimes AM is referred to by the names of specific applications, such as Rapid Prototyping (RP), Rapid Tooling (RT), and Rapid Manufacturing (RM) (K. Boivie, et al, 2011).

2.2. History

AM technologies have developed since 1984 (G. Savoiu, C. Manea, 2013), and used to be recognised mainly for Rapid Prototyping, which produces 3D solid models without tooling or manual work. In the beginning, photopolymers were developed as the first materials to be used commonly, and prototypes generated by these early machines represented the general physical shapes of final parts mostly for visualisation, communication and inspection, e.g. pre-production samples for demonstration and evaluation, and tools for assembling.

With the rapid development of polymer material models produced by AM, the fabrication of conceptual and functional prototypes has been well established in the market. As visualisation and assembly testing has been conducted increasingly by using virtual prototyping (D. Pham, S. Dimov, 2003), AM has been moving away from some of its original applications and applied to a wider range of areas. During the 1990's, the metal and ceramic components generated directly by AM technologies were used to produce functional tools for the production of final parts in polymer and metal materials. As the trend at that time was to minimise the time needed for prototype tooling and production tooling, this application was called Rapid Tooling (RT), and has been the subject of much research (G. Levy, et al., 2003). More recently, the focus for AM has shifted to the fabrication of end use parts, and the term "Rapid Manufacturing" arose to differentiate it from Rapid Tooling, partially as the next natural step. However, the AM processes used are actually quite slow compared to conventional techniques and so this term has largely fallen out of favour. AM technologies have experienced a progression from creating prototypes to tooling, end-use parts and developed manufacturing solutions; the general progression is shown in table 2-1.

Table 2-1 Expansion of additive technology

Terms	Time
Rapid Prototyping (AM for models and prototypes)	1980s
Rapid Tooling (AM for tools and dies)	1990s
Rapid Manufacturing (AM for end-use parts)	2000s
Additive Manufacturing (recognised Manufacturing Technology)	2010s

Functional parts produced via AM could be used in end-use applications once some deficiencies of early version AM systems were overcome, such as limitations of materials properties, lack of CAD solid modelling software compatible with AM and unreliable AM systems capabilities (N. Hopkinson, et al., 2006). As a consequence, AM-supported "mass customisation" arose as a new possibility for market needs with significant future potential. It is not difficult to imagine examples where customised products where only a few items are needed, like manufacturing for jewellery with different sizes, colour, and engraved letters, as well as medical equipment designed for individual patient.

AM technologies are well-suited to applications in many fields, especially those involving complex geometries. According to various research and development projects, AM also has the potential to produce robust components as end-use parts (N. Hopkinson, et al., 2006). Therefore, in recent years, direct manufacture AM technologies have been developing independently from RP and RT to become a new manufacturing technology, which eliminates tooling, and has profound implications on many aspects of the design, manufacture and sale of new products (T. Wohlers, 2009).

There is often an unfavourable comparison made between AM and conventional processes in terms of material cost, material properties, surface finish, and speed of manufacturing. In addition, there is a misunderstanding that AM is simply an extension of RP and that AM parts are not seen to be suitable or intended for end use (N. Hopkinson, et al., 2006). Such viewpoints overlook the fact that AM offers the potential to create new part designs that would be non-viable using conventional methods. Other constraints on the use of AM include support material removal, production of large scale parts and combination with non AM parts and these are also challenges for further research (G. Levy, et al., 2003), (R.I. Campbell, R. Hague, et al., 2003). Indeed, there are still many difficulties that need to be overcome and more evidence needed to enable AM to be commonly accepted as a new manufacturing method, which could take a long time. AM could also be a very useful technology for many non-manufacturing applications and could be used to build research bridges in overlapping discipline areas, such as for the sculpture industry and archaeological restoration, which is the focus of this thesis.

2.3. AM systems

These are numerous AM systems available today but many of them can be categorised under generic headings that describe their basic operating principles. Most commercially sold systems work on a layer-by-layer approach using 3D CAD data that is most often supplied in the form of an STL file containing a multitude of small triangular facets. This triangulated data is sliced by the AM machine software to produce the 2D profiles needed for every layer (see Figure 2-1). The most commonly used AM techniques are described below.

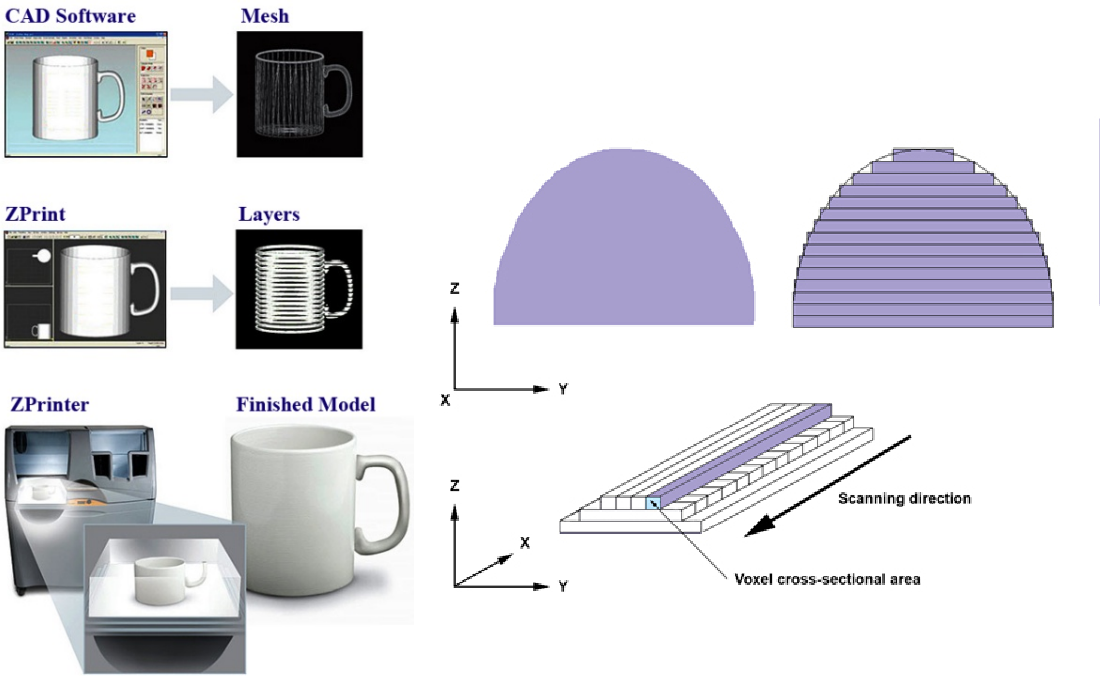

Figure 2-1 AM process (Admin, 2011), (http://en.wikipedia.org/wiki/File:Rapid_prototyping_slicing.jpg)

2.3.1. Printing onto Powder

Printing onto powder (often referred to by the Z-Corp trade name 3D Printing or 3DP) is a quick, low cost rapid prototyping process used primarily for concept modelling. The system applies a thin layer of powder on a level surface. The ink-jet style spray head deposits a liquid binder onto the powder in a 2D pattern, bonding the powder particles together to form a single layer in the object. Another layer of powder is deposited and the process repeated (see Figure 2-2). After all layers are printed, the layer loose of powder is removed to reveal the finished part (E. Sachs, et al., 1993). Materials used are starch or plaster, both of which are fragile to handle until impregnated with glue or wax after removing from the machine. The process yields a slightly rough textured surface with lower accuracy than other popular AM systems.

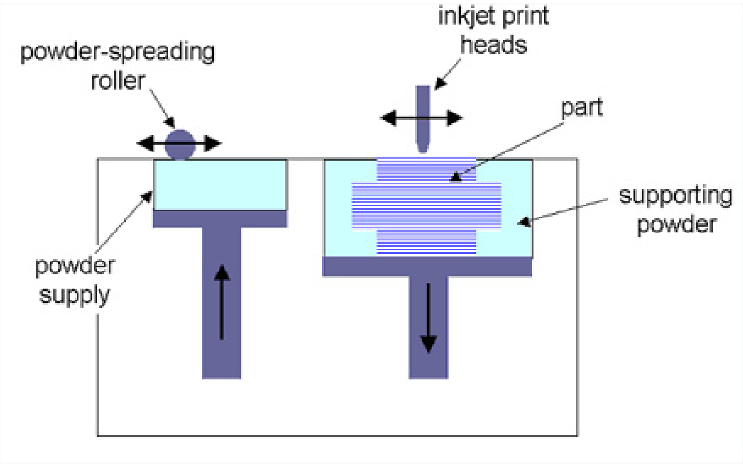

Figure 2-2 3DP process (http://www.xpress3d.com/zcorp3dp.aspx)

Direct Shell Production Casting

This variation of the printing on powder technique was developed at the Massachusetts Institute of Technology (MIT) and has been licensed to Solingen Technologies for metal casting. The system creates ceramic moulds directly from 3-D CAD designs and no tooling or patterns are required. The process works via a print-head moving over a fine layer of alumina powder, depositing a liquid binder layer-by-layer to define a cross section of the mould. The process is repeated until the entire mould is printed. This is then fired, resulting in a rigid ceramic mould. The process is for quickly producing castings with complex geometries.

2.3.2. Laminated Sheet Stacking

Originally developed as Laminated Object Manufacturing (LOM), this was a process which was able to create relatively low cost 3-D models since the raw material was paper. The LOM system utilises a laser to cut layers out of a glue-backed paper material that is supplied on a roll (see Figure 2-3). The layers are bonded together by heating during the process to form the solid model. The models must be carefully removed from the surrounding superfluous cross-hatched paper and have an appearance similar to wood. They are usually sealed with a protective lacquer to stop the ingress of moisture. The process is not commonly used today but was especially useful for creating sand casting patterns. A more recent laminated sheet stacking system is the Matrix 300+ machine from Mcor Technologies which works with a cutting blade and individual sheets of paper.

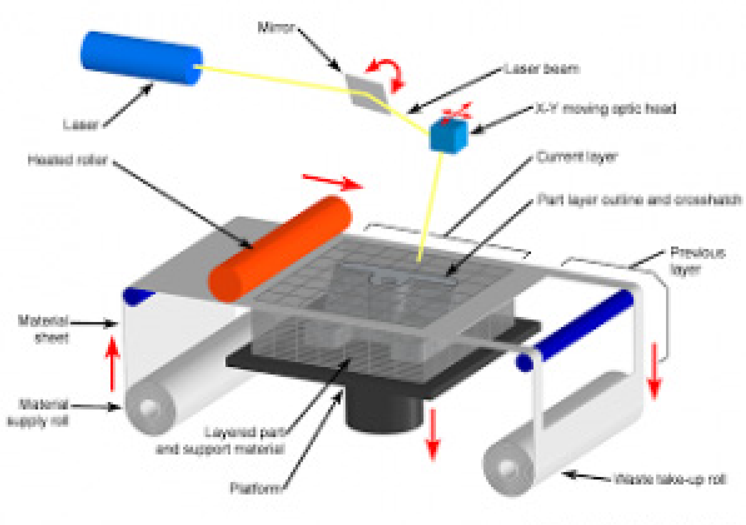

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Figure 2-3 LOM process (M. Jermann, 2013)

(http://www.makepartsfast.com/2013/08/6057/laminate-object-manufacturing-lom/)

2.3.3. Filament Extrusion

The most well-known filament extrusion system is Fused Deposition Modelling (FDM) from Stratasys, which produces functional thermoplastic models directly from CAD data, often in ABS plastic. The system utilises a CNC controlled extruder-head which squeezes a fine filament of semi-melted thermoplastic through a nozzle (see Figure 2-4). The nozzle deposits the heated plastic layer-by-layer to form the desired shape. The liquid material hardens immediately on contact with the cooler environment.

A secondary material is normally required to provide support for overhanging geometry and has to be removed either manually or through dissolving, after the model is removed from the machine. Several low-cost AM systems have come onto the market in recent years using filament extrusion technologies similar to FDM. These include RapMan from BitsfromBytes Limited and the UP! printer from PP3D.

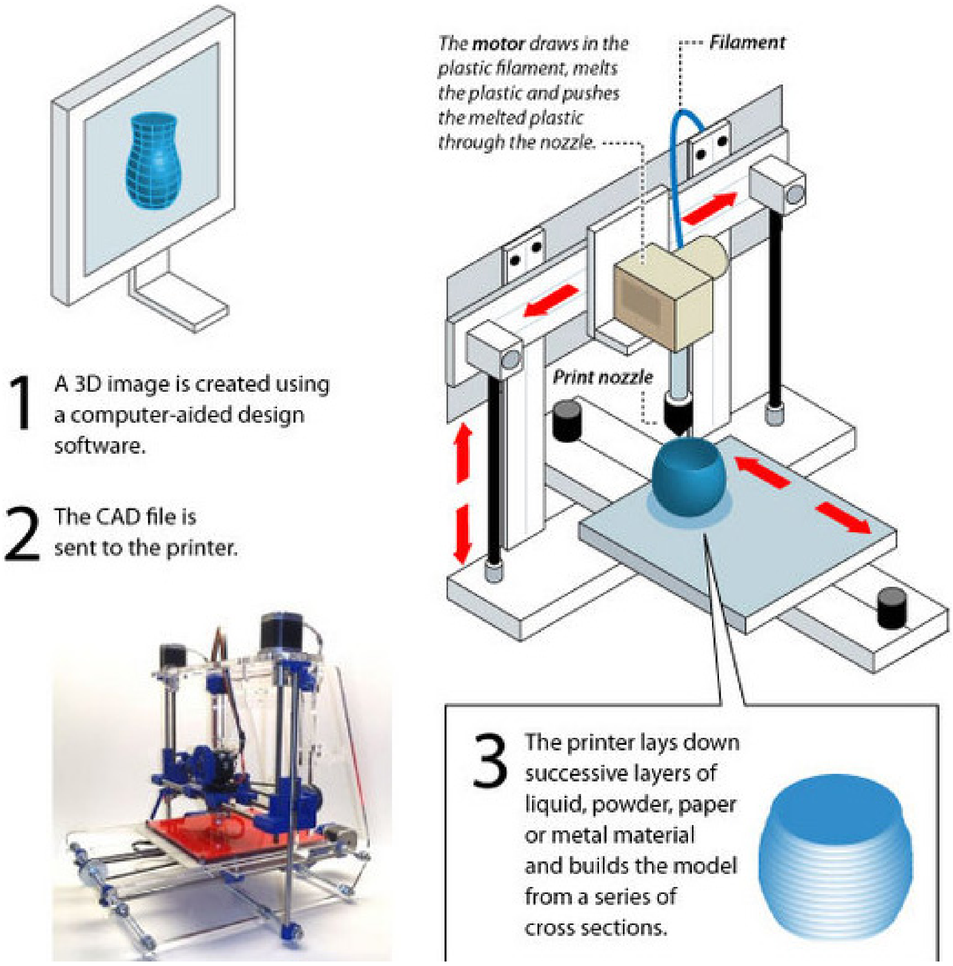


Figure 2-4 FDM process (http://www.livescience.com/37513-how-3d-printers-work-infographic.html)

2.3.4. Laser Sintering/Melting

There are several AM systems that work on the principle of using CO_2 a laser to selectively fuse together layers of powdered plastic, metal or ceramic materials (see Figure 2-5). The most commonly used of these is (selective) laser sintering from both 3D Systems and EOS. The materials used mean that these systems can create durable 3D models suitable for functional prototyping and end-use part production. An important feature of laser sintering is that the surrounding un-melted powder often provides sufficient support to overhanging geometry and so less post-processing is required. Selective laser melting (SLM) normally refers to systems which fuse metal powders together. In these systems, additional supports are nearly always required.

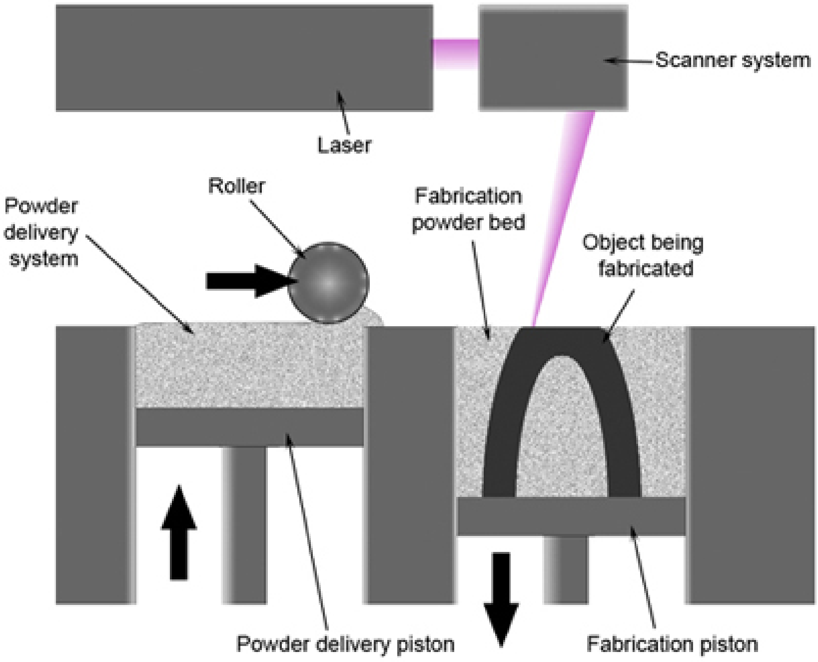


Figure 2-5 SLS process (http://proto3000.com/selective-laser-sintering-sls-rapid-prototyping-solutions.php)

2.3.5. Stereo-Lithography (Laser Curing of Photo-polymers)

Stereo-Lithography (often referred to as SLA) is the oldest commercial AM system having been introduced in 1984. The system utilises a computer controlled ultra-violet (UV) laser beam to selectively solidify the surface of a photo-curable liquid resin (see Figure 2-6). The cured layer is lowered into the vat of liquid, a new layer of resin is deposited on top and the process repeated. Overhanging geometry must be supported and removing these supports after building can be time-consuming and can cause damage to small features. The photo-curable requirements of the resin mean that material choice is rather restricted.

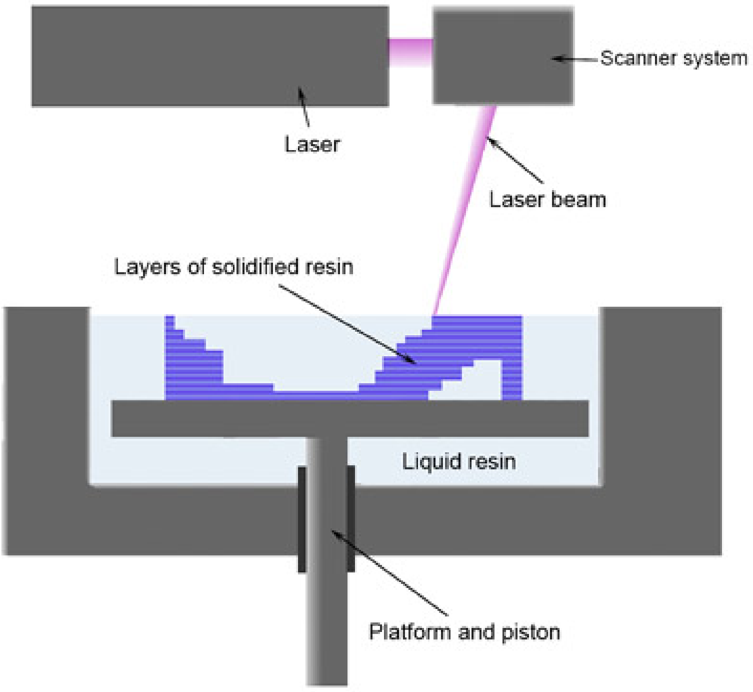


Figure 2-6 SLA process (T. Edwards, 2009) (http://www.mindtribe.com/2009/06/been-there-prototyped-that-what-process-and-when/)

2.3.6. Multi Jet Modelling

Multi Jet Modelling, uses a wide area print head with multiple spray nozzles that deposit wax, resin or some other build material, on a layer-by-layer basis (see Figure 2-7). With wax material systems (e.g. Thermojet), the jetting heads spray tiny droplets of melted liquid material which cool and harden on impact to form the solid object. With resin systems (e.g. Objet machines), the liquid resin is cured after jetting through the application of light. A secondary support material is deposited simultaneously and must be removed by melting or dissolving after the model is removed from the machine. Since it has very thin layers and high printing resolution, the process is commonly used for creating casting patterns for the jewellery industry and other precision casting applications.

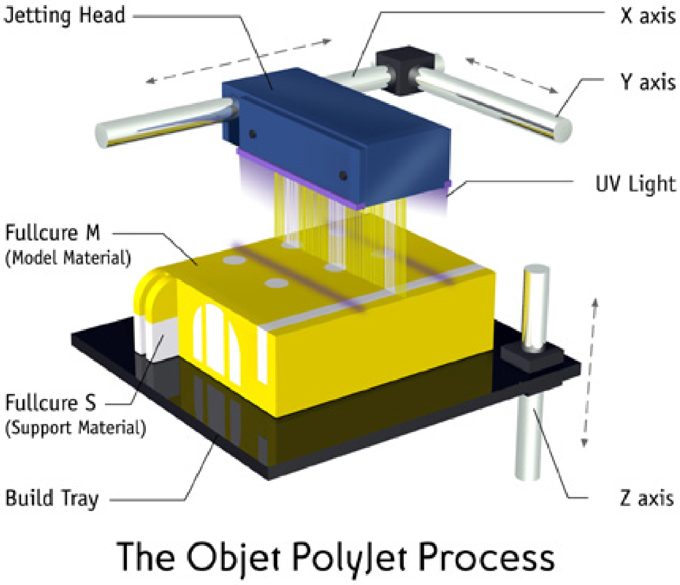


Figure 2-7 MJM process (http://www.engr.usask.ca/services/engineering-shops/facilities/rapid-prototyper.php)

2.3.7. Electron beam melting (EBM)

EBM is similar in some ways to laser sintering but is used only for metal parts. Once again, the parts are manufactured by melting metal powder layer by layer but with an electron beam in a high vacuum rather than a laser beam (Figure 2-8). The advantage of this technology is that the high-energy electron beam can quickly produce parts which are fully dense, void-free, and extremely strong.

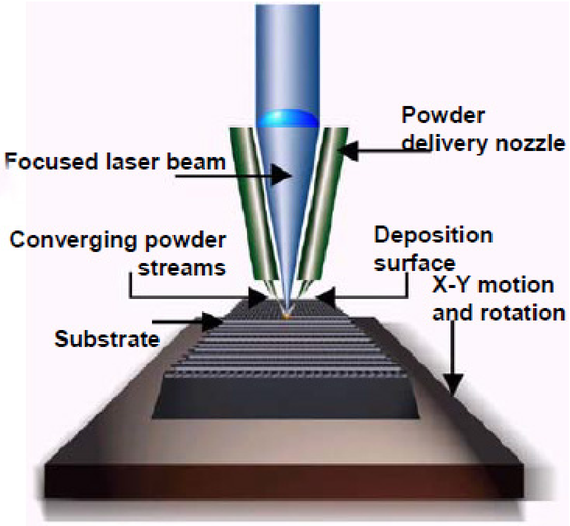


Figure 2-8 Laser processing for metal materials (R. Grylls, 2003) (http://www.moldmakingtechnology.com/articles/additive-toolmaking-process-cuts-cycle-times)

2.3.8. Laser cladding/direct metal deposition

Laser cladding is a method of melting and consolidating powdered or wire metal material by use of laser to coat part of a substrate or fabricate a near net shape part. Unlike other AM systems, this technology can bond together dissimilar metals. It is used to improve mechanical properties, increase corrosion resistance, repair worn out parts, or to fabricate metal matrix composites which allow a reduction in cost or weight by using a cheaper or lighter metal as the filler (F. Bruckner, S. Nowotny, C. Leyens, 2012).

2.4. Benefits of AM

Based on the rapid development of its capability, the wide range of application areas is an obvious benefit of AM. Specifically, in the industrial design field, AM brings new freedom for component design and whole product design. Virtually any shape of component or product that can designed in a CAD system can be produced as a physical by AM irrespective of the complexity of its geometry. Optimising product designs through increased numbers of design alternatives is another benefit. The STL file format is compatible with most major 3D software, and this gives the capability of producing physical models for test and demonstration rapidly. AM can improve product value through an increase in desirability using innovative aesthetics and nature inspired designs, as well as reducing manufacturing cost through less material and labour requirements. Since complex structures can be produced in a single build, possibly even with different materials, there is a reduction in the conventional design for assembly rules that need to be followed. Operating costs can also be reduced through weight saving or performance efficiency, e.g. using hollow structures. At the end of product life cycle, disposal costs can be decreased through easier disassembly of a reduced number of parts.

The future potential of AM shows benefits as well. The design features made feasible by AM for one product could be used in future products, which could be facilitated by a database for storing and retrieving feature information (S.B. Maidin, R.I. Campbell, E. Pei, 2012). Due to the strengths of AM in producing complex geometry, individualised parts, and a short product design and manufacturing cycle, a wide scope is opened up for mass customisation, which has been indicated as a current trend in consumer markets.

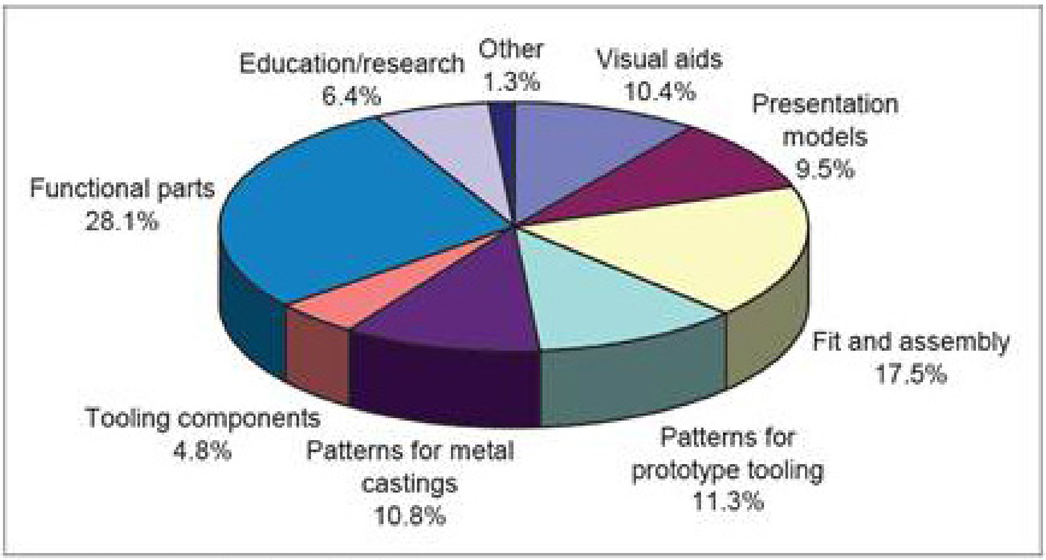
In addition, some AM benefits are particularly helpful in the fields of sculpture and archaeological preservation. Greater geometric freedom offers unique opportunities for creative artistic styling in 3D space, and both the digital model and the physical model are accessible for evaluation of expected effects. The manifestation by AM to make dreams and ideas come true can be more accurate and accessible compared with traditional methods, which opens a new door for artistic design. If an image contains the information of a hundred sentences, a physical model will present the information of a hundred pictures, which could greatly reduce design cycle and communication time to obtain the best results in the face of fierce competition.

As for archaeological preservation, the process of using AM technologies applies to both forward engineering (FE) and reverse engineering (RE). For archiving, RE provides a new approach to obtain entire sets of accurate 3D data that show measurements for any angles and positions automatically; monitor and record defects, movements and cracks accurately; create multi-media archives that not only include images of shape, colour, measurements and repairing marks, but also 3D dynamic presentations. For artefact repair, AM offers seamless defect repair using diverse materials; the strength of rapid production could reduce complicated skilled work and training time dramatically to improve efficiency; virtual manipulation of models reduces the risk of mistakes caused by manual techniques to avoid wasting expensive materials. For artefact reproduction, besides the advantages mentioned in the previous paragraphs, the 3D data could be used in many different ways, such as in animation/film for publications and virtual tours, exhibitions for sharing resources with the public and researchers, high quality replicas for teaching presentations, souvenir design for commercialisation, etc.

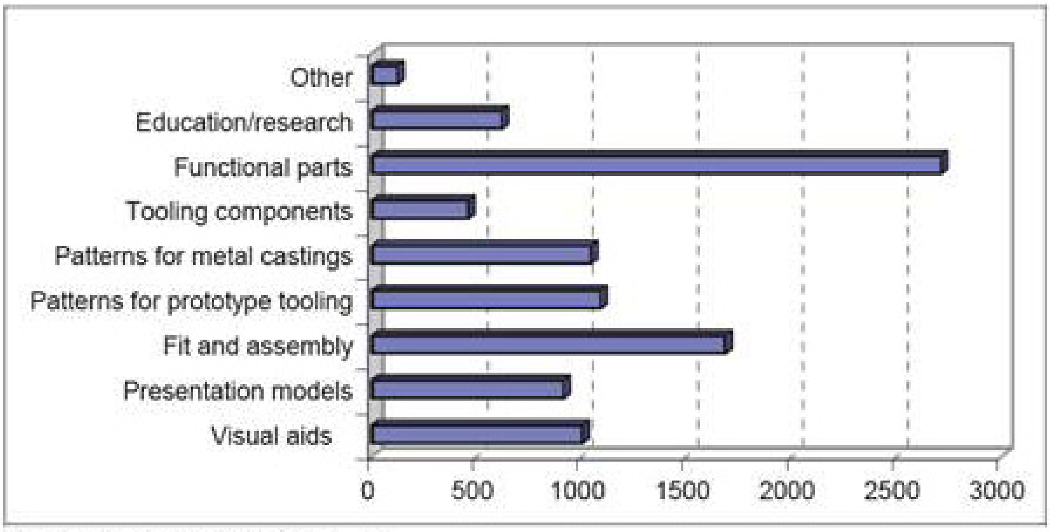
In later chapters of the thesis, the benefits of AM in sculpture and archaeological restoration fields are investigated further and demonstrated by case studies obtained through a literature review and through practical experiments.

2.5. Application areas for AM

AM technologies are powerful tools that can be used in almost all sections of product development and production, from visualisation of early concept models to production of high performance parts in end-use applications. Although it may not be applicable to all types of products, the development potential should not be overlooked and strategic process chains will be the deciding factor of successful applications in various fields. Figure 2-9 shows the proportion of relevant application fields and popularity of the applications, table 2-3 shows the application areas from an earlier report.



Source: Wohlers Associates, Inc.



Source: Wohlers Associates, Inc.

Figure 2-9 AM application areas - From Wohlers Report 2013, State of the Industry, Worldwide Progress Report

Popularity of Additive Manufacturing Applications - From Wohlers Report 2013, Worldwide Trends in Additive Manufacturing

Table 2-2 AM application areas - From Wohlers Report 2011, Additive Manufacturing and 3D Printing State of the Industry Annual Worldwide Progress Report

1. Custom manufacturing	8. Fit and functional testing
2. Communication	9. Prototyping
3. Engineering changes	10. Metal castings
4. Powerful ideas and proposals	11. Requests for quotes
5. Concept models	12. Tooling
6. Verifying CAD databases	13. Bio-manufacturing
7. Styling and ergonomics	14. Unlimited potential

2.5.1. Fine Art

Reviewing the advantages of AM and the needs of fine art, AM should be very useful in the fine art area, especially for 3D art such as sculpture and archaeological sculpture restoration. The highest value of AM is in its effective application rather than the technical capability itself. Specifically, the virtual working environment brings more possibilities and manifests innovative designs to reality; the entire process is under control by accurately reproducing copies from original digital data to avoid transformation (detailed shape changes) and limitations of scale; the strength of generating complex geometry including inner structures meets the need to produce complex shapes and inner support frames; the rapid method of creating physical models and the diversity of materials allow evaluating the results of imagination and presentation easily and efficiently.

There are some notable experiments and successful case studies that have been undertaken by engineers and artists. For instance, a digital stone sculpture was designed by computer, and the CAD data used for the carving of marble that optimally combined traditional and AM methods (B. Beasley, et al., 2009). The artistic style of furniture and jewellery built by AM used RE to borrow elements from nature for innovative design (L. Dean, et al., 2012). The idea of applying mathematic models into fine art sculpture was brought to reality by AM (B. Grossman, http://www.bathsheba.com)

However, there must be a reason why the application of AM in the fine art field has been limited up to now compared with the applications in other areas, even though it is theoretically needed and feasible. The barriers could be the traditional thinking model around the nature of art and the value attributed to hand-made artefacts. Communication is the key to remove this obstacle since AM does not necessarily change the nature of art or the feeling of being hand-made, but should be seen as another useful tool to assist the artistic design and manufacturing process. Communication between engineers and artists is also a difficulty because of their completely different thinking models. Therefore, the development of interdisciplinary knowledge is essential to build a bridge for communication and to close the gap between theory and practice.

2.5.2. Industrial product design

Functionality, ergonomics, and appearance are vital factors for product design and manufacture. AM can convert design concepts to 3D physical models rapidly, simulating required effects and facilitating functional testing, which provides direct and accurate data for product evaluation and decision making. Visual samples can be modified in a timely manner, and according to user needs, to aid project bids, and to help win valuable opportunities in a competitive market. Figures 2-10 to 2-14 show some examples of products created using these digital technologies.

Figure 2-10 Shoe heel designed and manufactured by AM (H. Lipson, 2011)

Figure 2-11 Multi-size model cars with fully coloured functional parts (http://www.zcorp.com/en/home.aspx)

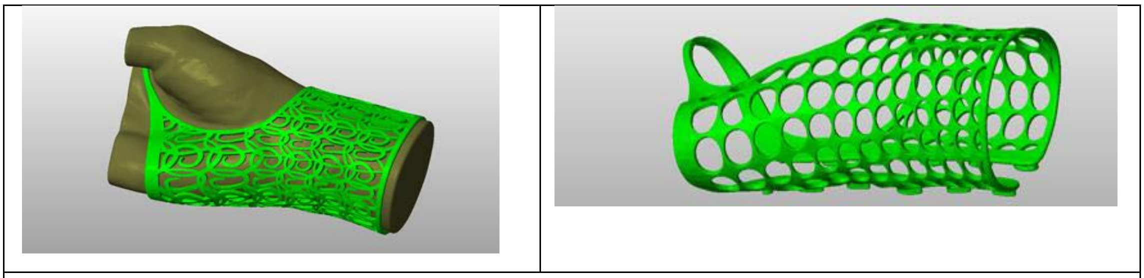


Figure 2-12 AM ergonomic wrist splints (AMJ, Paterson, RJ, Bibb, RI, Campbell, 2010)

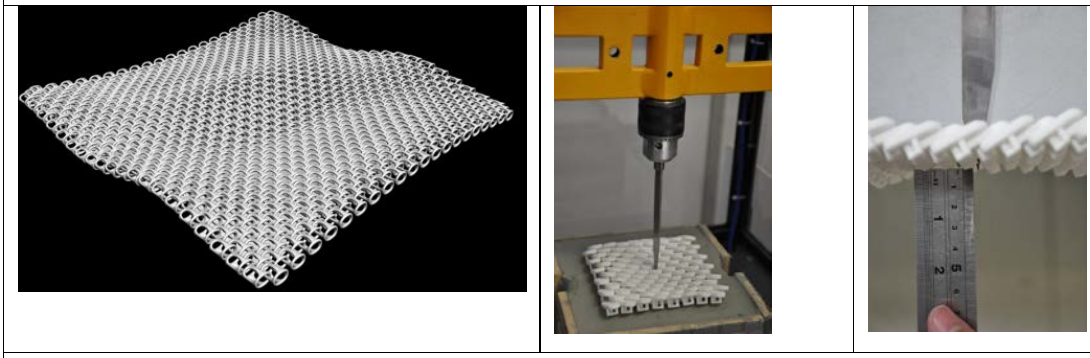


Figure 2-13 AM stab-resistant textiles (JJ, Crookston, AC, Long, GA, Bingham, RJM, Hague, 2008)

Figure 2-14 Digital prosthetics (customisation) (RJ, Bibb, D, Eggbeer, P, Evans, 2010)

2.5.3. Architectural design

Large scale AM machines can use robust and low cost sand-like materials to produce building structures or large sculptures (see Figure 2-15 and 2-16). All internal structures are modelled in a single build, and cost, time scale, and accuracy are not affected by complexity. For example, in the “Dynamic Building/Rotating Tower” in Dubai, where each layer can be moved around the axis of rotation, the individual layers were built in Italy and shipped to Dubai for assembling <http://www.dubai-architecture.info/GALL/DUB-DT.htm>. (see Figure 2-16)

Digital model | Large scale AM sand model | Final appearance

Figure 2-15 building structures or large sculptures

One Italian engineer Enrico Dini is still doing research on large scale AM technology (Monolite UK Ltd.) and plans to use this technology to solve many challenges that are not implemented currently, such as building an operational site on the moon. <www.D-Shape.com> (Figure 2-15)

Figure 2-16 Dynamic Building/Rotating Tower in Dubai

2.5.4. Animation creative production

Digital technologies greatly expand the manifestations of creative ideas, reduce production cycle, and diversify the transmission mode of geometry and materials.
Areas of AM technology application

2.5.4.1. Anime roles creation by AM

The traditional method of role design depends on hand drawing and manual modelling. Using digital technologies, human face and body data could be collected by 3D scanning, then, according to the motion laws of facial expressions and artistic exaggerated deformation, used to build a database to generate realistic role effects of different characteristics.

2.5.4.2. Dynamic manifestation by AM

Since motion capture technology can combine real-life motion with a virtual model by using sensor points stuck on key parts on the actor, the facial expressions and motion of a virtual role are consistent with that of the real actor. Or the virtual model can be controlled directly to show a special combination of reality and a virtual role.

2.5.4.3. Special effects makeup

The facial features of an actor can be captured by 3D scanning, and combined with a virtual role in the computer. Then, by importing the digital models into an AM machine to produce the required mask, braces, etc. special effects make-up can be made more realistic and follow the actor’s facial movement (see Figure 2-17).

2.5.4.4. Scene construction & virtual reality

Virtual scene construction and rapid production of physical models using AM to simplify the traditionally complicated procedure and to enable convenient modification whenever necessary (see Figure 2-18).

	
Figure 2-17 Silicon mask make-up	Figure 2-18 Digital scene construction

2.5.4.5. Downstream products

Merchandise products derived from popular movies and animations bring a golden opportunity for digital technologies. Using 3D scanning to collect data from actors and using RE software to manipulate the data could produce new products rapidly in various styles, size, and materials (see Figures 2-19 and 2-20). AM is not affected by the complexity of inner structure and shapes, and parts can be built in a ready-assembled mode.

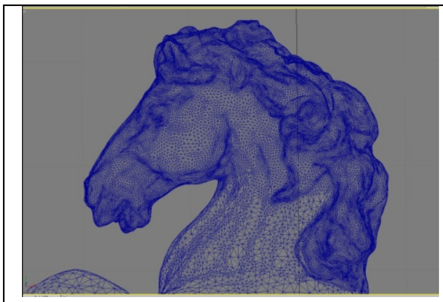
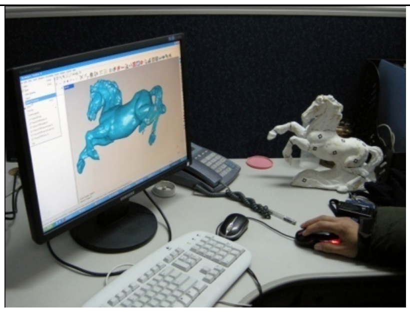
	
Figure 2-19 Bruce Lee doll	Figure 2-20 Mechanical animation toy (photos taken in the animation exhibition Hong Kong 2011)

2.5.5. Spatial design (space/environment design)

Urban landscape construction is developing rapidly and is presenting higher requirements in terms of scale, artistic standard, and speed. Hence, innovative thinking and breaking new technological ground is necessary to win contracts against fierce competition.

Areas of AM technology application:

- As the traditional method is the design of the original by the principle author and then enlarging it through a professional assistant team, this method requires many complicated processes and it is difficult to control the artistic effect of the final results. Much effort is wasted on coordination and modification. AM could greatly simplify this process, which would save cost and improve accuracy, allowing artists to pay more attention to their creative expression.
- In order to meet the tender requirements of urban sculpture planning, all the renderings, engineering drawings, animation demonstrations, sand models and detailed physical models could be produced by digital technologies (see Figures 2-21). These enable fast modification for appearance, scale, and material to complete the task with low cost and high efficiency, not only showing the original effects accurately, but also conducting some work that is difficult to implement manually.

	
3D digital model	Animation demonstration

	
Shrinking & enlarging virtually	Layered manufacturing
	
Small original & enlarged model	AM sand model of human sculpture

Figure 2-21 Urban sculpture digital manufacturing process

- Optimally combining RE and FE brings broader prospects to creativity. Taking portrait sculpture as an example, using digital technology to manipulate the scanning data by artistic processing can make the sculpture more accurately, conveniently and universally for commemorative activities and mass customisation. This always has high demands and high cost when using conventional methods.
- The 3D scanning data could have many uses, such as generating engineering drawings and digital models, which could be manipulated by RE for combination, transformation, converting circular sculpture to relief sculpture, 2D images to stereoscopic effect, etc. AM can enable artistic performance to be richer and freer as they provide new modes for working.

2.5.6. Archaeological preservation

According to the benefits of AM, its applications in archaeological preservation area have a strong developing potential, such as for artefact restoration/replication, garden landscaping, public art, product design, animation, etc. (see examples in Figure 2-22) The potential benefits including reduction of cost and time scale, more importantly, improving accuracy of reproduction and save labour resource from tedious work.

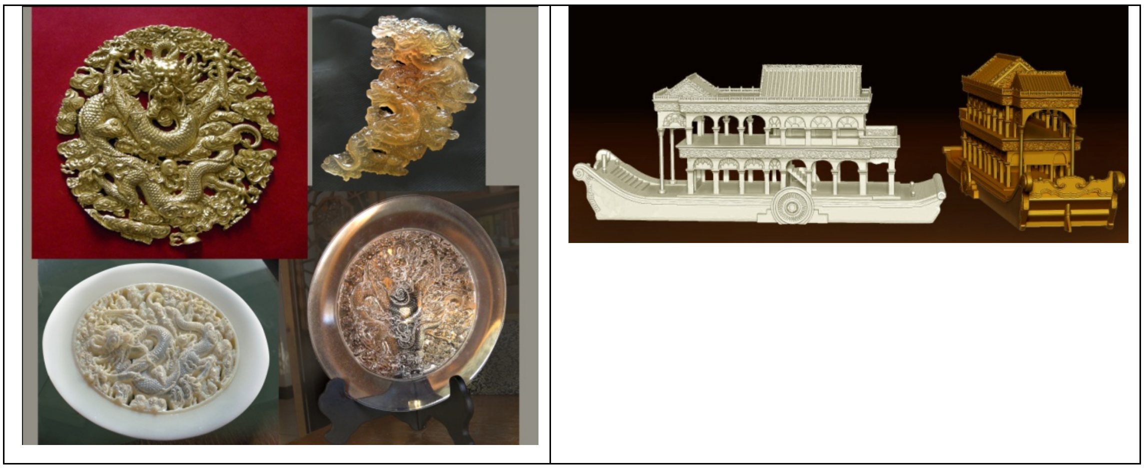


Figure 2-22 AM souvenir design with Chinese heritage elements

2.6. Creating data for AM

2.6.1. Generic AM process

Most existing AM systems require a number of generic steps to produce physical models, and the basic process is summarised below (J. Munguia et al., 2008), (I. Gibson et al., 2010).

- Create a 3D CAD model of the part or product – Most CAD solid modelling software / Forward Engineering software (FE) or Reverse Engineering (RE) equipment can be used to create the 3D CAD data.
- Convert the 3D CAD file to the STL format. Almost every AM machine accepts the STL file format.
- Part orientation and placement for building – Every machine has a specific work volume and the ability for re-orientation in the X, Y, and Z axes which could affect the part's final properties.
- Support structure generation (not needed for some systems) – Generation of support structure to support overhanging part features. The support structures are normally constructed with a different material that can be easily removed after the build process.

- Part construction – AM is generally a fully automated process however the machine needs to be monitored from time to time to detect any shortage of material or power failure.
- Post processing (not needed for some systems) – Part removal, cleaning and post-processing. This often involves manually removing the part from the machine, cleaning off the support structure and removing the excess material, which requires much time and skill.
- Some systems produce a “green part” which requires removal of binder followed by sintering to obtain the final state.
- Finishing such as sanding or painting if needed – The final step is the surface treatment of the part to give an acceptable surface texture and finish.

2.6.2. Computer Aided Design (CAD) / Forward Engineering (FE)

Computer Aided Design is defined as the use of computer hardware and software to assist users in the creation of 2D and 3D design data (S. J. Schoonmaker, 2003), which was developed from the advancement in electronics, software and computing technology. CAD traditionally refers to computer tools for visualisation, description, editing and testing manufactured artefacts, which are significant steps in all manufacturing and production processes. CAD Applications have been developed across a wide range from large scale building modelling to small scale mechanical component modelling with complex geometry, and also for free style artistic modelling. CAD systems allow designers to design, view, edit, save and share data effectively, and reduce product development time and cost. Forward Engineering refers to the process whereby 3D digital models are created “from scratch” using CAD software, and it is normally the first step as well as the most time consuming part of the entire AM process (C. K., Chua and K. F., Leong, 1997).

CAD systems provide a reliable way for specification and visualisation of complex 3D shapes, which is difficult to perform using manual techniques. The main benefit from powerful 3D modelling CAD systems is that they can build the general shape of components, render the material effects, assemble complex structured components and transfer between 3D modelling and 2D drawings. However, the data created by CAD systems is much more comprehensive than just 2D drawings and 3D shapes, as they also offer information such as materials, textures, processes, dimensions, and tolerances. CAD works in cooperation with several other applications of computer integration within engineering, manufacturing and simulation disciplines. These include Computer Aided Engineering (CAE) that assists with most stages of engineering design analysis work, and Computer Aided

Manufacturing (CAM) that utilises computers to control and monitor tools and machinery in manufacturing (S. J. Schoonmaker, 2003).

Thanks to research into 3D curves, splines, NURBs (Non-Uniform Rational B-Splines) surfaces, rendering, GUI (Graphical User Interface) and the addition of increased computational power, CAD has been transformed into an essential tool for today's designers and engineers. Development during 1990s enabled the transition from wireframe into surface and solid models. Another major step was to enable CAD systems to keep track of design dependencies so that when changes to any value are made, all other values that depend on it are automatically changed accordingly. This is commonly known as parametric modelling and is widely used throughout the range of commercial CAD systems currently available. Nowadays, the capability of CAD systems allows the combination of freeform surface modelling and solid modelling operations that can create almost any complex geometry. This, combined with high quality photo realistic rendered images, has finally made it feasible to apply these engineering technologies within the field of art.

With more elements and new capabilities being integrated into CAD systems, software packages with different strengths are suitable for different uses. For example NX, CATIA, and Creo have emerged from a fiercely competitive market to offer numerous engineering analysis and simulations whilst Rhinoceros, 3D Max, and MAYA have become more popular in the styling design and animation fields. However, there are specific constraints when using conventional CAD systems for AM (R. Hague, I. Campbell, P. Dickens, 2003). These include translating highly complex design shapes into STL data, which is a time consuming and sometimes labour intensive process. Also, conventional CAD systems are not able to represent repeated complex patterns and multi-material models very efficiently. In contrast, successful examples for both complex surface texture patterns and multi-material models can be easily found in current AM applications. When using AM the slowest part of the total manufacturing process has become the creation of suitable 3D data, i.e. the CAD stage of the process. This has replaced the most time consuming task of conventional manufacturing, which is the production of tools (tools are eliminated in the AM process and hence little preparation time is required for manufacture).

2.6.3. Reverse Engineering (RE)

The basic understanding of Reverse Engineering is (as indicated by its name) to reverse the normal design process by starting from an object that already exists and then duplicating the object by taking it apart to see how it works and to enhance its performance (E. Bagci, 2009).

Specifically, for hardware-based reverse engineering, an object may be taken apart, either for re-assembly or replication, to figure out its structure, functions, and performance. The aim can be to produce a similar object to compete against the original in the market. However, hardware-based RE may cost too much because of the great deal of expertise needed and also to avoid intellectual property violation. Using RE to produce 3D data models is the most useful and important aspect of RE in this research. RE is a helpful tool with which to generate CAD models for parts when engineering drawings are not available. Thus, 3D images or CAD models in the STL file format could be created by RE in order to reproduce the parts.

The 3D information of parts is normally collected by a coordinate measuring machine (CMM) or different types of 3D scanners, such as laser scanners, structure light optical grating scanners (see Figure 2-23) and infrared scanners. The process of capturing digital information concerning the shape of an object begins with measurement of the distance between the scanner and the object to define numerous points in 3D space. The data generated with this process is termed a “point cloud” and represents an unconnected set of points on the surfaces of the object (I. Gibson, et al., 2010). The points are then connected and manipulated using RE software, which has basic functions like hole filling and smoothing, etc. As with CAD software, different RE software has different strengths, such as Geomagic being used for industrial product design, Magics for preparation of RP, Netfabb for fixing STL models, Z-Brush and 3D Coat for the manipulation of free style surfaces, and Freeform with a hardware sensor device as a haptic modelling tool for artistic styling just like playing with a block of clay in virtual space (see Figure 2-24). Generally, increasing the overall accuracy and improving the productivity of the manufacturing process are the basic advantages of RE (E. Bagci, 2009).


Figure 2-23 3D scanning process


Figure 2-24 Haptic modelling with Freeform

2.7. AM system selection

AM systems have different strengths and constraints, and the parts they produce also have different characteristics and, so the basic principles for AM system selection need to be understood. There are a number of AM system selection tools that have been developed since 1993. Burton produced a paper-based strategy for system selection which considered five top-level reasons for using AM (production volume, part or product form, product function, product construction and logistics issues) which could be used to confirm that a part is suitable for AM (M. J. Burton, 2005). The criteria for selection of a particular AM machine typically includes build volume, dimensional accuracy, range of materials, range of layer thickness, build speed, and other machine related parameters such as well as price and surface finish (S. H. Masood and A. Soo, 2002). However, the selection tools and strategies have been developed so far are mostly suitable for industrial or engineering design purposes. Selection of AM for reproducing artistic and archaeological parts is affected especially by criteria such as scale factor, complexity of geometry, material texture, resolution of details, storage environment and cost compared to manual techniques. With the rapid development of AM technologies and changes in the commercial market, it is difficult for any selection assistant system to keep up to date and provide enough information on cost, material properties, and capabilities. Hence, specific projects need to adopt appropriate solutions by optimising the process chain according to the most up-to-date information on capabilities. This needs professional knowledge in specific fields that can optimally combine AM and conventional methods.

2.8. Optimising the use of AM

Nowadays, driven on a wave of “innovation”, many organisations have set up their own product design and manufacturing labs, most of them having access to Traditional Prototyping, Rapid Prototyping and Virtual Prototyping (virtual reality and visualization). However, although many new users have theoretical knowledge of AM technology, they have little knowledge or expertise for using AM in practice. To address this issue, a design methodology and roadmap has been developed by Bastiaens (2010), who suggested the roadmap should plug in to a traditional four stage design methodology, and for every stage, prototyping techniques should be selected based on six validation criteria: Product Personality, Use, Function, Materials, Shape and Manufacturing Process. The roadmap claims to raise awareness, increase returns on investment, shorten time to market, and also balances out Traditional, Rapid and Virtual techniques, resulting in an efficient use of prototyping during the design process.

2.9. Summary of Chapter

An introduction of AM technologies has been given in this chapter, which included definition, history, applications, creating AM data and system selection issues. AM has developed rapidly and has matured in the last decade into a significant engineering tool, particularly in the product development process. One of the main advantages of AM is that it is capable of manufacturing without the need for tooling, and the manufacture of end use AM products has become a reality. Other improvements in AM, such as the diversity of materials, freedom of geometry and greater resolution of the processes, has led to innovative applications, not only in the industrial design and engineering fields, but also in some newer areas such as artistic modelling and archaeological restoration.

Different methods to generate CAD models for AM processes are available including forward engineering and reverse engineering. The guidelines and requirements for AM system selection can vary, depending on the applications area. The routes to further commercial success for AM will be in developing new AM systems for specific market needs, finding new market opportunities for adopting AM, and optimising overall process chains for the most effective use of AM.

In conclusion, AM has been identified as a new and developing area of technology that can be applied in most product design and development processes. However, the application of AM to fine art sculpture and archaeological restoration is still at an early stage, although the needs of the market and potential of the technologies would indicate a bright future and broad prospects.

3. Chapter Three: Fine Art Sculpture and Archaeological Restoration

3.1. Review of Fine Art Sculpture

Artistic sculpture is a key area in this research and communication between engineers and artists has been recognised as one of the greatest barriers to adopting AM in the fine art field (N, Hopkinson, 2010). Therefore, an understanding of definitions, conventional creation methods and the general requirements and constraints of artistic sculpture in both terms of aesthetics and manufacturing is significant and essential. Hence, a review of artistic sculpture, taken from diverse resources, is presented in this section.

The history of sculpture is almost as long as that of humans. In prehistory, the first step for humans to become different than animals is the creation of tools, and the second step of human development is the creation of images and artefacts (C. Renfrew, 2012)

Primitive men fashioned stone into tools for everyday activities, and when they became aware that their tools should have certain appearances, they already had the ability for artistic creation, which developed into the basic form of sculpture (A.S. Murray, 2012)

So, what is sculpture? Generally, it means using natural or artificial materials to create 3D objects, which are considered as art works. Sculpture and painting both belong to the Formative/Fine Arts field. However, to differentiate it from 2D painting, sculpture uses solid volumes to create 3D shapes, in order to create senses of existence, texture and weight, and also to enhance human experience from the perspective of sight and tactility. This forms the unique essence of sculpture as well as its point of differences from other formative arts.

3.1.1. Definitions of Sculpture

In terms of a formal definition, the **Collins English Dictionary** defines sculpture as both a noun and verb as follows:

sculpture [skʌlptʃə] ***n.***

1. (Fine Arts & Visual Arts / Art Terms) the art of making figures or designs in relief or the round by carving wood, moulding plaster, etc., or casting metals, etc.
2. (Fine Arts & Visual Arts / Art Terms) works or a work made in this way
3. ridges or indentations as on a shell, formed by natural processes
4. (Earth Sciences / Physical Geography) the gradual formation of the landscape by erosion

Vb. (mainly tr.)
1. (Fine Arts & Visual Arts / Art Terms) *(also intr.)* to carve, cast, or fashion (stone, bronze, etc.) three dimensionally
2. (Fine Arts & Visual Arts / Art Terms) to portray (a person, etc.) by means of sculpture
3. (Fine Arts & Visual Arts / Art Terms) to form in the manner of sculpture, especially to shape (landscape) by erosion
4. (Fine Arts & Visual Arts / Art Terms) to decorate with sculpture Also (for senses 5-8) sculpt
[from Latin *sculptūra* a carving; see SCULPT]

However, a more useful definition for this research has been taken from a Chinese expert's explanation:
"**Sculpture**" is represented by two individual words which are "carve" and "modelling". So, literally it means making 3D solid items by two traditional ways, one is removing materials, and another is adding materials, both manually and with assistant tools. (S. Wang, 2010, Interview).
This definition is preferred because the chosen expert is the director from Sculpture Department of Central Academy of Fine Arts, which is the top art university in China, his reputation is well known in fine art sculpture field. Also, a few other artists agreed with this definition when they were asked without knowing from where this answer came.

3.1.2. The Language of Sculpture

Following on from the definition of sculpture, it is necessary to explore some of the basic art language of sculpture, which comprises terms such as appearance/structure/form, space, material/texture, and artistic treatment (C. Carter, 2010)

1) Appearance/structure/form:
The terms shape and volume make up the most basic language of sculpture. Sculptors use points, curves, surfaces, solids, and texture as resources to produce varies appearances, either for realistic or abstract models. A statue should transfer senses of image, volume, weight, texture, etc.

2) Space: The "spacial language" of sculpture has two meanings.
The first one is the spacial property of the sculpture itself, which means a kind of relationship called "virtualness and reality". Specifically, the relationship is between the space that taken by statue's shape/volume, and its surroundings.
The second meaning is an expansion of the relationship between the sculpture and environmental space, and can be described such as enclosure, segmentation, equilibrium, coordination, etc.
Space is a key element of sculptural expression, since a sculpture is an entity in space, and space is a component of sculpture.

3) Material/Texture: The carrier of sculpture.
The aesthetic of texture is an inseparable contributor to the overall aesthetics of sculpture arts, and a significant characteristic of sculpture is the perfect combination of modelling and texture. Every material has different properties, "personality" and can transfers different feelings. Selecting precisely, controlling and translating material language tests the knowledge and quality of artists.
Commonly used materials include clay, plaster, china, wax, wood, stone, iron, copper/bronze, plastic, and resin. With development of both the creative language and modern technology, the use of new materials as media for sculpture is continuously advancing. Alloys, fabrics, light, virtual reality, nature, humanistic environments, etc. now all appear in the field of sculpture.

4) Artistic treatment
So-called “artistic treatment” is a procedure which means raw materials need be technically processed and transformed by artists to become art works. Every material has its unique way to be processed, and a single material processed in different ways could create different effects. First of all, the artist needs to comprehend material properties, master corresponding operations and procedures for manufacture. Then, they must try their best to enable products to have a perfect combination of concept, form and texture.
Generally, there are 5 kinds of artistic treatments:

4-1) Adding – Modelling from inside to outside by adding soft materials
4-2) Removing – Removing material from the outside by carving (for stone) or graving (for wood)
4-3) Transform material shape – No adding/removing is involved, so this basically means forming the shape.
4-4) Knitting, etc. – Methods for soft sculpture, include knitting, binding, twisting, convolution/intertwining, etc.
4-5) Composite – Using different kinds of materials to produce a certain a shape that is composed or connected; also refers to the mixing of natural materials and artificial materials.

Artistic treatment is the last process of sculpture creation, and without scientifically directed artistic treatment, no matter how good is the creative concept is, the desired effect cannot be accomplished. Therefore, a unique creative concept coupled with "high-tech" artistic treatment can produce special effects that are beyond the normal expectation of the public.

3.1.3. Classifications of Sculpture

Different types of sculpture can be classified according to their form and their style. Typical form types are alto-relievo/full relief, relief sculpture (high relief; low relief/bas-relief) and hollow-carved sculpture / openwork carving, which are all explained below.

1) Alto-relievo/Full relief

3D solid, independent sculptures mounted or hung in space, so that they can be viewed from any angle.

2) Relief sculpture

A form that lies between painting and full relief sculpture, being compressed towards a plane. It can achieve its objectives by using both sculpturing skills such as volume, space, etc. and painting skills such as perspective and visual illusions. When relief sculptures are based on "bottom boards", which is the flat board or wall used as a background, the thickness of a body is compressed from the real shape. According to different types of compression, it could be classified into three categories which are high, low, and thin relief. Example applications can be seen in some existing works (see Figure 3-1).

Sacrifice of Isaac, by Filippo Brunelleschi, 1401-1402.
Bronze relief, h: 45 cm, l: 38 cm.
Museo Nazionale del Bargello, Florence.

Battle between the Greeks and the Persians, north frieze, Temple of Athena Nike, Acropolis, Athens, c. 425-421 B.C.
Marble. h: 45 cm. British Museum. London.

Figure 3-1 Examples of high relief, low relief and thin relief sculptures (E. Mach, 2012)

3) Hollow carved sculpture/Openwork carving

This is a kind of one sided or two sided relief sculpture without a bottom board. The reason why it can be seen as an independent category of sculpture is because it has several advantages and a unique expressive force, which other types of sculptures find hard to reach. It has the characteristic of compression and yet meets the requirement of being appreciated from any angles; it can both divide and connect neighbouring spaces.

Sculpture Styles

Generally, as one form of Fine Arts, sculpture is undertaken for the aesthetic pleasure of the viewer and can be separated into the following main styles (H. Liu, 2009)

- Realistic – Pursuing the same appearance as the reference or original appearance.
- Abstract – Take the most obvious characteristics of the reference and simplify them.
- Modern – Import mathematics, physics and applications of new materials / resources to create unusual effects.
- Pro-realistic – Using solid form to express the imagination of virtual objects.
- Expressive – To express a kind of emotion or to convey particular situations.

3.1.4. Review of relevant sculptures and conventional manufacturing methods

Well-known sculptures are introduced in this section as examples made from different materials and using different methods with different styles. These examples are all chosen from horse sculptures to show the same kind of animal sculptured in different styles. They are also used to illustrate various techniques and materials.

3.1.4.1. “Angel of the South” – British sculpture

Figure 3-2 Angel of the South sculpture by M. Wallinger

The winning design for a £2m public art commission “Angel of the South” in north Kent is a giant white horse sculpture (Mark Wallinger, 2009). The design is a horse that stands on all four hooves at 33 times life-size, which is more than twice as tall as the 20m high Angel of the North sculpture in Gateshead.

The giant horse has been erected at Springhead Park area to dominate the landscape and will be seen by up to 60 million people per year. There was some very tough competition and also manufacturing difficulties make it be an exciting project, which was expected to last at least 12 months according to the planning process. The function of such a large sculpture should be to act as a symbol for the new Ebbsfleet Valley development and Ebbsfleet International railway station. This is an example of the realistic style and has been made by using conventional manufacturing methods.

3.1.4.2. Horse and Rider – British sculpture

Figure 3-3 Horse and Rider sculpture by E. Frink

Horse and Rider is an important bronze sculpture in Frink's career that was built in France (Elisabeth Frink, 1990). This sculpture reflects the sense of well-being that Frink experienced particularly when working with horses in the country. The static shape reflects the affection for horses from Frink's childhood, such as her father being a brilliant horseman, a good polo player and an amateur jockey which may have added to the passion for horses throughout her life. Moreover, the Horse and Rider subject did not only develop modelling skills from an interesting theme in the sculptor's life, but also provided the possibility of combining the most desirable of masculine qualities with those of the most beautiful of man's fellow creatures; free sensuality , intelligence, loyalty, affection, speed, resilience, beauty and courage. The shared and complementary qualities of man and beast also enhance the empathy that resonates with audience (Lucie-Smith, 1994). It is a prime example of the combination of realistic and modern style.

3.1.4.3. Horses – American sculpture

Horses have been sculptured in bronze, steel, and mixed media by an internationally acclaimed sculptor and displayed at the Norton Museum of Art. Horse sculptures have been the single, sustained focus of Butterfields's work for over 30 years. Her early sculptures were horses standing or resting on the ground, in fragile materials of mud, sticks, straw, and scrap metal. Medium and full-size horses in driftwood branches and bronze casting have been produced since the mid-1908s. The complicated manufacturing process can involve twenty people taking two to three months for a large horse sculpture (D. Butterfield, 2005). They are an example of the abstract style.

Figure 3-4 Wooden and metallic horse sculptures by D. Butterfield

In terms of manufacturing, the original was carved by wood and the basic posture of the particular horse was assembled by fastening logs, branches, sticks, planks and boards onto an armature. Photographs from all sides and angles of the piece, especially the area where individual pieces are joined, were needed for reconstruction of the various elements after casting. Ceramic-shell moulding material, which is capable of picking up exacting detail, was used to cover the natural wood for subsequent bronze investment casting, where the wood was completely burned away by firing. After molten bronze was poured into the mould and solidified, the ceramic shells were broken away to obtain a metal copy of the original wooden structure. A metal shop applied a series of finishing to the entire bronze sculpture, such as tooling the welds and creating blemishes to texture the entire surface like wood, sandblasting to prepare it for patina, spraying and brushing a combination of white pigment and chemicals onto the heated bronze and coating with heated wax. The final sculpture became durable and still had a wood effect, which looked so realistic that viewers even needed to touch the surface to distinguish the material.

3.1.4.4. Equestrian – Italian Sculpture

A series of stylised equestrian statues have been developed since 1936 by an Italian sculptor named Marini, who began with a horse and rider theme as poised and formal figures. The forms became more abstract and the proportions were changed in 1940. Then, after the Second World War, horses were posed standing in tense positions and the riders with outstretched arms.
Marini's artworks combine tradition and modernity, and the complicated content is set by the meeting of life with human, spiritual and aesthetic nature. (S. Hunter, M. Marini, D. Finn, 1993) They are examples of the realistic human body and animal style.

Figure 3-5 Horse and human sculptures by M. Marini

Another meaningful finding from research into the equestrian theme was the lighting issues especially for relief sculptures. For instance, a low-relief sculpture displayed according to the lighting principle in Marini's museum was conceived from a medieval equestrian statue of a knight in a German cathedral, in which the crowned-knight appeared to audience to be lonely and far away, as if in a fairy tale. Natural light was considered as being necessary for interpreting some sculptures to allow each piece to showing the expected effect from different possible points of view.

3.2. Constraints/limitations/difficulties in the current manufacturing process for large scale sculptures

The main difficulty of sculpture is the arduous manufacturing process. Although larger and heavy sculptures can express momentum and power, the larger their volume is, the more difficulty it causes in terms of materials and manufacturing.

3.2.1. Problems associated with modelling

Firstly, during the modelling process, it requires the calculation of structural weight bearing, building large metal or wooden frames and scaffolds and then forming all the clay onto these frames. Also, enough space is essential for observation and evaluation. Furthermore, designers have to consider the foundations of interaction between subjective feelings and objects, properties of materials and the effects from many other elements, such as environment, ergonomics, lighting, etc. Such complicated procedures require an understanding of many interdisciplinary subjects.

3.2.2. Problems associated with manufacturing processes

Secondly, the key point of sculpture creation is the ability of observation and modelling, but it needs experience of a manufacturing process to turn the original ideas and forms into the final presentation. Thus, the creation process has constraints or limitations due to manufacturing, such as changing mould materials and types or the need for producing in a diverse range of materials. Specifically, taking a few cases as examples, marble sculptures should be full and thick, especially avoiding sharp corners or thin walls; wooden sculptures should follow the timber grain; sheet metal forming should consider the ductility, e.g. bronze is better than steel, and should avoid too many concave and convex surfaces, which increase manufacturing cost as a result of a greater amount of metal pieces.

3.2.3. Existing solutions, on-going research and new ideas

So far, there has not been any satisfactory solution to optimising the sculpting process or improving the communication between artistic designers and manufacturers. Some artists have tried to use CNC or carving machines as assistants, but their functions are limited and bring many other troubles, e.g. the limitation of materials, scales, software skills and data formats. Also, the cost of adopting machine work is not really any lower than traditional manual methods. Hence, in terms of both efficiency and effectiveness, technologies have not been widely accepted by the sculpture industry (C. Kuhn, 2009). In response to this, research on optimising process chains and experiments for combining traditional methods and innovative technologies are introduced in later chapters. A case study was undertaken to review an example of introducing digital technologies for an abstract style sculpture creation.

Case study based on literature review- Design and Implementation of a large, bronze, abstract style sculpture

This case study presents an innovative process using digital technologies for creating a large scale abstract style bronze sculpture, as well as the requirements, difficulties and solutions, which provided evidence and inspirations for the research of enlarging sculpture by AM methods. (B. Collins, S. Reinmuth, C. Sequin, 2007)

1) Background

This case study describes the computer-aided re-design process that started from the original *Pax Mundi (World Peace)* wood sculpture created by Brent Collins, as well as the fabrication and installation of the final bronze sculpture. The final sculpture is a ten foot tall and established in the courtyard of the H&B Block headquarters in Kansas City, US.

2) Design and Forming of an original

Firstly, many concepts of abstract style sculptures were still sketched and modelled by traditional means to clearly present the author's ideas. According to the author's original concept, it was modelled in 3D software as a generalised sweep along a guide curve embedded in the surface of a sphere. In addition, some of the promising looking designs were realised as maquettes on AM machines such as the Fused Deposition Modelling (FDM) machine from Stratasys. The overall look, material, scale and the way to divide it were discussed by the principal sculptor and the engineer/computer scientist Carlo H Sequin. Once the size was decided as about 750mm in diameter, a virtual model was scaled to that desired size and blueprints were then generated to define the detailed geometry at the proper slicing intervals. Based on the digital model, the convoluted shapes were then cut out by hand from boards and assembled together, being properly registered to one another. The carving process lasted about two months until the stair-casing produced by the boundaries of the cut-out boards was removed. Then, the surface was smoothed to perfection.

3) Software

A generative program – Sculpture Generator - was created for free style surfaces modelling, as it was less clear how the sweep curve itself should be parameterised. The development of this modelling system was a complicated process, and like other 3D systems, it needs to be operated by engineers/computer scientists. At this stage, the result of the wood original clearly demonstrated that this collaboration between an artist and a computer scientist could be successful and produce sculptures that neither of them alone could have created (Figure 3-6).

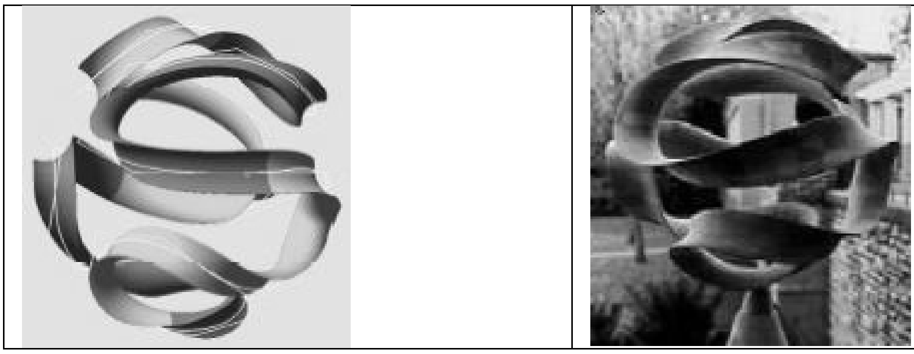


Figure 3-6 Digital model with divided segments; Wood original

4) Scaling up/Enlarging

The challenges were brought by the mission to scale up Pax Mundi to a bronze sculpture of about 1.8m in diameter. As it was not possible to cast such a large sculpture as a single piece, it was decomposed into four pieces of the master shape, each in the form of giant 3D S-curve. Although this caused another difficulty which was re-locating the segments and welding them together in a perfectly straight continuous manner. Alignment tabs were added at the joints to allow clamping together of the individual pieces in perfect alignment during the assembly process. One of the junctions had an extra large tab which is kept as an integral part of the assembly and became the support of the sculpture on its pedestal.

However, the S-shapes master patterns were still too big for any AM machine based on layered manufacturing to make in one piece. Therefore, CNC milling machine was adopted at economical rates to process hard, dense foam plastic, but the limited clearance of the machine could also not handle the bulky parts in one piece. As a result, two much flatter U-shape sub-master patterns were obtained by cutting the S-shape at the inflection point, and extra alignment tabs were added to accommodate the extra junctions for final assembly.

The machined master patterns were used to make negative moulds in plastic and silicone, which in turn were used to cast multiple positive copies in wax. Those wax replicas of the master shape are then sacrificed in an ordinary investment casting process, which created the four bronze copies needed to assemble the entire sculpture. Since it was a relatively expensive and time consuming part of the process, reducing the number of master patterns and moulds that to be generated was a significant economic strategy.

5) Assembly and Shape Adjustment

The assembly process followed where twenty individual pieces were cleaned and freed of the extraneous spurs and risers, based on a bottom-up manner, and progressing in a symmetrical way to guarantee perfect balance of the overall sculpture (Figure 3-7). Also, to compensate the transformation under its own weight after all pieces were welded together, several slits were cut and then refilled with bronze welds to lock the elongated state of the sphere when the sculpture was hung upside-down before being put into its normal position.

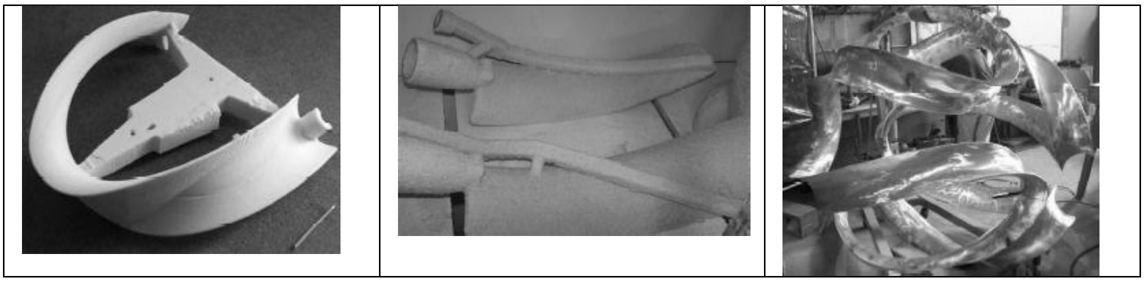


Figure 3-7 Plastic foam segment; Wax pattern with ceramic shell; Bronze model

6) Finishing

All the welded junctions and adjustment slits were ground down to seamlessly blend into the flow of the ribbon after the overall shape had been formed. A tan-coloured patina was applied with a judicious combination of heat and chemicals for the polished surfaces, and protected from further oxidation with a thin coating of wax. This enabled the colour to be refreshed easily and maintained for a very long time by rubbing over the whole surface of the sculpture with a block of wax on a hot day every few years.

3.3. Archaeological restoration

3.3.1. Introduction

Archaeological restoration basically includes archiving, renovation, and replication of 2D paintings and 3D objects ranging from small artefacts like jewellery to large scale architecture. The need for research in this area has changed with the development of technologies. For example, the restoration process traditionally requires recording by photography, analysing the changes and defects, obtaining measurements, repairing defects and reproducing missing parts, all done manually. Recently, however, more and more museums have started to build digital models by using both forward engineering (FE) and reverse engineering (RE) technologies for archiving as well as for virtual tours, animation, website images, and publications (D. Casado-Neira, F.B. Rey, 2012) (J.D. Richards, 2010) (W.P. Page, 2011)

Due to the complex geometry of 3D historical heritages and the diversity of materials used, the renovation and replication processes for archaeological artefacts shares many things in common with the reproduction of sculptures. The design process is the key difference. Whereas a sculptor has a great deal of design freedom, there are strict limitations on styles and material effects for restoration that are based on archaeological research. Many restoration works require reproducing a missing part of a sculpture or relief sculpture, but it is really about solution design rather than creatively artistic design. As to the manufacturing process, both traditional and digital restorations are always closely related to fine art sculpture.

Computers have started to change the world of archaeology just like digital technologies have changed many aspects in life. However, digital archaeology is not only about graphics, databases and the internet, but also about the entire archaeological process (Isakson, L., 2008). Almost every stage of the archaeological process can adopt digital technologies, which have become an integral part of archaeology for surveying, researching, report writing, interpretation, illustration, dissemination, renovation, conservation, etc. Applying digital technologies into the archaeological restoration field requires knowledge from many other disciplines to be applied and integrated to develop new knowledge. Likewise, the application of AM needs to be about more than just making some of the restoration activities easier and more efficient, it should enable entirely new methods to be explored. The investigation of new process chains can make what has been discovered in one area accessible for application to new uses, and also enables the rethinking of possibilities.

3.3.2. Cultural Heritage

Although, since the nineteenth century, a series of international conventions and agreements have changed the conceptualisation and definition of world cultural heritage as well as the principles of preservation, the most influential agreement should be taken to be the World Heritage Convention (WHC), which is adopted by the United Nations Educational, Scientific, and Cultural Organisation (UNESCO). In this agreement, the following definition is given: "Cultural heritage designates a monument, group of buildings or site of historical, aesthetic, archaeological, scientific, ethnological or anthropological value" (M. Vecco, 2010). UNESCO’s original interpretation has been expanded by seeking subsequent conventions to include more heritages such as underwater and intangible heritage which are not physical or visible objects but reflect history and culture, and world heritage sites have been protected by taking measures against various threats such as globalisation, which sometimes blurs the origins of heritages that actually belong to and brings higher chance for damages during shipping and road shows. The process of world cultural heritage identification and preservation has been the subject of comprehensive attention in the WHC with a view to formalising the new rules and preservation.

The term "historical relic" implies human cultural heritage that has historical, artistic and scientific value. Historical relics can be considered to be valuable assets and a non-renewable cultural resource for a country. Physical remains of human activity, no matter if they were originally spiritual or substantial, advanced or backward, serving in a revolution or anti-war, they reveal certain historical phenomenon from different aspects and areas. They reflect the thoughts and moral history as well as scientific and cultural levels of the earlier inhabitants, and their value and effect are never ending. People can give different comments for the same part of history, but the value of relics is that their reflection of history is objective and not affected by these the comments. Hence, it is crucial that all, historical relics should be properly protected, studied and utilised.

Several types of cultural heritage are defined in UNESCO’s Convention concerning the Protection of the World's Cultural and Natural Heritage (S.M. Titchen, 1995).
1. Monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;
2. Groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science;
3. Sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view.

Several countries have taken these UN definitions and used them to help draft their own national legislation. For example, several types of cultural relics are defined by law in the People's Republic of China (Cultural Relics Protection Law of the People's Republic of China, 2007 Amendment, chapter 1 article 2).
1. Sites of ancient culture, ancient tombs, ancient architectural structures, cave temples, stone carvings and murals that are of historical, artistic or scientific value;
2. Important modern and contemporary historic sites, material objects and typical buildings that are related to major historical events, revolutionary movements or famous personalities and that are highly memorable or that are of great significance for education or for the preservation of historical data;
3. Valuable works of art and handicraft articles dating from various historical periods;
4. Important documents dating from various historical periods, and manuscripts, books and materials, etc. that are of historical, artistic or scientific value;
5. Typical material objects reflecting the social system, social production or the life of various nationalities in different historical periods.

"In work concerning cultural relics, the principle of giving priority to the protection of cultural relics, attaching primary importance to their rescue, making rational use of them and tightening control over them shall be followed". (Cultural Relics Protection Law of the People's Republic of China, 2007 Amendment, chapter 1 article 4)

It is particularly important for the reader to understand the Chinese context as many of the case studies covered later in the thesis were based in China.

Preservation of cultural relics means preventing, limiting and prohibiting threats, interference and damage to protected objects. The aim of preserving cultural relics is to lengthen their life as much as possible, for further utilisation in research, publicity and education, giving full play to the social and economic benefits. Preservation of cultural relics is therefore a continuous historical task for all nations and all generations.

The conservation process is an informed decision making process, which ensures that conservation at all levels will respect the values and significance of the cultural heritage location. (Getty Conservation Institute, 2008)

Heritage protection means taking care of the natural and cultural heritage values of a place and includes legislation, policies and management frameworks. (Y. Wang, B. Bramwell, 2012)

Restoration is taking actions to modify the existing materials and structure of a cultural property in order to represent a known earlier state, which is based on respect for the remaining original material and clear evidence of the earlier state. Revealing the culturally significant qualities of a cultural property is the aim of restoration. (Canadian Association for Conservation of Cultural Property and the Canadian Association of Professional Conservators, 2000)

3.3.3. Conservation methods

In practice, conservation work aims to save, maintain, preserve effectively and utilise cultural heritage (J. Zeng, Y. Song, M. Zheng, 2010). The practical working process can basically be divided into two stages. The first is developing a structured archive according to checking/screening, photographing/verifying and listing/documenting in order to provide references for future research and operations (see Figure 3-8). The second is planning and executing the operation based on an evaluation of feasibility, followed by validity feedback on the effectiveness of the operation.

Stage 1

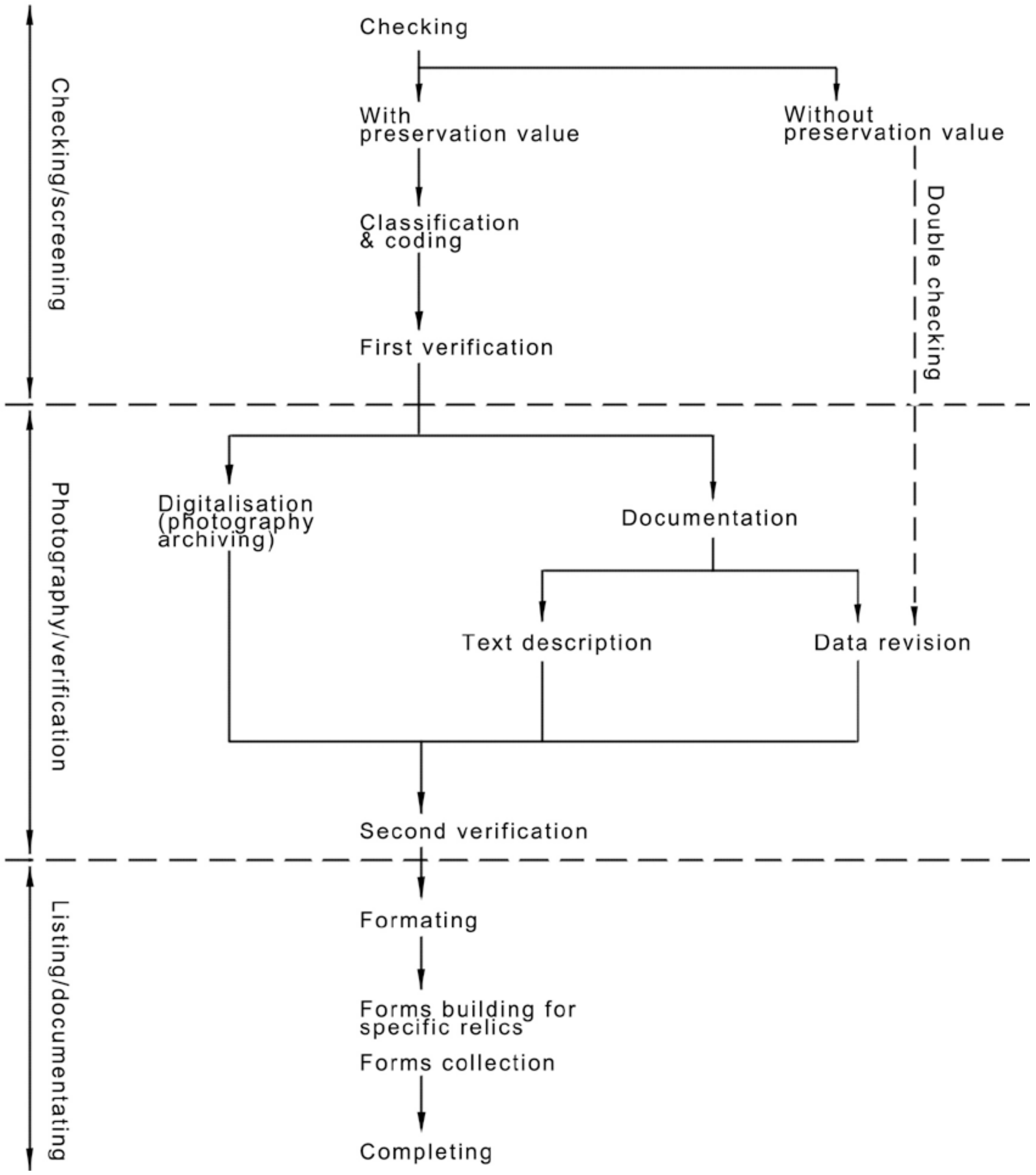


Figure 3-8 Checking/Screening method flow chart (J. Zeng, Y. Song, M. Zheng, 2010)

General process of stage 1: Analysis and archiving for different types of cultural relics (refers to the definitions in section 3.3.2)

1. Documents (types 3 & 4 in section 3.3.2)

Classification → Subdivision → Photography & coding → Measuring & recording → Description & annotation

2. Landscapes and architectures (types 1 & 2 in section 3.3.2)

Literature review & interviews → Reconnaissance on the spots → Classification & subdivision → Photography & coding → Recording & archiving

3. Heritage objects (types 5 and remark in section 3.3.2)

Classification → Cleaning → Subdivision → Photography & coding → Measuring & recording → Description & annotation

General process of stage 2
Firstly, checking the heritage damage situation, such as breakage, oxidation, mustiness, insect attack and rustiness, as well as testing the display environment, such as temperature, humidity, lighting control and chemical reaction between different materials. Secondly, making plans for maintenance and restoration. Thirdly, undertaking the operation and giving feedback for future maintenance and restoration. Lastly, evaluating the feasible applications of the conservation and making plans, e.g. for research, filming, publications, exhibitions, developing downstream products and tourism. The specific processes of archiving, restoration and product development will be introduced in later chapters.

3.4. Summary of Chapter

Sculpture definition, general requirements, and existing manufacturing methods with relevant examples have been introduced in this chapter. There is an interesting relation between artistic sculpture creation and historical relic restoration, they have a definite link as well as some important differences. The needs of optimisation of manufacturing process can be seen clearly, and current attempts to introduce digital technologies into sculpture and archaeological fields have been shown with some barriers that need to be overcome.

The last step in the process chain before shipping and installation is finishing, which is essential in the sculpture industry and especially significant in archaeological restoration. Therefore, a review of finishing techniques for both hand-made and AM artefacts is presented in the next chapter.

4. Chapter Four: Sculpting Techniques

This section explains the reasons for discussing these techniques in the thesis and how they relate to AM. Actually finishing techniques are needed on manually made models and especially on AM models – due to the stair-step effect and generally rough surface finish. Most of the information provided here is related to manually made pieces but many of the techniques described, such as sanding and painting, could also be applied to AM made models.

4.1. Technique 1 - Moulding and casting

Basic process of moulding

Clay modelling is normally the first step in sculpture production. After completing the designed shape, the second significant step is moulding.
Moulding can also be undertaken with an AM model, rather than a clay model. Generally speaking, there are two types of moulding from the original model: so called "live moulding" and "dead moulding". Live moulding simply means that the mould is re-useable, such as a soft silicon rubber mould which can be retained well after peeled off from the original and reused a few times for producing more copies. Dead moulding is producing a mould which can be broken off after moulding, such as a plaster or ceramic mould (M.A. Clarner, C.M. Gallant, 2010). If only one model is needed during the manufacturing process, a dead mould can be chosen for convenience and efficiency, as the production of a live mould is more complicated, but necessary when multiple copies of the original are required.

The most commonly used materials for sculpture moulding are plaster and glass fibre. Traditional sculpture moulding usually adopts a plaster mould, which has the advantages of low cost and reasonable stiffness, but the disadvantages of being heavy and fragile. With large scale sculpture, different moulds are made for different situations. If modelling and manufacturing are at different sites, the original model needs to be shipped for marble carving or bronze casting, In which case a glass fibre mould is adopted for convenient and safe shipping, although the cost of mould production is higher.

Moulding can be done in two steps: producing a female mould first, then using the female mould to produce a male model which is the same shape as the original sculpture model. The two steps are described in detail below.

Production of the female mould

- Sub-dividing the clay original

The female mould is the negative shape taken from the original model. Creating dividing/parting lines for the mould depends upon geometry and the size of surfaces. If the final design material is stone, it should be sub-divided based on discussions with a stonemason, in order to reduce the subsequent workload to a minimum.

Initially, the parting lines are drawn in ink to present the size of each block (Figure 4-1). Vital areas, such as the face and hands, should be avoided, as subtle shapes can be easily misplaced during registration. The next tasks are cutting metal sheets of similar sizes and inserting them into the parting lines to divide the clay model (Figure 4-2), then using clay strips to seal the top of the metal pieces for the purpose of convenient division after plaster solidification (Figure 4-3).

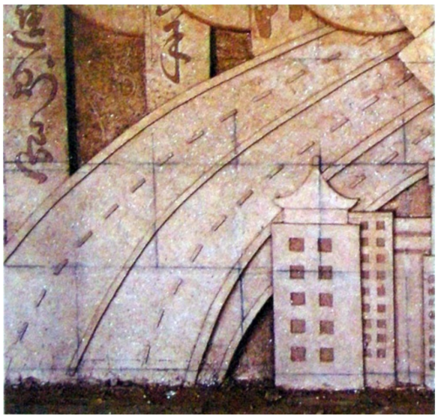


Figure 4-1 Parting lines

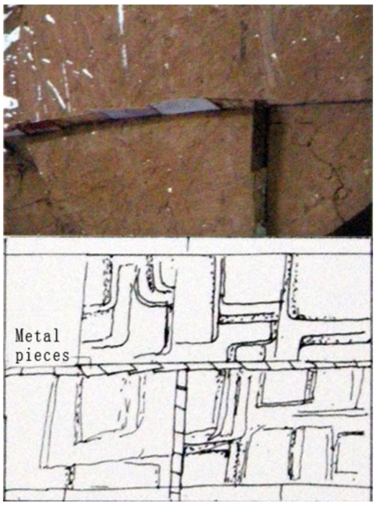


Figure 4-2 Metal pieces for division

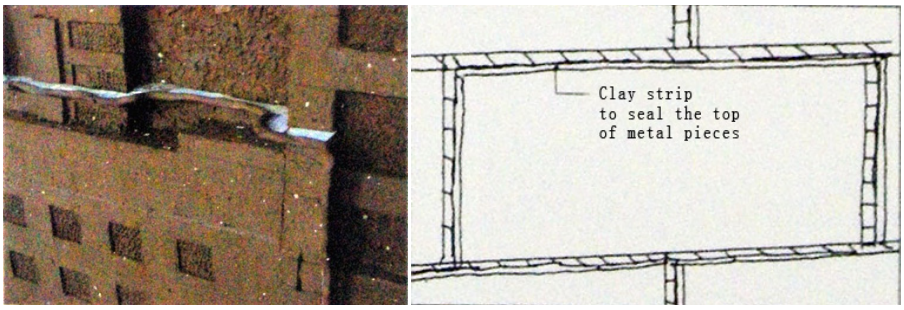


Figure 4-3 Parting lines, metal pieces and clay strip on top of metal pieces (B. Lin, X. Chen, 2007)

- Applying plaster on the clay original

The first layer of plaster must be diluted so that it can be applied by hand, making sure that the liquid plaster covers all the clay surfaces including holes and gaps, and avoiding the generation of bubbles. The second layer is then applied using a thicker liquid, and further plaster is added layer by layer until a 2.5 to 3 cm thickness is reached (Figure 4-4). Next, every block enclosed by metal pieces is identified and reinforced using wooden sticks arranged according to the block's geometry (Figure 4-5). Finally, sufficient waiting time is required for the plaster to become solid and completely dry (Figure 4-6).

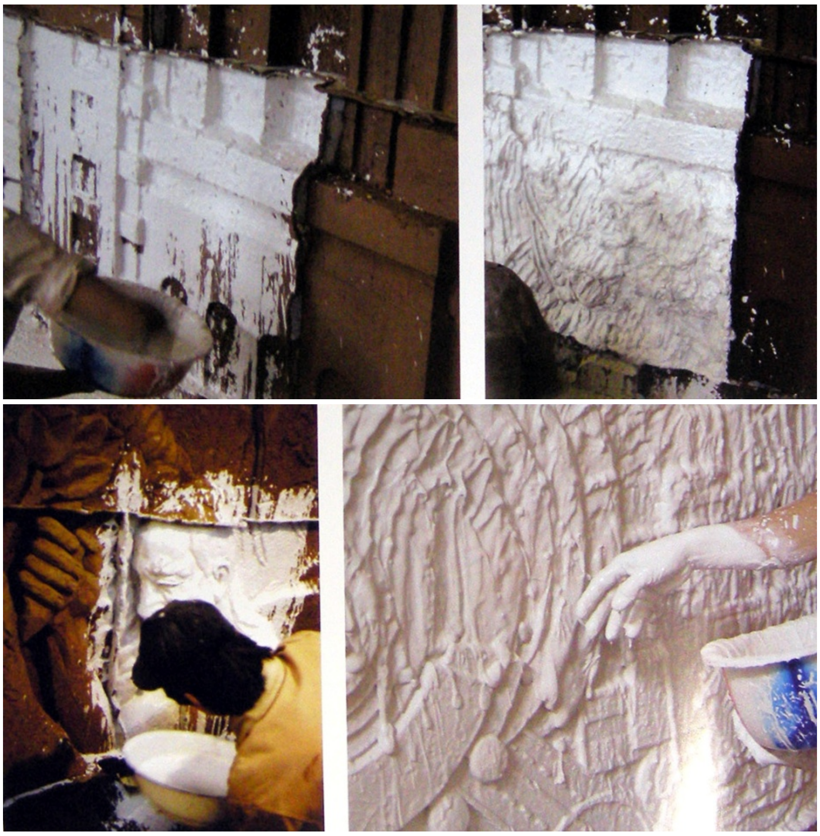


Figure 4-4 Applying plaster on the divisions of clay original

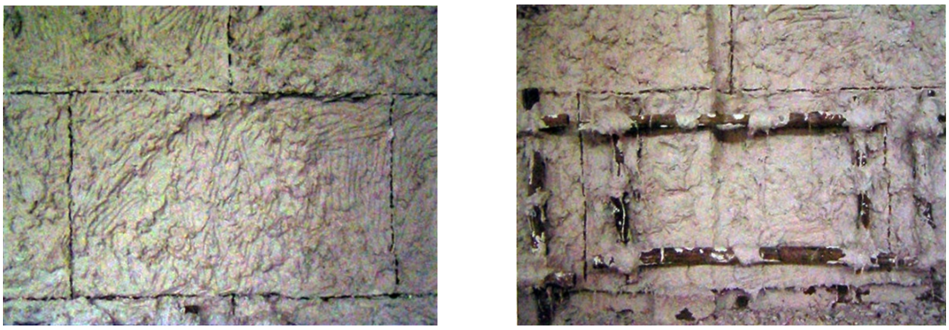


Figure 4-5 Divisions with metal pieces Reinforced with wood sticks

Figure 4-6 Overall effect after reinforcement (B. Lin, X. Chen, 2007)

- Completing the female mould manufacturing

This involves finding every block of female mould via the clay strips that were put on the top of the metal pieces, disassembling the female mould blocks and cleaning off the clay attached on the inner surfaces. Modifying areas that were damaged using plaster or clay may also be required as the final task in completing the female mould (Figure 4-7).

Figure 4-7 Disassembling the divisions and cleaning the clay off the inside (B. Lin, X. Chen, 2007)

Production of male model

- Alternative 1 - Plaster moulding process

Firstly, metal or wood sheets about 4cm deeper than the female mould are fixed around the boundaries of each female block to enclose the sub-division area (Figure 4-8). This is followed by applying a layer of soapy water to the inner surface, and pouring a gypsum slurry with appropriate concentration into the female mould, keeping the depth of the slurry to about 2 to 3 cm. The thickness of the male model depends on the overall scale of the sub-divisions and total sculpture, with larger sculptures requiring a greater thickness. Finally, after the gypsum slurry is completely dry, the female mould is broken and cleaned off with soft tools, to obtain the male model (Figure 4-9). With the soapy water acting as an isolation layer, it is quite easy to separate the female mould and male model even though they are made from similar materials.


Figure 4-8 Female mould with enclosure


Figure 4-9 Male model (B. Lin, X. Chen, 2007)

- Alternative 2 - Glass fibre moulding process

Firstly, a wax barrier is brushed onto the female mould, to make separation easier at later stage. This is followed by attaching glass-fibre cloth with temper paint / blending agent on to the inner surface of the female mould. The method is to brush on a layer of temper paint / blending agent to act as an adhesive, stick a layer of glass-fibre cloth onto it, and then repeat these steps for a few layers. Finally, the glass-fibre is left to dry completely and the plaster is knocked out to leave, the glass-fibre model (Figure 4-10 and 4-11).


Figure 4-10 Female mould section


Applying temper paint


Figure 4-11 Drying glass-fibre sections in air


Model assembly (B. Lin, X. Chen, 2007)

The key point in this process is the thickness of the model, which depends upon the number of layers used. For a small surface area, two layers of glass-fibre cloth should be enough; for a larger area, it may need three to four layers. As glass-fibre models are normally thin shells, deformation may be caused by a lack of stiffness and so wooden sticks are commonly used behind each section to support and strengthen the model. Some other materials such as "angle iron" are also adopted for strengthening larger scale models. Sometimes, because of cost concerns, a glass-fibre model can be installed outdoors as the final sculpture since it has relatively good strength and toughness. Pigments can be added during the moulding process to let the colour infiltrate into the glass-fibre material, although surface painting on this kind of material is more durable. However, the life cycle of a glass-fibre model outdoors is limited, normally lasting about five years. This suggests that important large scale public sculptures should adopt more durable materials to ensure the longevity and value of cultural property.

4.2. Technique 2 - use of resin-based materials

- Glass-fibre (here is a general introduction of glass-fibre material, the compositions and specific forms such as GRP is presented in the later "Epoxy" section)

Glass-fibre is a composite material, usually the preferred material for the intermediary step in sculpture manufacturing, i.e. moulding. Its advantages come mainly from two aspects. One is its properties, i.e. good simulation capability and light weight making it easier for installation, especially at places that have limited facilities for installation. Another is its low cost, which is only about one third of stone and one fifth of copper. This are the reasons why glass-fibre is popular in many fields.

There are also some disadvantages such as the fact that the simulated effects cannot always replicate the realistic surface textures required for a sense of real materials. Also, durability is not as good as stone or copper, the usable life of glass-fibre is a maximum of 15 to 20 years if installed outdoors.

Glass-fibre models with simulation of other effects are quite suitable for small to middle scale sculpture samples, which need to be attractive with good texture effects to win in a competitive bidding process. The finishing techniques and user experience in simulation have a significant impact, and can make glass-fibre look like stone, stainless steel, forged copper and cast copper.

- Stone effects

The simulation of stone mainly includes the need to achieve white marble and various granite effects, for example, a granite surface must have a non-uniform stain (Figure 4-12). Pigments that are close to the required texture are added during the moulding process, and surface painting is applied after moulding. White marble can be basically simulated by a similar method and is even easier as it has even colour on smoother texture with light grey grain on the surface.

Figure 4-12 Glass-fibre simulating granite effect (B. Lin, X. Chen, 2007)

- Metal effects

Stainless steel is one of the most commonly adopted effects, which is achieved by spraying silver paint or chromium paint onto the glass-fibre surface (Figure 4-13).

A forged copper effect is normally achieved through gold powder or spray painting, but this method has a usage time limit in that it only lasts for about six months.

As for casting simulation, a bronze effect is often simulated. Black iron oxide powder or ink is used to make a colorant, which is added into the glass-fibre to make it appear dark, almost black, during the moulding process, and then a ready mixed paint is applied for surface finishing. Ready mixed paint can consist of red, black and green tones to create a dark burnt umber, with a certain proportion of gold powder. This colorant is applied to the surface, allowed to dry, and then a mix of green acrylic powder and water is applied on the low areas with the high points being brightened using propylene gold dust. This method can usually achieve a realistic effect if it is performed well (Figure 4-14).

Figure 4-13 Simulation of stainless steel

Figure 4-14 Simulation of casting bronze (B. Lin, X. Chen, 2007)

Epoxy resin

Epoxies are a large family of resins with excellent insulating properties and adhesion, as well as good physical strength and chemical resistance. Epoxy resin is produced using various formulas, such as a thin liquid for spraying; a sticky paste for brushing, bonding, pouring and sealing; an adhesive for caulking, patching, and connecting irregular surfaces. Plasticiser can be added to increase its flexibility. Also, a large number of pigments and non-active additives, such as sand, sawdust, mica, marble and metal powder, can be added to change its properties for cold casting. High strength glass-fibre reinforced plastic (GRP) is made of glass-fibre cloth covered by epoxy. Unconsolidated epoxy gives off toxic gases that irritate the human skin, but when consolidated epoxy has good chemical stability and is harmless to health. The commercial uses of epoxy include production of high pressure vessels, rocket casings, radar housings, spacecraft windows, capacitors in industrial fields, and in liquid form paint, varnish, binders, and sealants in sculpture industries.

Phenol resin

There are several kinds of phenol, all based on the aggregate effect of phenol and formaldehyde. As one of the earliest sorts of plastic, phenol is still popular today and is normally combined with a filler such as wood dust, cotton rags, soaked fabric or quartz. Phenol can be used for electronic products and in multi-layer board as a binder. Phenol products are normally opaque brown, black or deep-red in colour. Although the polymerisation is an industrial process that is not suited to most artistic workshops, some artists who create mechanical and electronic works like to use phenol as an interesting parts of their artwork.

Polyester resin

Compared with other composite materials, the application of polyester resin is more popular in the art field. It is light, robust and has good anti-weather erosion properties when strengthened by plastic fibre. It can easily be formed into various shapes, textures and colours (see Figure 4-15). Porous surfaces can be glued together using polyester, and it also has very good adhesion to wood, but not to metal or paint, or even the dry surface of polyester itself.

Polyester fibre can be used to make a kind of light fabric, and thin polyester film (with thickness of 0.05 to 0.1 mm) can be used in its natural transparent form, or coloured (see Figure 4-16) or plated with aluminium, silver or gold. As one of the basic ingredients, polyester fibre is commonly used to produced GRP, which is used for industrial products and moulding.

Figure 4-15 Transparent polyester resin

Figure 4-16 Coloured resin model

Silicone

There are many forms of silicone, i.e. moulding composite, resin, binder, paint-coat, lubricant, fluid and artificial rubber. Silicone rubber has different grades of hardness, which provide an alternative to natural latex as a moulding material (Figure 4-17). Also, silicone lubricant can make de-moulding easier and protect a rubber mould from erosion. Silicone maintains its properties between 38 °C and 260 °C. (Figure 4-18 shows an example of silicone rubber steering wheel protection in a high density polyester foam model)

Figure 4-17 Silicone rubber model

Figure 4-18 Example usage of silicone & polyester

Silicon rubber casting

Silicon rubber is a material with good plasticity/mould-ability and simulation capability, which is easy to use, easy to release from moulds, aging resistant and can produce moulds that can be used repeatedly within a simple moulding process. For these reasons, it is widely used for making art casting models. Silicon rubber can take the form of a flowing liquid or have a thick "doughy" consistency but becoming solid through a reaction with a catalyst and firming agent. Silicon rubber moulds are flexible and capable of accommodating complex shapes without being divided into many pieces. This reduces the difficulty of the moulding operation, making it popular in the investment casting industry where lost wax masters are required. In this case, a tool for wax injection comprises a silicon rubber mould and a plaster supporting mould. Prototypes made from various materials can be cast from silicon rubber moulds, with polyurethane resins being particularly useful for simulating engineering plastics. Small scale, complex geometry parts and fine details of large scale sculptures are both suitable for silicon rubber casting. Considerations and solutions for this process are summarised in Table 4-1 below.

Table 4-1 Considerations and solutions for silicon rubber casting

Considerations	Solutions
The milky white jelly of silicon can easily stick to desks, chairs and skin.	Acetone needs to be used for cleaning the silicon off skin, as normal soap and hand washing cannot remove it.
Acetone is a strong irritant.	Put newspaper on the desk, wear gloves and a mask to avoid inhalation of the chemical, reduce the use of acetone with a disposable brush.
Accuracy for the wax model	Be careful and patient during the casting process to ensure the mould has the same details as the original
Lifecycle of silicon rubber mould	Carefully control the proportion of agents for good quality moulds which are more durable, in order to avoid future workload.

Silicon rubber mould casting process:

1) Brushing

The brushing method is the most widely used approach for silicon rubber casting in the sculpture industry. The method is to brush liquid silicone rubber mixture onto the original model layer by layer and allow it to dry until a certain thickness is reached depending on the size of model or master piece.

2) Pouring

This is a very old method and best suits relief sculpture casting. The process is to produce a support mould first, leave a little space between the support mould and the relief surface, pour the silicon into the gap, wait for it to dry, take the relief out, and a set of moulds is then completed (Figure 4-19).

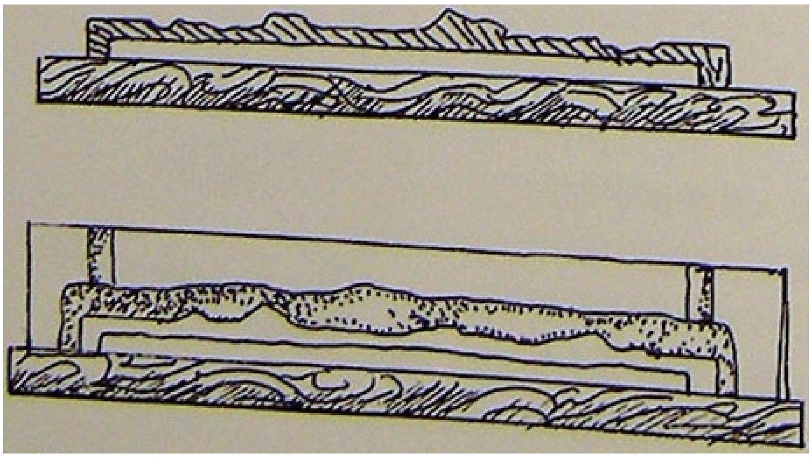


Figure 4-19 Silicon rubber casting by pouring method (B. Lin, X. Chen, 2007)

The main materials and tools for silicon rubber casting is summarised in Table 4-2 and Figure 4-20 shows some of them.

Table 4-2 Materials and tools for silicon rubber casting

1. Silastic latex (provided with curing agent and catalyst, the detailed proportion required and the setting time instructions)
2. A dozen paper cups, two plastic basins
3. A few brush with one to four inch in width, one wool pen
4. Floor wax or Vaseline as isolating agent, one portion of bamboo chips
5. Raw gypsum powder, a few strips of wet clay or plasticine
6. Scissors, a roll of fine gauze, a bundle of linen, a pair of thin rubber gloves, a few triangular pieces of modelling clay
7. For complex geometry model, a wooden case that is larger than the model, containing some fine sand for the divisional plane.

Figure 4-20 Part of materials and tools for silicon rubber casting (B. Lin, X. Chen, 2007)

4.3. Technique 3 - Sculpting in stone

Stone is a popular material in the sculpture industry, and there are many kinds of stone that are commonly used for different effects with different tools. Common types of stone with suitable processing tools are summarised in table 4-3 shown below.

Table 4-3 Common types of stone and suitable manual finishing tools

Classification	Subdivision	Characteristics	Finishing tools
Igneous rock	Granite	Crystallised, very hard, high density. Different colours such as red, black, white.	Tungsten carbide chisel tip, diamond wheels
	Basalt	Fine texture, hard. Dark grey or black.	Granite tools
	Diorite	Similar to granite but without silicon, sometimes called "black granite"	Granite tools
	Obsidian	Hard and glassy, breaks into thin slices under pressure. Black or brown	Granite tools
	Pumice	Light, soft, porous, dark grey variegated	Wood carving tools. Grinding generates sharp glassy particles.
Sedimentary rock	Limestone	Pure limestone is white, but is coloured by impurities such as iron oxide - yellow & red; carbon - grey; sulphide; pyrite - blue;	Iron cutting tools. Normally not hard enough for grinding / polishing

		chlorite - green. Hardness varies from soft to hard.	
	Sandstone	Mainly soft and easy to abrade, some types contain quartz and are hard and have good endurance. Layered sandstone is called "flag-stone".	Easy to be processed, but the grit would wear tools, not suitable for cold or wet storage.
	Slate	Thin layered shale, fragile.	Wood or steel files, emery tools.
Metamorphic rock	Marble	Crystalline form of limestone.	Light steel tools with fine edges, subtle details can be achieved by fine polishing
	Agate	Transparent marble with yellow, brown, red grain.	As above
	Soapstone /Talc/Steatite	Smooth, soft. Black or green.	Cutting by knife or wood carving tools.
	Serpentine	Non-crystallised, soft, smooth. Blue and green, called "green marble"	Softer types can be cut by knife, harder types require marble tools
	Alabaster	Translucent, yellow, pink, white. Cannot withstand outdoor environment.	Wood carving tools or marble tools, can be fine polished.


Figure 4-21 Stone carving hammers

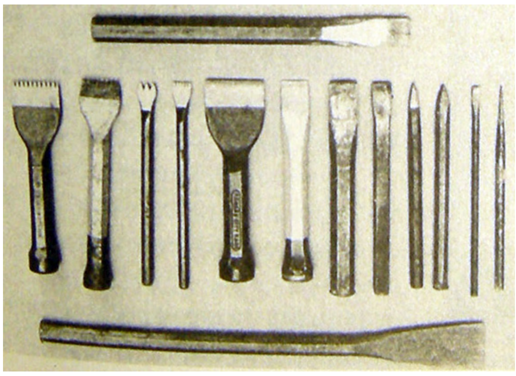


Figure 4-22 Stone carving chisels (O. Andrews, 1988)

- Manual finishing tools

Stone carving hammers and chisels were originally used and still popular as manual finishing tools. Hammers made of iron, steel and bronze are used to hit large pieces of rock directly for forming a rough shape (Figure 4-21), and chisels with different shapes such as claw chisels with teeth, straight chisels and needle chisels for carving details (Figure 4-22).

- Powered finishing tools

Powered stone carving tools are not as easy to control as manual tools and therefore are normally most useful at the beginning stage to remove bulk material. However, rich practical experience can also enable powered tools be operated with great sensitivity.

Air tools are more satisfactory than electric hammers and polishers, as they do not overheat when used continuously for several hours. Powered tools also produce a lot of dust which is very harmful to electric motors. Recent technology allows the cutting of stone by flame, and although it is expensive for artists, it brings a positive possibility for speeding up the cutting process for massive stones.

Stone dust is harmful for human lungs and eyes and so protective goggles and masks should be worn when operating powered tools. It is also necessary to keep good ventilation in the working area and to isolate tools that are vulnerable to dust. Wet grinding and polishing can significantly reduce the dust problem.

The cutting edge of air tools can be re-shaped by welding tools, different cutting head can be placed on the electric hammer for stone and concrete carving, and there are impact and spin modes available on the electric tools (Figure 4-23).

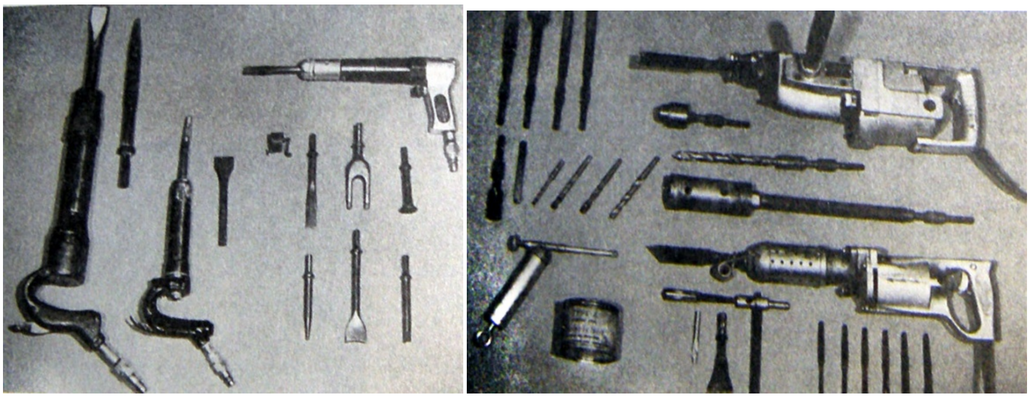


Figure 4-23 Air tools and electronic tools (O. Andrews, 1988)

- Final finishing

Many works require the use of wood, iron or small carving files to finish the surface after the sculptor has completed their final modelling. Wet or dry sand paper with different mesh sizes are adopted for abrading, where fine sand paper needs wet grinding to get the best finish. Cloth and buffing wheels are used for polishing. Stone with a beautiful grain, such as marble, needs fine polishing, whereas rough stone, such as sandstone, does not need polishing at all.

Compared with high density stone, rougher stone is more prone to cracking in winter, as it absorbs humidity from the air which then freezes and expands to make the stone crack. Hence, a stone sealant can be injected before putting the stone outdoors to help prevent cracking.

4.4. Technique 4 - Sculpting in wood

- Manual tools

There are different sizes and shapes of wood chisels, flat chisels or gouges that are used at the beginning stages of the carving process (Figure 4-24). The size of the tool depends on the type of work being done. Some wood carving chisels have quite weak handles which are not suitable for hitting with a hammer and so they need to be changed to a hard wood or plastic handle. Also, the hammer should be quite heavy so that the weight itself can save muscle power during the work. A hand axe is also a useful tool for wood work; various kinds of axe can be used to shape large scale objects down to fine details.

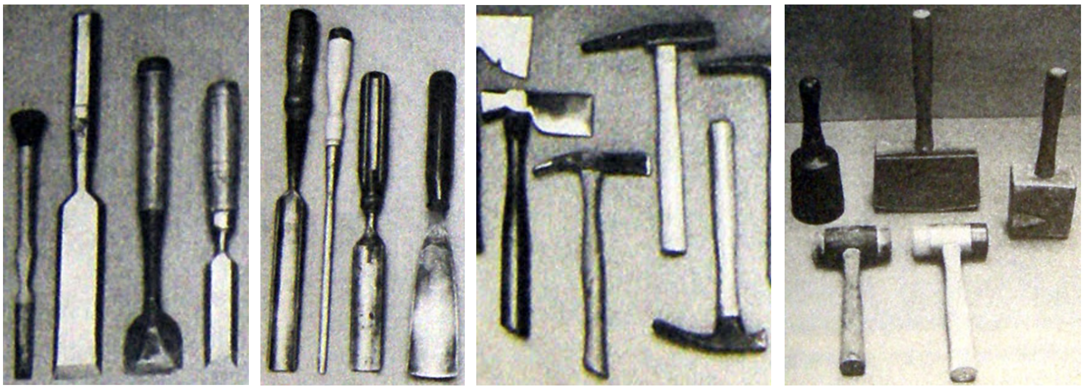


Figure 4-24 Flat chisels, gouges, hand axes, hammers (O. Andrews, 1988)

- Powered tools

Bench saws, junction saws, electric drills, planers, belt sanders, flat sanders, and disc sanders are all common powered tools in wood workshops. Electric and petrol driven chain saws can cut the general shape quickly, and different types of sanders can be used to abrade the complex surfaces, such as the vertical axis sanding machine shown in Figure 4-25, left image. Electrically powered tools are usually used for small jobs, whereas for large jobs, petrol driven tools are needed (Figure 4-25, middle image). In terms of portable power sources, a compressor providing compressed air for air tools can be used, or a petrol driven generator can provide enough electricity for one or two portable electric tools, such as the hand-held electric saws in Figure 4-25, right image.

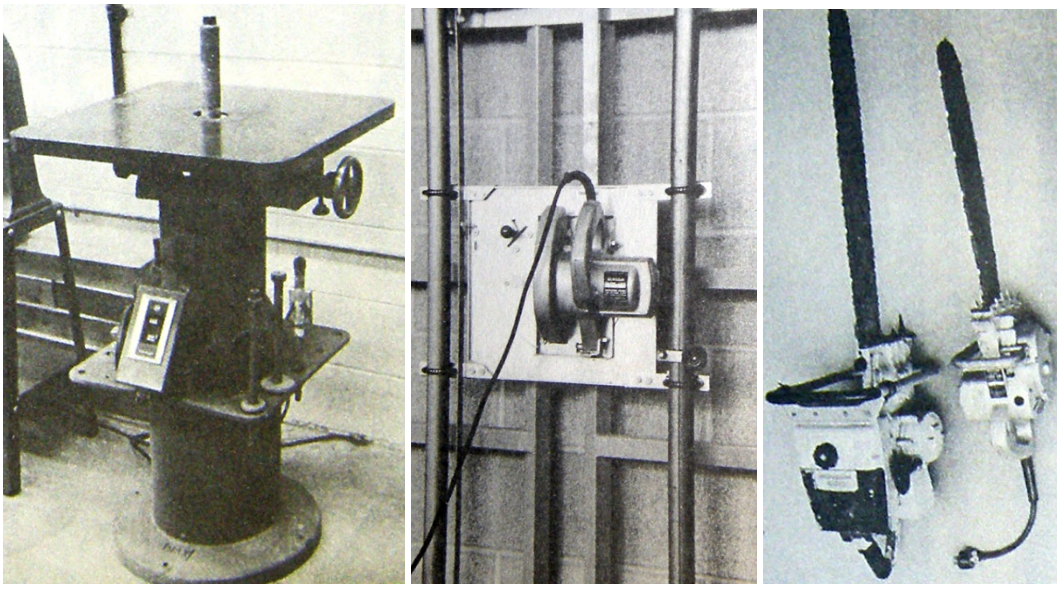


Figure 4-25 Vertical axis sanding machine, line board saw and electric saw (O. Andrews, 1988)

- Joints and adhesive

Wood sculptures are not always carved from one piece of wood; many modern works are structural compositions, which are joined by adhesive, screws, or customised parts made from other materials acting as a rigid connection. Alternatively, a flexible construction system based on bundling and tying can be used. Epoxy and resorcinol-based glues can join multi-layered wood structures together to save cost and also to achieve special effects, for example, to make the wood look like it has a soft texture or that it has been formed by bending (Figure 4-26).

Figure 4-26 Wood work shows soft texture (left) and combination with metal (right)

- Bending

Wood can be formed through bending, by the correct use of steam. A container with a cover is filled with continuously boiling water, and the wood is kept a little higher than the water's surface, so that it is impregnated with the moisture. Every face needs to be steamed for approximately 20 minutes, then taken out with heat-resistant gloves and formed immediately. It is necessary to keep the wood in this shape until it is completely dry. Steaming and adhesive methods can be used in combination.

4.5. Technique 5 - Sculpting in metal

Stainless steel

After all parts are assembled, a unified grinding process needs to be applied to a stainless steel object. In this process, suitable types of abrasive paper are selected to grind the surfaces in the same direction, in order to ensure an even appearance of colour in different lighting conditions. Otherwise, the surface may easily appear uneven and messy, which will affect the overall quality of appearance.

In the majority of stainless steel sculpture, matt and glossy effects are commonly used to accentuate the beauty of the material's texture. Typically speaking, a matt effect is used for a large area whereas a localised area or pipe section will adopt a glossy effect. A matt effect main body and glossy spherical region can create good contrast. This is also a commonly used finishing technique in the urban sculpture industry.

- Matt effect

Tools for grinding stainless steel include sanding machines (disc, flat and belt sanders, with the most commonly used being disc and flat sanders), abrasive cloth and paper, and grinding wheels. During the grinding process, a very large number of abrasive grains (equivalent to numerous high hardness blades) apply cutting to the metal surface, in order to achieve the purpose of smoothing. Abrasive cloth is installed on an electric wheel or handheld wheel to grind the stainless steel surface. In order to achieve a smooth surface, cloth with a smaller particle number is used for coarse grinding and then cloth with a larger particle number is used for fine grinding. The purpose of grinding wheels is to grind the surface coarsely, which is normally sufficient when finishing inner structure surfaces. There are two types of abrasive paper, dry abrasive paper and water-resistant abrasive paper; water-resistant abrasive paper is used with water or oil to grind the metal surfaces.

- Glossy effect

Mirror finishing has two steps which are pre-polishing and precise polishing. Pre-polishing uses hard or relatively hard polishing wheels to process the stainless steel surfaces that have already been ground. Precise polishing adopts soft polishing wheels to further process the pre-polished surfaces, removing the signs of pre-polishing for mirror like luminous surface results.

- Painting

Coloured stainless steel is usually created by painting onto a surface that has already been processed to the desired geometry. Sometimes, painting is also applied to surfaces that have been produced in carbon steel plate to save cost. However, the former method produces more durable results, as paint on carbon steel plate will normally last for only one to two years, requiring regular re-painting and maintenance.

Copper / Bronze

- Forging

Metal forging can refer to both hot processing and cold processing.

Hot processing involves heating the metal sheets constantly during forging, to make them turn red hot and softer, so that they can be more easily forged to different shapes. Hot forging is usually chosen for copper. Cold processing is normally applied to sheet materials like stainless steel, iron, etc. which can be forged directly without heating, just by continuous beating and hammering to create the required shapes. This process needs to be repeated many times and the entire shape is created gradually.

The materials' appearance can take display various different textured effects during the forging process. The grain can be circular, square, flat shaped, long shaped, triangular, oval, irregularly shaped, thread shaped, worm shaped, etc. (see examples in Figure 4-27) This gives expression to the sculptor's thoughts and feelings.

Figure 4-27 Examples of forging grain

When forging irregular, complex relief sculpture geometry, easily forged, ductile, resilient materials should be adopted. Copper sheet with 0.5 to 1 mm in thickness is suitable for forging, as it is easy to work and can be modified repeatedly. The pre-forging process comprises heating the material to make it soft, putting it on the forging desk (Figure 4-28), knocking it flat with a wooden hammer, putting it on a gluing platform to bond the copper sheet tightly with the platform (Figure 4-29), and pasting the design sketch to the copper sheet, or using carbon paper to copy the sketch onto the copper sheet.

After this preparation, a flat engraving tool is used to chisel the outlines and structure lines of the design (Figure 4-30), in order to keep the shape accurate during forging. When the essential lines have been chiselled, the copper sheet is heated, removed from the gluing platform, so the heated sheet is soft and bendable. It then needs to be made flat again and put back into the glue to continue working on the platform, the gluing platform is always needed during forging in order to fix the sheet and keep it soft, so the shape is under control as desired. It is then chiselled and forged to the required shape with recessed and proud features using a small square hammer, square chisel and round headed chisel. This is followed by modifying the general shape on sandbags and forging desks (for support), and repeating the above steps several times to achieve the required shapes, depths and shape hierarchy. This completes the rough forging stage.

After rough forging, fine processing needs to be undertaken. Both sides of the copper sheet have to be forged repeatedly to create the subtle changes of details and hierarchical relationships. During this process, the copper sheet should be heated for annealing purposes to avoid breaking the completed shape (Figure 4-31).

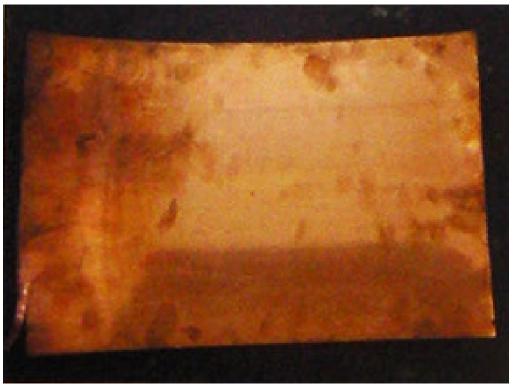


Figure 4-28 Copper sheet


Figure 4-29 Bonding copper sheet to gluing platform


Figure 4-30 Chiselling the outlines


Figure 4-31 Annealing copper sheet with shapes (B. Lin, X. Chen, 2007)

When the copper sheet turns soft after heating, a small chisel can be used to beat the fine details. Depth characterisations are achieved step by step, from global to local areas. The sheet is reversed repeatedly to modify the shape and structure, in order to make the lines strong, the structure clear and make the profile image lively. According to the form and content of the relief sculpture, some forging signs such as thumping marks and texture characters can be kept to expand the artistic appeal.

As for three dimensional sculptures, the forging process is divided into two steps. The first step is similar to stainless steel inner structure modelling, which involves producing a plaster mould or glass-fibre model based on the design to act as a master model, cutting the copper/bronze sheet into small pieces and chiselling their shape to follow the inner surface of the plaster mould or outer surface of the glass-fibre model to complete the general shape (Figure 4-32 is shown after the section below). The second step is similar to the relief forging process, which aims to create fine detailed outer surfaces. The plaster mould is broken or glass-fibre model is removed and the metal pieces are welded together to create the final piece. Large scale sculpture adopts this method as well, forging small pieces, assembling the whole shape, welding together, and using angle-iron for reinforcement.

- Grinding and polishing

For the entire work to be completed after forging, it needs to be examined carefully to find welding marks and burrs on the edges, which should be removed by grinding and polishing. The grinding process normally includes rough finishing and fine grinding especially for complex geometry. Rough finishing uses an angle grinder to clean the welding marks and burrs, then fine abrasive cloth and paper, multi-use files etc. are used for fine grinding. A polishing machine is applied for precise polishing after grinding, which aims to remove all traces of processing to achieve smooth, consistent and beautiful surfaces.

- Surface finishing

Suitable surface finishing techniques should be selected depending on properties of the different materials used, such as copper or brass. For example, to clean copper, dilute sulphuric acid solution needs to be used, first by brushing the surface to remove greasy dirt and oxidation, and then rinsing off the corrosive sulphuric acid solution with water. Surface shading can then be undertaken as follows. First, pour the etching chemicals into glass containers, then use a clean brush to apply the chemicals onto the surfaces for etching. After a short while, when the colour has attached to the surfaces, polish with a copper brush, wash with water and wipe to dry. Finally, glaze, apply wax to maintain the surface finish, thus completing the final work (Figure 4-33).

Figure 4-32 Chisel shape with plaster mould

Figure 4-33 Final forged work (B. Lin, X. Chen, 2007)

- Dyeing and maintenance of metal sculptures

After forging or casting a metal sculpture and the subsequent surface finishing, dyeing and maintenance are generally needed. The methods of dyeing are typically divided into coating colouring, chemical colouring, electrolytic colouring, chemical plating, electro-plating colouring, heat colouring, gold plating and gold leafing. Chemical colouring is the most commonly used method, especially for copper and copper alloy castings. Another emerging technique is the combination of ceramic thermal spraying and chemical colour spraying as a synthetic colouring method. This section presents the general process of chemical colouring.

1) Pre-colouring treatment

Cleaning is an essential step before colouring in order to make the surface colour uniform, and to form a strong, corrosion resistant, anti-oxidative colour layer (Figure 4-34 shows the manual cleaning with a cloth wheel). There are three basic cleaning methods:

Mechanical cleaning methods

Sand blasting is one of the three most common mechanical cleaning methods (Figure 4-35). Another is using a steel wire brush to scrub the surface, and the third is washing with a grinding media. The grinding media can be sand, washing powder or another cleanser, which is used with a sponge to clean the surface of metal casting. Sand blasting gives the best results amongst these three methods, as the metal is easy to dye afterwards and has an even surface after colouring.

Figure 4-34 Pre-colouring treatment

Figure 4-35 Sand blasting (B. Lin, X. Chen, 2007)

Chemical cleaning methods

Using acid or alkali solutions to wash the surface can remove any oxide crust and dirt on the metal, and enhance a casting's lustre. One drawback is that the solution may seep into tiny holes on the surface of copper, and create ugly spots when it oozes out later. The way to address this is to rinse the solution off thoroughly, although not every piece of work can be cleaned in this way due to the complexity of geometries, for example, some areas are difficult to reach, and timing or scale because the spots cannot be eliminated completely if the solution has been absorbed into the holes.

Electric cleaning method
This method is mainly used for mass production of industrial products rather than artistic works.

2) Chemical colouring for copper base alloy
Chemical colouring is the most commonly used surface colouring method for copper based alloy. The tincture of any chemical colouring depends on the composition of the membrane generated and the specific properties of the alloy. The alloy casting can be dyed by either cold or hot tinting. Cold tinting reacts more slowly and the colour of the membrane is more permanent, whilst hot tinting reacts more quickly and gives a thicker membrane, which fades more easily. Table 4-4 below gives a summary of the different methods used to apply chemical colouring.

Table 4-4 Methods for applying chemical colouring

1. Dipping (Figure 4-36)	Dipping the object into the chemical solution with certain formula. The solution is contained in a large tank for repeated use until it is in-effective. This relatively simple method works reasonably well for small scale sculpture.
2. Spray brushing (Figure 4-37)	This method is to dye the object by a combination of spraying and point-brushing. Using sprayer to spray the chemicals on the surfaces like spray painting, and brushing the areas without paint. This method is more suitable for large scale sculpture.
3. Burying	Burying the object into soil with chemicals for a few weeks to a few months. This method can create surprising effects such as colour of bronze relics.
4. Smoky steaming	Putting the object into a sealed container with chemicals and heating the container, using the gas evaporated from the chemicals to dye the object. The object needs to be turned often to avoid un-even colour. This method is not commonly used as the colour on the surface is easily removed by water.

Figure 4-36 Dipping method of chemical colouring

Figure 4-37 Spray brushing method of chemical colouring (B. Lin, X. Chen, 2007)

3) Chemicals for colouring

Art works impress an audience by aesthetics, most sculptures have simple colouring but bronze/copper sculptures are well known by their rich colours (Figure 4-38), and their colour is incomparable with other art works. This section introduces a few kinds of chemicals which are most commonly used.

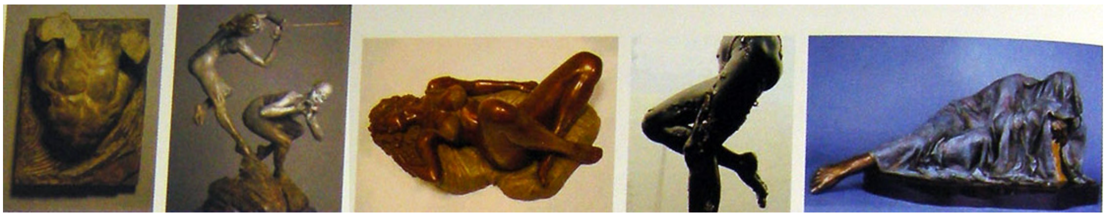


Figure 4-38 Bronze/copper sculpture with rich colour (B. Lin, X. Chen, 2007)

Sulphide potassium nitrate

The chemical appears brown, smells like rotten egg, and is the easiest way to surface colour. Specifically, about 30g Sulphide potassium nitrate is added to 1000mL hot water which is contained in a glass container with a large opening. The hot water melts the chemical quickly and a kind of yellow colour appears (the chemical loses effectiveness if the yellow colour does not appear).

Brushing or spraying this solution on the surfaces should turn them brown (if the surfaces are heated before brushing or spraying, the colour turns darker and can even become black). This colour is beautiful and can be treated as the foundation or base colour, other colours can be added onto it. It is better to rub the rest of the solution into gaps with a clean sponge, in order to make the shadow side darker; and brush the convex parts with a metal brush slightly to increase the brightness, so that the entire object looks more vivid. (Figure 4-39) This chemical needs to be kept dry for storage, or it would lose effectiveness.

Figure 4-39 Effect with sulphide potassium nitrate colouring (B, Lin, X. Chen, 2007)

Ferric nitrate

This kind of chemical is applied on surfaces with a foundation/base colour. When the object is heated until water sprayed on it evaporates, brushing ferric nitrate solution on the surface (just a little with an almost dry brush) makes the cold looking brown turn warmer and redder. The colour becomes stable and calm by brushing repeatedly to make the art work look more exquisite and rich (Figure 4-40).

Figure 4-40 Effect with ferric nitrate colouring (B. Lin, X. Chen, 2007)

Cupric nitrate

Similar to the application of ferric nitrate, cupric nitrate also needs to be applied on a heated surface which has a foundation/base colour. This chemical can make the original surface appear green; this kind of green is not apparently visible in the beginning and looks like a layer of mist, but becomes more and more clear with repeated brushing for a saturated effect (Figure 4-41)

Figure 4-41 Effect with Cupric nitrate colouring (B. Lin, X. Chen, 2007)

These chemicals can be used interchangeably to create rich colour and surprising effects, although the application amount needs to be controlled carefully (Figure 4-42). The chemical colouring techniques are summarised in table 4-5.

Figure 4-42 Simulation of (a) copper; (b) Bronze with rust; (c) Blue bronze (B. Lin, X. Chen, 2007)

Table 4-5 Chemical colouring techniques for bronze/copper

Colour	No.	Formula of solution		Processing conditions		Note (applicable scope)
		Composition	Amount (g/L)	Temperature (C°)	Time (min)	
Red to Brown	1	$[Fe(NO_3)_3 \cdot 6H_2O]$	50	Heating	Brushing repeatedly	Tin bronze Bell metal Silicon brass
	2	$[Fe(NO_3)_3 \cdot 6H_2O]$ $(Na_2SO_3 \cdot 7H_2O)$	2 2	75	Dipping for a few minutes	Silicon brass

Red to Brown	3	Fe_2O_3 PbO_2	30 15	Heating	Brushing repeatedly	Tin bronze Bell metal
	4	Fe_2O_3 $[Pb(CH_3COO)_2 \cdot 3H_2O]$ (NH_4Cl)	15 10 10	Ordinary temperature	Brushing repeatedly	Tin bronze Bell metal
Red to Brown	5	(K_4S) $[(NH_4)_2SO_4]$	5 2	Ordinary temperature	Brushing	Tin bronze Bell metal
	6	(NH_4Cl) $(NaCl)$	5 5	Heating	Brushing	Tin bronze Bell metal
	7	$[(NH_4)S)]$ $(FeCl_2 \cdot 4H_2O)$	0.5 2	Ordinary temperature	Rest after brushing	Tin bronze Bell metal
	8	$[Cu(NH_3)_2 \cdot 3H_2O]$ $(H_2C_2O_4 \cdot 3H_2O_4)$	55	Heating	Brushing repeatedly	Silicon brass
Chocolate	1	$[CuSO_4 \cdot 5H_2O]$ $(KMnO_4)$	50-60 5-8	80-98	2-10 mins	Tin bronze Bell metal Silicon brass
	2	$[NiSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O]$ $[CuSO_4 \cdot 5H_2O]$ $(KClO_3)$	25 25 25-34	40-70	10-20 mins	Tin bronze Bell metal Silicon brass
Black	1	(K_2S)	10-50	Ordinary temperature - 80	Brushing repeatedly Brown - Blue black - Black grey	Bronze uses low content with heating; brass uses high content with brushing
	2	(K_2S) (NH_4Cl)	30 30	Ordinary temperature	Brushing repeatedly	Tin bronze Bell metal
	3	(K_2S) $(NH_3 \cdot H_2O)$ 28%	125 500 mL/L	Ordinary temperature	Brushing repeatedly	Tin bronze Bell metal
	4	$[(NH_4)_2S]$	500 mL/L	Heating	Brushing	Tin bronze

					repeatedly	Bell metal
	5	$(K_2S_2O_8)$ $(NaOH)$	15-40 50-120	Ordinary temperature - 65	5 min - a few hrs	Bronze uses high content with heating 5 min; brass uses low content with dipping a few hrs in Ordinary temperature
	6	$[CuCO_3 \cdot Cu(OH)_2 \cdot H_2O]$ $(NH_3 \cdot H_2O)$ 28%	40 200 mL/L	15-30	5-15 mins	Brass with mass-fraction lower than 65%
Blue	1	$[Cu(NO_3)_2 \cdot 3H_2O]$ (NH_4Cl) $(NH_3 \cdot H_2O)$ 28% $(C_2H_4O_2)$ 36% (H_2O)	110g 110g 440mL 440mL 110mL	Ordinary temperature	Brushing, repeat after dry	Tin bronze Bell metal
	2	$(KClO_3)$ (NH_4NO_3) $[Cu(NO_3)_2 \cdot 3H_2O]$	100 100 1	Ordinary temperature	A few mins	Copper Tin bronze Bell metal Silicon brass
Green	1	(NH_4NO_3) $(NaCl)$	200	Ordinary temperature	Brushing repeatedly	Tin bronze Bell metal
	2	$[Cu(NO_3)_2 \cdot 3H_2O]$ (HNO_3), $\rho = 1.40 g/cm^2$	100 40mL	Heating after brushing		Tin bronze Bell metal
	3	(NH_4Cl) $[Cu(CH_3COO)_2 \cdot H_2O]$	50	Ordinary temperature	Brushing, repeat after dry	Tin bronze Bell metal
	4	$[(NH_4)_2SO_4]$ $(CuSO_4 \cdot 5H_2$	100 10	Heating	Brushing repeatedly	Tin bronze Bell metal

		O) ($NH_3\cdot H_2O$) 28%	10mL			
	5	(NaCl) (NH_4Cl) ($NH_3\cdot H_2O$) 28% ($C_2H_4O_2$) 36%	150 150 125 125	Ordinary temperature	1 day	Tin bronze Bell metal Silicon brass
	6	[$CuSO_4\cdot 5H_2O$] (NH_4Cl)	75 12.5	100	A few mins	Silicon brass
	7	[$NiSO_4\cdot (NH_4)_2SO_4\cdot 6H_2O$] ($NaS_2O_3\cdot 5H_2O$)	50-60	60-70	A few mins	Tin bronze Bell metal Silicon brass Sodium thiosulfate needs to be added at any time
	8	($NH_3\cdot H_2O$) ($CuCO_3$) (Na_2CO_3)	250mL/L 250 250	30-40	A few min	Silicon brass

4) Electro-plating

Electro-plating can be applied to bronze/copper sculptures for surface colouring, and includes gold plating, silver plating, titanium plating and chromium plating. The colour of the coating film is pure and even, and the membrane is firmly attached to the surface, which makes electro-plating more suitable for modern style art works (Figure 4-43).

Figure 4-43 Colouring effect by electro-plating (B. Lin, X. Chen, 2007)

5) Post processing and maintenance
Wax polishing preserves art works for a few years indoors and for about one year outdoors. Transparent finishing varnish also works very well as a surface protection for outdoor sculptures. Commonly used wax polishes include floor wax and transparent liquid wax whilst finishing varnishes include polyurethane clear varnish, propylene drying varnish and acrylic baking varnish. These varnishes are normally sold in building materials outlets.

Selecting a finishing technique for sculptures
Generally speaking, the decision depends on the specific requirements of each project. If large scale sculptures need to keep the processing marks of clay modelling or chiselling, then polishing cannot be applied. If art and craft works are to attract customers by showing them smooth surfaces and subtle details, they will need professional polishing and painting.

4.6. Digital sculpting techniques

Until fairly recently, only traditional sculpting techniques have been used, but now some new sculpting techniques have emerged with the development of digital technologies. Referring to the case study that was presented in the previous chapter, the current digital sculpting techniques involves Forward Engineering to create the 3D digital models according to the design, and using machining to produce physical models as master pieces for production by traditional manufacturing. Thus, the finishing is similar to that applied to hand-made models. Additional sanding or polishing may be required to remove the machining marks, and assembling may be needed as a result of the size limitations of machining capability. This method is only used to create abstract style sculpture at the moment.

4.7. Combining additive manufacturing with traditional sculpting techniques

The link between AM and digital sculpting is very clear with AM typically acting as a "3D Printer" to create a physical manifestation of the virtual sculpture. However, AM processes can also be combined with traditional sculpting techniques, since these can often be applied directly or indirectly to AM models. For example, the casting of silicone rubber from AM models to create female moulds can be used for converting the AM models into other materials. Another method is to use soft materials such as clay, plaster or glass-fibre inside AM made female moulds to produce master models.

Grinding, polishing and painting can be applied to both AM models and models made from other materials where AM was used for the master models. However, whereas some AM materials, such as different compositions of polymer resin, can be easily polished to create a smooth surface, other AM materials such as plaster or particulates are more difficult to polish and paint. Even so, these materials can be useful for simulating some stone effects. Manual carving and machining can use AM models as a reference when reproducing copies in stone and wood, sometimes at a different scale. As for the forging of metal objects, AM models can act as templates, when used with support moulds, around which the forging of the general shape takes place. Colouring and maintenance can be applied directly to AM models or to the models that are cast or forged from them (see table 4-6).

Table 4-6 Sculpting techniques that have been applied to AM models

Sculpting techniques	Direct or in-direct AM	materials
Moulding & casting	AM models act as master models	Clay, plaster, silicon rubber, glass-fibre
Grinding, polishing, painting	Direct AM or AM models act as master models	Resin, simulation of marble & metal
Manual carving & machining	Using 3D measuring device to reproduce copies from the AM models	Stone & wood
Forging, colouring, maintenance	AM metal models, AM models act as female moulds	Metal - stainless steel, bronze/copper, etc.

4.8. Summary of chapter

Both traditional and digital sculpting techniques for different materials including polymer resin, plaster, metal, wood and stone have been introduced in this chapter. Many of the techniques can be applied directly or indirectly to AM models. The literature based knowledge that has been studied is sufficient to understand the needs and experiences of other people. Understanding the old and new techniques used in sculpting and how they can be combined, provides a firm foundation for determining solutions to practical case studies and identifying the areas that need to be explored further.

5. Chapter Five: Archaeological Restoration

Going back a long way into history, human civilisation has generated a rich cultural heritage, which embeds spiritual values that represent vitality and creativity. Manifestations of this heritage include ancient buildings and other archaeological artefacts, which currently exist in varying states of completeness. Preservation of these "world treasures" has been recognised as a means of maintaining cultural diversity, and for promoting a common understanding of world history. This has been acknowledged by the United Nations in the creation of its "World Heritage Sites" (M. Zhou, Z. Wu, G. Geng, 2012) and the numerous archaeological restoration projects that are being sponsored by national governments. Traditional methods and techniques for archaeological restoration and replication find it difficult to reproduce the original appearance of heritage artefacts completely, realistically and vividly (G. Wang, 2009). In attempts to overcome these issues, digital technologies including 3D scanning, virtual reality, multi-media presentation, the Internet and digital archive have proved to be useful tools for archaeological conservation. This chapter gives an overview of existing methods for archaeological restoration and reviews emerging techniques for optimally using digital technologies to help society inherit historical culture, promote heritage protection, and achieve digital restoration. This topic is a significant challenge for contemporary research since it covers several overlapping disciplines.

5.1. Definition and Rationale

5.1.1. Fundamental knowledge

- Definition of cultural heritage

The "Convention Concerning the Protection of the World Cultural and Natural Heritage" indicates that cultural heritage is the treasure of historical civilisations, which is rare, non-renewable and non-reproducible, and not only belongs to the countries where it is found but also belongs to all mankind (Z. Li, M. Zhong, 2012) Cultural heritage originally included relics, architecture and monuments, but has been expanded to include the verbal presentation of the cultural landscape and other "intangible" cultural items.

- Classification of cultural heritage

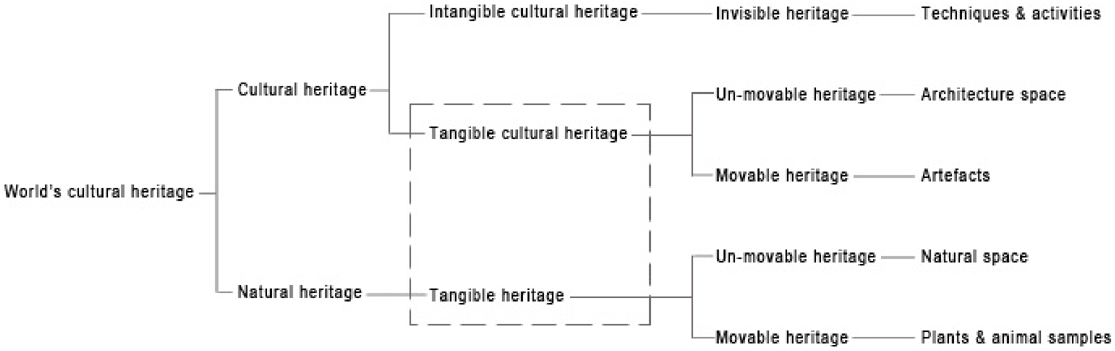


Figure 5-1 Classification system for the world's cultural heritage (X. Zhang, 2010)

Tangible cultural heritage includes relics with historical, artistic and scientific values. Un-movable relics are those that are stationary, including architecture space, natural space, ancient monuments, ancient tombs, caves, stone carvings and wall paintings. Movable relics refer to significant cultural objects, such as artefacts, documents, scripts, books and plant and animal samples from different historical periods. Intangible cultural heritage (also called invisible heritage) does not occupy physical space, but refers to the means of inheriting culture from generation to generation in different ethnic and traditional cultural forms that are relevant to daily life, such as customary activities, performance, conventional knowledge and techniques that related to hand-made artefacts. A summary of classification of cultural heritage is shown in Figure 5-1. Archaeological restoration mainly focuses on tangible cultural heritage.

- Archaeological restoration

Archaeological restoration is based on respect for the historical, scientific and artistic value of cultural heritage. It involves analysing the damage condition of relics via natural science theory and then utilising various techniques under the guidance of that theory, in order to restore and maintain their original appearance, and extend their life cycle (G. Wang, 2009).

Archaeological restoration is a process of synthesis that relates to every stage of relic preservation. This process brings together conservation methods for on-site data collecting, cleaning, strengthening, binding, replacement, storage, and exhibition.

There are diverse materials used for applications in archaeological restoration, and specific requirements will vary for different materials. There are a number of more general requirements that can be summarised as follows: materials should not be used without knowing the ingredients, their properties, composition, and purity; materials should be convenient for use in different environmental conditions, e.g. both indoor and outdoor; materials should not be harmful to the relics or the operators during application; materials should have reasonable cost, be easy to transport and store; materials need to be verified and tested by experiments in advance.

The aims of research into archaeological restoration materials are firstly to achieve a better understanding of the material properties that will enable their effective use, and to enable professionals to select appropriate materials suited to different conditions from a scientific point of view. Researchers working in the archaeological restoration field also need to explore new materials in order to address the problems with current materials.

- Reasons for and value of archaeological restoration

Cultural heritage embodies the wisdom of human civilisation, and thus represents the process of creation and development throughout history. It is rich in culture, and exhibits the accumulation of knowledge over the centuries. Archaeological restoration harnesses the desire for heritage preservation with the aim of protecting the results of human history and creativity. Historical treasures have experienced weathering and erosion, wars and historical changes sometimes over thousands of years, and yet it is the rapid development of modern society and recent human activities that have caused unprecedented impact and destruction. Many cultural heritages should be conserved as a whole (including both buildings and artefacts), but serious damage and missing parts means they cannot be conserved in this way either in their original environment or in museums. This can lead to dispersal of the relics and this also is a kind of damage to the characteristics of the whole heritage. Archaeological restoration can now adopt both traditional techniques and modern technologies to reproduce relics physically or virtually, so that it enables the complete restoration of entire heritage space.

Replication of relics can also be used for archaeological preservation, and should aim to reproduce copies of the originals accurately, without any changes or additions. The main reasons for replication are as follows: relics are seriously damaged and cannot survive for long even with repair treatments and so replicas can be used to represent the original for posterity; relics are being repaired or else cannot be fully restored and replicas are displayed as replacements; the display environment is not suitable for showing originals and so using replicas that are more robust are used instead; for richer contents of exhibits and for resource sharing, replicas of relics from other museums or countries can be displayed (sometimes in rotation with the originals); some relics that donated by other governments or individuals, replicas need to be given in return, which means replicas are needed to be reproduced and kept by donators to exchange the original artefacts.

5.1.2. Digital preservation/restoration

- Definition

Collecting and saving digital data to cyberspace accurately and completely by utilising modern sensing, mapping, and virtual reality technologies, in order to achieve a 3D digital archive for preservation, restoration, replication, archaeological research and data exchange (B. Frischer, 2008).

- Application levels

Applications of digital preservation is used at different levels to meet different needs, such as collecting digital data for building archives and utilising the digital data for repairing physical artefacts. These applications can be seen in a few levels, as the digital data is the foundation for all needs, which is used for reproduction of physical models, and the replicas can then be used for research since one physical model contains more information than hundred images, the research progress is shared for cultural exchange and transmission. In relation to Figure 5-2, digital archiving is the foundation of cultural heritage inheritance; preservation and restoration reproduce the original appearance of relics; archaeological research explores the connotation of cultural relics; cultural exchange and transmission carries forward the knowledge of great ancient civilisations.

Figure 5-2 Application level (X. Zhang, 2010)

- Technologies

Technologies used in digital restoration include high quality simulation and holographic (photography including information of all angels and views) storage and access systems for cultural heritage preservation; classification of cultural heritage, information-based storage, building digital resource symbol library and element/material database; virtual museums, virtual reproduction of monuments, digital simulation and reproduction of relic repair, cultural space and process; utilising virtual technologies to reproduce life styles, usages, consuming methods, circulation, transmission and inheritance modes within traditional skilled techniques; digital demonstration and transmission of cultural heritage. Table 5-1 shows how the different technologies are used for different aspects.

Table 5-1 Technologies for different aspects

Technologies	Aspects
Photography	Simulation & Holographic Storage
Imaging & scanning techniques	Classification storage & element/material library
Forward Engineering	Virtual reality & simulation of repair/reproduction
AM & CNC with manual finishing	Physical repairing & reproduction
Reverse Engineering & Flash/PPT	Demonstration & presentation

Indeed there is much effort and research in digital archaeological restoration as a foundation for computer aided archaeological preservation. The areas in which these technologies are being used can be summarised as rapid digital model production; simulation and engineering drawings for heritage sites, scenes and relics; matching and registering of rigid 3D objects, offering restoration solutions and assisting repair process; accurate demonstration of heritage models and scenes to support exhibitions, measuring and transmission; digitalisation of cultural heritage resource, providing sketches, sectional drawings and dimension annotation as support tools, in order to achieve digital production of archives, databases and reports.

- Objects to be restored

The objects that are the target for digital restoration should be the same as those that are currently preserved by conventional restoration. UNESCO indicates the range and objects of tangible heritage preservation in the Convention on the Protection of the World Natural and Cultural Heritage, which include relics, architecture groups, and monuments.

- Current situation

Digital technologies and virtual reality techniques have made great progress since the 1990s', which is shown in the impressive effects that have been achieved in heritage preservation. Technology centred preservation theory and specialisation provides effective support and open new paths for cultural heritage preservation. At the same time, cultural heritages have moved into the global market place as information products, and are subject to economic laws and affected by consumer culture, just like other commodities. The potential for greater market presence has encouraged governments and researchers to attach even greater importance to digital restoration.

Nowadays, the widespread application of digital technologies in the heritage preservation field has led to increased opportunities for research funding and publications. Some conferences for media, virtual technologies and information graphics have included streams on heritage restoration topics, such as International Symposium on Cutting Edge Digitalisation at Beijing China in 2011, The Digital Building Heritage Conference at Leicester UK in 2012, and International Symposium on Cultural Heritage Conservation and Digitisation at Beijing China in 2012. Government and research institutes have also developed relevant projects and research funding calls. Integrated use of digital technologies for heritage preservation has become a common research theme around the world, with the aim of exploring better solutions to the challenge of protecting world's archaeological treasures.

- Strategies/Requirements

The number of heritage sites which are targets for preservation is growing and the levels of potential restoration are becoming increasingly rich. However, at the same time, historical relics are being damaged by wars, natural disasters, and tourists. Therefore, adopting advanced digital technologies to integrate information control, preservation management and decision making, in order to follow a realistic, systematic and comprehensive strategy is vital. This will create a record of endangered relics with their historical values, and reproduce them virtually to build a permanent archive for cultural heritage preservation.

This requires using digital methods to collect and process the data accurately (without risking damage to the original relics), and then saving and transferring the images and 3D models in suitable formats for safer and longer term conservation. Such a digital database can then be used to display relics and monuments virtually in various ways, such as a digital museum, which can not only show the passive objects but also the original manufacturing processes, background stories and the original environment of the objects. Therefore, the data handling needs to meet numerous requirements for classification, management, repair and display, based on a range of digital and multi-media formats. Moreover, optimising the use of both virtual and physical modelling technologies to reproduce historical heritages efficiently, will require a combination of photography, 3D scanning, reverse engineering, forward engineering, additive manufacturing and CNC machining. Digital models can be used for building virtual experiences and exhibitions, where physical models can be used for repair, experimental research, replication, and souvenir product design. Also, there is a desire to integrate intangible and tangible cultural heritages for a more profound experience using stereoscopic storage, transmission and display.

5.2. Conventional Methods

The substance of heritage preservation is to maintain the historical, artistic, and scientific value of the relic. In order to achieve this, the original state/appearance has to be determined together with the most appropriate method of achieving maximum maintenance ease. Therefore, verifying the various connotations of the heritages' original state and the principles of maintaining it in practice become the primary strategy. The actual methods used will depend largely on the geometry and materials of the relics being considered.

There are many manual techniques appropriate for different materials that have been used up to the present day, and a few examples that are particularly relevant to this research are described in this section.

5.2.1. Technique 1 -- Bronze artefact reproduction and repairing

Replication is a basic and commonly used technique for bronze artefact restoration. Measuring is the first step for manual reproduction. Detailed dimensions need to be recorded as accurately as possible, although it is difficult to obtain these using only rulers and callipers, especially for complex shapes.

- Replication - Clay modelling of a "master"

A suitable working platform needs to be chosen for forming the master in clay. If the artefact is a round shape (such as the vase seen in Figure 5-3), a revolving platform of the correct size is appropriate. According to the dimensions of the artefact, the pedestal should be fixed accurately on the platform. Clay modelling is used to form the general shape on top of the pedestal (Figure 5-4). During this process, metal pieces can be cut to correct radii for removing the material while revolving the platform. The completed general shape needs to be measured again by rulers and callipers to ensure it as close as possible to the original artefact.


Figure 5-3 Original artefact


Figure 5-4 Clay modelling

- Replication - Non-reusable mould casting

After the clay master model is completed, a plaster non-reusable mould needs to be cast from it. This is done by mixing plaster and applying it to an appropriate depth (around 40 mm for) so that the overall shape still can be seen after the plaster shell has solidified (Figure 5-5).

The plaster-covered model is then removed from the working platform, a knife is used to take all the clay out of the bottom of the shell, the inner surface is cleaned with water and the plaster mould dried using a cloth. A layer of petroleum jelly is applied on the inner surface and more plaster mixture poured into the empty mould. When the plaster inside is completely dry, the outer plaster mould is broken off carefully using a small hammer and chisel without damaging the model inside. The new plaster model needs to be dried over a period of time until all its water content has evaporated. Then, the surface is polished using fine sand paper to produce a smooth surface (Figure 5-6). The smooth even texture of the surface is for perfect for carving the pattern at next stage of the process (Figure 5-7).


Figure 5-5 Plaster mould

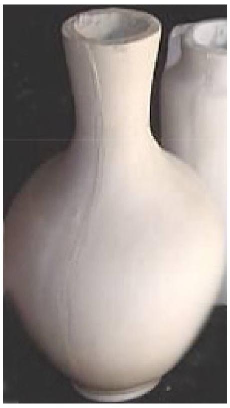


Figure 5-6 Plaster model


Figure 5-7 Carving pattern

- Replication - Master model carving

This starts with sketching the pattern with pencil on the surface before carving. The centre of each area has to be positioned correctly. Then the proportion and scale need to be controlled carefully in order to ensure integrity and uniform distribution. As it is not easy to keep the carving to an appropriate depth following the sketch, normally a plaster board is adopted for practice in advance. After the carving is completed, coating colour chips are added onto the surface. The colour chips can infiltrate into the plaster to fix the pattern, in order to protect the patterns from any possible damage during mould casting.

- Replication - Reusable mould casting

Reusable moulds can be repeatedly used which is especially suitable for mass production or the need of reproducing more than once. A clear mind needs to be kept during reusable mould casting as some pieces are overlapping and some need to be connected so that there is no room for any mistakes. Every section needs to be made with positioning holes that will register the parts together during assembly. Normally starting from the bottom up wards, the bottom section needs two layers of mould which is divided into three pieces. For each piece of mould casting, clay is used to enclose the plaster model, with well mixed plaster being poured into the gap between the clay enclosure and the model. Placing a small iron hook into the bottom before the plaster mould is dry helps with mould opening later, and the process is finished by making the surface flat with a knife after it is completely dry.

Following the bottom section, there are two symmetric groups of moulds for the body section, making four pieces in total. Using the same method as that for the bottom section, position holes are placed at the adjacent edges for later registration. When the four symmetrical pieces are cast, clay sheets with similar thickness are stuck on the inner surfaces, and one or two small holes are drilled in each sheet. This is followed by bonding of the four symmetrical pieces of mould for the body section with the two layers of moulds for the bottom section, together with a layer of clay on inner surface. Finally, there is the pouring of thick liquid plaster into the cavity, so that the thickness of clay sheet is the same thickness of the final metal vase.

When the central part of the plaster is dry, the six-piece mould is opened and the clay cleaned off with a knife and water. By re-assembling and bonding the mould with cloth strips, fixing the outer mould and inner mould together via nails through the holes that were prepared at previous step a cavity is created in between the outer and inner moulds that is the shape of the final model.
The last piece of mould covering the top section needs to have air holes and spurs. A simple way to make them is to position writing brushes at designated

places, removing them before the plaster is completely dry (Figure 5-8). Hence, sprues are left when the mould becomes dry. Then, by using small files it is possible to make the holes funnel shaped for easy flow of the liquid metal. After this, the whole reusable mould is finished and can be used for metal casting (Figure 5-9).

Figure 5-8 Mould holes & sprues

Figure 5-9 Final mould

- Replication - Tin casting

The mould is baked for one week before tin casting. Tin is melted in an oven and poured melts into the mould with a spoon. The intervals between every poring should not be long in case the artefact is formed un-even by cooled-down. Finally, removing the mould piece by piece, cutting the sprues off with a saw and cleaning the nail parts reveilles obtain the final model (Figure 5-10).

Figure 5-10 Unpacked mould to obtain the final Tin model

5.2.2. Technique 2 -- Stone artefact restoration

- Traditional restoration methods

Some traditional restoration methods are still being used to protect stone artefacts, such as using an anti-seepage and draining system, awnings to improve the storage environment; adopting materials that are available at the site and suitable for the artefacts. For example, a mixture of lime, raw tung oil and hemp in the radio of 100 : 20 : 8 is used to fill the gaps between stone parts. To glue damaged stone parts, a kind of "welding medicine" is conventionally used, which is produced by mixing bees-wax, white wax and rue in the ratio of 3 : 1 : 1, heating in a hopper and compressing tightly. Bees-wax, wood oil, sticky rice juice and natural rosin are used to protect stone from water. Also, for large scale ancient sculptures, holes are made, wooden sticks placed inside, and then they are filled with limestone to support the weight and fix the position.

However, some old restoration methods are not in use anymore as they are harmful for the stone artefacts. For instance, applying a layer of gold leaf on the stone surface makes it difficult for the water inside to evaporate out, and the stone easily becomes loosen due to water immersion. Using easily corroded iron parts to fix the stone may cause new cracks; concrete replacement can corrode stone; oil paint can protect hard stone from eroding by sun burn, rain, water and salt, but when it is peeled off it may damage the stone surfaces that have poor quality and severe weathering.

- Restoration processes

Historical relics are not renewable and much damage may have accumulated over a long period of time. Sufficient research in advance is necessary since an inappropriate process plan and requirements definition without verifying may cause disaster. Every step should be based on the previous step to avoid subjective and non-scientific procedures.

Data collecting and archiving

The literature research and data that need to be collected mainly include: historical background of the stone artefact, establishing time available and aims; changes in the relics and environment, especially restoration history; specification and drawings of previous repair work; restoration materials and techniques used. Also, recording the environmental elements including rain, evaporation, temperature, humidity, wind direction and speed, sunlight, etc. the stone property, water erosion, chemical composition, cracks, earthquake activity, air pollution, etc. Organising the above data into a table with text to build an archive and database is useful for later work.

Verifying and evaluating relic value

To evaluate the value of a relic, the standard measure of value needs to be verified first, otherwise the definition of value can be subjective. Basically, the main value of relics is the mass historical information, including social, political, economic, cultural, historical, scientific, artistic, etc. which are physical evidence of historical activities. This information is not renewable or replaceable. The main content of evaluation is the historical, artistic and scientific value; storage situation and management conditions. The evaluation should be based on research, which refers to analysis of previous records and observation of current objects.

Identifying objectives

Identifying objectives involves making a preservation plan for the relics, which normally includes restoration approaches, personnel functions, exhibition plans, and management methods. These plans need to be approved by the relevant heritage preservation authorities before implementing.

Making restoration solutions and plans

Restoration solutions and plans need to meet standard requirements and rules, and need to be approved by the relevant administration. Significant restoration projects need go through pre-research, experiments, observation, solution design, discussion, reporting and implementing. If any problems are found during the project, the work needs to stop immediately to amend the solution and report again. Moreover, regular summaries need to be made at agreed intervals, in order to discuss and modify the plan over time, especially for new material, new technologies and new techniques. Beside the experiments in the lab, on site experiments, testing and observation for a part in a certain time period are also essential before applying methods to on the real relics. This will provide, proof that the method is truly useful for preservation and not harmful to the relics.

Recording the restoration process, implementing routine maintenance and management

This step is the most basic and important step for preservation, since making and following a routine conservation plan with rules will eliminate dangerous elements and avoidable damage.

- Case study - Weathering protection for Forbidden City marble carving

The Forbidden City (part of the Palace Museum in Beijing) is one of the most complete royal gardens, which plays a significant role in the world's architecture. However, many stone artefacts are seriously damaged by weathering, such as the middle joining line of stone enclosures, where some parts have become powdered by wind effects. The Palace Museum has conducted research and experiments over eight years, using a kind of silicone material for preservation and maintenance to achieve the desired results.

Classification is based on the degree of weathering damage. Taking middle and severe damage levels to marble enclosures as an example, water is commonly used for cleaning as the first step. If some dirt cannot be removed by water, then a neutral solvent can be adopted. Drying in natural air for two days follows cleaning. Then there are two ways for water proof processing.

One is a pouring method, which involves wrapping the stone carving in cotton, applying a layer of plastic film to the outside, adding the water proofing agent every six hours, and repeating this process five to six times. This method is complex procedure that costs much in materials, and the result is not very obvious so it is not a commonly used method. Another way is the brushing method, which requires repeated brushing with a one hour interval between two applications. Spraying was tried also, but too much agent was kept in the air during that process, which can be quite harmful for operators so that spraying was not adopted. After brushing on the water proofing agent, the artefact must not be touched by water for about two days, so this method is normally done in the dry season with the whole operating process taking around six days.

Although the stone surface initially turns darker after brushing on the water proofing agent, comparing these surfaces with those without protection after two years, the difference was very subtle. The agent material is durable and compatible with marble, which allows infiltration to a depth of over 20 mm, and keeps its protection effect for over 10 years. In addition, the water proofing material is a neutral agent which solidifies the stone powder on the surface but does not generate any elements that are dangerous to the original stone.

5.2.3. Technique 3 -- Lacquer, wood and bamboo artefact restoration

- Principles of lacquer repairing

Lacquer ware has been processed through dehydration and after finalising the shape, it should be put in a normal humidity environment to help it keep its natural moisture content. Optimally combining traditional techniques and advanced technologies and materials is useful in repairing the damaged artefacts. The aim is try to restore the original appearance without affecting the general look and texture.

To repair minor damages such as cracks or small pieces lacquer film peeled off, using shellac alcohol solution to fill the seams; larger gaps can be fixed by combination of epoxy resin or acrylic resin with wood. As to the film that peeled off but not yet drop, using hot water to soften it, put microcrystalline wax film underneath and heat by electronic iron to melt the wax, in order to fix the lacquer film and allow to modify the position repeatedly.

Due to the long time they spent in underground conditions before being discovered, lacquer relics have often been soaked by water and affected by biological, chemical and physical elements. This has caused different levels of erosion, with some areas of lacquer film having peeled off from the base. To repair this kind of damages, the remaining cloth and base coat should be cleaned first, then shellac varnish, polyvinyl acetate emulsion and acrylic resin should be used to repair the general shape and to re-fix the lacquer film. Finally, aging treatments are applied to local areas.

A method to repair severe damage including large areas where lacquer has peeled off and a wooden base being too fragile for fixing, is as follows. The lacquer wares are carefully peeled from the original and immersed in water; the wooden inner base is then remodelled according to the original shape and size; the lacquer films are then fixed to the new base with microcrystalline wax; finally, raw lacquer, wood dust, plaster and paint are used to fill any seams and cracks.

- Wood and bamboo repairing techniques

The traditional restoration procedure for wood artefacts is relatively simple as there is usually no paint, lacquer film or base coating, etc. For small scale wood carvings that consist of one entire block or a few blocks of wood, the repairing method is similar to that for a lacquer ware base. Some wood furniture with a complex assembly structure needs to be restored according to the original structure, i.e. any replacement parts must fit exactly with the original parts. Large scale wood artefacts such as building parts, should be restored based on ancient architectural principles; if the parts are fragile from being found underground, then bamboo or wood connectors are used to fix the damaged parts and binders, epoxy resin or acrylic resin can also be applied for chemical fixing when necessary. Wood board or bamboo strips are adapted for physical fixing before the glue/binder has solidified, especially for large scale artefacts with thin shells.

Bamboo artefacts made from an entire section of bamboo are restored with a similar approach as when repairing a lacquer base. Thin and long shaped artefacts also need to be fixed using wood boards, epoxy or acrylic resin. Restoration of bamboo wickerwork is different with that of bamboo carvings. A single piece of bamboo strip should be repaired first, using old bamboo material or new material with an aging treatment, simulating the original colour and texture before weaving it according to the original structure.

Lacquer, wood and bamboo artefact restoration requires professional and skilled techniques, normally through specialists who have been trained for years to operate in this way. New staff need to spend significant time following old staff with rich experience to learn from. They will only be able to conduct the restoration work independently after accumulating much knowledge and experience over many years and after passing a national class test storage conditions

- Storage conditions

Generally speaking, there are three lighting methods in the museum, natural light, artificial light and a combination of these two; all three can emit ultraviolet light, which is the main harmful element for lacquer artefacts. This is because the lacquer film is a kind of polymer that contains unsaturated hydrocarbon, which can easily change the lacquer film's property by a photochemical reaction. Ultraviolet light also generates ozone (O_3) by ionisation with air, and the ozone can breakdown the lacquer film through an oxidising reaction, which makes the lacquer change shade, become fragile, develop bubbles and even peel off. It also reduces the strength of the wood base by decomposing the wood fibre. The International Illumination Association suggests that the luminous intensity of ultraviolet light for relics should be kept under 75 lm/μW. Therefore, the storage condition for lacquer artefacts should avoid them being in the sun, and should protect the artefacts by using only fluorescent lamps that do not emit ultraviolet light. A filtering film, ultraviolet-proof coating, or indirect lighting combined with a translucent material that can absorb, filter and scatter light such as frosted glass and Plexiglas, can be used to decrease the luminous intensity. Thermal radiation is another key element that can damage lacquer artefacts. Although pursuing artistic effects during display is almost as important as protection, strong light and long term un-evenness in lighting must be avoided.

5.3. Digital Methods

The main digital technologies used to produce physical models are AM and CNC machining. AM was introduced and reviewed in Chapter Two and CNC machining can be seen as a reverse process to AM since it creates 3D shapes by removing material. This technology was developed much earlier than AM and has been widely used in processing freeform surfaces (A. Lasemi, D. Xue, P. Gu, 2010). The 3D digital data can either be obtained by Forward Engineering, which is building digital models using CAD modelling software, or Reverse Engineering, which involves manipulation of 3D scanned data. 3D scanning refers to collecting data from a physical object, and can be likened to using 3D photography for the object to obtain data from every angle/view. The RE working process and strategies are introduced in case studies two and three below. At the current moment, some geometric modelling software such as Freeform, ZBrush and 3D Coat emphasizes the use of solid models or volumes rather than surface-based models. Although this kind of software offers a convenient way to modify a general shape, the data that is transferred from point cloud or facet format to voxel format may lose sharp edges and corners.

Case studies within the literature

Introduction

The case studies in this section show progress made and problems encountered in previous work that introduced digital methods into the archaeological restoration field. The work was undertaken through a combination of AM, CNC machining and manual techniques; the manual techniques referring to traditional sculpting and finishing techniques described in Chapters Three and Four. The four case studies were found within the literature, and were selected because they demonstrate particularly well the use of digital technologies in this field. The case studies are as follows:

1. digitalising an ancient Thailand temple site
2. data acquisition of a large scale sculpture in an Italian museum
3. merging 3D scanning data by using a hybrid system
4. the replication of King Tutankhamen's mummy

These case studies will provide the reader with a better understanding of related research and the progress that has been made as well as highlighting the existing problems in this area. The first two studies provided the author with significant insight into RE and data archiving issues, while the latter two provided inspiration for the practical experiments that are introduced in the next chapter.

5.3.1. Case study one -- Computer-based reconstruction of the temple site in Phimai, Thailand

This project serves as a specific case study to highlight many issues raised during computer-based visualizations for ancient architecture with relief sculptures. Issues of time, scale, geometric representation of form, and resolution of surface detail were covered. This project aimed to combine the needs of a museum to promote tourism with the enhancement of the communication process between computer modellers and archaeologists.

5.3.1.1. Context

The temple that was the focus of this project is the most important Khmer monument in Thailand. The reconstruction was undertaken by Thailand’s Fine Arts Department. Adjacent to the site, the Phimai Museum contains many of the artefacts and architectural sculptural elements that were retrieved. Visitors today have the opportunity to experience a complex of temples in various states of reconstruction. The prototype digital model produced by FE aims to promote the site through the generation of images, animations, and interactive VR worlds. These form the basis of a multimedia presentation, with the virtual environments also addressing important safety and accessibility concerns, and also offering an alternative to actually visiting the site. Thus, creating the temple model began as a demonstration project to illustrate the value of new media in the promotion of an historic site.

5.3.1.2. Time & scale

Scanning data was collected during the autumn of 1999 and initial assessment indicated the potential uses of computer modelling, as well as the type of information that would be needed to create a more detailed model. Due to the huge amount of data and the complex data structures required to handle this, the digital model could only be completed during the Autumn of 2000 (See Figure 5-11). A questions emerged as to whether a single model could serve the needs of both scholars and tourists, and to what standard should it be made? The desire for fully detailed re-creations could easily result in the addition of features that may not be feasible for the tourism industry to achieve. As in a traditional restoration process, drawings and models were important for manufacturing, and some artistic awareness was needed to create a complete and credible 3D reconstruction of the site.

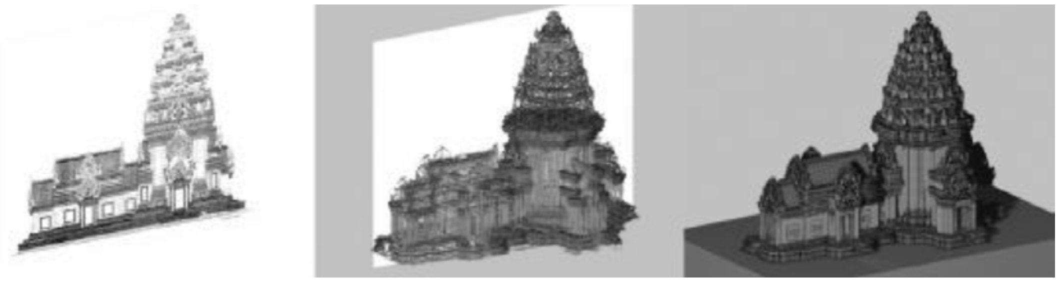


Figure 5-11 Drawing, wireframe, texture-mapped view of the computer reconstruction of the central sanctuary, Phimai (R. M. Levy 2001)

5.3.1.3. Geometric representation of form

Appropriate strategies must always be selected depending upon the intended use of the model. Images and animations from highly detailed digital models were actually just intended to give the observer a sense of architectural space, so that it may be possible to reduce the complexity of the geometry and sculptural details. Interactive VR worlds offer a more exploratory framework for the analysis and presentation of archaeological data, but for an application to perform within acceptable ranges, the developer must consider hardware performance. What is more, limitations in data storage, computation, and video display prevented creation of a model that was accurate in every detail. Also, the generation of complex structures and sculptural details had to be completed within a reasonable period of time. Therefore, one strategy was to build fully detailed models only for selective areas. In this case, for the 3D scanning technology adopted, the accuracy was 2mm, which offered reasonably fine detail but also presented a serious data handling obstacle. A 3D model of a single piece of wall sculpture would contain meshes with millions of vertices, whose demands upon rendering would exceed the computing capacity of even high-performance graphic workstations. Overall, constraining the scope and goals of modelling was an important consideration needed for success.

5.3.1.4. Resolution of surface detail

Establishing a database of every artefact with all of its cultural, geometric and materials information is time consuming and can only be a long-term goal for most archaeological projects. In this case, building a model of the site complete in every detail was an impossible task. As most of the objects demanded standard views, such as front, back, left and right, they could be build separately and selectively, and the whole architectural reconstruction could be assembled like solving a 3D puzzle. However, constraints in the accessibility of data collecting, different demands of hardware and software, different scales, format and styles of recording would bring deviations from actual measurements. Therefore, drawings and photographs were essential for showing the details of geometric structures, especially for models that were to be used for walk-through in a VR environment, such as the example shown in Figure 5-12. As a result, not only high resolution 3D scanning data and modelling were used, but also drawings and photographs as references to guarantee accurate geometric and surface detail. In the absence of any detailed data (due to parts of the structure being missing) the process must be based on information drawn from other historic sites that share a common cultural and artistic tradition. Another approach is to model areas that are lacking details as an overview, eliminating any architectural or sculptural details and instead going for a map which contains sufficient information from a simple extrusion of plan elements, such as walls, columns and floor. This view could indicate the user's location and show the virtual tour route without misunderstanding or confusion.

Figure 5-12 Interior perspective, wireframe, shaded, texture mapped view of the computer reconstruction of the central sanctuary, Phimai (R. M. Levy 2001)

5.3.1.5. Conclusion

Presenting architectural and sculptural details that were destroyed or lost over the centuries posed a significant challenge, especially for scholars who required reliable and valuable resources for future research and reconstruction. Each element had to be modelled as a unique object and detailed drawings and photographs were required to assemble these together. Unfortunately, time and computing limitations made such an approach extremely difficult. One strategy used in the modelling was to focus only on selective areas or objects in detail and build these separately in a database. In addition, creating a VR environment for the entire site which enabled the use of images as bump maps to provide an impression of relief when the object is rendered also met the requirements of tourism and public education.

5.3.2. Case study two -- A hardware and software system for digitizing the shape and colour of large fragile objects under non-laboratory conditions

5.3.2.1. Context

With the development of laser range-finder technology and algorithms for combining multiple ranges and colour images, the shape and surface characteristics of many physical objects can be accurately digitized. As an application of 3D data collection, a team made up of 30 faculty, staff and students from Stanford University and the University of Washington spent one academic year in Italy to do research on digitizing sculptures and architecture created by Michelangelo.

The aim of this project was to collect 3D data of statues and make an archive that was as detailed as current scanning and computer technology would permit. Specifically, this ranged from capturing the geometry of chisel marks which required a resolution of 0.25mm, and scanning the sculpture of David that stands 5 metres tall without its pedestal, which required a dynamic range (a range to recognise from the largest figure to the finest detail) of 20,000:1. Additionally, the colour was also captured by extracting the surface reflectance of each point on the statues for further rendering and study. A difficulty that soon became clear was that the old statues were covered with a complex mixture of marble veining, dirt, waxes, other materials used in prior restorations, discolouration and other effects of weathering, since many of them had stood outside for hundreds of years.

There were relatively few groups who had tackled the problem of digitizing large 3D art works, although digitization of 2D artwork is a mature field and has been widely adopted in the museum and library communities. Two notable previous exceptions are the National Research Council of Canada (NRC) efforts which focused on building robust systems (G. Godin, J. A. Beraldin, et al. 1999) and IBM's efforts which scanned a statue under field conditions using a structured-light scanner with relatively good resolution (H. Rushmeier, et al. 1997). Their equipment was light-weight and therefore more portable, but the resulting models were not very detailed or realistic.

5.3.2.2. Scanning system

Due to the demanding requirements of capturing chisel marks smaller than a millimetre, maintaining a safe scanning distance, reaching the top of the sculpture of David which is about 7 metres tall on its pedestal, the main hardware component was a laser triangulation scanner with a motorised gantry customised for large sculptures.

As to capturing the chisel marks, a lower resolution would have blurred the marks significantly and anything higher would have made the datasets unmanageably large. Therefore, a Y sample spacing (along the laser stripe) of 0.25mm and a Z (depth) resolution at least twice this fine were used, which allowed a field of view 140 mm wide (along the laser stripe) by 140 mm deep, and provided a satisfactory resolution. The narrow beam of laser light, when shone over a long distance, offered great latitude in choosing the distance between the camera and the target surface. Although a scanner with a variable standoff would have been helpful, such devices are difficult to design and calibrate. A 25 mm lens, which at 1120 mm gave a 250 mm × 190 mm field of view on the statue surface, was employed to acquire colour at the same resolution as the scan data. Due to the significance of controlling the spatial and spectral characteristics of illumination, a 250-watt quartz halogen lamp was used to produce as uniform a circle as possible on the sculpture surface.

The most original part of the scanning system was the mechanical gantry, which was unusual in size, mobility, and re-configurability. Translating and rotating the scan head to sweep the laser area across the target surface both had their drawbacks. Hence, the scanning system was designed with a vertical truss, a horizontal arm that translated vertically on the truss, a pan and tilt assembly that translated horizontally on the arm, and a scan head that mounted on the pan-tilt assembly, which allowed it to move freely in four directions (see Figure 5-13 and 5-14). The scan head contained a laser, range camera, white spotlight, and digital colour camera.

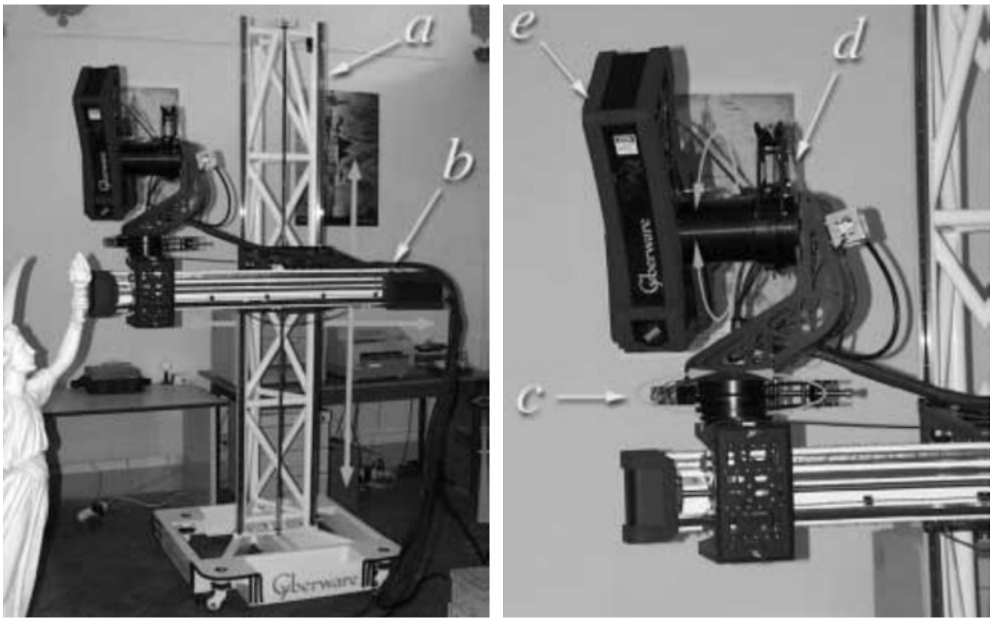


Figure 5-13 Mechanical gantry of the 3D scanning system (M. Levoy, 2000)

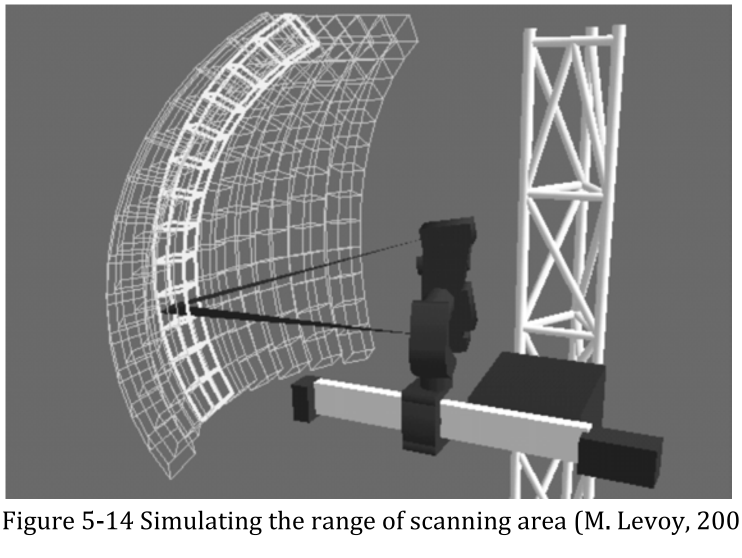


Figure 5-14 Simulating the range of scanning area (M. Levoy, 2000)

5.3.2.3. Scanning Procedure

The biggest problem during the scanning process was the lack of an automated method for planning scans. Scans were planned "by eye", which was a slow and error-prone process. Moreover, smooth and steady motion was difficult to obtain because of hand tremors, and it was fatiguing to hold the scanner for long periods of time while trying to avoid harming the sculptures.

To produce a polygon mesh with valid information at each mesh vertex, a lengthy post processing procedure was needed, as soon as a scan was acquired. The post processing had to include aligning the scans, merging the scans and filling holes to output an acceptable triangle mesh.

5.3.2.4. Strategies

Against the significant challenge of large sized datasets, an efficient global alignment algorithm and a limited range image merging algorithm were adopted (registering global and local data). However, in order to plan scans, each scan was quickly added to the 3D models and loaded into memory. Since there was no simplification algorithm that could be reasonably run on the mesh of a 2-billion polygon model, a lot of time was spent on writing code for handling large scanned models. Storing the data as range-images instead of polygon meshes was the first technique to save space and time, and range-image pyramids were constructed on demand, at only those levels requested by user, and never storing them. In addition, with the demand of viewing a 3D model but not performing geometric operations on it, a viewer that combines a multi-resolution hierarchy based on bounding spheres with a rendering system based on points was developed. With modest hardware acceleration, the viewer could permit real time navigation of scanned models that contained hundreds of millions of polygons. (Table 5-2 with summarised statistic information from this project is given below)

Table 5-2 Statistics about scanning Michelangelo's statue of David
The area, volume, and weight of statue are estimated from the data

The statue	
Height without pedestal	5,17 m
Surface area	19 m^2
Volume	2.2 m^3
Weight	5,800 kg
Raw dataset	
Number of polygons	2 billion
Number of colour images	7,000
Lossless compressed size	32 GB

Other statistics	
Total size of scanning team	22 people
Staffing in the museum	3 people (on average)
Time spent scanning	360 hours over 30 days
Man-hours scanning	1,080
Man-hours post processing	1,500 (estimated)

5.3.2.5. Conclusion

Firstly, the scanning of masterpieces is not always permitted and it may not be possible to move or touch the target objects. Secondly, the difficulties of digitizing under field (non-laboratory) conditions were underestimated, such as shipping 4 tons of equipment to a foreign country, moving them into the museum, a scanning time of 5 months, the high cost of scanning work as well as hiring guards, and a constant stream of other questions. Lastly, there were several disappointments, although the original plan did work out. It might be considered too geometrically complicated to scan using laser triangulation technology. The datasets were manipulated and the team tried to assemble them into a map. Efforts were made to make the models freely available for further research.

5.3.3. Case study three -- Efficient 3D shape acquisition and registration using hybrid scanning data

This case study provides significant knowledge about merging scanning datasets with different resolutions, which is especially useful for antique restoration since building a large data base and repairing large scale antiques with fine details are major problems in this research. An animal skeleton was taken as an example of target geometry shown in Figure 5-15 (H. Zheng, etc. 2008), with the hybrid scanner system introduced in this case study.

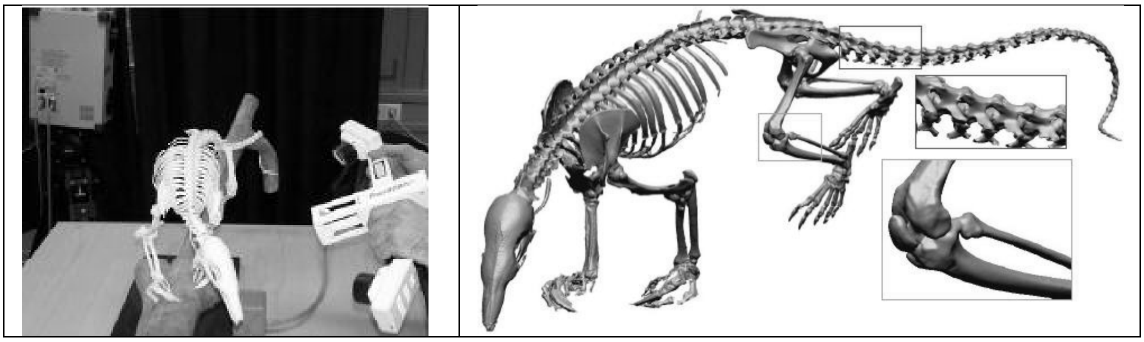


Figure 5-15 Target geometry with stationary scanner & hand-held scanner; target hybrid data of the 3D model

5.3.3.1. Background

Efficient and high-quality 3D acquisition and surface registration are always difficult problems, so solutions using a hybrid laser scanning system were investigated in this case study. The system was based on a hand-held scanner for the coarse global low resolution data coupled with a stationary high resolution line scanning system. Low resolution scanning data supplied the global shape structure prior to registering the high resolution local 3D surface patches, which could then be registered optimally with less overlapping and redundancy. The results showed that, based on geometric data alone without using texture information, the proposed hybrid 3D scanning approach outperformed previous approaches in the presence of noise and outliers, and that it should be possible to further apply it to other practical 3D shape applications.

5.3.3.2. Hybrid system

Basically, 3D shape laser measuring techniques used can be classified into two groups according to the measuring mechanism and scanning hardware. One method could achieve high resolution when scanning patches, and actually included two techniques. One system was stationary and the focal length of the camera was adjusted according to the scanning facades, while another one needed to rotate and translate in relation to the 3D object to cover the entire 3D shape. A hand-held laser scanner was the other method, which was light and portable. It could easily acquire the global shape with relatively low resolution within a continuous scanning period.

Although many methods were available theoretically, due to the large number of possible 3D shape deformations, transformations, and noise complexities, registration of local surface patches may lead to mass local data and uncertainty of matching with global data in practice. The problems of registration using only high quality scanned local surface patches could be summarised as follows. Firstly, the most suitable scanned local surface patch was difficult to select from the many scans available as the local area of surface appeared in several different scans. Secondly, small alignment errors for local patches might accumulate to a large distortion without global measurement criteria. Thirdly, prior existing global shape geometric information, which could be used to optimally adjust local surface registration, was difficult to find.

The approach of the new data acquisition system that used hybrid scanned data sets from a stationary and a hand held non-stationary laser scanner can be described as follows. Firstly, the fundamental 3D scanning trade-off was defined as being between covering a large amount of the global shape in each scanned patch and having numerous local surface patches. A global scan worked together with fewer local scans instead of having many small local patches. Secondly, the local scans were registered in pairs simultaneously with being registered to the global shape model. In this way, different types of registration errors and distortions were minimised. Finally, this approach was simple and robust in the presence of noise and outliers, and experiments showed that the prototype hybrid scanning method could achieve high-quality 3D shape acquisition and surface registration more efficiently than previous approaches.

5.3.3.3. A 3D shape scanning trade-off

To achieve good quality surface matching and registration efficiently, a compromise was significant between local geometric surface patches and the global shape structure. The increasing of local surface patches, which might improve the accuracy of local geometry, may also cause accumulation of distortion and mistakes. So that certain global shape structure information was essential for adjusting and controlling the registration of local surface patches optimally to avoid such distortion and errors.

As the size of objects, geometric complexity, and material reflection would affect overlaps and scanning noises among scanned local surface patches, different numbers of scanned local patches were needed to cover the global shape of different models. On the one hand, each local surface patch might have high resolution but lower coverage of the global shape if more local scanned surface patches were used. On the other hand, a model with higher coverage of a global 3D shape could supply more geometric structure features and global shape geometric information. So a hybrid stationary and non-stationary hand held laser scanning system was adopted to enable these two types of 3D laser scanners to complement each other.

5.3.3.4. Surface registration using hybrid data

A new approach to align the local surface patches in a local-to-global manner was designed for using the hybrid data. That is, pair-wise local surface were aligned in the rigid method to keep more accuracy of those aligned local surface patches, and each local surface was non-rigid adjusted using a global non-rigid method. A simple explanation of this method is shown in table 5-3 below and detailed explanation is presented in the next section.

Table 5-3 Surface registration method

Local data	Registering in pair with adjacent patches using restricted algorithm method
Global data	Registering automatically by software and adjusting manually
Local data with global data	Registering automatically by software and adjusting manually

5.3.3.5. Rigid local surface registration

Local surfaces were registered by iteratively performing two operations until convergence. The first operation consisted of finding the closest point in one point set for each point in the other set. Then the minimal distance between the two point sets was estimated using only the corresponding point pairs in the second operation. However, the complexity of searching a good alignment was simplified by using hybrid scanning data, as accurate initial global feature points were supplied, and the low resolution global shape was directly used to learn a probability distribution, which provided an adaptive weight for refining pair-wise local surface alignment.

5.3.3.6. Non-rigid global surface registration

Global registration was designed by mapping each local feature point onto its global position, which meant all local scans needed to be warped to align the global features when they were positioned, as the low resolution global shape model supplied geometric feature points prior as the global feature positions. The resolution of 3D shapes could be improved by using non-rigid aligned local surface patches or merging hybrid data after the registered surfaces were warped to the entire scan. Precise local-to-global non-rigid alignments were essential for using low resolution global geometric prior, although automatically accurate correspondence of local-to-global feature points on complicated 3D models still needed to be further investigated.

5.3.3.7. Comparison

Firstly, registration errors appeared when using only local surface patches even with a lot of human supervision, and this was improved by using hybrid scanning data. Secondly, the local surface patches fitted together well when using the hybrid method and the resulting model was very close to the original object. Small distortions still appeared due to some gaps in the low resolution scanning data. Thirdly, more robust performance was shown by using hybrid data according to the results of experiments.

5.3.3.8. Conclusions

The advantages of the hybrid approach could be summarised as: it provided information for global optimisation, reduced the number of required scanning patches, easily filled holes, eliminated accumulated alignment errors, and was robust to noise and outliers. More 3D shape and outdoor 3D acquisition and registration in various research domains should consider adopting this proposed method.

5.3.4. Case study four -- Building a 3D replica of King Tutankhamen's Mummy using a Stereolithography Machine

<http://www.materialise.com/cases/3d-replica-of-king-tut-s-mummy>

5.3.4.1. Context

The tomb of "The Boy King" Tutankhamen (aka King Tut) who died around 1324 B.C. was discovered in 1922 and artefacts from it were displayed to the public during the 1970's. A cloned body of King Tutankhamun’s mummy was produced by Staab Studios and Materialise in 2010. Gary Staab is a natural history and prehistoric model maker, and Materialise are well known in the AM industry as a leader for software solutions.

5.3.4.2. Reproduction process

The process started with 3D data collecting using CT scans of the mummy artefact. Then the data was import into Materialise's Mimics software to create 3D digital models of the actual mummy accurately (Figure 5-16). Data manipulating was an essential step to hollow out the digital model as a shell in order to reduce the building material and the weight of the physical model.

Another reason was that since a hollow structure uses less material and has decreased surface area of each layer, building time as well as cost were reduced. After that, Magics software was used to fix the file for obtaining the final 3D digital model in the STL format with an appropriate number of triangular facets and a "watertight" model that was ready for Additive Manufacturing.

Figure 5-16 3D digital model figure

Figure 5-17 AM building process

The final digital model was imported into a large scale Mammoth Stereolithography (SLA) machine to build the physical model. Thanks to the large working platform, the full size model that was about 1.7 m in length was produced in a single build (Figure 5-17). As the building material was a liquid photosensitive resin, support structures were generated in advance by e-Stage software in order to support the model while being built. Then, manual post processing was needed to remove the support material which was built in the same polymer resin, and attached to the model with small contact points that were designed in the software.

Although the initial physical model was produced relatively accurately and efficiently, the AM model needed to be shipped from Belgium to the US for finishing (Figure 5-18). This was because the model that was produced by AM was in a single colour and lacked some details needed to meet the high simulation requirements. Significant finishing techniques were applied based on the complex surfaces which included adding details, colour, and texture to create an object that looked identical to the original (Figure 5-19). This case study provided an example of reproducing a large size artefact by combining the SLA AM process with manual techniques. It can be seen that the manual tasks still required professional modelling or finishing skills from someone with rich experience. , A good understanding of both the requirements for archaeological restoration and digital technologies as well as good communication between co-workers are all significant issues in the AM/manual combination method.


Figure 5-18 Completed physical model figure


Figure 5-19 Final replica with finishing

5.4. Chapter Summary

Archaeological restoration has similar aims and activities to some fine art sculpture work, for example, capturing a shape and replicating it in appropriate materials. One of the problems to be addressed in this research is that digital replication is often done in an "ad hoc" manner with a lack of knowledge about what alternatives exist and when they should be used.

Finely detailed cultural heritages sculptures may need to be repaired with exactly the same materials as the original for their special properties. If this is the case then it is likely that a process similar to the original process, e.g. casting or carving, will also be needed. When the design cannot be manifested by traditional methods or relics are not able to be repaired or replicated using the original process and material, then a combination of different techniques must be used.

Conservation of the large number of relics and heritage sites around the world is an enormous task. Any help in making this task more efficient is to be welcomed. The development of heritage preservation strategies should optimally integrate traditional techniques and advanced digital technologies, since both have their advantages and limitations. Attention also needs to be paid to the following aspects: rescuing and repairing damaged relics; identifying more appropriate storage environments and strengthening preventive protection; future research into traditional restoration and maintenance techniques; research into developing and using new materials; discussion and amendment of restoration principles; cultivating high quality talents in the relevant fields; promoting academic exchange and technological collaboration.

The next phase of research was to explore how the latest development in AM could advance the field of digital replication, and this will lead into the case studies that the author conducted.

6. Chapter Six: Case Studies Undertaken by the Author

6.1. Introduction

According to the reference methods, and in order to better understand and adopt AM in the 3D art work reproduction process, several cases were set up in association with companies and students in both the UK and China. In this research manufacturing process chains have been optimised to support users in selecting the right AM technique for every stage of the art work reproduction.

Three practical projects were undertaken by the author as part of an action research agenda. These were the enlarging of sculptures for the Mongolian and Tibetan governments, and antiquities restoration in the Forbidden City, Beijing. The purpose of these case studies was to gain further knowledge of Fine Art, Digital Art and the conjunctive area between them. This knowledge contributed towards finding answers for the research questions. The cooperation with people working in different fields allowed the author to obtain interactive feedback efficiently and therefore find effective solutions. In addition, the case brought opportunities to integrate action research with other research methods for problem solving in the real world.

6.2. Case study one – Mongolian Large Horses Sculpture

6.2.1. Context

Ordos city in Mongolia is the location for a government-led urban design project called “a thousand horses galloping ahead”, representing the area’s nomadic ancestry and its recent vigorous development. Mongolia is called a "horseback proud nation" which thrives on livestock husbandry. It is also a vast and sparsely populated area that needs artworks of a large scale that effectively use space so that they can be viewed from a large distance away. The project required at least 100 horse sculptures installed alongside a river, with each horse being 4 metres in height and manufactured in marble. The sculptures were designed and manufactured by The Sculpture Workshop in Beijing, and 10 samples were completed first for the purposes of specifying materials, manufacture, general style and appearance. It was during this stage that the action research case study was conducted.

The reason for choosing this case study was that the characteristics of this project particularly suited the research. Firstly, a large number of horses had to be created and every one of them had to be different. This meant that "mass individualisation" could take advantage of AM and other digital technologies since they can generate various models based on one original. Secondly, the large size horses (3 to 4 metre tall) needed to be enlarged ten times that of the original model, so the benefit of using layered manufacturing for section enlargement could be shown. Thirdly, a hundred small scale horse models had to be produced quickly as sand models for demonstration and evaluation. This allowed the demonstration of another strength of digital technologies and AM, i.e. that they allow digital shrinking and efficient production of small physical models. Lastly, easy manipulation of digital models and the production of accurate full size models for marble carving played a significant role in the innovative process chain.

6.2.2. Challenges

The estimation of the timescale, cost, modelling complexity and manufacturing process requirement, showed this to be a huge project for both the artists and the manufacturers. Firstly, sculpture as one of the fine art practices is normally not for mass production but rather a unique creation. However, this project required many sculptures to be created within a tight time schedule and therefore much high quality work had to be completed in a short space of time. Secondly, for the sculpture workshop that was in charge of the entire project, the benefits of undertaking the work were affected by many aspects including prices of material, quality of assistants, reproduction and manufacturing cost, etc. which brought much uncertainty. Thirdly, the demanding requirement of aesthetics as well as a uniform, realistic style was definitely a challenge for the artists’ modelling skills. Finally, due to their large size and marble material, the final products required the original models to be enlarged several times and turned out of moulds, which usually leads to some shape deviation. Many manufacturing difficulties existed in the complicated reproduction process. Moreover, communication between co-workers with different backgrounds and good organisation of the whole project were imperative. Specific conventional modelling and manufacturing methods that were available are discussed later.

6.2.3. Opportunities

Against the challenges indicated above, the positive side was the unique opportunity to utilise AM for large scale sculpture reproduction and manufacturing. In this case, AM could be seen as an assistive tool in the manufacturing process, which aims to improve the manufacturing process chain but not replace the artistic treatments. The specific objectives of this case study were to improve efficiency and accuracy, to reduce the time requirements for professional skills and the uncertainty of outcomes from skilled work and to reduce labour costs and complicated tedious work. At the same time there was a need to investigate the feasibility of integrating AM with conventional sculpture reproduction and the prospects for advances in this interdisciplinary area.

6.2.4. The traditional process

Design and evaluation were carried out by the principal sculptors on the project, lead by Prof D. Zhang. 10% scale detailed originals were made from clay and used to produce plaster moulds for plaster casting (Figure 6-1). 2% scale clay models (known as 'sand models') were also made to show the overall design and layout (Figure 6-2). These originals showed the general appearance and were used for evaluation and as references for enlarging.

Figure 6-1 10% scale detailed original

Figure 6-2 2% scale clay model

Step 1. Sketch

As a means of summarising essential information according to key requirements, concept design started with sketching on paper. This step was to reflect the principal author's understanding of the project and as a way of expression, to also record his inspiration and design ideas.

The design elements of space art include orientation of individual models and the general effect when they are merged into an environment; material properties that affect artistic treatment and finishing techniques; aesthetic shape matching of the characters to their location, as well as to historical, cultural and spiritual contexts.

Step 2. Scaled original

After confirming the design with the clients, it needed to be turned into a 3D solid model from the 2D sketches using manual modelling skills. Such a scaled original is normally made from clay at 10% of full size, and so for this project, required 30 to 40 cm tall clay originals. These utilised a simple inner frame to support the soft modelling material, and this was a reasonable scale to allow them to be made on a desktop working platform. The clay models were easy to manipulate and move around for viewing from different angles, as a continual modification process was part of reaching the finished design. When each clay original was completed, a silicon rubber or plaster mould was used to produce a plaster or resin copy for evaluation, in order to confirm the design and aesthetic style (see Figure 6-3 Plaster copies of the originals for evaluation).

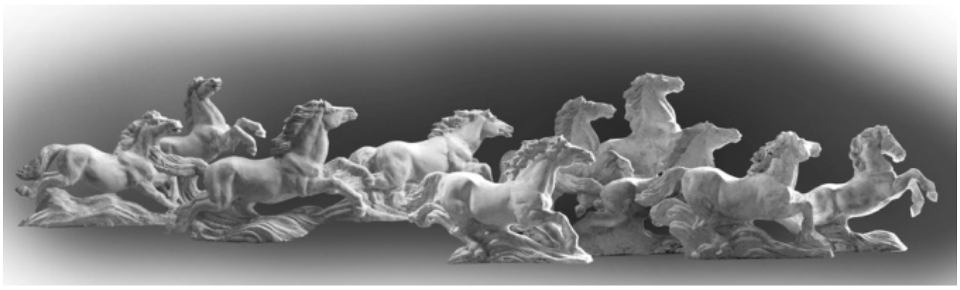


Figure 6-3 10 plaster copies of originals as samples for evaluation

Step 3. Sand model

The sand model was a set of small scale physical models that presented a group of horse sculptures in the target environment including a river, buildings, trees, etc., which demonstrated the overall effect directly and much more tangibly than 2D drawings or renderings. According to the confirmed style of the 10% scaled original, 2% scaling equated to about 6 to 8 cm tall scaled clay models (Figure 6-4). These were made by hand with fewer details, and silicon rubber moulding was once again used to produce plaster models. This was a huge workload, although no heavy work was involved.

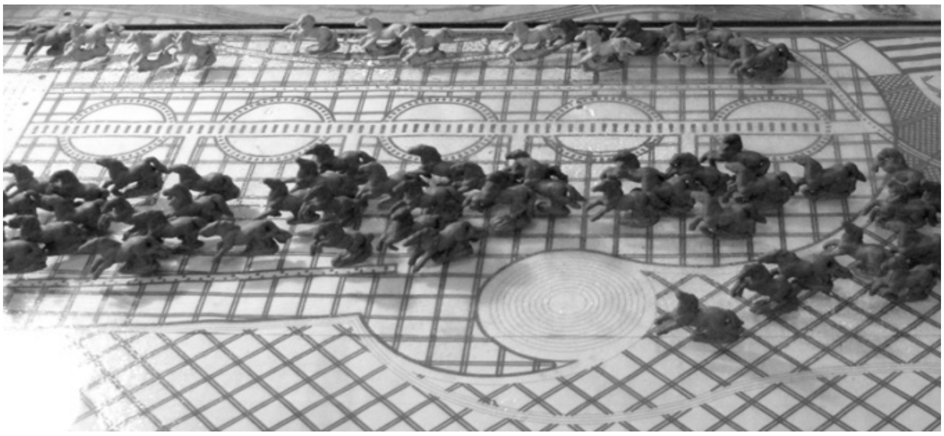


Figure 6-4 2% scale clay and plaster models as sand model

After evaluation of the original and sand models and confirmation of the design, the work progressed to the next process -- enlarging the original model to a full size final model. The entire process had to be led by the principal sculptor who worked with different levels of assistants. Firstly, an inner support structure was built with metal and wood according to the size and general shape of the model. Thick metal with wood sticks and thin metal wire with small wood pieces were used to produce a "skeleton", that was similar to the bone structure of the horse. Secondly, clay was wrapped onto the inner frame tightly to create a rough general shape, much like the flesh of the horse. Thirdly, the clay was modelled into the desired shape by looking at the original model as a reference. Fourthly, artistic treatments such as adding details and modifying angles to suit the viewing points were applied, based on professional modelling skills and rich experience (see Figure 6-5 the full size clay model). Applying finishing on the surface of final model for subsequent moulding was the final step. **The enlarging process** required the following manual work input:

- Full scale metal and wood frames built up over 2 days by 2 assistants.
- Detailed modelling and sculpting processes by 2 higher-skilled assistants working for a further 2 days.
- Final modifications of the model by the principal sculptor for around 4 days

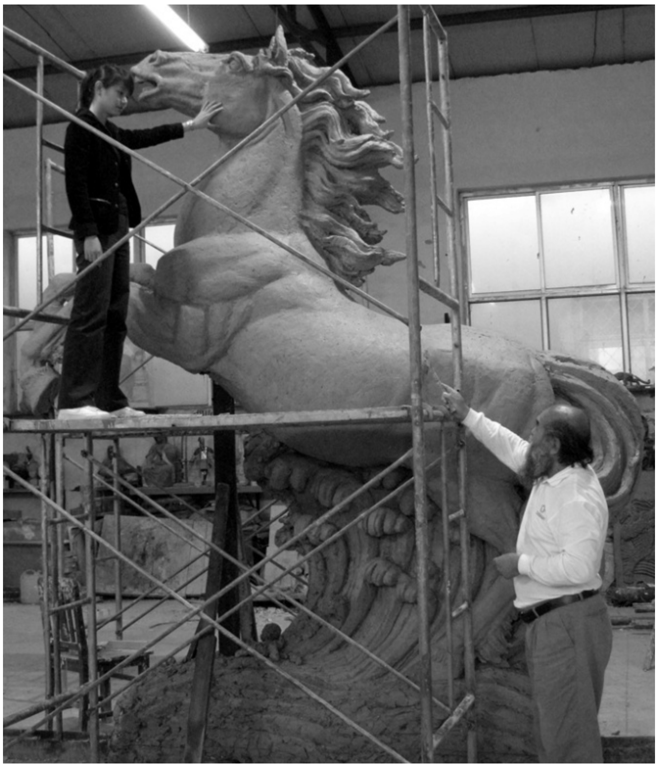


Figure 6-5 Part of the final result with the author inspecting the horse's head

Final manufacturing and finishing involved the full-size clay model being used to create a negative mould in reinforced plaster, which in turn was used to produce a fibreglass replica model supported internally by a metal frame (at least 4 days work for 4 people). This was transported to a factory for final production. In this case, the final material was marble, and the replica model was used as a reference by skilled assistants who carved the final sculpture (Figure 6-6). This was then finished by the principal sculptor, the whole production process took around 1 month in all.

Figure 6-6 Full size marble sculpture carving

1) Moulding

As the completed heavy and soft clay model could not be transported or used as reference for marble carving, moulding needed to be conducted at the workshop. A traditional moulding technique that is similar to that described in section 4.1 was used. The application here was a challenging case because of the large scale and selective areas of fine details.

2) Marble carving

The resin replica was then shipped to the factory for marble carving. A block of material was chosen for appropriate colour and size, and then unwanted material was removed by workers to an initial very rough shape. The large block of marble was placed next to the resin model, a replication device was set up with the material and model. The device consists of three axes with marks like three rulers, each axis recording one mark on the resin model's surface to indicate the position in space, so that another device can orientate the same point on the marble material. The orientation points can be marked by pencil or marker pen on the resin surface. More and more points are gradually added between the original points, reducing the distance between them, during carving since the more points there are the more accurate and more detailed the result. However, during the last round carving with a 1 cm distance between each marked point, there were still some details missing and geometry with deviation. The sculptor then needs to modify the model in person. After that, a final marble replica was completed.

3) Finishing

Finishing techniques were applied on the final model, which basically included grinding and polishing with electronic grinders, sand papers and fibre wheels. Some parts needed to be kept rough and some parts had to be polished smooth; this is monitored by the author as well according to the material property and geometry of model. Finally, the marble model was shipped to the required place for installation. So far, this is a whole process for one individual full size model, and group sculpture needs to repeat this process or manufacture a few models at the same time.

6.2.5. Layered manufacturing

There were some problems that needed to be solved within the conventional process, such as a large workload in a short time and the high demands of direct visual demonstration; the misunderstandings and resultant deviations caused by different levels of assistants' skills during the enlarging procedure; inevitable deviation during the moulding process; and compromising time and accuracy/details during duplication by marble carving. Based on the author's literature review of AM and sculpture, a new approach that integrated the conventional method with digital technologies was adopted in this case study, which took advantage of AM for small scale models and explored the principle of using AM to address other problems for enlarging.

Design and evaluation this time started with 10% scale detailed models made from clay which were used to produce plaster-cast originals. 3D stereoscopic scanning using Chinese 3DSS brand hardware was used to capture digital data from these originals, which was in turn manipulated using Geomagic RE software. The CAD models were altered by the author (guided by the principal sculptor) in the virtual environment, to produce variations of the horses in different poses. The digital models were scaled down to 2% size and built by the SLA AM process for the overall layout model (see Figure 6-7).

Figure 6-7 2% scale model produced by SLA AM process

In this method, the 10% scale clay model was still designed and created by the principal sculptor, and this was still the key reference needed to generate several other models with the same style but different poses, which was achieved using RE software. Also, several detailed originals were enlarged for full size sample production.

Specifically, one 10% scale clay original was used to produce a rubber mould for a plaster replica, and 3D scanning was used to collect the data from this plaster replica (since plaster is more robust and easier to transport compared to clay). As the digital model needed to be modified and changed, this project adopted a 1.3 and 2 M lens white light 3D stereoscopic scanner to give acceptable resolution. The data was manipulated in Geomagic software and a technician worked with the sculptor to divide the horse into head, neck, body and legs sections, change the poses and muscle shapes and then re-assemble these sections to generate a new virtual model. By this method, one original physical model could be used to produce about 9 more different digital models. The models were scaled down to a 2% scale and exported as shelled STL models. The process was repeated with 10 original models to produce a total of 100 virtual models. The STL files of the hundred small scale models were imported into a SLA AM machine to produce relatively robust physical models directly without tooling, and position them on a small-scale version of the sculpture's environment, modelled in sand (see Figure 6-8). As the sand model was basically to demonstrate the overall effect of the group sculpture, the size of the individual horse was quite small and omitted many details. The Objet and SLA AM machines used were both capable of meeting the level of resolution required.

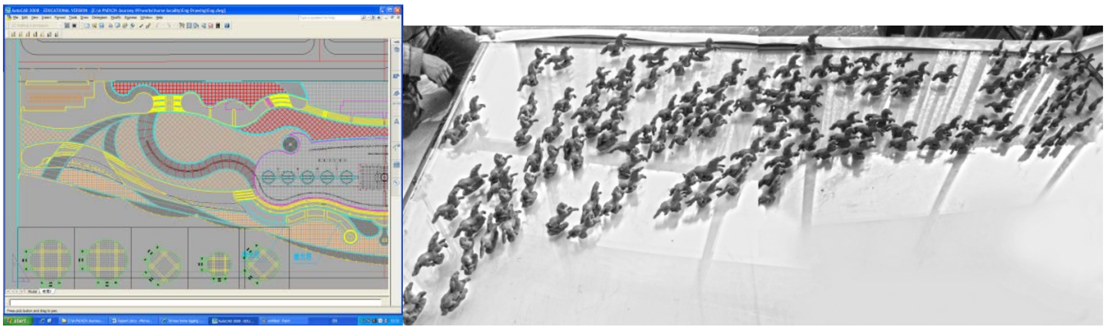


Figure 6-8 Part CAD planning of the sculpture's environment & physical sand model

Since 10 original models had been made by the principal sculptor for creating the sand model, these 10% scale originals were also enlarged to create 10 full size marble samples for evaluation of the final effect before approving mass production. These 10 originals were first enlarged digitally to the required size and then the data was manipulated in preparation for layered manufacturing.

Enlarging was conducted by undertaking two experiments, both starting with data manipulation of the scanning data of the detailed originals. The correct size digital models were transferred to DWG/DXF CAD compatible format, to enable slicing up of the full-scale CAD models into various thicknesses to create a "contour model" (Figure 6-9). This process was supervised by the sculptor who decided upon the layer thickness for different regions in order to maintain sufficient details whilst also upholding the efficiency of the work. This was because using thin layers kept more detail but the greater number of increase workload and time. In addition, numbered reference axes were designed to orientate each slice for assembling (Figure 6-10).

Different sizes and thicknesses of foam boards with acceptable density were purchased according to the contoured digital models. In the first experiment, the contours of each slice were printed on to paper and used as guides to cut the foam boards, using a heated metal wire (Figure 6-11). The foam boards with the outline shape of each slice were marked with a number and stacked in order. Then, using metal sticks to represent the reference axes, the foam slices were assembled sequentially to create the finished contour models (Figure 6-12). These plastic foam board contour models were shipped to the sculpture factory for marble carving using the duplication device (Figure 6-13), which is just like three rulers acting as the x, y, z axes in space; one is used to orientate the points on the original and mark them with pencil, another sets the same position of each point for producing the copy, so theoretically the more points that are set the more accurate shape of the copy should be.

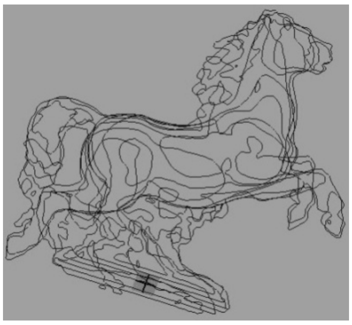


Figure 6-9 Contour model

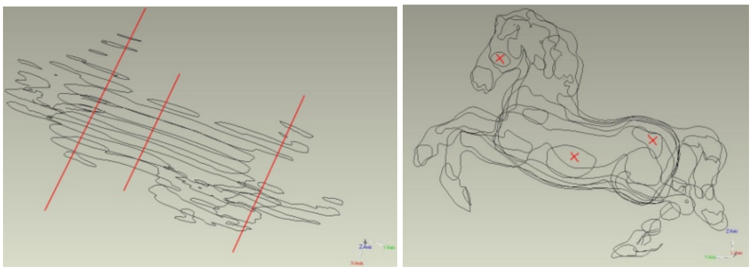


Figure 6-10 Reference axes in top view and front view

Figure 6-11 Cutting foam boards (left image)

Figure 6-12 Full size physical contour model (middle image)

Figure 6-13 Carving duplication device (right image)

In the second experiment, an interesting variation of this technique was used for important parts such as the head, bone structure and muscle shapes. Thinner and slices of varying thickness were used to achieve better detail, and the axes were redesigned for a new assembling procedure. An overhead projector was fixed on the ceiling and used to project the outline of each contour onto the foam boards at the correct scale. These were then cut using a heated wire as before. The main difference was that this time the internal portion of each cut foam board was removed to leave a "negative" form of the profile. These negative were then stacked to build up what was effectively a foam mould for the required shape (Figure 6-14). In fact, each horse model was actually divided into two halves and the foam boards for each half were assembled according to the designed reference axes. Palm fibre was mixed with plaster to give enhanced strength for supporting the large scale model, and this plaster mixture was applied to the inside surface of the foam mould layer by layer until a safe thickness (about 5cm) was reached. The foam was easily removed after the plaster was dry to obtain the two large plaster shell models (Figure 6-15). Some wooden bars fixed with metal wires were built as inner structure frames in the moulds for supporting their weight and enabling safe transportation. The two sides of the plaster model were then assembled and fixed together to form one completed model, which was modified by sculptor using sculpting knives and liquid plaster. When the final models were completed with robust dry plaster and surface finishing, they were shipped to the factory to act as references for marble carving.

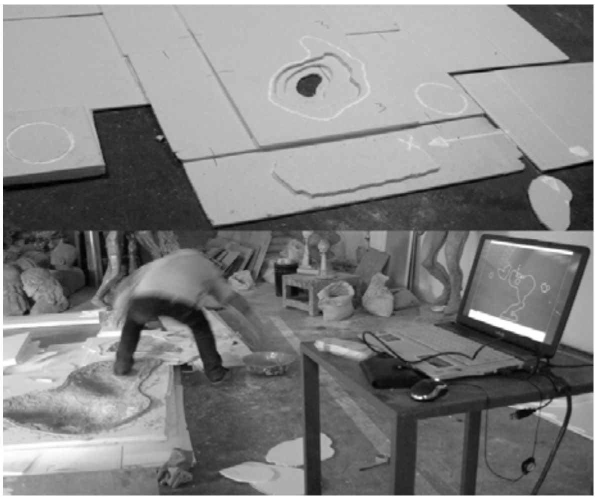


Figure 6-14 Negative foam mould with plaster

Figure 6-15 Detailed plaster model part

The two layered manufacturing experiments showed that using digital technologies to assist enlarging in sculpture industry can reduce tedious manual work and labour costs and also greatly avoid communication and management issues during the manufacturing process. Although the new method may bring new problems, the results of each slicing process are both acceptable and they are complementary to one another. The first one with less materials and workload is preferable for relatively simple shapes and the second one is suitable for complex geometry with more details; these two processes can be used for different sections of one sculpture as well.

Final manufacturing and finishing were the same as that in the traditional method.

6.3. Case study two -- Sculpture of the Anglo-Saxon epic hero "Beowulf"

6.3.1. Context

The overall project was to build 48 sculptures at Qinghai Lake International Poetry Square on the Tibetan Plateau in two stages, with 24 sculptures to be built for both stages. Every sculpture to be established represented a different country or ethnic group's memory of an old story, a point in history or some aspect of their culture (Figure 6-16). This case study was to create an epic hero sculpture called "Beowulf" from one of the oldest English stories, dating from Anglo-Saxon times.

Figure 6-16 Part of sculptures at the square

The general appearance of this sculpture was designed by an invited sculptor according to a review of literature, paintings and films. The final design was confirmed as a realistic style human body sculpture that showed Beowulf standing on the monster Grendel with his sword drawn and which was to be produced as a 3 metre tall statue in bronze. As with the previous “horses” project, a scaled original was needed for evaluation which would then be enlarged to the required size. In addition, small scale models or relief sculptures would also be developed as downstream products.

The original model was again produced at 10% of full size, which was about 30 cm. Although it was a single customised human sculpture, more stringent requirements brought about different challenges compared to a sculpture of an animal. For example, with respect to physical appearance, the identification of the face, muscles in movement, and the complex geometry of detailed armour; and in regard to the psychological aspect, the facial expression, the body language needed to indicate emotion and even the whole spatial relationship with the surrounding environment. For this reason, the enlarging process needed to be more accurate and also to facilitate more convenient modifications on the full size model. In addition, bronze casting needs a moulding process that may cause inevitable deviation, as a large scale model needs to be divided into several sections, then reassembled, welded and surface finishing applied. The small scale models and relief sculptures should have the same shape as the original but with a different size and made in a different material. To explore better solutions for these challenges, research questions were investigated further and a general solution method for this interdisciplinary area was developed.

6.3.2. The conventional process

Design and evaluation was basically the same as for the previous "horses" project, i.e. a scaled clay original was created by the principal sculptor and reproduced as a plaster and/or resin replica for evaluation by the local government (Figure 6-17). Once the design was accepted and confirmed, the contracted work that specified size, materials, time and cost, manufacturing needs, etc. had to start as soon as possible.

Figure 6-17 Clay original & plaster replica

The enlarging process was also similar to animal sculpture manufacturing but with higher requirements for modelling skills. It took, 4 lower skill level assistants about 10 days to build the inner structure and another 10 days to add clay onto the framework. After this, 2 middle level skill assistants took around 10 days to make the general shape according to the original model. Finally, 2 high level skill assistants worked with the principal sculptor and spent a further 10 days modifying and finishing the final full size clay model. (Figure 6-18) All the details of the original model had to be represented since the full size clay model was used as the final shape for bronze casting without any further changes.

Figure 6-18 Full size clay model and modification

Figure 6-19 Final bronze model

Final manufacturing and finishing

To facilitate casting in bronze, the clay model was used to produce a fibreglass replica for shipping to and moulding in the factory. The fibreglass replica was then used to produce a negative mould in rubber (as described in section 4.1) from which a wax casting was produced. This wax model enabled final checks and modifying by the principal sculptor at the factory before the bronze was cast. The bronze casting process was basically the same as that introduced in the previous chapter (section 3.3.3 and 4.2). The final bronze model is shown in Figure 6-19.

Derivative products

Derivative product design and development was based on the full size final model, since during enlarging and reproduction many minor changes were made. The small scale original did not have enough detail for delicate handicraft production. Taking the eyes for example, the sculptor created the eyes to let the audience feel that the statue had a vivid expression. However, the eyelids were very small and the eyelashes did not actually exist on the small scale original. Therefore, when enlarging to the full size model, the 1 mm eyelid became 1 cm in size and needed to have more structure, not just a flat simple surface. As a result, for every different scale or form, such as designing products with a sculptural element or transformation into a relief sculpture, the process actually needs the principal sculptor to re-create detailed originals by hand, which is much more complex than simply changing scale. One newly designed original in a relatively small scale needed one week to be created on a desk working platform, and then also needed moulding and manufacturing, using especially good quality moulds with different materials for mass production. This stage was done with digital methods in this case study and examples shown in the next section.

6.3.3. The digital process

Although some of the problems with the traditional process were similar to those in the "horses" projects, there was no mass individualisation problem in this project. However, there were some issues particularly associated with human sculpture manufacturing, such as misunderstandings and deviations caused by different skill level assistants, the high requirement for professional modelling skills and moulding techniques. So, this case investigated research questions further and besides achieving similar objectives to the "horses" project, also served to obtain a better understanding of the sculpture industry. It was treated as an interdisciplinary subject, and also aimed to optimise AM for product development in the fine art field, exploring opportunities to extend art projects and academic research to commercial enterprises.

Design and evaluation still started with the scaled clay original which was used to produce a plaster replica for evaluation and 3D scanning. Subtle details of hair, armour and sword decoration were not shown very clearly on the scaled original due to the size limitation, so 2M (2 mega pixel) optical scanner was still acceptable. The scanning data was manipulated to add some details onto the digital model, such as the pattern on the armour (Figure 6-20).

Enlarging to the desired size was undertaken in the same way as the "horses" project. The author created a contour model in a compatible 3D CAD format, with designed orientation axes and slicing thickness, under the supervision of the principal sculptor. This case study was the third experiment in enlarging sculptures (after the 2 undertaken in the "horses" project), which also used a projector to project each contour of the digital model. However, this time foam boards were not adopted since the details needed for a human could not be duplicated clearly, especially the facial expression, hand gesture, etc. and plaster was not so easy to modify if many minor changes needed to be made. So, after communication with the sculptor, traditional modelling clay was adopted instead with the contours being used to produce the full size sculpture. As a result of this decision, a metal framework with wood pieces was still needed as an inner structure to support the weight of the clay (Figure 6-21).

In contrast to conventional methods, the framework could be built layer by layer by workers with no modelling skills according to the contour model, using a metal net/metal mesh to wrap the metal wires. The large metal model was offset a certain thickness from the required size, (around a few centimetres smaller) to allow the adding of clay onto it. Then, clay was made into many strips to be added on the frame based on the projected contours (Figure 6-22). This step could also be done quickly by less skilled workers. It took 4 workers 10 days to build the full size model. As the layers were relatively thin (down to a minimum of half a centimetre for important parts, such as face and hands), the completed clay model was enlarged very accurately from the original, so that the principal sculptor just needed to make some minor changes and adjustments. Final details were undertaken with 2 assistants, (e.g. applying surface finishing and checking the patterns on the clothes) to complete the full size clay model in another 10 days.

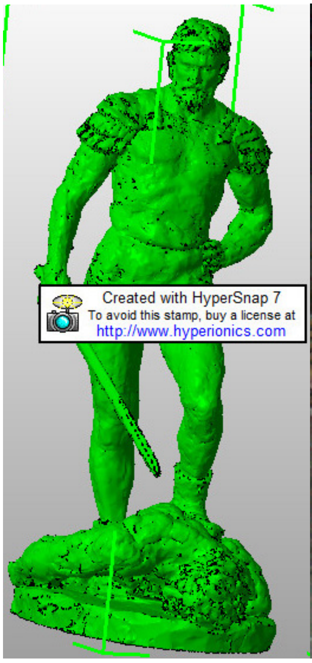


Figure 6-20 Scanning data of the original (left image)

Figure 6-21 Metal & wood framework for the contour model (middle image)

Figure 6-22 Detailed clay model part with minimum projected contours (right image)

Final manufacturing and finishing involved converting the full size clay model to a negative mould in silicone rubber or reinforced plaster (with palm fibre), which in turn was used to produce a fibreglass replica. This was undertaken in the same manner as for the "horses" project. The replica was then shipped to a factory for bronze casting using the conventional process.

Derivative products

Thanks to the digital technologies employed, the design cycle for derivative products was greatly shortened by appropriate manipulation of the scanning data. For example, compressing the original digital model into a relief sculpture with various angles (front view, side view, or 3/4 view) using RE software to optimise the triangles and data size, and modelling software such as Freeform and ZBrush, took only one day to create a new design. After the design was confirmed, STL files were exported to produce samples using AM without the need for any tooling. Also, the virtual domain was used for changing scales and adjusting details digitally to produce samples or moulds for mass production in various materials, such as bronze, wood and stone (see Figure 6-23 of examples). All these design and creation processes needed the sculptor and software technician to work together in close cooperation.

Figure 6-23 Examples of sculpture/relief in different size and materials/simulation

6.4. Case study three -- Forbidden City Renovation

6.4.1. Context

The Forbidden City in central Beijing was built during the 15th Century. It houses the Palace Museum, and is the location of a renovation project started in 2006 and planned to last 10 years. The project, involving buildings, gardens, furniture, objects, clothes, paintings, etc., covers both extensive restoration and the reproduction of lost or destroyed artefacts. A database of engineering drawings, virtual tours, publication and other media etc. is also being compiled.

This project is managed by the Museum’s Ancient Architecture Department, with support from the Technology Department and others. The restoration project members are investigating the use of new technology to improve both quality and efficiency. Several institutions from America, Japan and Britain (e.g. the Prince's Charities Foundation) have provided support, and a film about the work premiered at The British Museum in May 2010. Also, the Discovery Channel's "How do they do it" series producers, WAG TV, filmed an episode on the author's project in summer 2013 following the topic of Optimising AM for Archaeological Restoration, at both Loughborough University in the UK and the Palace Museum in Beijing (It is shown on TV).

6.4.2. Challenge

As one of the most amazing heritages of China's imperial history, the Forbidden City has plenty of resources for tourism, research, and education, and is full of artefacts that represent the highest standard of traditional craft. The full range of relics, which were produced in different forms, sizes, materials and periods, makes the restoration work unique and challenging. For instance, most previous repair work has been done manually, using engineering drawings and 2D renderings based on hand drawings and photographs. Nowadays, one route of progress is to use 3D software to build digital models by FE from these manual drawings. However, all the measurements were taken in traditional ways, and this may cause too many deviations from the original. For example, in some areas it may be not possible to measure accurately, especially for those artefacts that do not allow direct contact, or for delicate patterns and furniture with complex inner structures. Therefore, the Forbidden City are now trying to adopt RE for 3D data collection, but it still has constraints in terms of training, budget and technical problems. As to reproduction and reparation, carving machines and CNC have been used to assist hand making. However, these currently adopted technologies are used mainly to address difficulties in 2D, such as aligning the bases of mosaics.

6.4.3. Opportunities

Although theoretically, digital technology could be helpful for a whole range of tasks, (including collecting 3D data, generating 2D engineering drawing, building virtual models, small scale physical models, full scale copies or replacements of missing parts, etc.) but its feasibility in practice still needs to be discussed and tested. Generally speaking, all replacements or copies of artefacts should preferably be made of the same materials as the originals, such as wood, bronze, marble, jade, gold, shell, etc. or at least be visually identical. Hence, some materials could be simulated by using AM process combined with appropriate finishing techniques. This is especially true for those heritages with complex geometry and relief or hollow structures, which should be easier, more economical and more accurate to produce than via manual means. Also, AM can help to reduce the requirements of professional skills, manual workload, labour cost and the risk of wasting materials and help achieve a more seamless repair. In addition, AM brings opportunities for both virtual and physical archives as well as downstream product development.

6.4.4. The traditional process

A few artefacts with different scales and materials were chosen for the action research to be undertaken (Table 6-1). These included a hard wood fan base for supporting and fixing a large decorative fan beside the emperor's dragon chair in the main conference hall; a bronze plaque with a gold leaf surfaced five-dragon relief sculpture installed above the emperor's bed in the Chanlong Garden and a wood ceiling and marble enclosure with a flower tree relief sculpture in the Green Conch Pavilion. A few other relics were also chosen to investigate specific issues, such as the scanning of wooden furniture for a digital archive and a multi-material mosaic for simulation of diverse materials. Based on the literature review and interviews with staff, the traditional repair processes used "behind the scenes" were investigated in order to obtain a better understanding of the requirements, the high level of professional manual skills available and the difficulties encountered.

Table 6-1 Chosen projects

Artefact	Material	Dimension (mm)	Task	Character
Fan base	Hard wood	640 * 370 * 370	100 mm replacement section	Low relief
Dragon plaque	Bronze with gold surface	2200 * 800 * 500	500 mm diameter reproduction section	High relief up to 60 mm
Pavilion ceiling	Wood	1490 * 675	Scaled replica	Low relief
Pavilion enclosure	Marble	820 * 320	Scaled replica	Both sides low relief on arc-shaped surface
Furniture desk	Wood	3000 * 900 * 500	Virtual assembly	All pluggable structure without screws & glue
Multi-material mosaic	Shell, Bamboo, Bone, Jade, Amber, Ceramic	2500 * 600	Many replacement sections	Relief up to 30 mm

Archiving involves the artefacts being photographed from various angles and the pictures being compiled in order to analyse degradation and defects, and also to be used as references for repair and future archiving. However, since photographs are not enough for producing engineering drawings and recording essential information for restoration and comparison, manual measuring is also a significant step in the process. To date, measurements have been mostly taken manually with different kinds of callipers (Figure 6-24). Although manual techniques can be quite precise, they are very time consuming and have many constraints that may cause deviations. For instance, when artefacts are stored in strict conditions which do not allowed them to be moved, some features are not easy to measure in the limited space; also, some relics are very fragile or vulnerable and are not allowed to be directly touched, so that traditional methods of measuring with rulers and callipers which need to touch the actual surfaces cannot guarantee the required precision. After photography and measuring, the recording and compiling of all the data is also quite time consuming and normally requires professionals with rich experience as this is process creates important original material to guide all the follow up work.

Engineering drawings are produced by hand based on the photographs and measurements and annotated for future use (Figure 6-25). Even though a huge amount of preliminary work has been done, the reference material is still relatively limited. Therefore, the professionals still need to spend much time and energy in order to produce finely detailed engineering drawings. A complete archive may consist of many photographs, literature records, engineering drawings of different sections and styles for different use, and will contain many documents that need to be stored in a well organised manner and also confidentially.

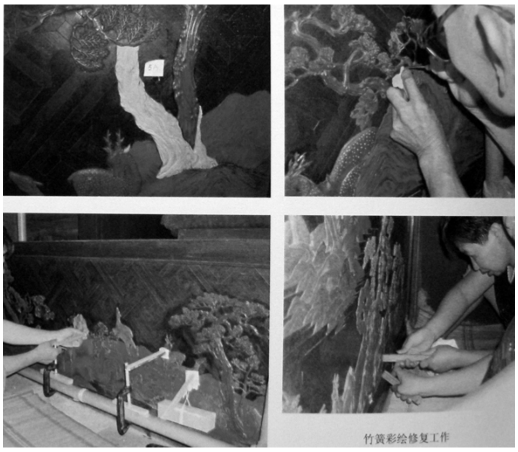


Figure 6-24 Manual measuring

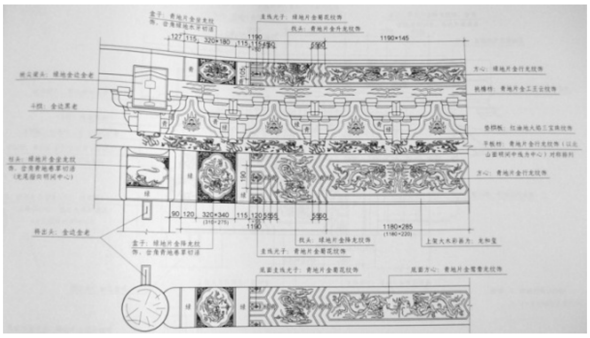


Figure 6-25 Hand-made engineering drawing

The last step in this "traditional" archiving process is a limited use of digital technologies to create rendered CAD models to produce images for publications and virtual tours. The digital models are built using generalised shapes according to the available resources. Surface texture is added by combining with photos which normally need to be processed in 2D image software such as Photoshop. The archives including images, engineering drawings and CAD models are used for all the relevant preservation activities, such as research, repairing, publication and demonstration.

The repair process starts by identifying the defects in the relics with reference to the photos and engineering drawings. These defects are marked up on the drawings. Labels with different colours, numbers and letters are used to indicate different sorts of defects, such as degradation, broken and missing parts, etc. so that all the artefacts needing to be repaired can be separated into different categories that will be handled by different departments. Solutions are designed for specific projects and feasibility evaluation is normally conducted in advance to help make a sound purchasing decision. Materials for replacement sections are sourced that are as close as possible to that of the original object. The dimensions of these replacement sections are specified manually and manufactured using traditional craft skills with the mating surface often needing to be adjusted several times to remove visible seams. Finally, the manufactured sections are artificially ‘aged’ using a variety of superficial techniques, such as painting, and chemical/mechanical aging techniques before being combined with the original relics (Figure 6-26). Then, finishing techniques are applied to cover all traces of the repair.

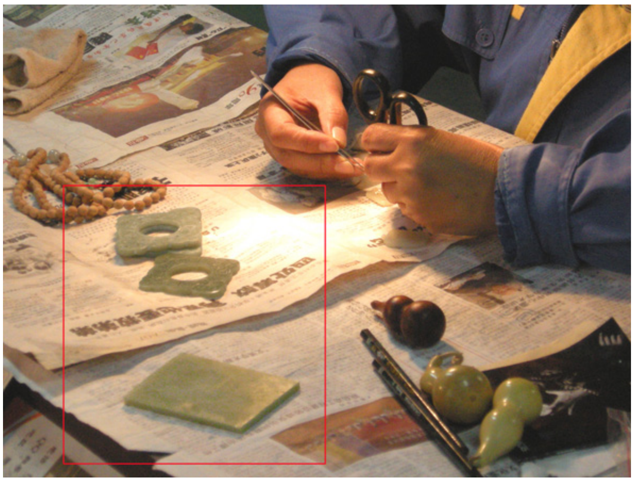


Figure 6-26 Manual finishing techniques

Downstream product development

Some cultural heritages with classic patterns can be developed into downstream products for both education and enterprise. The design cycle starts with observation of the original artefact to produce concepts by hand sketching on paper, and discussion of the concepts' details including validity, aesthetics, functionality, scale, material, cost, price, volume of production, etc. Then, producing a handmade original for sample evaluation, once the design is confirmed, the manufacturing process is generally similar to producing a sculpture.

The sketch and handmade samples cannot fully represent the final effect of the product due to the constraints of material property. For example, it is difficult for a clay or plaster model to simulate jade or bronze effects, and it is also not feasible to use the real material for sample production as time and cost is not affordable. Moreover, when different sizes of products are in demand, every size needs an original for moulding, and even symmetrical geometry still requires the creation of one half by manual techniques. This kind of product can be treated as a combination of artistic creation and archaeological replication where the requirements of accuracy and fine details are relatively high and is definitely a challenge for manual techniques in the competitive souvenirs market. The examples using a combination of manual and AM methods are shown in the next section.

6.4.5. AM and finishing techniques

Archiving also involved collecting data but this time using 3D scanning alongside photography (Figure 6-27). The 3D scan data was manipulated to produce 3D CAD models, on which defects could be annotated. The 3D models were used to produce simplified engineering drawings and also optimised to fulfil a variety of needs such as the creation of virtual tours. Utilising digital technologies it is possible to build a database with 3D digital models including high resolution and low resolution coloured models, optimised engineering drawings, deviation analysis models, section models and assembly models; annotations and notes can be associated with these to provide sufficient information and accessible retrieval. Experiments were carried out with the specific research projects as follows:

Figure 6-27 Original artefact (left), 3D scanning process (middle), the scanning data (right)

Fan base -- Engineering drawing
After taking photos from various angles, a 1.3 M laser scanner was adopted to collect data of the entire artefact. The scanning process took 2 technicians about half a day (without touching the surface or applying any developing agent) under normal office conditions. Data manipulation was first conducted in the software that supports the scanner to register different scans, and then the digital model was imported into the RE software Geomagic to fix the model including filling the holes, removing bad triangles and edges, repairing flipped normals, etc. This was followed by extracting the complex relief and hollow parts from the body and saving them separately, which was for convenient use at later stage. The main body part was exported to generate simplified engineering drawings with only necessary dimensions, and the relief parts were used for the restoration work that is described later (Figure 6-28).

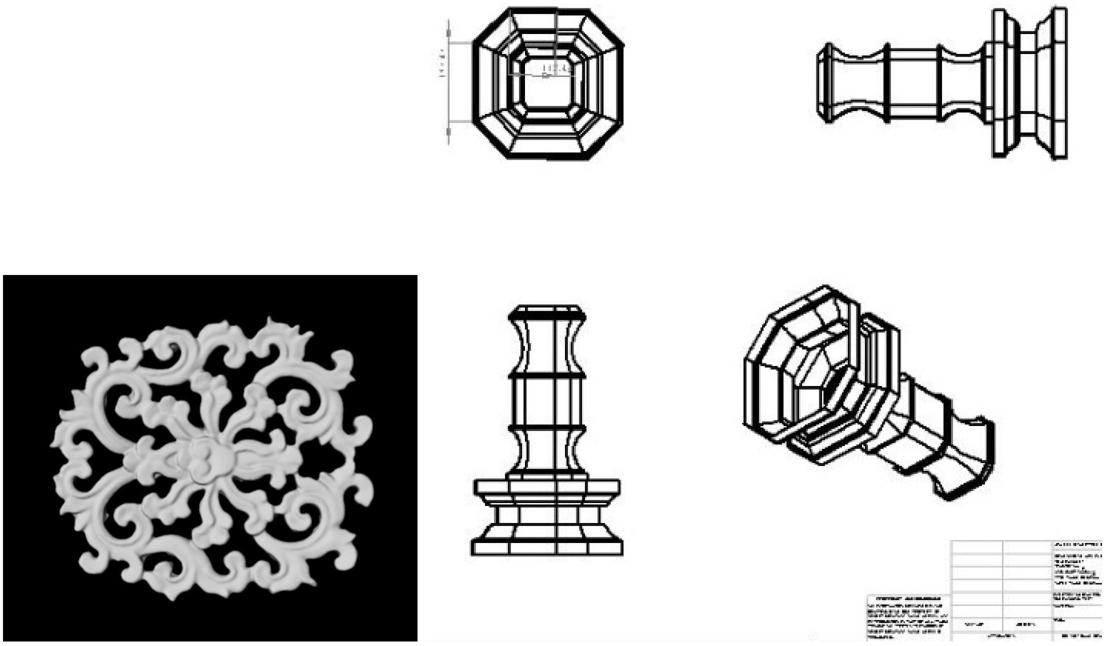


Figure 6-28 The digital model of relief part and simplified engineering drawing

Dragon plaque -- Defect and deviation analysis

The bronze plaque with the five-dragons relief had a highly reflective gold surface and could not be touched. Therefore, an ATOS 5M blue light scanner was chosen to collect data for the required size and for fine details. The scanning process took 2 technicians around two days without applying a developing agent, with some areas needing up to 8 scans to obtain complete data including undercuts of the high relief. The scanning data was registered in GOM software to generate a digital model, and exported in a compatible format (STL file) for manipulation in RE software Geomagic.

The original digital model was shown in different colours to indicate defects and changes according to curvature. For example, the concave or convex areas should have continuous gradation of colour. If there is a small gap on the continuous curvature surface then a contrasting colour will be shown obviously at that place. In this case, a sectional cut can be taken at the defect region to analyse and view with detailed dimensions (Figure 6-29). This model, together with notes, could be saved in the archive to record the changes caused by weathering or human interaction to aid future research and restoration.

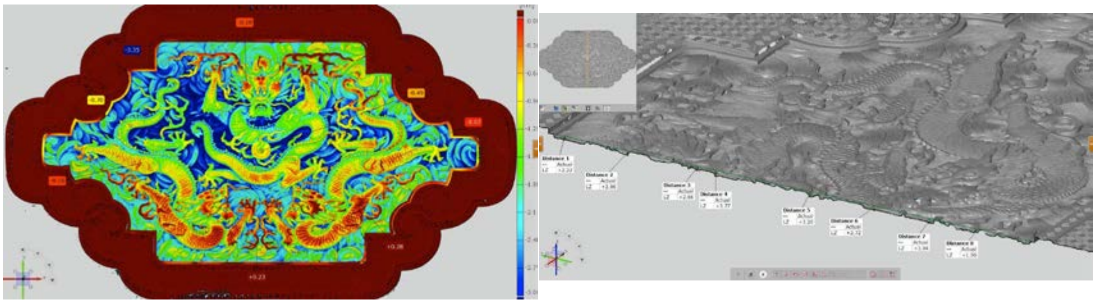


Figure 6-29 Coloured model and section view with annotations

Pavilion ceiling and enclosure -- Virtual demonstration
One piece of the ceiling and enclosure were chosen for the experiment. For such artefacts with a large area and fine details, the ATOS 5M scanner again best suited the needs, and a scanning area of 600 * 600 mm with 0.03 mm point spacing was adopted. One piece of the ceiling was removed from the pavilion and moved to an office for photography and scanning. The scanning process took 2 technicians about one day to complete. The digital model was generated in GOM first and imported into 3D Coat for texture rendering. The colour and texture were captured by photography and imported into the software. Then mapping of the digital model with the texture photos (Figure 6-30) and adjusting the model to the desired size was performed to present the final look of the replica in 360° in virtual space.

The same process was repeated for the enclosure, with the only difference being the scanning conditions. Since the marble enclosure could not be moved like the wood ceiling, a temporary darkroom was built using a large piece of cloth to reduce the impact of outdoor environmental light. This scanning process for the chosen piece of marble enclosure with relief took the two technicians round one and a half days to complete. The models were saved as an archive for publication, virtual tours and product development.

Figure 6-30 Rendered 3D images of wood ceiling and marble enclosure

Furniture desk -- Digital archive
Ancient Chinese furniture pieces were mostly made from wood without screws and glue. A method for conservation of this "smart structure" and some classic patterns was needed for research and restoration purposes. One desk with relatively simple geometry was selected for the first experiment, which started with 3D scanning by an ATOS 2M scanner. The desk was disassembled in advance by staff in the museum and each part named (Figure 6-31 left image). Then, scanning data of every part was collected under office conditions also without touching the surface, which took 2 technicians three days. The most challenging work was the data manipulation to build an entire archive that could be easily viewed in most computers without the use of professional software (PDF files), and which was understandable for staff to guide their repair work. Adding dimensions and marking defects were the first steps in this process (Figure 6-31 right image). This was followed by using numbers and letters to organise the parts and

grouping adjacent parts in different sections according to the general rules (S. Wang, 2010). Finally, the author exported the digital models in the STL format and imported them into ProEngineer to simulate the manual assembly procedure.

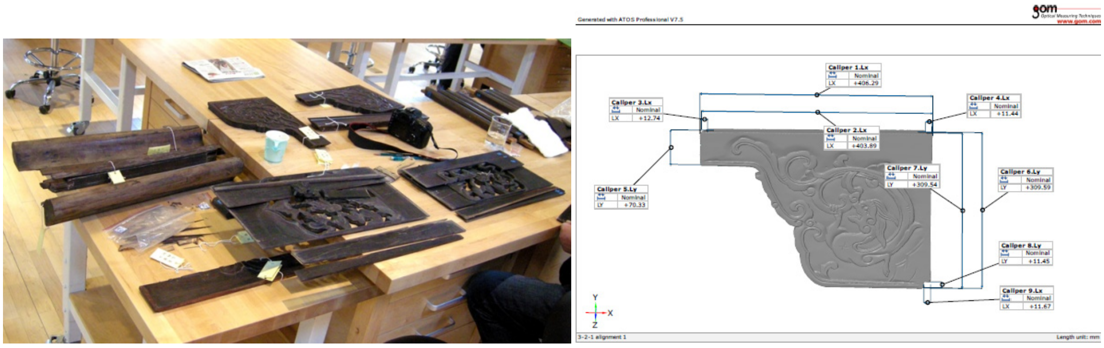


Figure 6-31 Disassembled parts (left), dimensions and annotations of each part (right)

Fan base - replacement section

In the light of earlier analysis, the fan base was treated as being basically a geometrical shaped body with symmetrical relief patterns and a simple hollow structure. A relief on one side was cracked and needed to be repaired by reproducing a replacement. Digital models were retrieved from the database, and using the same pattern on the opposite side as a reference, the relief with the defect could be fixed virtually using modelling software such as FreeForm or ZBrush. Although the geometry was theoretically symmetrical, the same patterns on each side were still slightly different because they were originally made manually. Therefore, it was suggested not to simply replace the cracked one with the perfect one on the opposite symmetrical side; this would only be done if one part was completely missing.

The fixed part was then exported as a single STL file for AM. The file was imported into Magics for final error detection and for adding some support material before building it in an AM machine. As the part was about 100 * 100 mm with low relief and no inner structure or sharp corners, both SLA 4500 set at 0.05 mm layer thickness and Objet Connex were adequate to produce the fine details; Objet machine was chosen in this case for better surface finish. A few pieces of relief models were produced for research purposes (Figure 6-32 left image).

A series of finishing techniques were applied on one of the photosensitive resin models to simulate the original wood material effect. Firstly, this involved grinding off the printing marks after removing the support material and polishing the surface with fine sandpaper. Secondly, mixing of the appropriate colour was performed and a brush was used to apply the mixture onto a piece of resin for inspection. Since the colour of the wood was not even because of its grain, applying the pigment mixture with a brush required artistic skill and it was better to practice a few times in advance before applying it to the AM part. Thirdly, a layer of clear coating was applied on the surface to protect the colour after the pigment was completely dry (Figure 6-32 right image). Finally, a little aging treatment was applied to adjust the final effect. When combining the replacement with the original, the interaction needed to be carefully recorded to observe if the original was compatible with the new part.

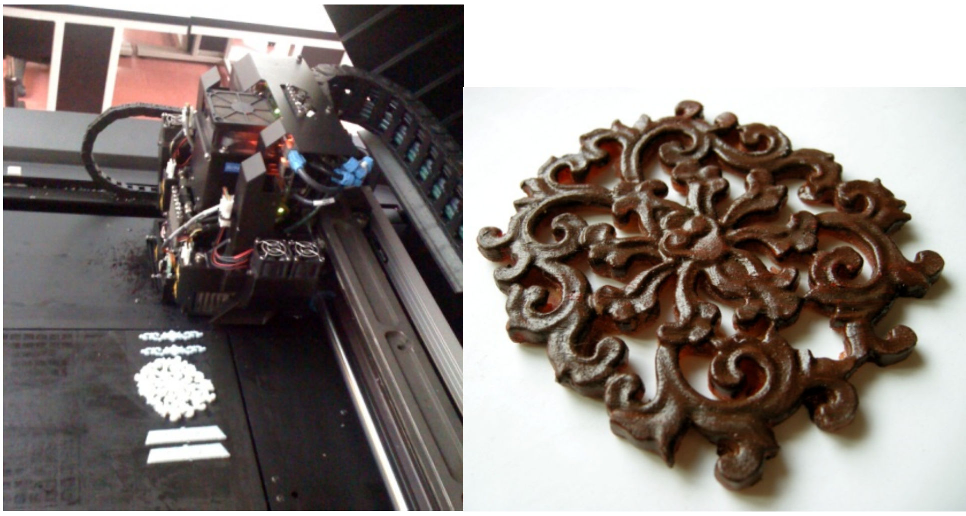


Figure 6-32 Relief pieces by AM process (left), AM part with wood simulation (right)

Another experiment was undertaken using the other replica AM model to test the simulation of other material effect. A silicon rubber mould was produced from the photosensitive resin model, and a plaster support mould was applied to the rubber mould. When the plaster was dry, the moulds were turned over and the plaster support mould removed. The rubber mould was then peeled off to take out the original AM model. The rubber mould was then put back into the plaster support mould to avoid any distortion (Figure 6-33 left image). Different liquids were prepared in order to simulate jade or amber by mixing clear resin with talcum powder to adjust transparency and then adding translucent pigment for the uneven colour and grains inside the translucent texture. Then, the mixture was poured into the rubber mould layer by layer to minimise bubbles since the uneven colour prevents the use of a vacuum pump. The resin was allowed to dry completely and then taken out from the rubber mould for the last step which was polishing. To simulate lacquer, the same rubber mould used for resin casting, was this time used with colour resin mixture that was opaque. The lacquer effect was also achieved using a brush to apply a layer of pigment mixture onto the resin model and applying a little aging treatment if necessary after polishing (Figure 6-33 right image).

Figure 6-33 Rubber casting from AM parts (left), simulation of different materials (right)

The repair process was started in much the same way as before, but with analysis of the defects being based on the 3D digital models as well as the photographs. Reproduction of missing parts was addressed virtually by making changes within the CAD environment with all the advantages that this offers, such as the ability to copy, rotate, mirror and transform similar parts. Parts that were not able to be built via the software were reproduced by sculptors in clay and imported to the CAD model via 3D scanning. New parts were produced with AM machines and different external effects were created by various finishing techniques (see Figure 6-33). The new parts were then combined with the original relics.

Dragon plaque -- replacement of section & new product development
A 500 mm diameter replacement area was cut out from the digital model of the entire plaque, and some small defects were repaired virtually (Figure 6-34 left image). A shell of the model with 1 mm thickness was exported as an STL file for AM, and Magics was used to check minor problems in the model that needed to be fixed. Since the plaque had high relief with fine details and therefore contained a mass of data, the triangles were optimised in Geomagic to reduce the file size and to fit the capability of AM machine. An Objet Connex 500 AM machine that could achieve 16 µm layer thickness was chosen to meet all the model production requirements. However, although the working platform could handle diameters up to 500 mm, the full size replica had to be divided into two parts to fit onto the build envelope. The division was made in Magics following the dragon tail contour for best result in terms of an "invisible join". White photosensitive resin (known as Vero White) was adopted to produce the two parts separately. After the support material was washed off in a water spray machine, the two parts were registered together and combined with Epoxy Milliput (Figure 6-34 right image). The Milliput could be easily modelled according to the gap shape and became very strong after completely drying. Using fine sandpaper to polish some of the model surfaces eliminated all traces of printing and gluing. Gold leaf was chosen as a finish since it was close to the colour of the original and could be applied in the same way as for the traditional method. This was done by firstly applying a layer of clear coat of blending agent as a binding agent and then using a brush to stick every piece of gold leaf onto the surface very carefully. This had to be done before the agent was completely dry, as the gold leaves were very thin and could float away with air flow and even one's breath (Figure 6-35 left image).

Figure 6-34 The chosen area from original artefact (left), the AM full size model with dividing line marked in red (right)

In addition, a few more experiments were conducted to further investigate the feasibility of high quality souvenir product development. This involved converting the data from the replacement plaque section into different forms and scales, such as decoration plates and a pendant, and then rendering with different material effects for inspection and evaluation. When producing the souvenir samples by AM, different AM materials were chosen for different simulations. A translucent plate having 25 cm diameter was created by manipulating the surface model into a hollow female form and adding a plate shape to the outside of this. When built using the Objet Vero Clear material, the surface finish was quite impressive and required almost no post processing (Figure 6-35 right image). All the details of the high relief and hollow structure could be seen clearly inside the plate just like a delicate glass art-craft. The only issue was that the cost was relatively high since it could not be a very thin shell, and the cost of AM mainly depends upon the weight or volume of material used. Another souvenir product was designed as a smaller plate with 15 cm diameter, produced with Vero White resin. This plate was produced as a very thin shell relief down to a minimum of half a millimetre thickness with a hollow structure behind, so that it was semi-translucent when lit from behind (Figure 6-36 left image). The price of this would be more reasonable as it did not use so much material. It could also be used a mould for casting. Another model of the relief section that was produced in the Vero White resin was painted with metallic pigment, applied manually by a brush to simulate a bronze or gold effect. Once again, the effect was quite impressive and it was difficult to tell this model apart from a version that had been CNC machined in bronze (see Figure 6-36 right image).


Figure 6-35 Replica with gold leaves finishing (left), simulation of clear glass plate (right)


Figure 6-36 Semi-translucent hollow structured plate (left)

AM part with metallic pigment (the model at left bottom corner in the right image)

Pavilion ceiling & enclosure -- Physical archive
The digital models of the wood ceiling and marble enclosure were reduced to about 20 to 25 cm to create scaled models. A different experiment was conducted to reproduce the physical models of this project. Based on analysis of the character of the ceiling and requirements of the scaled model, CNC machining was adopted to process the low relief without undercuts using real wood material. In contrast to AM, CNC machining requires set-up tooling and extensive professional knowledge of tool-path programming and tool selection. The digital model has to be transferred to the IGES format or imported into CNC software that accepted STL format to generate tool paths. A 3 axes CNC machine processed the piece of wood with three different tools to produce a scale model of the ceiling, which needed almost no finishing as it showed few machining marks (Figure 6-37 left image).

The scaled version of the arc-shaped marble enclosure with relief on both sides was produced using the Z-Corp AM process. In this experiment, a coloured digital model was exported in the OBJ and PLY formats to directly produce coloured physical models on a ZPrinter650 machine. The colour was adjusted and evaluated digitally, and a very small scale physical model was pre-printed as a test part. As the Z-Corp system was using a powdered material, it gave a textured effect that ideally suited the simulation of the surface of marble texture. The physical model was produced with no support material and only needed to be cleaned off and dipped into clear "super glue" for strengthening. Without any other finishing, the colour of the model was seen as being reasonable similar to the original (Figure 6-37 right image).

Figure 6-37 CNC wood ceiling part (left), coloured AM part simulating marble (right)

Multi-material mosaic -- replacement sections

Experiments for reproducing mosaic parts with different materials were undertaken to evaluate the details, material effects, ease of assembly and time scales. The individual mosaics parts that needed to be repaired or missing parts that needed to be reproduced were retrieved from the previously created digital database. Where parts were missing, similar parts from other regions of the mosaic were used instead. To obtain a smooth surface and fine details, the Objet Connex 500 machine was adopted. The resin models were used with the same methods as those used in previous experiments (direct manufacturing or rubber casting) in order to simulate jade, amber, bone, lacquer, bamboo, etc. After applied finishing techniques and aging treatments, the new parts were easily assembled seamlessly with the original (Figure 6-38).

Figure 6-38 Simulation of multi-material effects by AM & finishing techniques

6.5. Summary of chapter

Several practical case studies were undertaken to find the answers for research questions. Digital technologies can be useful tools to optimise the manufacturing process in both sculpture and archaeological restoration fields, the point is to make the best use of them in applications, in order to fill the gap between knowledge and practice. Better understanding of the general requirements and technology constraints was obtained during the action research, and valid results, valuable feedbacks and data were also collected for further analysis which is discussed in the next chapter.

By undertaken these practical case studies, the author observed the traditional process that managed by other experts to learn conventional techniques and find opportunities to integrate AM technologies. So that the digital processes were managed and supervised by the author, using novel and innovative manufacturing process chains, in which the author involved in every step working with engineers and artists, and carried out project planning, data manipulation, some manual moulding and finishing with AM models. The process maps are based on the results of the practice-led research, which will be shown in later chapter.

7. Chapter Seven: Results and Data Analysis & Analysis of AM

7.1. Results and data analysis for case studies

7.1.1. Discussion on the overall value of the case studies

These case studies touched on all the main issues to be addressed by this research. To help illustrate this, the research objectives and questions were listed and numbered from I to VII and 1 to 6, respectively, as shown below.

Research Objectives:
1. Provide definitions of Fine Art Sculpture and apply them to usefully constrain the research.
2. Clarify the natural boundaries to, or classifications for, 3D digital art.
3. Specify how historical & contemporary practice in sculpture is disseminated.
4. Find out what materials/tools are used for traditional sculpture and 3D digital art.
5. Find out what manufacturing processes are used for both traditional sculpture and 3D digital art.
6. Develop a method for comparing the different processes that are available.
7. Develop a tool to assist practitioners in this area to decide which processes to use.

Research questions
A**.** What are the general requirements of Fine art sculpture in both terms of aesthetics and manufacturing integrity?
B. What are the conjunctive areas of 3D digital art and fine art sculpture?
C. What is the benefit of using AM for fine art sculpture? (In terms of measurable outcomes for validating the research)
D. To what will 3D technology be accepted by practitioners in the fine art field and what are the barriers to acceptance?
E. How can the optimal combination of FE, RE and traditional techniques be determined? (As specifically applied to fine art)
F. How can the capability of digital technology best be promoted within fine art field?

To help illustrate which aspects of the projects contributed towards each objective and question, the particular stages of the projects were given codes from a to h, as follows.

Codes:
a. Project requirements
b. Product design
c. Virtual demonstration
d. Manufacturing material selection
e. Process chain determination
f. Finishing techniques

g. Communication & technical issues
h. Data manipulation

Table 7-1 and 7-2 show the links between each case study project and the research objectives and questions. The particular aspect of the projects that contributed to the objectives and questions can be seen from the use of the a to h codes. It is not strictly necessary for the reader to analyse these links in detail, but the distribution of codes across all the objectives and questions shows that all the projects contributed significant knowledge.

Table 7-1 Links between case study projects and research objectives

	1	2	3	4	5	6	7
Horses	a		a	d	e	a, f, g	g
Beowulf	a		a	d	e	a, f, g	g
Fan base			a	d	e	f, g	g
Dragon plaque		b	a	d	e	f, g	g
Ceiling & enclosure		c	a	d	e	f, g	g
Furniture		c	a			g	g
Mosaic			a	d	e	f, g	g

Table 7-2 Links between case study projects and research questions

	A	B	C	D	E	F
Horses	a	e	d, e	a, g	h	e, g
Beowulf	a	e	d, e	a, g	h	e, g
Fan base		e	e	d, g	h	f, g
Dragon plaque		b, e	e	d, g	b, h	f, g
Ceiling & enclosure		c, e	e	d, g	c, h	f, g
Furniture		c, e		a, g	c, h	g
Mosaic		e	e	d, g	h	f, g

The combined lessons learnt from the case studies can be listed under three categories shown in table 7-3.

1. General requirements for artistic design and manufacturing

Artistic design is based on aesthetic appearance with different forms and materials as decoration or landmark, which normally contains expression of emotion or symbolic significance. The design requires aesthetic form and expression rather than functionality. The manufacturing desires to manifest the design accurately into physical forms, which does not mean "accurate" in engineering terms, i.e. dimensions, but aims to transfer the "expression" faithfully and vividly.

2. Digital art and fine art

Digital art brings inspiration to fine art, and utilises digital technologies to fulfil manifestation which is difficult to be achieved using traditional manual methods. In contrast, fine art has its unique characteristics in aesthetics, the so called "hand-made feeling" which is a constraint of digital art. Digital art can be seen as a kind of interdisciplinary subject that lies between fine art and engineering technologies, with most of its overlap with fine art being the different methods used for creation. Also it is complementary with fine art in this digital age with rapid development of technologies.

3. Process chain/application (industry and art)

The significant point of filling the gap between knowledge and practice, and developing interdisciplinary subject between engineering and art is "application". Optimising the process chain to make the best use of AM technologies and optimally integrating digital technologies with conventional manual techniques has valuable benefits in both manufacturing industry and art related fields.

4. Technical issues and human factors (training and communication)

Technical issues always exist in every stage of development in terms of both technologies and art. These include limitations of hardware and software capability, accessibility of digital technologies in sculpture industry and archaeological restoration and feasibility of cost and time scale. Also, human factors are an important aspect in practice and cannot be ignored. For example, communication between co-workers with different background is still difficult and time consuming, and artistic training for engineers or technology training for artists is also an issue that needs to be solved.

5. Analysis / comparison system

Based on literature and action research, collecting and analysing data to create a valuable comparison system is very meaningful to guide current practitioners as well as future research. Further details of analysis and comparison systems are introduced in following sections, and combined lessons learnt as explained above are summarised in table 7-4.

Table 7-3 Three categories under which the combined lessons learnt from the case studies

Table 7-4 Combined lessons learnt in summary

Feasibility of using digital technologies in an artistic environment
☐ The value of art: Human factors, subjective feelings, expression of aesthetics or emotion.
☐ The value of artists' /sculptors' work: Creative ideas & modelling skills.
☐ Manufacturing plays a significant role in sculpture industry, Taking even more time and cost than design/creation.
☐ Digital technologies could be useful tools to reduce tedious work and draw more attention to design/creation.
Benefits
☐ According to observation and analysis of antique restoration, a better understanding of profound traditional culture and skilled craftsmen's expert techniques has been obtained
☐ Current manufacturing processes are manifestations of culture and art which developed throughout history; digital technology is the equivalent of these in modern societies and needs to inherit culture as well as improve in efficiency and quality
☐ Every technology has its pros and cons, the most important thing is to make the best use of it, designing the best solution for specific projects
Constraints
☐ Concerns that digital technologies could replace human work to some extent, which would somehow change the nature of the result.
☐ Communication between artists and engineers
☐ How to position interdisciplinary subjects
Combined lessons learnt in summary
Feasibility of using digital technologies in an artistic environment
☐ The value of art: Human factor, subjective feeling, express aesthetics or emotion.
☐ The value of artists' /sculptors' work: Creative ideas & modelling skills.
☐ Manufacturing plays a significant role in sculpture industry, even takes more time and cost than design/creation.
☐ Digital technologies could be useful tools to reduce tedious work and draw more attention on design/creation.
Benefits
☐ According to observation and analysis of antique restoration, a better understanding of profound traditional culture and skilled craftsmen's expert techniques has been obtained
☐ Current manufacturing processes are manifestations of culture and art,

which developed throughout history; digital technology is the equivalent of them in modern societies, which needs to inherit culture as well as improve efficiency and quality
☐ Every technology has its pros and cons, the most important thing is to make the best use of it, designing the best solution for specific projects
Constraints
☐ Concerns that digital technologies could replace human work to some extent, which would somehow change the nature of the result.
☐ Communication between artists and engineers
☐ How to position interdisciplinary subjects

7.1.2. Analysis Discussion of sculpture projects

Horses

Using the traditional process, the production of originals is carried out by a highly skilled sculptor on each of one hundred horses because every individual horse is different. In the AM process, only 10 samples needed to be created by the principle sculptor and each one could be used to generate 10 more different models digitally. All this was achieved by the sculptor working with a software operator/technician in an office which needed no physical workload or material, and very little working space, i.e. no workshop.

As to the sand model, one hundred handmade clay models needed to be created previously, although they could be produced with less detail and cast in several groups at the same time. By using the AM method, the small scale models were obtained when the hundred digital models were being created, and physical models were produced as final "sand models" using SLA AM process without tooling and moulding. So, in the layered manufacturing process, the sand model and originals for design and evaluation could be obtained within less than 10% of the time scale, compared with the traditional manual process. In addition, the models were made with better details using the easier and more flexible working practices for a designer/sculptor.

A conservative estimate for the enlarging process is that the conventional process costs at least double the labour time and with higher skill levels as compared to the layered manufacturing process. In the first of two experiments, a full size solid model was made in plastic foam board for direct shipping without moulding, but it was difficult to modify and lacked the level of detail needed for marble carving, after which a further optimised method for artistic treatment was found. Therefore, in the second experiment, a full size detailed plaster shell model was made, and the team were able to make changes before shipping it to the factory, saving time and making it much easier for both the designer/sculptor and the workers in the factory. In addition, it was no longer necessary to create a clay model since it was possible to obtain a full size detailed plaster model directly. A comparison of traditional and layered manufacturing methods is shown in Table 7-5.

Table 7-5 Comparison of traditional with layered manufacturing for horses sculpture

	Traditional manufacturing	**Layered manufacturing**
Quality	Inevitable transformation	Accurate reproduction
Time scale	3 months for sand model and originals 12 days for enlarging one	1 week for sand model and originals 6 days for enlarging one
Relative Cost	100%	70%
Labour	2 non-professional workers 6 professional assistants	1 software technician 4 non-professional workers
Procedure	Enlarge once/twice Turn mould type 2/4 times Designer/sculptor modifies every step	Enlarge once No need of moulding Designer/sculptor modifies when finished
Material	Plaster, large amount of clay, metal, wood, resin, glass-fibre	Plaster, plastic foam boards, small amount of clay, resin, glass-fibre
Other issues	Difficult transport & garbage disposal 60% tedious work	Easy transport & garbage disposal 20% tedious work

Beowulf

Overall, the design and original creation processes were similar for both the traditional and layered manufacturing methods. Enlarging by layered manufacturing only took about half the labour resource and time as that for the traditional method. Although they both used clay as the modelling material and went through moulding twice to get to the final glass fibre model, the clay model built by layered manufacturing used less than a quarter of the amount of clay.

More importantly, using layered manufacturing for reproduction was much more accurate and reliable, since it did not rely so much upon human factors such as modelling skills and experience. Also, it saved the principal sculptor from much of the tedious work and repeated modifying associated with the traditional method. Indeed, the main reason to use clay for the full size model (which needs moulding twice to obtain a final fibre glass model) is that clay is the most commonly used modelling material and is convenient for sculptors to modify. As mentioned in the sculpture review in chapter three, many details need to be added when the scale is being enlarged 10 times, and sometimes the angle and proportion need to be adjusted considering the viewing distance and angles. Thanks to the accuracy of digital processing, layered manufacturing can keep the shape almost the same as the original, so that the sculptor only needs to modify once on the final model rather than monitoring and working with assistants all the time as in the traditional process. In terms of material cost, the traditional method is to build a full size solid clay model with a robust inner structure to support the large amount of clay which is extremely heavy. With the layered manufacturing method, it was possible to build the inner structure using metal wire mesh with a near net shape, which only need a clay shell to be added. As a result, a great deal of clay and wood bars were saved and it was easier to remove the clay from the inside of the silicon rubber mould during the casting procedure, which thereby further reduced labour time and the amount of tedious work, especially for models of this size.

However, layered manufacturing still requires professional knowledge and the skills/experience of operating the software for data manipulation, and also needs the trained engineer be able to work well with artists. Although the software training takes months rather than years, as for manual modelling skills, it is still difficult to train an artist to achieve the basic level for data manipulation. Artist and engineers have been trained to have different thinking modes. For example, engineers emphasise accuracy and resolution in general, but they do not see the so-called key points that artists care about. In contrast, artists pay more attention to style and vividness, but they usually overlook the differences between digital work and manual work with solid material. This can easily cause misunderstanding between co-workers. Hence, communication is a significant potential barrier in the integrated digital and manual process, and the project manager should have knowledge in both engineering and artistic fields. Theoretically, this has not yet been made feasible based on current education systems, as the development of such interdisciplinary courses are limited. A comparison of these two different processes is shown in Table 7-6.

Table 7-6 Comparison of traditional with layered manufacturing for Beowulf sculpture

	Traditional manufacturing	**Layered manufacturing**
Quality	Inevitable transformation	Accurate reproduction
Time scale	40 days for enlarging	22 days for enlarging
Relative Cost	100%	70%
Labour	4 non-professional workers 8 professional assistants	1 software technician 4 non-professional workers 2 professional assistants
Procedure	Enlarge once/twice Turn mould type 2/4 times Designer/sculptor modifies at every step	Enlarge once Moulding 2 times Designer/sculptor modifies when finished
Material	Plaster, large amount of clay, metal, wood, resin, glass-fibre	Plaster, small amount of clay, metal wire mesh, resin, glass-fibre
Other issues	More attention needed for safety and garbage disposal 60% tedious work	Less attention needed for safety and garbage disposal 20% tedious work

7.1.3. Analysis of archaeological restoration projects

Using traditional methods for archiving purposes, i.e. taking photos and creating hand drawings, requires professional skills and is time consuming. Also, the required measurements are not very accurate as they are taken manually. Building 3D digital models from 2D images is a huge project for even one individual artefact, and it needs accurate dimensions and good quality photos from several views, which is also a significant issue. For relic repair, every step of manufacturing requires many hours of input from skilled people of different professions who have been trained for many years. Materials are expensive and are easily wasted if any small mistakes are made. Some special materials and geometric structures are almost impossible to repair.

Using the AM method, the measurements taken are much more accurate, and engineering drawings and digital models are much easier to obtain through 3D scanning and RE. Reproducing parts virtually by copying symmetrical parts is more efficient and reliable than hand-making of replicas using just photos and drawings as references. Generally speaking, according to the case study results for artefact restoration, the conventional approach takes months for professionals with manual skills, whereas the AM process takes weeks for different types of professionals with knowledge of digital technologies, and also greatly reduces tedious physical work. Also, producing AM parts can save much time in avoiding the need to find rare materials for purchasing and in avoiding the potential waste of expensive materials. What is more, AM brings greater possibilities for preservation and product development.

The specific differences between traditional and AM processes are discussed below:

Fan base - defect analysis, symmetrical replication

To obtain measurements, create hand drawings and produce confidential documents for repair for an artefact such as this can take a month when using traditional manual techniques. However, collecting the data for the entire fan base shape and identifying defects in detail using 3D scanning only took one day. A few more days or at maximum 2 weeks were needed to manipulate the data to obtain almost all the essential documents, such as a simplified engineering drawing with only necessary dimensions, sectional models for defect analysis and a coloured virtual model for archiving and demonstration purposes. Also, in this case, the damaged or missing parts were similar to a symmetrical relief which was on the opposite side. Currently, skilled professionals look carefully at the existing part as a reference to re-create new parts, because the similar wood material can be quite expensive. The accuracy and match with the adjacent area depends on their carving skills and rich experience, so it is reasonable that currently the repair work is time consuming. However, in the AM process, the symmetrical relief was readily available as a digital model to be built by an AM machine in resin material. Finishing techniques were applied to create the final part. Alternatively, CNC machining with wood could have been used, which would only have needed minor post processing using manual skills. The digital process reduced the time scale and need for manual skilled work, and more importantly, guaranteed accuracy and efficient material utilisation.

Dragon plaque - change analysis, reproduction in different sizes and materials

Currently, hand drawings with annotations are still the main method for recording the changes in an artefact, and this analysis is very important for archaeological preservation and research. Using manual means to measure the artefact, especially subtle changes and defects, requires the curator to touch the surface, otherwise it is difficult to be accurate enough if only based on observation. Therefore, one dragon image high relief sculpture with complex geometry may take professionals months to complete drawings and mark on them changes/defects where it needs to be repaired. One of the main benefits of using digital technologies, was that a curvature analysis could be done efficiently in the GOM software that accompanied the scanning system, and changes and defects were shown obviously in different colours and accurately with a numerical value. This design cycle for creating reproduction parts was greatly shortened by AM methods, through importing the digital model into RE software such as Geomagic, separating the region that needs to be reproduced and adding design elements. This was followed by exporting the designs as STL files for AM to create parts with a bone or glass effect, or for CNC machining in wood or bronze. Indeed, the digital method reduced time, labour and material cost, and guaranteed an accurate shape. The cost of individual products and the use of moulding for large-scale production are issues that need further research.

Ceiling & enclosure - real and simulated material reproduction without tooling or moulding

The ceiling and enclosure in the outdoor pavilion would have required purchasing wood and marble that were the same as used in the original to repair and reproduce scaled models. All the work would be conducted by professionals with modelling and carving skills which would be very time consuming. Since recreating the general shape is not a problem with the AM method, the key issue is now the production of models in an appropriate material. Therefore, in this case study, both real wood and a simulation of marble material were tested for evaluation. Digital models were scaled down to the desired size and exported as STL files and as an OBJ/PLY format coloured model. The scaled wood ceiling was produced by CNC machining with real wood board, and the scaled marble enclosure was produced by a ZCorp machine with coloured ceramic powder to simulate marble. The results showed that the effects for both were acceptable almost without any finishing, and resulted in significant time saving for research and archiving models compared to the tedious manufacturing methods used in traditional processes.

Furniture - digital archiving with virtual assembly

There is a huge demand for archiving of furniture together with repair and assembly guides since there are numerous pieces of furniture in the Imperial Palace. Every piece of furniture requires much time and labour to produce hand drawings with complicated documents. Now all this work can be done virtually by creating a digital archive. In this case study project, parts of a wood desk were scanned separately and dimensions were added automatically when manipulating the scanning data. Defects were marked accordingly within the digital models, then all the parts could be re-assembled virtually in CAD software such as ProEngineer. This digital process is much more efficient and effective to guide the repair process and it saves much of the physical space needed for storing manual archives. A remaining research issue is optimising the digital archiving system to enable craft workers to use it easily based on their habits and experience of reading conventional documents.

Mosaic - multi-material simulation and seamless assembly

The mosaic restoration project demonstrated the advantages of using AM for multi-material simulation and seamless assembly. In the traditional process, replacement sections are grouped according to the materials, and the reproduction of parts in each group is led by one high skilled professional. Every replacement section is measured and modelled carefully to reduce the risk of wasting expensive material, and the reproduction of every new piece is similar to sculpture manufacturing. Although it can be measured from different angles, typically, the new part still needs to be re-ground a few times to fit the base's complex geometry. Using AM, it is possible to produce a group of small parts in a single build with the digital models obtained from 3D scanning. Even though a range of finishing techniques can be applied to simulate different material effects, it is still sometimes necessary to use a moulding process for materials that look like jade and amber. This case study was a kind of "mass individualisation" as every part was unique with no possibility of copying. Another large benefit was that, the surfaces of the broken edges could be scanned accurately so that the new part produced by AM fitted exactly with no visible seams.

A general comparison of traditional methods and AM processes for all of the artefacts is summarised in Table 7-7, the cost in this calculation based on Chinese labour cost rate, which may save more using digital methods in the UK as the British labour cost rate is higher.

Table 7-7 Comparison of traditional and AM processes for all of the artefacts

	Traditional manufacturing	**Additive manufacturing**
Quality	Inevitable transformation	Accurate reproduction
Time scale	Measuring & Engineering drawings 1-2 months Reparation 2-3 months	Measuring & Engineering drawings 1-2 weeks Reparation 1-2 weeks
Relative Cost	100%	30%-50%
Labour	Professionals who have been trained for a few years Artists/sculptors	Engineers who have been trained for a few months Artists/sculptors
Material	Bronze, wood, marble, jade, etc. Pigment, chemicals	AM materials, silicon rubber, plaster, resin, pigment
Finishing techniques	Requires professional finishing skills & rich experience	Requires interdisciplinary knowledge & basic finishing skills
Other issues	Mistakes may cause wastage of expensive materials	No waste in virtual working environment

7.1.4. Summary of data analysis

Having undertaken a number of practical case studies in this area, it was clear that there were significant benefits and limitations of using AM and other digital technologies. In order to create recommended paths for future implementation of these technologies, it was first necessary to devise an objective means of evaluating their strengths and weaknesses. The overall comparison system and evaluation matrix that aim to guide applications of AM in relevant sculptural areas are presented in the next section.

7.2. Analysis of AM as Applied to Sculpture and Restoration

Analysis of strengths and weaknesses of AM for sculpture industry
A comparison method was designed to analyse the strengths and weaknesses of both traditional and AM manufacturing methods using a number of important criteria. The evidence for the effectiveness of this method is in this chapter. It has been derived from the practical case studies undertaken and evaluation of their results, the full evaluation feedback from the Forbidden City can be found in section 1.2.4.

7.2.1. Introduction of analysis system

AM and other digital technologies have both positive and negative effects on cost and time making it necessary to evaluate these for different options, so that the method that gives the best compromise between cost and timing can be identified. Thus, it is necessary to analyse the impact of AM and other digital technologies upon the sculpture industry; the analysis system is presented in this section.

7.2.2. Cost

The different costs that need to be evaluated (labour, machine and material, etc.) and how can they be estimated is introduced in this section.

As every project in real industry has different requirements and characters, project analysis is an essential step for calculating cost and time. This step includes understanding the requirements, mind mapping all the feasible solutions and selecting one solution to best suit the project. Generally speaking, the case studies in this research used an integrated method of digital technologies and manual techniques that can be summarised as the following process:
Project analysis - Original creation / Solution design - Scanning - Data manipulation - AM - Machining - Layered manufacturing - Post processing - Moulding - Finishing (- Shipping and Installation)

The calculation of cost consists of two parts: labour cost and machine and material cost. In labour cost, the unit rate of labour depends on the working content and qualification, number of labourers and time needed. Any compromise reached more importantly needs to consider the quality of the result. The unit rate is how much per person per hour or per day, so the total labour cost is equal to unit rate multiplied by the number of persons multiplied by time (number of hours or days). In addition, special conditions need to be considered and indicated as comments and the extra charges should be added in the total cost. For example, the unit rate for the same person is different in normal working hours compared with over time or working during night time. In addition, insurance should be covered for working under difficult conditions, such as working at height and operating machines with harmful light or radiation.

As for machine and material cost, the unit rate relates to device model, number of devices, and time, or material and amount of material, which all need to be compromised with each other, also taking quality into consideration. The total cost of this part is unit rate for machine rental multiplied by the number of devices multiplied by time needed, plus unit rate for material multiplied by the amount of material. Also, special conditions need to be considered, such as cost of equipment parts wastage, material wastage and cost of necessary accessorise. Table 7-8 and 7-9 provides a cost model that can be used to input data for specific projects for cost calculation.

Code:
P - procedure (e.g. Scanning, AM, finishing, etc.)
L: labour working content (e.g. Coordinator, Software operator, etc.)
N: number of labourers
U: unit price/rate (e.g. GBP/person/day)
T: time (e.g. Hours, Days, etc.)
Q: qualification (e.g. Worker, Intermediate engineer, etc.)
S: summary (e.g. U × N × T = Sum)
C: comments (e.g. night working charge, safety insurance, etc.)

Table 7-8 Labour cost model

P	L	N	U	T	Q	S	C
1...							
2...							
etc.							

Code:
P: procedure (e.g. Scanning, AM, finishing, etc.)
D: device model (e.g. ATOS 5M scanner, Objet Connex, etc.)
N: number of devices/amount of material (e.g. 3 CNC machines, 1kg, etc.)
M: cost of material used (e.g. photosensitive resin, wood plastic, etc.)
U: unit price/rate (e.g. GBP/device/hr, GBP/g, GBP/m^2, etc.)
T: time (e.g. Hours, Days, etc.)
S: summary [e.g. (U × N × T) + M = Sum]
C: comments (e.g. night working charge, safety insurance, etc.)

Table 7-9 Machining & material cost model

P	D	N	M	U	T	S	C
1...							
2...							
etc.							

7.2.3. Time scales

The principle of time scale calculation is similar to cost calculation except that a cost per unit time is not considered. It also consists of two parts, namely labour and machine working time. Time scale calculations need to consider the compromise between selecting manual skills, digital work or a combination of methods to obtain acceptable results. Generally speaking, the main aspects that need to be considered in this research included qualifications of labourers, number of labourers, device model, number of devices and material used. The information about qualifications includes manual skills, experience and background which have a significant impact upon communication and training time. Device model and materials affect unit rate and waiting time, such as the size of working platform and material drying time when applying finishing techniques.

7.2.4. Comparison system

A comparison of conventional and AM manufacturing processes used for the different projects is shown in Table 7-10. It can be seen that in almost all the cases, the AM process was quicker and required fewer workers. However, the workers that were used needed to have higher skills.

Codes:
C - conventional; A - AM
d - day; w - week
ph - professional handmade; pd - professional digital work; u - non-professional
r - real material that as closest to the original; s - simulation
m - much workload; l - little workload; n - not necessary
Unit: cost - thousand GBP; labour - person(s); moulding - time(s)

Table 7-10 Comparison of conventional and AM manufacturing processes

	Cost		Time		Labour		Material		Moulding		Finishing	
	C	A	C	A	C	A	C	A	C	A	C	A
Horses	100%	70%	12d	6d	2u 6ph	1pd 3u	r	r	2	0	l	n/l
Beowulf	100%	70%	40d	22d	4u 8ph	1pd 4u 2ph	r	r	2	2	l	l
Fan base	100%	40%	1m	2w	4ph	3pd	r	s	0	0/2	m	l
Dragon plaque	100%	30%	3m	3w	6ph	4pd	r	s	2	2/0	m	l/n
Ceiling & enclosure	100%	50%	2m	4w	5ph	4pd	r	s	0/2	0	m	n
Furniture	100%	40%	1m	3w	4ph	4pd						
Mosaic	100%	30%	2m	2w	4ph	3pd	r	s	0	2	m	l

A quality evaluation was undertaken using the results of the discussion presented in the previous chapter and also the results of the customer evaluation that as follows.

The most tedious aspect of the work was the non-professional labour, the moulding and the finishing operations.

Evaluation Criteria for Application of AM in Antique Restoration

Consideration: Antique Repairing, Replica, Souvenir Design, Archiving Data-base (2D, 3D, Engineering drawing), Defect/Changing Analysis, Animation, etc.

Standard: Evaluate each category: Excellent, Good, Acceptable, Poor

Participants: Three experts from Architecture, Technology, and Information Department; two non-specialists from Sales Department and Administration

Number in the brackets means the number of people who choose that option

Symbol: () means experts, [] means non-specialists

1. Quality (overall: good) [overall: excellent]

1.1 Accuracy

  1.1.1 Measurements (excellent 3) [excellent 2]

  1.1.2 Visual effects (excellent 1, good 2) [excellent 2]

1.2 Resolution / Details (excellent 2, good 1) [excellent 1, good 1]

1.3 Colour (good 2, acceptable 1) [excellent 2]

1.4 Texture (good 2, acceptable 1) [excellent 1, good 1]

1.5 Surface roughness (excellent 1, good 2) [excellent 2]

1.6 Aging treatment / Match with the original (need further experiment)

2. Time

2.1 Measuring (excellent 2, good 1)

2.2 Design solution (good 2, acceptable 1)

2.3 Manufacturing (excellent 2, good 1)

2.4 Finishing (good 1, acceptable 2)

2.5 Transport (need investigate further)

2.6 Installation (good 3)

3. Cost

3.1 Labour (good 3)

3.2 Material (excellent 1, good 2)

3.3 Error/Failure (excellent 2, good 1)

4. Accessibility

4.1 Labour (acceptable 3)

4.2 Facility (excellent 2, good 1)

4.3 Material (excellent 1, good 2)

5. Feasibility of remote working (excellent 2, good 1)

Comments: (the numbers before the comments refer to the questions that produced the comments)

1.2 Some small details look a little different with the original

1.3 Gold could be more reflective, jade effects are acceptable for souvenir but should be closer to the original for repairing (expert)
Although the colour is different from the original, these look better (non-specialist)

1.4 The effects of gold, transparent glass and white resin like ivory are good, the texture of jade should be better, and the finishes could include more wood and white marble effects (expert)

1.6 Need further experiments to prove that the aging treatments are OK to be applied for AM materials, and will not affect the original materials if combined with them (expert)

2.1 & 2.2 If it is difficult to collect scanning data for some antiques, it may take more time for measuring and designing a better solution than when using traditional methods

2.4 Finishing processes are similar to the traditional methods (expert)

3.2 AM materials are expensive for large scale parts, especially for repairing which only needs one copy. The cost of moulding for souvenir design and customised products can be good. (expert)

Overall, the range of experiments and finishing effects are impressive, digital technologies are very useful for relic preservation. Further experiments are needed to solve minor issues, maybe combining new technologies with traditional methods will bring the best solutions. (expert)
Digital technologies should be able to bring better animation, products and expand the market. (non-specialist)

Points from a group discussion
Experts from: Ancient Architecture department, Technology Department, Information Department
Non-specialists from: Sales Department, Architecture Project and Art Design Section

Advantages:

Accuracy is better than that by traditional methods

Multiple perspective and Omni-directional measurements

Regular 3D scanning and comparative analysis

Repairing accurately, combining with the original parts seamlessly

Diversity of materials and effects brings developing prospects

Data-base can be used for archiving, repairing, demonstration and replication

Issues to be solved:

Storage and manipulation for a large mass of data

Feasible and easily operated process chains need to be applied universally in relic preservation area

7.2.5. Overall impression

This section gives a general guide about how a user should decide on the trade-off between cost and time. The following quotes comes from an existing viewpoint found in the literature review "Just as there is no such thing as perfectly pure gold and no completely perfect person, so no technology can be omnipotent" (L.Q. Zhu, et al. 2013). According to the literature review and the data recorded during this research, AM has its advantages and constraints for different sculptural applications. The general comparison of AM with conventional manufacturing processes for art works is shown in Table 7-11.

Table 7-11 General comparison of manufacturing methods for art works

Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional way**
Geometrical flexibility	Nearly arbitrary 3D form with internal and external features, curved channels, etc.	Arbitrary 3D with external features but limited internal structure and undercuts
Overall model size (mm)	Theoretically: unlimited (using assembly process) Normally up to: 500 * 500 * 300 with high resolution	Unlimited
Minimum feature size (mm)	About 0.5	About 1
Accuracy	About 0.1 mm	Sub-mm
Surface finish	Mostly little polishing	Mostly substantial polishing
Vividness (does the sculpture look lively or vivid)	Low	High
Assemblies with multiple components and materials	Single build or pre-assembled virtually to minimise the risk of mistakes	Assemble manually Risk of deviations and compatibility
Choice of materials	Paper, wood, plaster, plastic, (glass) resin, sand, metal-alloy, ceramic	Effectively no material limitation
Cost	Only depends on weight/volume of material consumed, but unit price is high	Affected by various elements, such as complexity, modelling skills, material
Lead time	Typically days - weeks	Typically weeks - months
Requirements for operators	Software operation and post processing / finishing	Modelling skills and manufacturing knowledge
Reproduction and copies	Flexible scaling and moulding for copies	Difficult to change scale and low production rates

Based on the summary in above table, it can be seen that when compared with conventional manufacturing process for art works, the main advantages of AM are geometrical flexibility, accuracy, assembling, lead time, and quality of reproduction. The disadvantages are model size, vividness, choice of materials, and cost (see Table 7-11). Therefore, for each project, the choice of using AM or the conventional route would depend upon the relative importance of each of these aspects. To help quantify this, a "weighting and rating" method was applied to each of the 7 projects undertaken. The relative importance of the comparison criteria was indicated by giving them each a weighted importance. The values of these weightings were set through discussion with the project leaders. The total of all the weightings for each project was arbitrarily set at 100. Then once again through discussion with the project leaders, both the AM conventional routes were given rated scores against each of the criteria. The rated scores were totalled to give both routes their score out of the maximum possible 100. As an example, the comparison matrix from the Horses project is shown in Table 7-12 and the comparison matrices for the other projects are given in Appendix 7.2.5. The comparison matrix could then be used to guide the decision making process for similar future projects.

Table 7-12 Comparison Matrix for Horses Project (different value was designed according to significance refers to research question one)

Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional**
Geometrical flexibility 9	9	3
Accuracy 9	9	3
Assembling 6	6	0
Lead time 9	9	3
Reproduction 13	10	6
Model size 13	4	13
Vividness 15	6	15
Choice of materials 13	10	13
Cost 13	10	6
Total 100	73	62

As shown in the comparison matrices, because of the wide range of criteria and special requirements of art works, AM does not have an overwhelming advantage in the sculpture industry. In some projects, it had a significant overall benefit, whereas in others, the scores were very close. This is one of the main reasons why it will be difficult to convince the project leaders to use these digital techniques in future. However, it must be noted that the analysis of the data reflects the current capabilities and existing applications of AM, which are mostly in the industrial design, engineering design and manufacturing fields. AM has not really been developed with sculpture manufacturing in mind.

With every problem comes an opportunity and AM has much potential to be optimised for sculpture manufacturing. Specifically, the cost of materials could be reduced by building thin shells since sculpture normally requires only detailed external features, and the excellent accuracy and reproduction quality can reduce the high labour cost. As for larger models, AM could be used to build only the complex surface regions and then be combined with manually created parts to gain maximum benefit from its advantage of geometrical flexibility.

Although the loss of vividness is an inevitable disadvantage of any type of machine-based process, it is not the aim of AM to replace the artistic aspect of sculpting. Rather the purpose of AM is to be an assistive tool for sculpture manufacturing, not to replace the artist's creative input or final treatments. From this point of view, it is certainly feasible to optimise AM for sculpture manufacturing, especially model reproduction. A better understanding of sculptors' requirements and communication with them would be helpful in finding the overlapping areas of interest. In this way, it may be possible to improve the vividness of using AM as well as reducing un-necessary repetition and associated tedious work.

7.2.6. Implementation (Integration into work-flow)

The alternative possible routes for creating a sculpture can be compared using cost and time estimation/calculation using the cost and time models described above. The minimum level of quality to be achieved will still be under the control of the project manager and/or principal artist. In this way, a general reference system can be built up from the comparative analyses of previous projects. Each time a new project is started, previous results can be accessed and used to help guide the decision-making process, i.e. whether to use conventional and/or AM routes. However, such an approach would be rather long-winded or inconsistent as it would either require the project manager to sift through all the previous projects or rely on his/her memory of which projects were similar. Some sort of decision-making tool created from previous comparisons and decisions would make this more practicable and easier to integrate into the overall work-flow.

7.3. Summary of AM analysis

The analysis of using AM showed that there was a definite relationship between the type of application and the way AM needed to be used. This was because the application of AM in this field (when integrated with manual techniques) has a direct impact of the quality of results, cost and time scale, which are three key issues in practical projects in the sculpture industry.

Having identified the market needs and the gap between knowledge and practice, it is the aim of this research to optimise the process chains for feasible solutions to assist in optimally adopting AM in the sculpture industry and for archaeological preservation. For others to be guided into making optimum use of AM, a method for representing the knowledge gained was needed, and the next chapter explains the development of such a method.

8. Chapter Eight: Development of Digital and Manual Techniques Process Maps

8.1. Introduction

A series of manufacturing process chains that were derived from the case studies were summarised according to the information collected from all the research activities, and they are presented in this chapter in a visual way. This method was chosen because the target audience was perceived as being more familiar with visual aids and more likely to use them. A final overall map was also produced as the major outcome of this research and is a complicated system that consists of a combination of several smaller maps, which have integral relations with each other. The maps can be used individually or integrally in any combination as assistive tools for the sculpture manufacturing process according to different material needs for different types of sculptures.

The manufacturing process chains can be seen as a reference system that assists practitioners to understand the complicated processes more clearly and hence make decisions more efficiently. There were many ways to present the knowledge derived from the research, such as written guidelines, software, training courses, etc. However, for the mass of information to be presented (including manual and digital techniques, the relation between procedures, alternatives and explanations), using written guidelines would have resulted in a bulky handbook that would take a long time to read and learn. Making a software system would have required all users to learn the system functions and they could only use it on a computer with the software installed. This is not always readily available in the sculpture manufacturing environment. As for training, this is a more complex topic that relates to the users' educational background, the available training time, the cost of running the course, and the need for follow-up consultation. Besides, according to this research, both artistic training for engineers and digital technologies training for artists are difficult to achieve. Therefore, paper based process maps were initially chosen as they can show the key techniques and their relations visually. They are quite easy to follow, and convenient to use under all the working conditions envisaged, without the need for computer hardware or software. The usefulness and accessibility of the maps are shown in later sections of this chapter, based on feedback from the validation process.

8.2. Development of process chain maps

The maps were originally created using the SmartDraw package, as the software was easy to use with simple flow-diagram drawing functions. However, Microsoft Visio was found to be a more powerful package for creating process maps as they could be shown at different levels or with sub-processes, either by using hyperlinks or simply different layers. As a result, Visio was adopted to create most of the process chain maps for this research.

The maps were designed for different user needs and to maintain different levels of confidentiality; for example, when the entire process or final result needs to be kept confidential during manufacturing, only part of the maps can be shown to people working in different departments or different processes. Decision making was a significant part of making this visual map system, which would allow the users to choose alternatives according to sub-maps of different techniques. The users can select methods best suited to their projects, and choose appropriate techniques based on up-to-date references, such as current AM machines, 3D scanners, CNC machines, software, different materials, manual techniques, and finishing techniques. Solutions for design work and project planning can be considered comprehensively with the cost and time models, which were introduced in the previous chapter. Back up plans can be made according to the alternatives provided in the maps to “work around” problems that emerge during the work.

Knowledge about manufacturing process chains obtained from the case studies in the literature review and from the practical projects undertaken by the author was summarised and transferred into flow-chart to form the maps. The research covered a great diversity of projects in the fine art sculpture and archaeological restoration fields, with different needs in terms of complexity of geometry, sizes and materials, as shown in a table 8-1. The table indicates that four types of artefacts have been covered (shown across the top of the table) with up to twelve different materials (shown in the left-hand vertical column). The blue shaded squares represent each type of artefact that has been covered in either large, medium or small sizes with various corresponding materials. For example, the case study Horses project presented in Chapter 6, section 6.2 belongs in category B - realistic animal sculpture, with both L - large size for the final models and S - small size for the sand models, in material 1 - Stone. The case study Beowulf in Chapter 6, section 6.3 belongs to category A - realistic human body sculpture, with L - large size in material 2 - Bronze. The product development from these project is in M - medium size in material 2 - bronze/copper. The case study in Chapter 3, section 3.3.3 belongs to category C - abstract modern sculpture, with L - large size in material 2 - bronze, the archaeological restoration case studies in Chapter 6, section 6.4 belongs to category D - antique restoration in various sizes and materials. Future projects will cover more regions of the table until the full picture has been created.

Table 8-1 Main needs in sculpture and archaeological restoration

	A. Realistic Human Body Sculptures			B. Realistic Animal Sculptures			C. Abstract / Modern Sculptures			D. Antique Sculpture Restoration		
Size	L	M	S	L	M	S	L	M	S	L	M	S
1. Stone (Marble)	🟦			🟦			🟦			🟦		
2. Bronze/Copper	🟦	🟦			🟦	🟦	🟦			🟦		🟦
3. Stainless Steel												
4. Gold												🟦
5. Silver												
6. Wood								🟦			🟦	
7. Bamboo												
8. Lacquer ware											🟦	
9. Ceramic												
10. Bone/Ivory												
11. Jade											🟦	
12. Amber											🟦	

Manufacturing processes were recorded from the case studies, and key steps were extracted to form the first layer of the maps to provide a clear guidance for projects in different areas. Sub-processes and alternatives were organised into sub-maps to offer examples and more specific information. For instance, the map-practical shown in figure 8-1 shows the general process chain for sculpture manufacturing and archaeological restoration at the first layer. Within Visio, clicking on the "A/B-L-1/2" box gives access to a second layer map for detailed sculpture manufacturing with both traditional and digital methods (shown in figure 8-2), and clicking on the "D" box gives access to the sub-map for restoration using conventional and AM processes (shown in figure 8-3). The first layer maps allow professionals to select appropriate routes in association with the cost and time models, and the sub-maps provide alternatives for specific types of work when further information is needed. Selection of scanning and AM systems, CNC machines and finishing techniques are shown in more sub-maps with specific tips and alternatives which can be developed in further research. In the paper version of the map tool, these sub-maps are provided as separate cross-referenced pages.

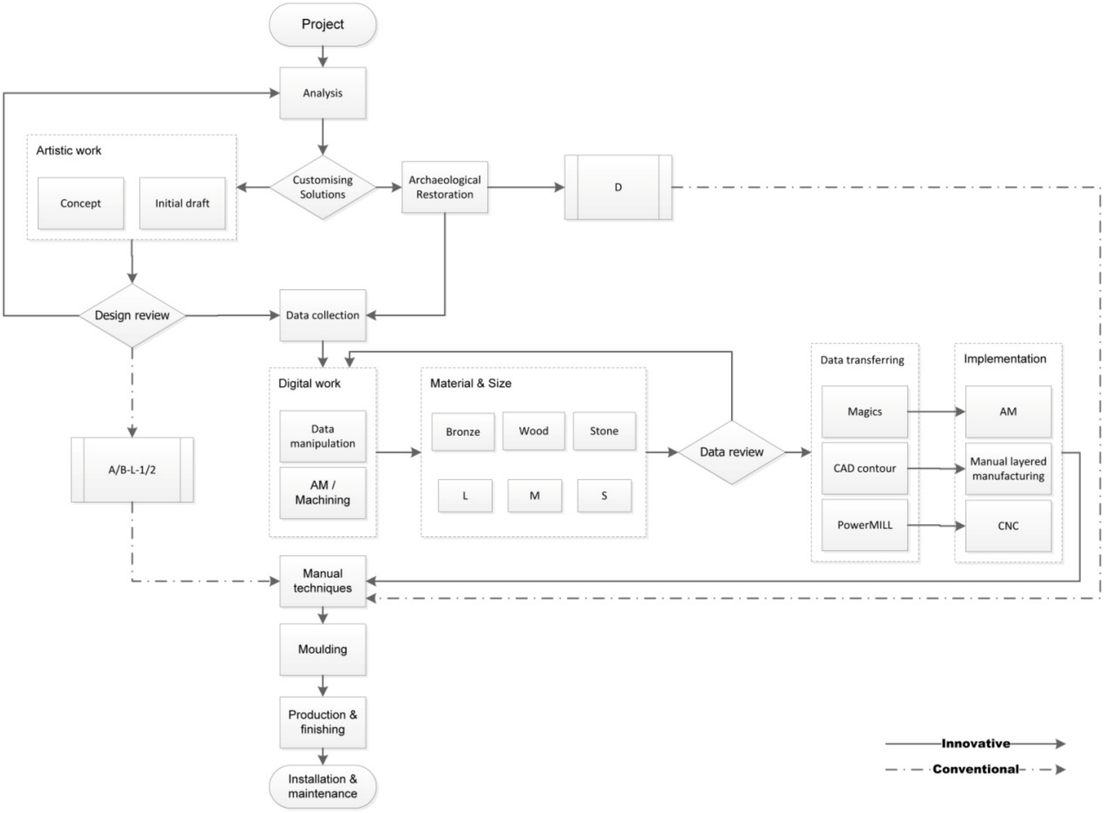


Figure 8-1 General process chain for sculpture manufacturing & archaeological restoration

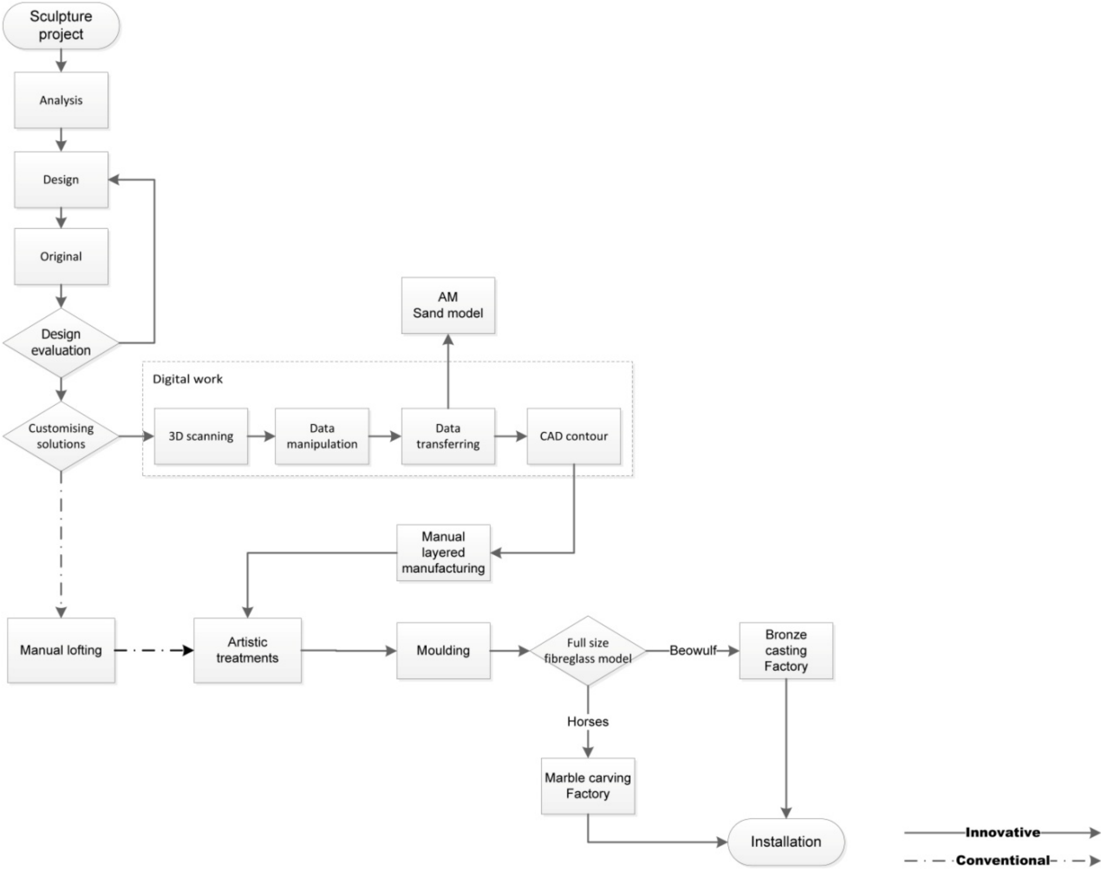


Figure 8-2 Sculpture manufacturing with both traditional and digital methods

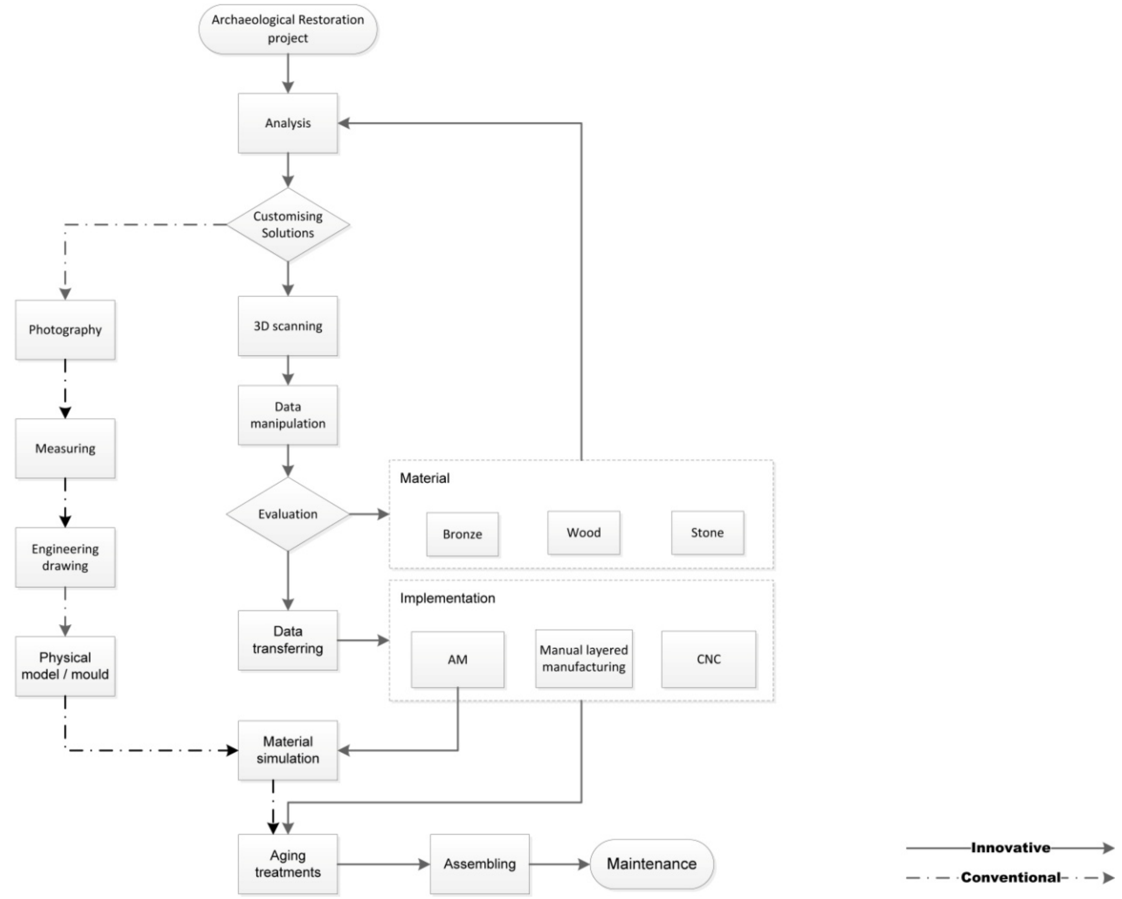


Figure 8-3 Restoration using conventional and AM processes

All maps including sub-maps are shown in appendix 11.3

8.3. Validation of process chain maps

Having used several case studies to generate the knowledge for the process maps and then drawn them using Visio software, it was then necessary to validate both their content and usability. The opportunity to do this came through two commercial sculpture projects that the author was asked to help with, a large relief sculpture at Beijing University and replication of a pair of large bronze lions at the Summer Palace in Beijing. These projects were undertaken by professionals and technicians in China, with the author acting as project manager for the first project and as an observer during the second. In both cases, the process maps were used to guide the decision-making process. The projects, the role of the maps and feedback gained from those people who were using them are presented below.

8.3.1. Beijing University group relief sculpture

Context

This project is a large group relief sculptures with realistic style fine details including natural sights, buildings and portraits, which is based on some old photos of Beijing University Health Science Centre (PUHSC). This group relief sculpture was designed for the 100 year anniversary of PUHSC in 2012, and established as long term exhibition on the walls at the ground floor entrance hall in the main building. There were six pieces of relief sculpture, two large ones that were 2.1m × 2.8m and four smaller pieces that were 0.8m × 2.4m with relief thickness of no more than 100mm, the material was a kind of resin called “artificial stone” that was used to simulate marble.

This project was chosen to validate the sculpture manufacturing maps and also to verify the use of sub-maps with additional alternatives. It aimed to achieve artistic creation using a combination of digital and manual methods, and efficient economical manufacturing with optimised process routes including 3D scanning, AM and CNC machining technologies. The difficulties included the large scale of the reliefs, with 66 portraits in total, the complexity of the buildings geometry, the design being based on several old blurred photos which had a lack of detailed information, and the fact that the project had to be completed in a very tight schedule of two months.

The positive results obtained were the successful use of digital creation using a method presented in the author's Master's research that compressing 3D digital models into relief sculpture; a new approach to accurately producing clay models using AM female moulds, which is explained in the manufacturing section; and the successful integration of AM, CNC machining and manual techniques. However, there were still some constraints such as the limited working platform of the AM and CNC machines, data manipulation difficulties caused by accessibility of training and communication barriers, and material availability for tooling and moulding. Overall, the usefulness of the maps was verified as the manufacturing process was greatly optimised as evidenced by the positive feedback and successful results obtained. However, some improvements were identified, which need to be the subject of further research.

Design and evaluation

According to the content and requirements of this project, old blurred photos were the only available resource for the design of the images to be incorporated into the relief. The original design was sketched by the principal sculptor including the arrangement of natural sights, angles of buildings and portraits of staff and students wearing clothing of the early 20th Century period.

Making use of the sculpture process maps, a solution was designed as an integration of both digital and traditional methods. After evaluation of the design and a feasibility analysis of the solution, the group relief sculpture was divided into three parts for manufacturing. Natural sights were created manually using clay modelling skills, geometrical buildings were created digitally by FE based on the photos and portraits were created by RE based on scanning data taken from human subjects.

Manufacturing

The natural sights section started with manual modelling in clay on the relief wall set up in the sculpture workshop (see Figure 8-5). As the design for this section was relatively simple and flexible, and the size was not too large, the full size models could be produced directly by assistants under supervision of the principal sculptor. One of sub-maps used for the Group Relief Sculptures is shown in Figure 8-4, with the chosen route of conventional process seen on the left-hand side.

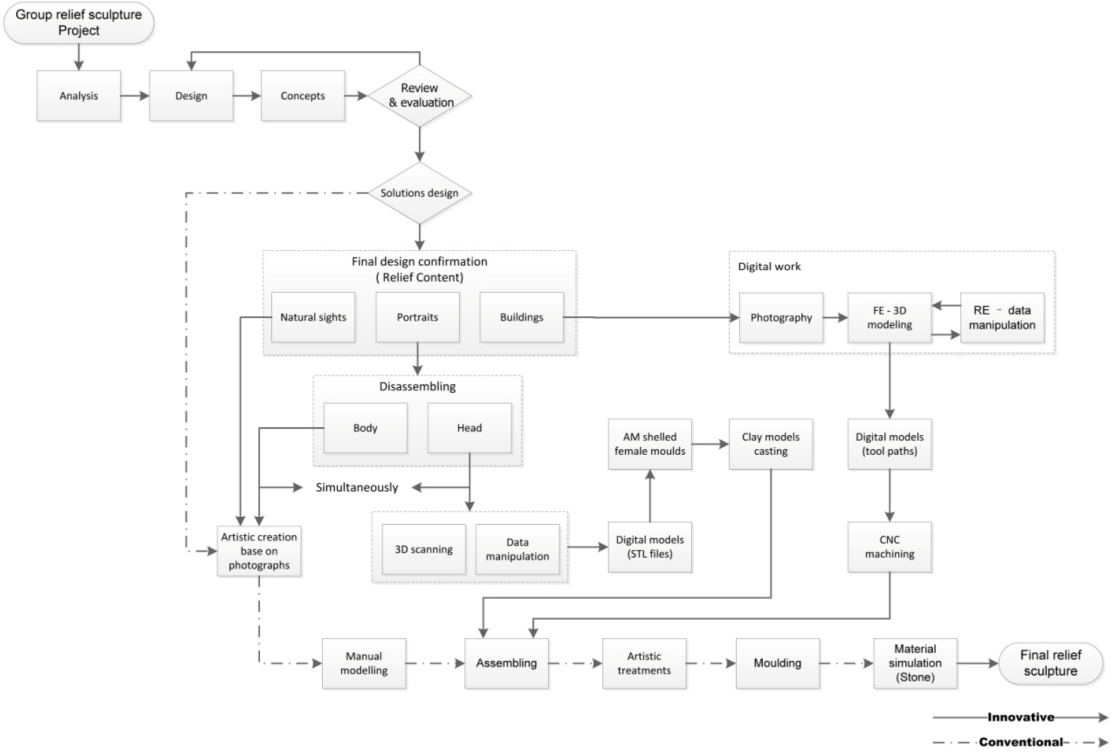


Figure 8-4 Sub-map for Group Relief Sculpture

The buildings section started with digital modelling in 3D Max and ProEngineer software according to the photos, as the geometrical shape was suitable to be produced by FE. Then, the 3D digital models had to be compressed to relief, which used the techniques previously developed in the author's Master's degree research. Firstly, an appropriate angle is significant for relief sculpture, as the 3D shape in space needs to be presented by such a thin layer of material (see Figure 8-6). Secondly, since the digital model cannot be compressed evenly, each building had to be separated into several sections and the furthest sections from the viewer needed to be compressed more than the closer sections, to obtain the correct perspective. As the relief section with buildings did not have undercuts, it was feasible to use CNC machining to reduce material cost. Therefore, the digital models of the relief sculptures were transferred as STL files to create the tool-paths, with each one being divided into several pieces to fit the CNC machining platform. The tool paths were generated in PowerMill software for three tools to process the material from rough cutting to detail cuttings. At the same time, a plaster mixture was poured into square containers that were made from plastic boards with the correct dimensions to contain the pieces. Then, the plaster blocks were fixed onto the CNC platforms and several machines were used together in parallel to reduce the time needed. In Figure 8-4, the chosen route connected to the steps for CNC machining is seen on the right-hand side.

Figure 8-5 Clay modelling of natural sights

Figure 8-6 CNC machining of buildings

The portrait section started with 3D scanning of real people, as the old photos were quite blurred and it was difficult to tell the exact appearance of each person. Volunteers were selected from friends and co-workers to simulate those people on the photos. A 3DSS optical scanner was used and was only focused on facial area. This was followed by manipulating the scanning data and combining the faces with pre-designed hairstyles to form portraits (done using the 3D Coat software). Each portrait was compressed to relief following the same principles as before, and then female moulds were produced as shell models and exported as STL files for AM. An SLA (RS 4500) machine was chosen to produce the physical moulds as originals, and these were used as containers to put clay or plaster in. After this, the AM moulds were heated with a welding torch held a few centimetres away, so that the moulds quickly became soft and were quite easy to remove from the clay or plaster. As a result, the clay or plaster relief portraits were obtained for convenient modifying to create the final design (see Figure 8-7). At the same time as this scanning, data manipulation and AM portrait production was being undertaken, bodies with clothes were created by manual clay modelling, which also required some novel techniques. The photos were enlarged to the desired size and projected onto a wall for the assistants to follow the general shape.

Manual modelling was sufficient as the Chinese style long gowns/robes were relatively simple and flat on the relief sculpture. Then, the portraits were installed onto the relief wall to be combined with the clothes and background for final modification by the principle sculpture. In Figure 8-4, the chosen route connected to AM female moulds seen in the middle

Figure 8-7 AM moulds and casted models then assembled with bodies

Finishing

After assembling all the plaster buildings, clay natural sights and clay portraits together, a little surface finishing was applied to smooth some areas. Moulding was needed to produce robust final models, and so silicon rubber moulds were cast from the combined clay and plaster model. Following this, a kind of liquid resin mixture (so-called "artificial stone") was applied layer by layer into the rubber moulds to simulate the marble effect. The last step was to ship the relatively light and robust final models for installation (Figure 8-8).

Figure 8-8 Final relief sculptures in artificial stone

8.3.2. Summer Palace relic lions duplication

Context

The project required the replication of a pair of bronze lions with bronze and marble pedestals that have been guarding the Cloud Dispelling Hall in the Summer Palace Beijing for about 600 years. The replicas would be established in position for opening of the new Garden Museum. This project was chosen for validating the archaeological restoration maps and verifying the use of additional alternatives in sub-maps. Thus, it aimed to utilise the maps to guide accurate reproduction of full size replicas in the same material as the original using an optimised technology combination method, which involved 3D scanning, AM, CNC machining and manual techniques. Also, the duplicated master models needed to be kept in good condition after being used for bronze casting.

One of the reasons for using the digital method was the failure of casting silicon rubber mould from the originals as there were too many fine detailed reliefs with undercuts. This was also a difficulty when using the digital method, especially for large scale artefacts with fine details, and the geometrical patterns and symmetrical parts were not actually identical since they were created manually in the past. The scanning and data manipulation were quite challenging for the large scale unmoveable historical relics and mass data of the fine details. However, the good result showed that accurate replicas were successfully achieved using new methods with relatively low costs and within the scheduled time of three months.

Although there are still some issues that need to be solved such as scanning under difficult conditions, data manipulation of mass data, compromising time and cost, robustness of AM shells and assembly with inner support structures for long distance shipping, the usefulness of the maps was verified by positive feedback from both the co-workers and the client. Improvements and further development of tools will be the subject of future research.

Project analysis

This was an archaeological replication project, and the main requirement was to accurately duplicate the pair of bronze lions with their bronze and marble pedestals. The replicas had to be made from a robust material as they needed to be kept in good condition after being used for bronze casting.

The particular difficulties associated with this project included the large size of the lions (dimensions: lions on plinths are 1.96m tall ×1.59m × 1.11m with the bronze plinths about 0.6m tall, marble pedestals are 0.92m tall × 1.94m × 1.46m) and the fine details with undercuts in the plinths they sat on. These fine details were the main reason that it was not feasible to cast silicon rubber moulds from the original. In addition, the two lions were fixed in position outdoors in the Summer Palace and were not movable (see Figure 8-9). For these reason, it was almost impossible to produce replicas of the originals using manual techniques, since the only feasible manual way to do this would be by observing the originals or photos of them, which would definitely not be accurate enough.

Thus, the solution was designed to follow the archaeological restoration process maps (the map-Project and sub-map Archaeological Restoration) using an optimised AM approach. Based on observation by the team leader, the bronze and marble pedestals under each lion were deemed to be almost identical with symmetrical patterns on each face (Figure 8-9). This made scanning and data manipulation quicker but there were still some practical issues that needed to be addressed, such as the large sizes involved which could not fit within any of the available AM machines in a single build. Also, there was an overall tight schedule and the team was not permitted to work during daytime Museum opening hours. This resulted in difficult working conditions since the outdoor temperature at night was very cold (about 0 °C) There were also some more problems discovered when implementing the selected process route, and the specific solutions found are explained in the following sections.

Figure 8-9 Original female lion Original male lion

Scanning

Collecting accurate 3D data was the foundation of this project, and after considering the above issues, an ATOS 5M blue light scanner with a TRIPOD calibration system lens was adopted. The scanning work had to be conducted during the night between 7pm and 7am to avoid affecting and being affected by visitors. All the scanning work had to be completed intensively before winter came, as the temperature had already dropped close to 0 °C at night since the first snow at the end of October 2012. The theoretically lowest temperature that allowed the scanner to work stably should be above -4 °C. Thanks to the compact design of the scanner, all the equipment including the scanner, cables, alternative lens, calibration boards and shock protection, could fitted into one large suitcase (Figure 8-10). A mobile work station and other accessory tools were prepared to solve other minor issues, such as the fact that there was no power source near the lions, no lights after the Summer Palace closed, and no ladder to reach the heads of lions that were almost 4m tall. Hence, a small ticket office next to the square where the lions were located was borrowed for connecting power cables, portable lights, and storing some chairs, desks, wood boards, hot water, etc.


Figure 8-10 Unpacked devices from the suitcase


Figure 8-11 Calibration marks

The scanning was planned to start from the bottom to the top as the lower parts were easier to reach. There were two sizes of reference marks to be stuck onto the marble pedestals in advance of the scanning, the larger mark point being used for the TRIPOD camera calibration system (Figure 8-11). There were actually two steps for the calibration, the first one was using the calibration square board or cross board to adjust the scanner and check the working status on the work station (Figure 8-12), and the second step for a large scale artefact like this was using the TRIPOD system to collect the global data similar to taking photos. After that, local data was collected by the scanner with a maximum 600 mm × 600 mm area per scan, with the local data being registered with the global data at a later stage, using a process similar to that reported in Chapter Five, sub-section 5.3.3. The actual scanning area depended on the complexity of the geometry, and normally one area required several scans to form the complete 3D shape.

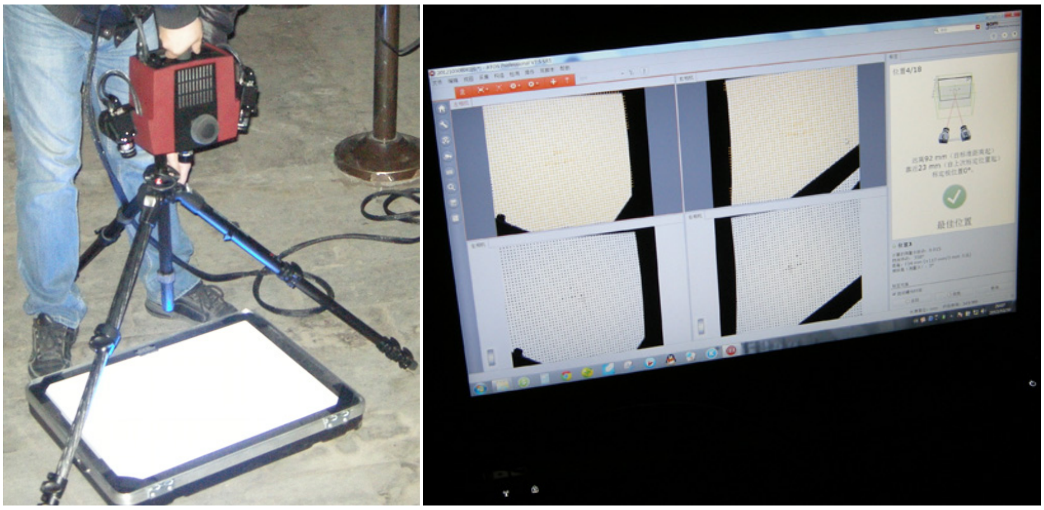
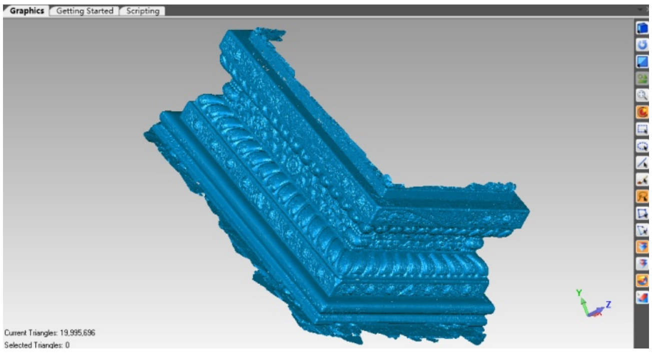


Figure 8-12 Calibration system and information shown on the workstation

According to the visual analysis, the patterns on the pedestal were symmetrical, so both marble pedestals were scanned on two sides only and the other side generated by reflection in Geomagic RE software (Figure 8-13). However, the total time scale was still a little longer than estimated in the light of the progress of the first part of the work. Reasons for this included the complexity of the geometry, a lack of experience, the depth of relief being different on the female lion's pedestal compared to the male lion's, sticking on and removing the mark points was more time consuming with cold hands and under spot lights in the dark, and the wind was much stronger next to the lake which vibrated the scanner requiring repeated scans to be necessary for the same area to obtain good quality data.

A similar strategy was adopted when scanning the bronze pedestals. Based on the analysis of symmetrical patterns, one lion's bronze pedestal was completely scanned, whereas for the other one, only the different shapes were scanned. This strategy caused a serious problem for the data manipulation as explained in the next section. Scanning for the bronze pedestals took around double the time of that for the marble pedestals, as there were many more undercuts and deep gaps, and the reflectivity of concave and convex surfaces was very different, requiring adjustment to the scanner to obtain complete data.

The height of the lions was also a problem as the team was not permitted to fix any climbing device onto the relics and it was impossible to drive cars to that area of the Palace or to bring a lift to fix the scanner on. Therefore, wooden boards were put on the protection bars and top of the marble pedestals to support the scanner and the operator, other devices were put on a desk next to the wooden boards outside the protection bars (Figure 8-14). Even so, there were still a few areas that were difficult to reach, one being the top hair parts and areas behind the ears, another being the hollow structures under the claws, and the third was the deep concave in the mouth and surfaces under the belly. Various angles were tried to obtain complete data in order to avoid trouble at the data manipulation stage.



Current Triangles: 19,995,696
Selected Triangles: 0

Figure 8-13 Half marble pedestal

Figure 8-14 Operating scanner on the wood boards

Data manipulation

After completing the scanning work under difficult conditions, the data manipulation also proved to be problematic. The first problem was that the 3D scanning and data manipulation were not automated, and no one could work during both night and day-time. Therefore, after the scanning team finished their work over-night, the data was passed onto another team for data manipulation during the day-time. This introduced some communication issues and problems caused by a lack of familiarity with the data.

The main data manipulation task was to organise all the files and to register the global data and local data together to complete an entire surface. Also, it was necessary to register adjacent surfaces scanned from different angles to form the complete shape. Although the blue light scanner worked in a relatively stable way with very little issues under environmental lighting, the scanning data had imperfections caused by other elements, such as the wind, positioning problems and the complexity of the geometry.

Another issue was mass of data to be handled, with one file being over 20Gbytes, which almost could not be manipulated in any workstation or software. Two strategies were adopted to deal with this issue. One was to optimally reduce the triangles in the STL file, which kept more triangles for areas with more complex geometry and simplified the areas with relatively simple curved surfaces. Another was to divide the whole model into several sections according to the processing methods to be used at later stages, i.e. some sections needed to be exported for AM while others would be exported for CNC machining, with all the individual sections needing to fit the working platforms of the specific machines used. In addition, the cutting lines between sections could not be straight as that would be too obviously visible on the physical model. Therefore, cutting curves that followed the geometry were used to hide the divisions, the same method as used to divide the Forbidden City dragon relief. Assembling and later issues were considered in advance as well, as every step had definite links with others in the process chain. After all the physical pieces were produced, they had to be easily assembled and had to allow removal of seams and marks, and also the structure had to be robust enough for shipping and post processing.

A serious problem emerged when all the scanning work was completed following the original process plan. As the original relics were handmade, the dimensions, geometrical shapes and symmetrical patterns were not accurate as estimated and observed, which could be seen quite easily within the scanning data. For example, the two marble pedestals were not exactly the same size, one bronze pedestal was not really rectangular but rather rhombus-shaped in the top view, and the symmetrical patterns were offset almost 10mm when comparing the two bronze pedestals (Figure 8-15). The original plan was to scan the entire female lion's bronze pedestal but only the top of male lion's bronze pedestal, because both bronze pedestals had the same symmetrical patterns, the only difference being a belt on the male lion's pedestal. However, to register the male top with the female bottom needed either a change in the pattern at the connection interface or else moving the offset patterns one by one. Obviously both were not possible as it was archaeological replication and not an artistic creation, and the huge workload and skilled work could not be achieved. Hence, only two options were feasible, one being to go back to the original lions and spend one or two more nights to obtain all the desired scanning data. However, the temperature had dropped to -4°C at night and the availability of the scanner could not be guaranteed as it required additional working time, at an additional un-budgeted cost. Another way was to find a solution for registering the data without obvious mistakes or and joining marks. After two days of continuous experiments and discussion, the belt part, triangle zone and lions bottom were separated and re-arranged, using some parts on one pedestal's to complete missing parts on another (Figure 8-16). Two complete bronze pedestals were finally formed with the integrated use of GOM, Geomagic, and 3D Coat software.

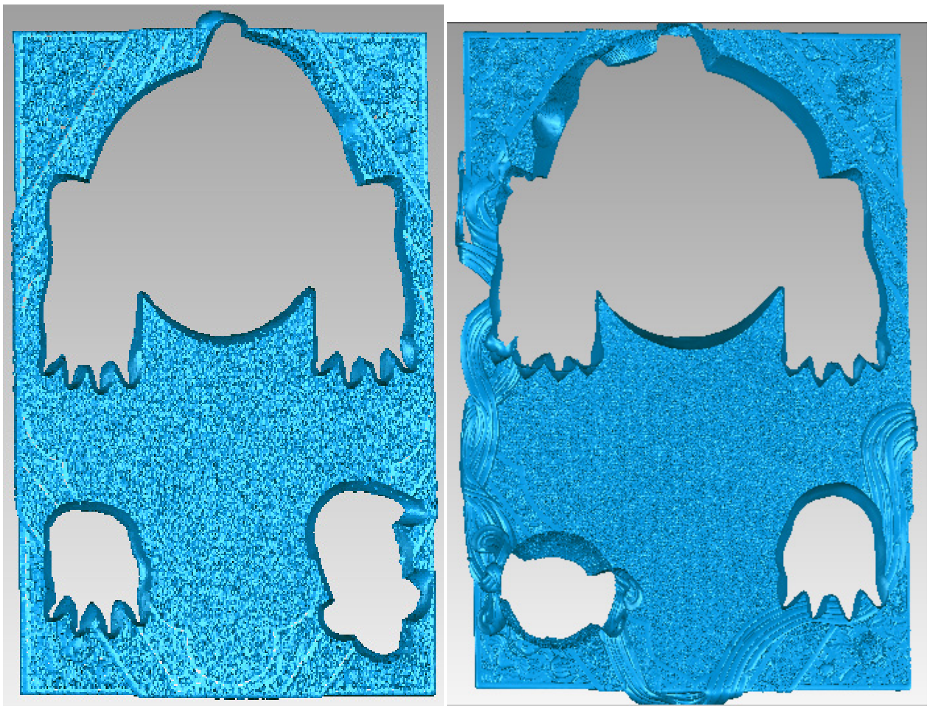


Figure 8-15 Bronze pedestals top view

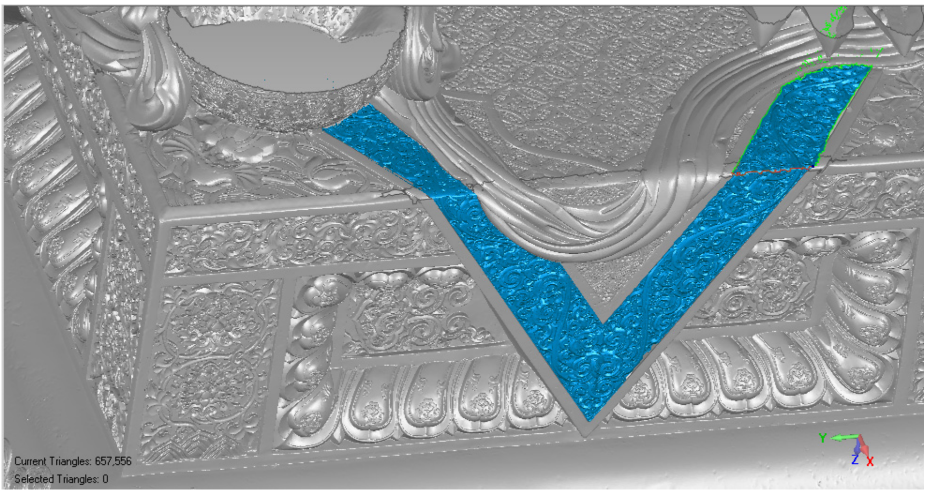


Figure 8-16 Using parts from female lion bronze pedestal to complete the male lion's

As for the marble pedestals, using a mirror function to duplicate the front and left sides to form an entire pedestal worked well, because the previous registration problem did not exist. The completed lions' data was divided into several sections for subsequent manufacturing. All the STL files were fixed using Magics software before exporting for manufacturing, i.e. filling holes, flipping normals, repairing bad edges, removing extra facets, etc.

Manufacturing

The well organised STL files were sorted into groups and sent to the manufacturing department. The STL files for AM parts had to be tested in Magics software to check that were they acceptable for building and to add a reasonable amount of supporting material, which was aimed at avoiding distortion during printing while also minimising costs. All the AM shells were set as 1.5 to 2 mm in thickness depending on their size, complexity of their geometry and their position in the sculpture, e.g. where they might support more weight or bear more forces during moulding. One advantage of using an AM machine was that as many parts as possible could be fitted into a single build to save time. Two SLA machines (RS 6000) worked together to produce all the complex or important parts, such as all the fine detailed relief with undercuts, the lions' faces and claws, as hollow structures (Figure 8-17). Moreover, the whole working process needed no tooling and or monitoring, so that other work could be conducted at the same time.


Figure 8-17 AM parts - relief with undercuts, lion's face, claws with baby lion

Other parts with simpler geometry or flat surfaces with low relief were processed by CNC machines to save material cost. High density foam was adopted for the marble pedestals and ABS plastic was chosen for other parts on the lions' bodies as well as for the top surface of the bronze pedestals. Tool paths needed to be generated for these parts, and four CNC machines with 1.5m × 1.5m working platforms worked simultaneously to process all the parts (Figure 8-18).

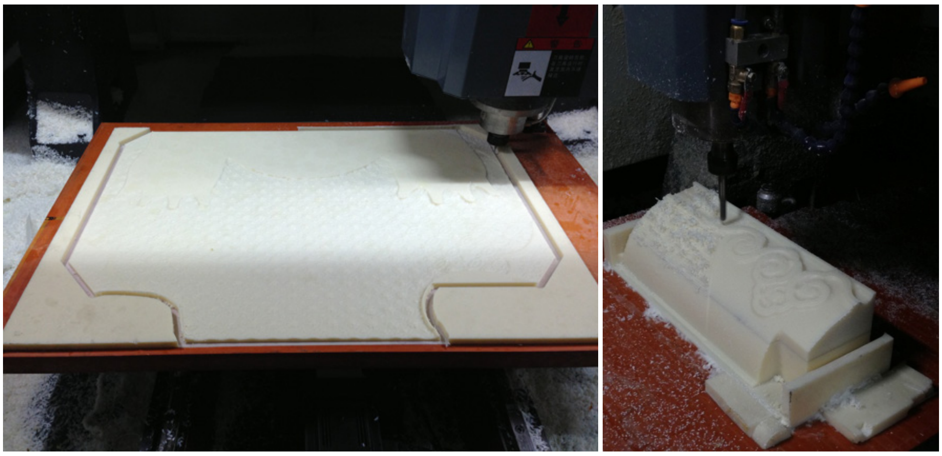


Figure 8-18 CNC machining process

Finishing

After all the parts were taken out from the machines, the AM parts were put into an oven for full curing with UV lights and the support material was then removed by hand. A little surface finishing was applied on necessary parts, and to remove any printing marks (Figure 8-19). Then, the models representing the lions’ bodies, bronze pedestals and marble pedestals were assembled separately with AB glue and MillyPutt, with the connection areas needing some polishing to eliminate the traces of joining. At the time of assembling, wood and ABS bars were installed inside the models according to the designed supporting structure. After assembling and polishing, a layer of atomic ash/putty was applied on all surfaces and allowed it to dry under a large fan.


Figure 8-19 Removing support material manually and surface finishing

The ABS and wood bars were designed in such a way that the majority of the sculptures' weight was actually supported by the inner structures to protect the models. The lions' bodies were installed on the bronze pedestals, but the marble pedestals were kept separate (Figure 8-20). The last step was packaging for safe shipping, and the lions with their bronze pedestals were packed into wooden boxes with ropes to fix them, and they were shipped to the bronze casting factory for a moulding process. At the same time, the marble pedestals were shipped to the marble carving factory where they would be used with a duplication device that would follow the surfaces and guide the sculpting process.

Figure 8-20 Master replicas

The bronze casting and marble carving processes were generally the same as that in previous projects, and the final replicas with aging treatments were shipped and installed at the new China Garden Museum (Figure 8-21), two months after scanning.

Figure 8-21 Final bronze replicas established

8.3.3. Feedback from users

The two projects were conducted following the process maps generated through the research. One used the sculpture reproduction maps for large relief sculpture manufacturing and the other used the archaeological restoration maps to replicate large scale relics with fine details. Real costs, time, labour and quality were verified in the commercial project, and co-workers with different backgrounds used the maps as a significant reference to obtain a better understanding of the optimised digital method. The author acted as a project manager and observer in these case studies to verify the usefulness of the maps as well as to collect feedback.

Interviews were held with key individuals in the projects to obtain their overall impression of the method and to determine what its advantages and limitations were. A summary of the feedback from the four parties involved in the lions project is shown in Table 8-2. More detailed feedback is presented below.

Table 8-2 Feedback for validation of the maps

	Is the method useful?	Is it convenient to use?	Is it easy to understand?	Is the information sufficient?
Project manager	Very useful	Convenient	Easy to follow and effective	Acceptable
Team leader	Useful	Convenient	Easy to follow and effective	Acceptable
Co-workers	Useful	Convenient	Understandable with explanation	More knowledge needed
Commissioning party	Useful	Convenient	Understandable with explanation	More knowledge needed

First of all, based on the maps, the basic process was understood clearly as it consisted of scanning, data manipulation, physical replica production and finishing. Then each sub-process was broken down to follow a specific path, which was especially useful for the team leaders who were in charge of that part of work. The time scale, labour, cost, and type of machine at each stage could be estimated and reported for the project manager to provide an entire solution.

Although the maps were mainly designed to assist practitioners, they also proved useful in showing the advantages of digital technologies and explaining the feasibility and other issues when discussing the projects with the commissioning parties. They helped everyone involved in the project to keep a clear overall view in mind and to concentrate on following the plan to complete the tasks. They also greatly improved communication between co-workers and connections between the different steps in the process. Cost and time was saved as the maps provided room to think and discuss at every step, also reduced the trouble of organising complicated processes and explaining the links between each step to different people.

The maps offered a comparison of digital processes with traditional methods, and showed the alternative possibilities needed for decision making. All the project manager needed to do was put all the requirements and existing facts together and find the best route for the project by working through the flow-charts in the maps. When any difficulties were met, the maps showed themselves to be useful resources in that they reminded the users of the remaining possible alternatives.

Each team leader who was responsible for a specific process was able to have a general image of the whole project and the other processes adopted according to the maps, so that they worked more efficiently and even provided useful ideas to further improve the processes. A comment from one of the team leaders was that the maps did not only let him understand the new approach, but also brought inspiration to better use the labour resources and optimise their techniques.

There were some minor issues raised with the method that will need to be overcome through further research. It was felt that there was a lack of information in some specific fields, and that as a result, some people might raise questions about techniques or machine selection. None-the-less, the process chain maps were generally useful for both the project manager and other people involved in the projects, and gained mostly positive feedback.

8.4. Conclusion to chapter

It was clear that the maps were useful for all people involved in the projects. They were convenient to use and easy to follow/understand for the project manager and team leaders with professional knowledge, but a little more difficult for other people without further explanation. However, it is likely that these people do not really need to understand all the specific manufacturing processes and that this level of understanding is acceptable. On one hand, the feedback results show that this method is useful and acceptable. However, on the other hand, there is room for the maps to be expanded further through future research. Further development is both feasible and desirable since every practical project is different and technologies change rapidly. Suggested further research is discussed in the next chapter.

9. Chapter Nine: Conclusions and Future Research

9.1. Introduction

This chapter summarises the answers to the research questions, lists the problems that still need to be solved, and suggests potential directions/projects for future research. The main conclusions in regard to achievement, results and future directions are summarised in Table 9-1 and explained in the following sections.

Table 9-1 Conclusion summary

Basic achievement	Machine partly replace manual work to achieve optimisation of process chain
Research result	AM assist art and archaeological preservation
Future directions	Complementation of AM and art - AM promotes art and demands of art guide improvement and innovation of AM

9.2. General findings

1. 3D scanning and AM were developed as advanced technologies for industrial production, and are an important part of the so-called the “next industrial revolution”. So far, most AM machines are still being developed for industrial use. There are many manufacturing processes used in the art field that are similar to those used in the industry field, such as CAD modelling, casting, finishing, etc. This means that interdisciplinary research involving both artists and engineers can be useful in the future development of AM.

2. The application of digital technologies in the art field can never replace artistic creation or the historical accumulation of original relics. The driving force behind this interdisciplinary research between engineering and art was to optimise process chains for manufacturing in the fine art sculpture and archaeological restoration fields, by identifying the best use of AM technologies in new application areas. The outcomes of the practical projects that were undertaken as part of the research showed that AM and related digital technologies were a valuable addition to traditional methods rather than a replacement for them.

3. Art oriented use of technologies supplement existing manual techniques, they are linked together in the digital era and not contradictory. Digital technologies can assist artists from original idea to physical reality and, more importantly, the new techniques they provide can offer new inspiration and expand their design ideas.

9.3. Specific conclusions

Conclusions in response to each of the research question are as follows:
A**.** What are the general requirements of fine art sculpture in both terms of aesthetics and manufacture and integrity?

In terms of aesthetics, fine art sculpture should satisfy the need to express emotions, meaning or to tell the story beyond the actual object and its surrounding space. The manufacturing integrity needs to guarantee the production of sculptures within reasonable cost and time scale, and with the maintenance of quality assurance. So the integrity of art and manufacturing needs to manifest artistic designs, which accurately transfer ideas to physical forms without compromising quality. In some ways, this is similar to industrial design and product manufacturing. However, the literature review indicated that although similar terms might be used, e.g. accuracy, the meaning within art and engineering can be markedly different.

B. What are the conjunctive areas of 3D digital art and fine art sculpture?

The questionnaires and interviews conducted revealed the conjunctive areas to be aesthetics, and using physical artefacts in space to achieve the same goal, such as expression or decoration. The differences are the methods and tools they use, digital art using digital technologies that can achieve some tasks that are difficult to achieve manually. Although digital technologies can bring new inspiration and create new forms, fine art using manual techniques is endued with a kind of "hand-made feeling" that is difficult to achieve with digital work.

C. What is the benefit of AM for fine art sculpture? (In terms of measurable outcome for validating the research)

The literature review, interviews and case studies indicated that the benefit of using AM for fine art sculpture is that it can greatly reduce the amount of tedious manual work that must be undertaken. This could be seen clearly from the comparison of processes using cost and time models developed in the research. An additional benefit is a great improvement in accuracy during reproduction tasks.

D. To what extent will 3D technology be accepted by practitioners in the fine art field and what are the barriers to acceptance?

The acceptable level of introducing 3D technology into fine art field depends largely on the artist's view of the nature of fine art. If an artist's attitude that "real art" must be done by hand, then any use of 3D technology will be resisted. There is also a common misunderstanding about machine work replacing manual skills and even artistic creation. This research has shown that this is neither desirable, nor feasible, since the most effective use of AM and other digital technologies was in combination with traditional processes. Another barrier to the use of 3D technology is the difficulty of communication between engineers and artists which makes explanation and cooperation more difficult and time consuming.

E. How can the optimal combination of FE, RE and traditional techniques be determined? (As specifically applied to fine art)

This research into optimising AM for artistic sculpture covered four overlapping areas, namely technology, communication, process chains, and business value. Manufacturing process chains were chosen as the main research focus as they showed most potential in improving the process of digital manufacturing technology in the reproduction of sculpture artworks, helping to reduce the tedious work involved in the traditional sculpture industry. The process chain maps that were developed through the research are able to guide users to select appropriate routes and to make the best use of AM in the sculpture industry. Most importantly, quality needs to be considered as the top priority, and compromises between cost and time must keep quality within an acceptable range. The choice of process routes depends heavily upon the type of project being undertaken, for example, as "regular" shaped geometry being produced by FE, accurate reproduction of artefacts using RE, and original artistic creation and finishing using traditional techniques.

F. How can the capability of digital technology best be promoted within fine art field?

Enhancing the geometric freedom of digital modelling and optimally integrating the modelling software with engineering software will make AM more accessible to artists. Other critical issues are the need to reduce AM material costs, an increasing diversity of available materials and increased building size. Improving communication between artists and engineers will help to minimise misunderstandings when trying to fill the gap between knowledge and practice in the use of AM in fine art.

9.4. Suggested future work

At the time of writing, the following problems still needed to be investigated:

- 3D scanning of translucent objects (e.g. jade and amber) and objects with very high or low reflective surfaces (e.g. gold and hardwood), especially those antiques where contact and the use of powders is prohibited.
- 3D scanning of finely detailed objects in awkward situations (e.g. confined spaces) that prohibit the use of a robot arm and yet require higher resolution than hand-held equipment currently provides.
- Finishing techniques to complement suitable and reasonably priced materials for RP / AM. Currently, time-consuming artistic methods must be used incurring a high cost.
- The improvement of communication between sculptors, designers and engineers and also the relationships between co-workers involved in the innovative process chains that these projects are creating.
- Making the maps more easily updatable and accessible. E.g. through creation of a web-based tool or even a mobile phone App.

Current difficulties for 3D scanning, AM finishing and human factors are summarised in Table 9-2:

Table 9-2 Difficulties that need to be solved

3D scanning	Transparent / Partly transparent objects
	Very high / very low reflective surfaces
	Fine detailed objects in difficult situation
AM	More variety of materials needed
	High cost for objects with high resolution and big volume
Finishing techniques	Little references in literature to previous work
	Limited literature on materials used
Human factors	Communication between artists & engineers
	Cooperation between co-workers with different backgrounds
	Lack of experience

Main Contributions to Knowledge

The main contributions to knowledge of this work are as follows:

- A thorough review of the use of AM in the fine art sculpture and archaeological restoration fields
- A comprehensive review of the opinions of artists and others on the impact that AM is having or could have on this area
- Novel application of AM processes and associate digital techniques within the fine art sculpture and archaeological restoration fields

A set of process chain maps, based on cost and timing models, that provide a resource for practitioners who want to make optimal use of AM, associated digital technologies and traditional techniques in the fine art sculpture and archaeological restoration fields

9.5. Concluding remarks

Art is primarily a vehicle for the expression of the subjective elements of aesthetics, emotion and meaning, although the value of sculptors’ work is often measured in terms of the technical modelling skills employed, as well as the ideas conveyed by their work. However, manufacturing processes play a significant role in the sculpture industry, and often consume significantly more effort overall than the initial artistic creative and design activities. Digital technologies are already proving, though these case studies and beyond, to be useful tools in improving on the traditional approach, by reducing the tedious aspects of the work and allowing greater emphasis on artistic activities

The impact of RE and AM on the sculpture industry may bear similarities to that which photography has had on painting over the last 2 centuries, i.e. (digital) technology will not replace artists, but in some way become absorbed from the scientific into the artistic domain. Although at present some concerns exist, and productive communication between artists and engineers is quite isolated, AM can certainly be further optimised as a tool for the manufacturing process chain in the sculpture industry, just as it has developed in other fields.

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http://www.zcorp.com/en/home.aspx

11. Appendices

11.1 Analysis of primary research results

Fine Art

Part 1: Background information

Codes

Abbreviation	Explanation	Abbreviation	Explanation
Nat	Nationality	**CN**	Chinese
		Amr	American
		Bri	British
Gen	Gender	**M**	Male
		F	Female
Ocp	Occupation	**At-Des**	Art and Design
		Sculpt	Sculpture
		Edu	Education
Edu	Educational background	**Fi-At**	Fine Art
		At-Des	Art and Design
		Fra	France
		Jap	Japan
Exp	Experience	**yrs**	Years
Style	Styles of sculpture	**Real**	Realistic
		Abs	Abstract
		Trad	Traditional
		Mod	Modern
		Comb	Combination of Eastern & Western
Mat	Materials	**Cly**	Clay
		Mou	Plaster/Rubber/Resin/Wax/Glass fibre
		W/S	Wood/Stone
		Met	Bronze/Copper/Stainless steel
Orig	Scaled form original?	**Lar**	Only for large scale
		Sma	Only for small scale
		Both	For both large and small scale
		No	No original or No large/small sculpture
Tech	Technologies used/heard	**CAD/M**	CAD/CAM
		AM	Additive Manufacturing
		RE/FE	Reverse/Forward Engineering
		CNC/CM	CNC/Carving Machine
		Oly-Tra	Only traditional methods

Information

	David Zhang	**Emma Zhang**	**Bruce Beasley**	**Jon Isherwood**
Nat	CN	CN	Ame	Bri
Age	67	55	70	51
Gen	M	F	M	M
Ocp	Sculpt & Edu	At-Des & Sculpt	Sculpt	Sculpt
Edu	Fi-At (Fra)	Fi –At (Jap)	Fi-At	Fi-At
Exp	50 yrs	30 yrs	45 yrs	25 yrs
Style	Real, Trad, Comb	Real & Modern	Abs	Abs & Modern
Mat	Cly, Mou, W/S, Met	Cly, Mou, W/S, Met	W/S, Met	Cly, Mou, W/S
Orig	Both	Both	Both	Both
Tech	CNC/CM	CAD/M CNC/CM	CAD/M, AM	CAD/M, CNC/CM

Part 2: Detailed data

Codes

A Definition	A1 Sculpture = Visual art in 3 dimensions
	A2 Sculpture = A kind of artistic form in 3D space
	A3 Sculpture = One category in fine art field which provides stereoscopic language speech
	A4 Relief sculpture = Compressed sculpture, and stereo/spacial painting
	A5 Sculpture = A kind of art that could be appreciated from any view in 3D space
	A6 Sculpture = 3D shape made of diverse materials
	A7 Relief sculpture = Must be 3D, now matter how thin/thick, or how many layers
	A8 Relief sculpture = A kind of artistic presentation that between painting and sculpture, which could have both the third dimension and background in space
	A9 Sculpture = A unique 3D dynamic that through its spacial occupation addresses artistic propositions that strive through non-verbal means to visualise and interpret our physical world
B Opinion	B1 = CAD & AM should not be considered a “must” for artists
	B2 = Relief does not only express volume, but also presents some virtual, perspective, scenario contents
	B3 = Art and industrial production are two separate matters
	B4 = The creation of art is human spiritual products
	B5 = Sculpture is treated as a heavy industry in fine art field

	B6 = The cooperation of a series modelling and manufacturing process are essential and significant
	B7 = If volume is in visual scope, mostly enlarged by visual estimation or measurement
	B8 = Sculpture as a category in fine art, should not gets progress only in schemes, forms and materials, but also should be in manufacturing and processing methods, since one is indicative of the other
	B9 = Digital beauty is a new form of art
	B 10 = Art needs the sense of freshness to keep charming
	B11 = Unique aspect of relief is the expression exists between the illusionary and the shallow reality of form
	B12 = The field of Fine Art is wide open, all media and approaches should be included
C Problem	C1 = Digital technologies fit some sculptors, but others not at all
	C2 = Troubles exist in modelling stage, as well as enlarging, turning mould types, materials treatments, etc.
	C3 = Every stage has problems about feeling deviations and continual re-adjustments
	C4 = Producing large scale sculpture needs many assistants
	C5 = Require assistants to understand the authors' intention and style
	C6 = How to keep the spirit, vividness and aesthetic sense
	C7 = Normally producing by machine works needs to be processed by authors again, which could be more trouble than conventional manual ways
	C8 = How to bring design/creation to reality and show off
	C9 = Downstream finishing makes the entire process to be a complicated project
	C10 = The strength of sculptors does not match the wishes, as need compromise knowledge, skills, experience and age, physical energy
	C11 = CNC milling still requires considerable development to reach the ultimate goal of true five axis milling
	C12 = The creative application is the challenge
D Benefit	D1 = CAD & AM are wonderful new tools for sculpture
	D2 = It could be acceptable to adopt some new manners on the basis of no contradiction
	D3 = Project bidding documents are made by 3D software for rendering and presentation
	D4 = Let technologies replace a part of manual work to avoid deviations from human feeling

	D5 = Effect of digital arrangements could be used for artistic creation
	D6 = New technologies and materials for presenting the eternal emotion and consciousness is an inexhaustible source of inspiration
E Process	E1= Digital technologies are several of the full range of tools and processes available to sculptors
	E2 = Manufacturing and reproduction process of sculpture are troublesome
	E3 = Sculptors' feelings and skills create art works, their ideas and inspirits run through the whole process of sculpture production
	E4 = The process of from original clay model to full size final product, which refers to assistants, workers team, load carrying structure design, materials restoration, scaffold establishing, plaster and glass-fibre moulding turning, etc. all need embody individual skills
	E5 = "Framework" method means making an original, dividing it into necessary amount of layers, enlarging every layer and form them together, finally the full size model is adjusted and modified by author in depth
	E6 = RE for very large scale sculpture is to catch the general appearance of original, melting and establishing the basic inner frame to support the clay according to the data, then modelling
F Solution	F1 = RP is a very important new development
	F2 = Using "framework" method to address the transformation of basic appearance when enlarging a model
	F3 = Shape milling machine has been tried for reproduction
	F4 = Relative abstract shapes could be enlarged and manufactured according to digital models or CAD data
	F5 = Very large scale sculpture could adopt RE to build the inner frame
	F6 = Creative learning without preconceived application will be the only way in which innovation is achieved
G Difference	G1 = Adding and removing of every piece of materials are different personally, this process cannot be replaced by any mechanical methods
	G2 = In the long history, sculptures use quiet language to present rich content, being called as "still dance". Nowadays, the forms of functional equipments, virtual reality and action/performance have all been possibilities
	G3 = Shrinking only could be done by artificial copying

Summary

Interview	1 David Zhang	2 Emma Zhang	3 Bruce Beasley	4 Jon Isherwood
A1			🟦	
A2	🟦			
A3	🟦			
A4	🟦			
A5		🟦		
A6		🟦		
A7		🟦		
A8		🟦		
A9				🟦
B1			🟦	
B2	🟦			
B3	🟦			
B4	🟦			
B5		🟦		
B6		🟦		
B7		🟦		
B8		🟦		
B9		🟦		
B10		🟦		
B11				🟦
B12				🟦
C1			🟦	
C2	🟦			
C3	🟦			
C4	🟦			
C5	🟦			
C6	🟦			
C7	🟦			
C8		🟦		
C9		🟦		
C10		🟦		
C11				🟦
C12				🟦
D1			🟦	
D2	🟦			
D3		🟦		
D4		🟦		
D5		🟦		
D6		🟦		

E1			■	
E2	■			
E3	■			
E4		■		
E5		■		
E6		■		
F1			■	■
F2	■	■		
F3	■			
F4		■		
F5		■		
F6				■
G1	■			
G2		■		
G3		■		

Solutions for Problems

	F1	F2	F3	F4	F5	F6
C1	■					■
C2			■			
C3		■		■		
C4			■		■	
C5		■				
C6	■					■
C7						
C8	■			■		
C9						
C10	■			■		
C11	■					
C12						■

Design & Technology

Part 1: Background information

Codes

Abbreviation	Explanation	Abbreviation	Explanation
Nat	Nationality	**Brt**	British
		Amr	American
Gen	Gender	**M**	Male
		F	Female
Ocp	Occupation	**Di-At**	Digital Art
		Di-Sculpt	Digital Sculpture
		Des&DDM	Design & Direct Digital Manufacture
Edu	Educational background	**Fi-At**	Fine Art
		At-Des	Art and Design
		MEng	Mechanical Engineering
Exp	Experience	**yrs**	Years
R-Area	Research Area	**At-Scupt**	Art Sculpture
		Antique-R	Antique Restoration
		Med-Apl	Medical Application
		Id-Product	Industrial Product
		Di-Sculpt	Digital Sculpture
Tech	Technologies used	**Hapt-M**	Haptic Modelling System
		Td-M	Traditional Methods
		AM/CNC	Additive Manufacture/CNC
		RE/FE	Reverse/Forward Engineering
2Sub?	Are Digital Art & Fine Art two different Subjects?		

Information

	Chris Dean	**Roger Moss**	**Michael Shaw**	**Lionel Dean**	**Bathsheba Grossman**
Nat	Brt	Brt	Brt	Brt	Amr
Age	54	62	37	45	44
Gen	M	M	M	M	F
Ocp	Di-At	Di-Sculpt	Di- Sculpt	Des&DDM	Di-At
Edu	Fi-At	Fi -At	At-Des	MEng	At-Des
Exp	11 yrs	5-10 yrs	5-10 yrs	9 yrs	Over 10 yrs
R-Area	At-Sculpt Antique-R	At-Sculpt Med-Apl	At-Sculpt	Id-Product	Di-Sculpt
Tech	Hapt-M AM/CNC	Td&Hapt-M AM/CNC	AM/CNC	RE/FE AM/CNC	Td-M AM/CNC
2Sub?	No	No	Conditional	Conditional	Conditional

Part 2: Detailed data

Codes

A Definition	A1 Fine Art = Architecture, painting and sculpture, also, land art, performance, installation and sound art
	A2 Fine Art = The qualities of artefacts that we might generally recognise to have value as Fine Art objects are not usually defined by technique of materials alone
	A3 Art = The art works are created for the same aim by different ways
	A4 Digital Art = A part of Fine Art, using new methods to create art works with the development of digital technologies
	A5 Fine Art = The nature is based on subjective feeling
	A6 Digital Art = Physical objects that is produced with computers as a major part of the creation or production process
	A7 Virtual Art = Intended to be experienced via computer
	A8 Sculpture = A form of static art to express the idea and generate empathy
	A9 Relief Sculpture = Included in ‘Sculpture’ definition, one special form of sculpture
B Opinion	B1 = They are not different subjects, the form of Art is of secondary importance, the only thing that matters is, is it any good? Does it move me? Does it show me something I don’t already know? And so on
	B2 = Talking more about qualities like soul, heart, passion, tension, balance and beauty, etc. Must be evaluated by the same criteria as other types of art
	B3 = Another revolution thanks to innovations by home users
	B4 = Technologies are just tools, much like pencil, albeit very complex ones; and manual modelling skills are irreplaceable
	B5 = AM is equally valid means of production for Fine Art, and artists will readily adopt any technologies
	B6 = Adopting digital technologies for art work is a natural/inevitable trend, as they extend the impression of traditional art in the field, but does not change the essence
	B7 = With the key word ‘traditional’, Digital Art is a different subject
	B8 = More people work in overlap areas to break the boundaries between different subjects and explore more opportunities
	B9 = Aesthetic is a human decision that cannot be created by technologies

	B 10 = Pursue sculpture as a published art form rather than one predicated on unique originals
	B11 = Conservancy or reproduction tasks are not art-making tasks, not all about creation
	B12 = AM is a distinct medium which has its own methods and challenges, you will never find out in that way what is capable of, when accepted on their own terms
	B13 = Accuracy issue for sculpture is different with that in engineering field, which is normally not about measurements but visual feeling
C Problem	C1 = How to make design manifest
	C2 = The small build envelope of RP machines
	C3 = Cost
	C4 = Limited by one’s virtual modelling skills
	C5 = Risk of everything looking too perfect, too right
	C6 = Limited range of materials and colours
	C7 = 3D modelling applications are too complex and mathematical for artists’ direct working process
	C8 = Current educational system is one of reasons for communication obstacle for cooperation between engineers and artists whose brain work in completely different ways
	C9 = Poor resolution and production quality
	C10 = Finishing techniques are complicated which require interdisciplinary knowledge and rich experience
	C11 = Intuitive working is immeasurable, which is not only by knowledge but also experience
	C12 = Computer processes are somehow cold, lacking of the sensual contact with materials, the familiar relations with tools, and not allowing intuitive working practices
D Benefit	D1 = Constrains of real world materials simply don’t apply
	D2 = Digital realm stretches your imagination
	D3 = Extend one’s vocabulary of forms, which in turns prompts research into materials unbeknown to the practitioner, and with it explorations of new themes or concepts
	D4 = The ability to produce any geometry (Geometrical freedom)
	D5 = Less limited by one’s own manual dexterity, easy to amend models virtually
	D6 = Show multiple views of the same object and even a ‘fly though’ or ‘fly around’
	D7 = Infinite scalability of digital files
	D8 = Look at whole range of subtle variations on a form

	quickly
	D9 = Haptic modelling system enables to use sense of touch to model and shape form in virtual space
	D10 = Ability of accuracy and virtual effects could bring unique inspirations and working experience, which create more opportunities
	D11 = Working in office based environment, tedious manual work could be reduced greatly
	D12 = More efficient and economical for the entire manufacturing process
	D13 = Digital technologies are ideal for mass individualisation (Reproducibility)
	D14 = Working in cooperation with an appropriate division of labour allows co-workers focus on their own expertises, for artists, who could spend more energy on creation
	D15 = Protect copyright of artistic creation
E Process	E1= Just to play around in CAD and doodle digitally
	E2 = Developing forms in CAD, copy and paste, shift it to one side in space and repeat infinitely
	E3 = Introduce and element of chance or mistakes into the making process
	E4 = Creative ideas are developed and realised faster and further in virtual space
	E5 = Sketch or build digital models when inspiration jump into the mind
	E6 = AM changes the traditional design/creation process and manufacturing ways
	E7 = AM requires a creative process that is sensitive to that context, and cannot be grafted retroactively onto other media
	E8 = Transfer dynamic track to static performance as an art work, and generate amazing inspirations
	E9 = Discuss the feasibilities before start the manufacturing process in order to avoid unnecessary wastes
	E10 = Re-assess some of fundamentals of sculpture, aspects that impact when working in the third dimension virtually
F Solution	F1 = Reigning in the CAD design
	F2 = Altering it to enable a similar form to be produced with real materials and techniques of forming that are readily available
	F3 = Manufacturing process is optimised by further research
	F4 = Using alternative traditional ways, such as separating the model for machinery work
	F5 = Haptic modelling system could be a good tool to amend

	the defects, all processes are reversible and nothing lost
	F6 = Call other commercial services (Satellite Models)
	F7 = Find literature materials of finishing techniques in conventional manufacturing fields
	F8 = Design must have high intrinsic value, or specifically exploit the unique advantages of this medium, or most likely both
	F9 = Create some sort of hybrid models by combining different methods, and to be inspired
	F10 = Depend on needs of projects, keep balance of issues such as quality, cost, time scale, etc.
G Difference	G1 = More intellectual and cerebral than physical skills
	G2 = Remove materials dynamics
	G3 = There is no big different of finishing techniques for AM with that for any other manufacturing
	G4 = Some problems exist in machinery works also, such as quality and cost
	G5 = Cannot really feel the weight and texture of materials in virtual space
	G6 = The most difficult thing, which is also the key feature, for artistic works is to keep them ‘lively’ by any methods

Summary

Interview	1 Chris Dean	2 Roger Moss	3 Michael Shaw	4 Lionel Dean	5 Bathsheba Grossman
A1			🟦		
A2			🟦		
A3	🟦				
A4				🟦	
A5				🟦	
A6					🟦
A7					🟦
A8		🟦			
B1	🟦	🟦			
B2			🟦		🟦
B3			🟦		
B4	🟦	🟦	🟦	🟦	
B5			🟦	🟦	🟦
B6	🟦	🟦			🟦
B7			🟦	🟦	🟦
B8				🟦	
B9				🟦	
B10					🟦
B11		🟦			🟦
B12					🟦
B13		🟦			
C1			🟦	🟦	
C2	🟦	🟦	🟦	🟦	🟦
C3		🟦	🟦	🟦	🟦
C4	🟦		🟦	🟦	
C5			🟦		
C6		🟦	🟦	🟦	🟦
C7	🟦				
C8	🟦	🟦		🟦	
C9					🟦
C10		🟦			
C11		🟦			
C12		🟦			
D1			🟦		
D2		🟦	🟦		
D3	🟦	🟦	🟦	🟦	
D4			🟦		🟦
D5		🟦	🟦	🟦	
D6	🟦		🟦		

D7			🟦		
D8	🟦		🟦		
D9	🟦				
D10	🟦	🟦		🟦	
D11	🟦	🟦			
D12				🟦	
D13		🟦		🟦	🟦
D14		🟦			
D15		🟦			
E1			🟦	🟦	
E2	🟦		🟦		
E3			🟦		
E4	🟦	🟦			
E5		🟦		🟦	
E6		🟦		🟦	
E7					🟦
E8		🟦			
E9		🟦			
E10		🟦			
F1			🟦		
F2		🟦	🟦	🟦	
F3	🟦				
F4		🟦		🟦	🟦
F5		🟦		🟦	
F6				🟦	🟦
F7				🟦	
F8					🟦
F9		🟦			🟦
F10		🟦			🟦
G1			🟦		
G2	🟦				
G3				🟦	
G4				🟦	🟦
G5		🟦			
G6		🟦			

Solutions for Problems

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
C1		🟦		🟦		🟦			🟦	🟦
C2		🟦		🟦		🟦			🟦	
C3		🟦		🟦					🟦	🟦
C4	🟦									
C5								🟦		
C6		🟦		🟦		🟦			🟦	
C7	🟦		🟦		🟦					
C8			🟦							
C9		🟦		🟦					🟦	🟦
C10							🟦			
C11			🟦					🟦		
C12			🟦		🟦			🟦		

11.2 Comparison matrices of case studies undertaken by the author

Table 1. Comparison Matrix for Beowulf Project

Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional**
Geometrical flexibility 11	10	6
Accuracy 10	10	3
Assembling 6	6	0
Lead time 10	9	5
Reproduction 13	11	7
Model size 10	3	10
Vividness 15	5	15
Choice of materials 12	7	12
Cost 13	10	7
Total 100	71	65

Table 2. Comparison Matrix for Archaeological Restoration Project

Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional**
Geometrical flexibility 6	6	3
Accuracy 15	14	7
Assembling 11	10	0
Lead time 8	8	3
Reproduction 12	12	6
Model size 10	4	10
Vividness 11	5	11
Choice of materials 14	8	14
Cost 13	10	6
Total 100	77	60

Table 3. Comparison Matrix for Group Relief Sculpture Project

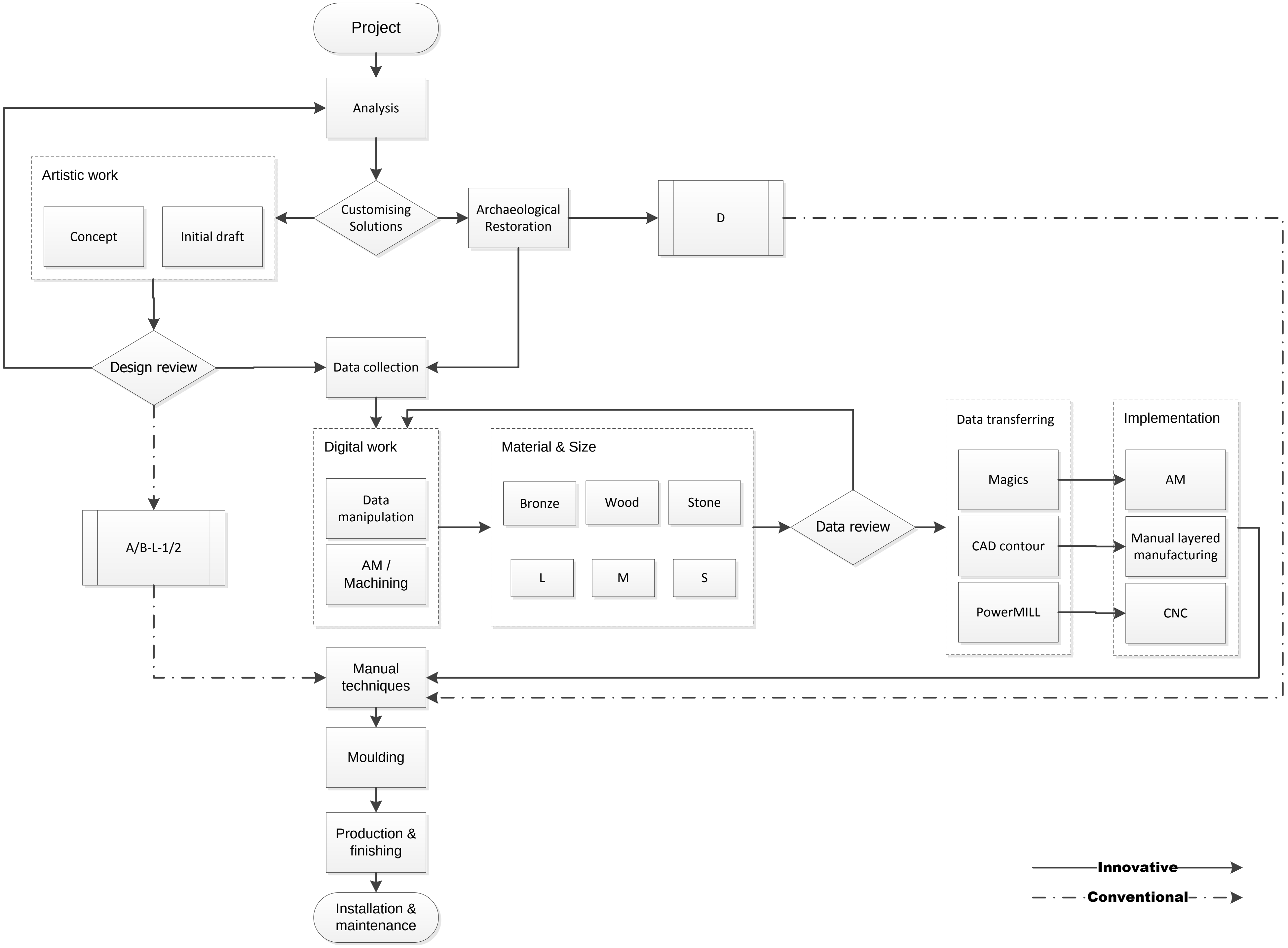
Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional**
Geometrical flexibility 13	13	7
Accuracy 9	9	3
Assembling 8	6	0
Lead time 12	12	5
Reproduction 10	9	6
Model size 11	5	11
Vividness 15	6	15
Choice of materials 9	4	9
Cost 13	11	7
Total 100	75	63

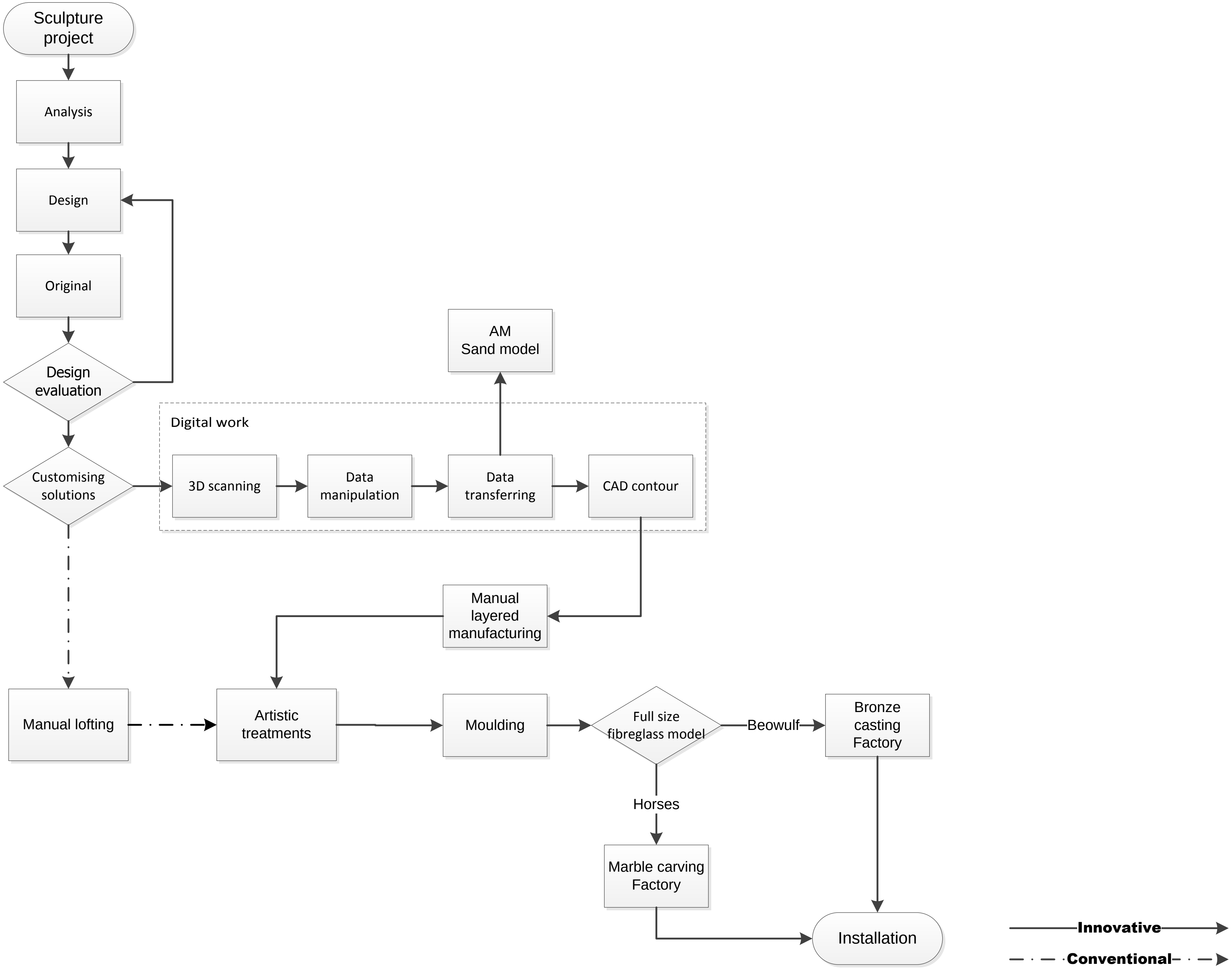
Table 4. Comparison Matrix for Replication of Lions Project

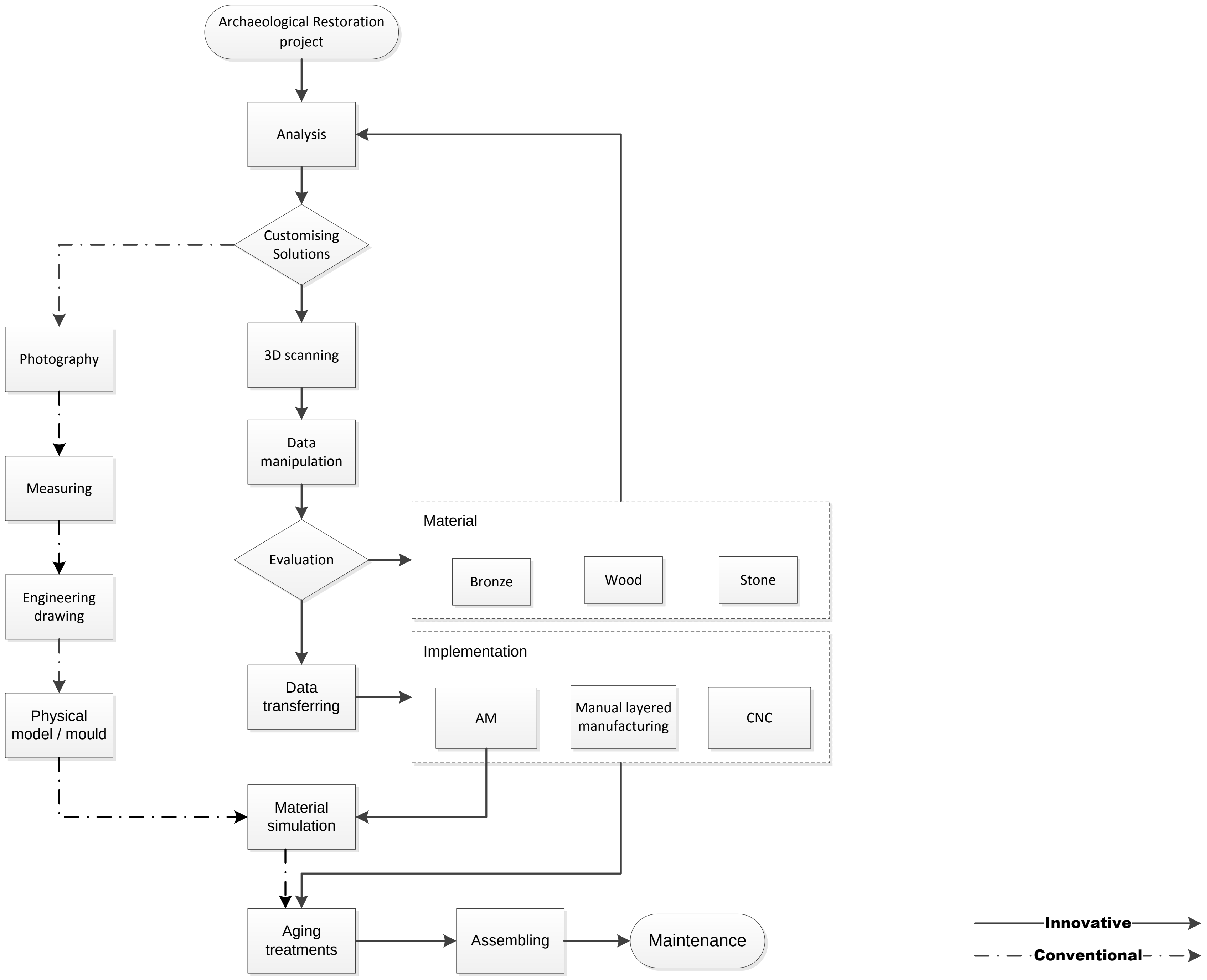
Comparison Criteria	**Manufacturing Methods**	
	AM	**Conventional**
Geometrical flexibility 6	6	3
Accuracy 15	15	6
Assembling 11	9	0
Lead time 13	12	4
Reproduction 14	13	6
Model size 12	5	12
Vividness 7	3	7
Choice of materials 9	4	9
Cost 13	12	6
Total 100	78	53

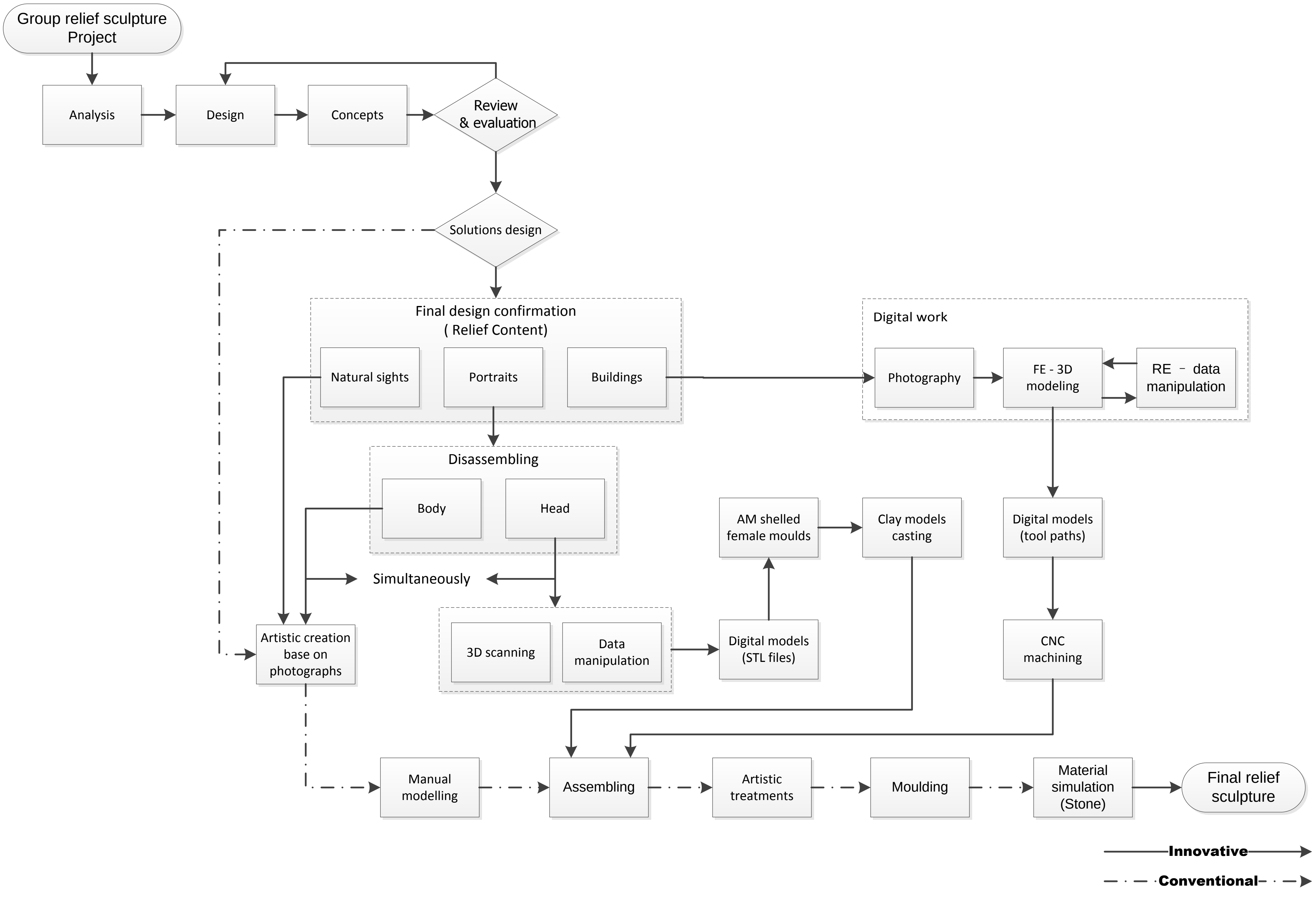
11.3 Process chain maps

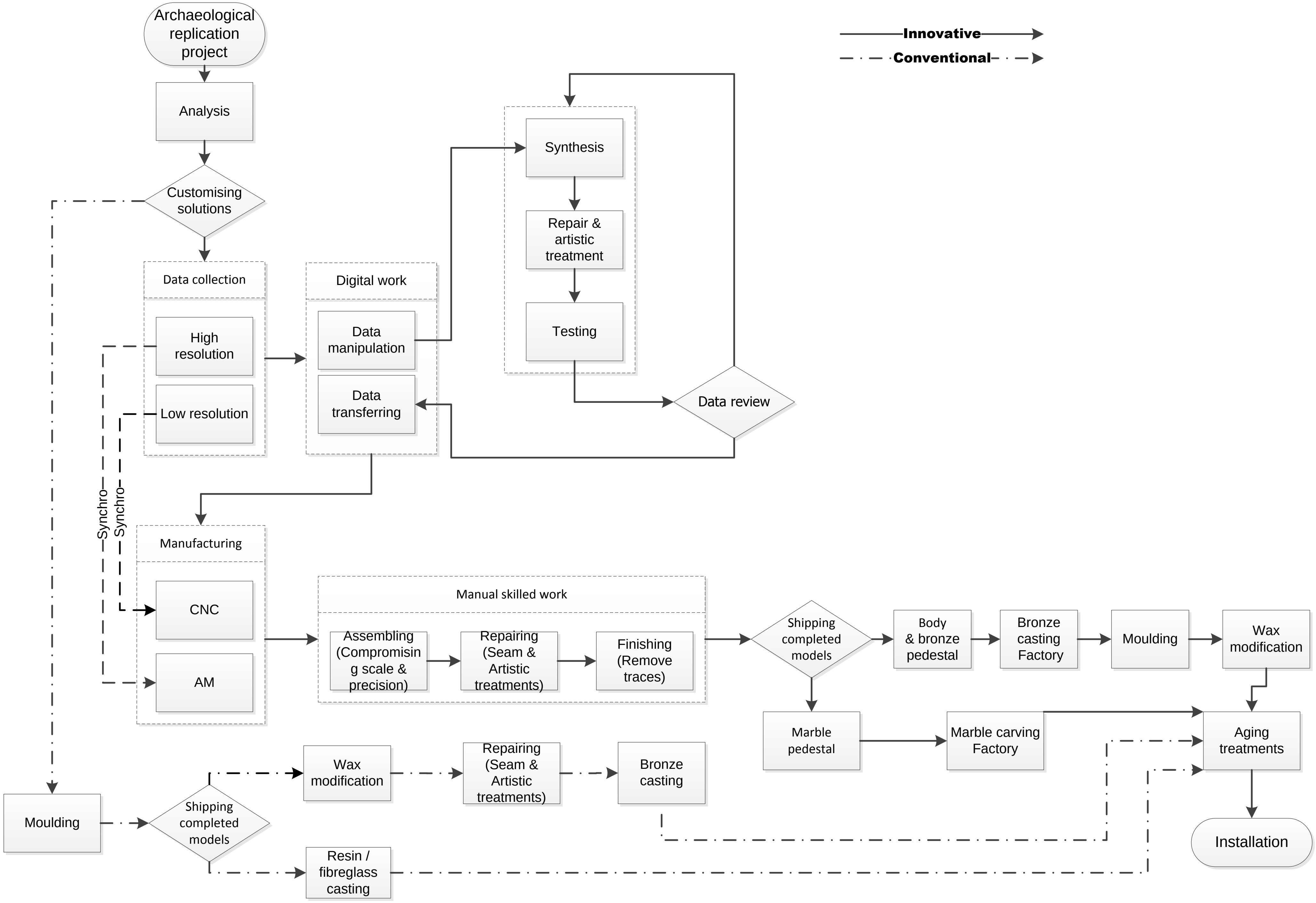
1 main map with 4 sub-maps follow (inserts)


Project
Analysis
Artistic work
Concept
Initial draft
Customising Solutions
Archaeological Restoration
D
Design review
Data collection
Digital work
Data manipulation
AM / Machining
Material & Size
Bronze
Wood
Stone
L
M
S
Data review
Data transferring
Magics
CAD contour
PowerMILL
Implementation
AM
Manual layered manufacturing
CNC
A/B-L-1/2
Manual techniques
Moulding
Production & finishing
Installation & maintenance
Innovative
Conventional


Sculpture project
Analysis
Design
Original
Design evaluation
Customising solutions
Digital work
3D scanning
Data manipulation
Data transferring
CAD contour
AM Sand model
Manual layered manufacturing
Manual lofting
Artistic treatments
Moulding
Full size fibreglass model
Beowulf
Bronze casting Factory
Horses
Marble carving Factory
Installation
Innovative
Conventional


Archaeological Restoration project
Analysis
Customising Solutions
Photography
3D scanning
Data manipulation
Measuring
Evaluation
Material
Bronze
Wood
Stone
Engineering drawing
Implementation
Physical model / mould
Data transferring
AM
Manual layered manufacturing
CNC
Material simulation
Aging treatments
Assembling
Maintenance
Innovative
Conventional


Group relief sculpture Project
Analysis
Design
Concepts
Review & evaluation
Solutions design
Final design confirmation (Relief Content)
Natural sights
Portraits
Buildings
Digital work
Photography
FE - 3D modeling
RE – data manipulation
Disassembling
Body
Head
Simultaneously
AM shelled female moulds
Clay models casting
Digital models (tool paths)
Artistic creation base on photographs
3D scanning
Data manipulation
Digital models (STL files)
CNC machining
Manual modelling
Assembling
Artistic treatments
Moulding
Material simulation (Stone)
Final relief sculpture
Innovative
Conventional


Innovative
Conventional
Archaeological replication project
Analysis
Customising solutions
Data collection
High resolution
Low resolution
Digital work
Data manipulation
Data transferring
Synthesis
Repair & artistic treatment
Testing
Data review
Synchro
Synchro
Manufacturing
CNC
AM
Manual skilled work
Assembling (Compromising scale & precision)
Repairing (Seam & Artistic treatments)
Finishing (Remove traces)
Shipping completed models
Body & bronze pedestal
Bronze casting Factory
Moulding
Wax modification
Marble pedestal
Marble carving Factory
Aging treatments
Installation
Moulding
Shipping completed models
Wax modification
Repairing (Seam & Artistic treatments)
Bronze casting
Resin / fibreglass casting