Applied Craft Science in Traditional Timber Framing Conservation

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M.A.Sc. Thesis

APPLIED CRAFT SCIENCE IN TRADITIONAL TIMBER FRAMING CONSERVATION

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Abstract

The first step in any heritage project is its understanding; which is a process analogous to reverse engineering. Traditional reverse engineering involved the disassembly and reconstruction of a product to obtain a higher understanding of it. Contemporary reverse engineering typically refers to replication via, 3D scanning, modelling, and prototyping; unfortunately, this can yield an incomplete understanding. As described by traditional reverse engineering: a high-level understanding is obtained through a broad range of information sourced from related designs, existing documentation, personal experience, and general knowledge that lie outside the product of interest. In this thesis, digital photogrammetry is used as a tool to augment the process of reverse engineering squared (hewn) timber in traditional timber framing. Specifically, the hewing techniques and tools are reconstructed. As a result of this recovered understanding, both tangible and intangible heritage are precisely documented and preserved.

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1 Chapter: INTRODUCTION

The Red House—built in 1816—is the oldest house in Perth, Ontario. Beside it, resides a smaller basic structure, a hand-hewn timber frame. Based on the historical photographic evidence and empty joist pockets in the timbers, it is evident that one entire bay of the timber frame is missing. The heavily deteriorated structure is now dismantled and donated to the Algonquin College Heritage Institute, where the school will use it as a case for teaching students the repair of timber structures.

Based on the ICOMOS International Wood Committee's *Principles for the Preservation of Historic Timber Structures,* the same type of wood should be used in the replacement/restoration/repair of historic timber. Additionally, the same tools and techniques should be used to convert, dress, and assemble the timbers (Wood Committee, 2017). Unfortunately, the skill of hewing is virtually a lost craft. The loss of this knowledge impedes the ability to faithfully conserve our wooden structures. With heritage timber structures, documentation is also required before and after replacement/restoration/repairs take place. Photogrammetry, laser scanning, and 3D modelling software are also popular and powerful tools in heritage documentation.

Experimental archeology—a subdiscipline of archeology—aims to reconstruct ancient knowledge via the reconstruction of the artifacts of interest. The ultimate example: the reconstruction of the 1000-year-old Viking ship, sailed from Norway to New York in

27 days. This test was devised in 1893 to verify the long voyage seafaring hypothesis of the excavated Viking ship. Similar projects in craft science—a similar discipline of experimental archeology—have aimed to recover lost building crafts in order to conserve built heritage. These craft-scientists study trace marks on historical building materials, supplemented with historical photographs/illustrations, and existing traditional craft knowledge. Their hypotheses are put to the test by attempting to imitate the craft processes thus, recreating the circumstances of their ancestors' practices. From recovered craft knowledge, built heritage can be faithfully restored, repaired and/or maintained.

Studying existing material without an original design is a process familiar to engineers; existing in the realm of reverse engineering. Experimental archeologists and craft scientists are also participating in similar processes; reverse engineering ancient/traditional man's activities and traditional crafts. The mechanical product reverse engineering process is usually augmented with digital measurement and modelling tools; scanners and computer-aided design (CAD) software. In this thesis, digital documentation techniques—photogrammetry, high-speed video, and time-lapse video—are introduced to augment the reverse engineering of hewing the Perth Timber Frame.

1.1 Objectives

The initial objective was to find an intersection between digital scanning/fabrication technologies and timber conservation. This evolved into the goal to find a place for digital scanning within the recovery, and reuse, of timber framing techniques. This goal is—of course—within an engineering framework; specifically, reverse engineering. Specific objectives were to:

1. develop a photogrammetric workflow for documenting timber surfaces;
2. while using photogrammetry to reverse engineer the tools and techniques for future repair;
3. resulting in recovering, recording, and preserving traditional craft skills.

My hope is that this thesis is a step towards reconnecting engineering with its respective crafts.

1.2 Outline

This thesis is split into two main parts: chapter 2—the literature review and chapter 3—the practice. The literature review covers reverse engineering and its relation to compatible heritage wood repair, axes, timber framing with axes, reading timber surfaces, and heritage documentation. The practice chapter introduces the case study: The Red House timber frame, then presents the developed method for photoscanning timbers and axes, and the analysis of new and existing axe marks.

1.3 Personal Motivation

This body of work—inspired by many events and people—is mainly influenced first from the Carleton Immersive Media Studio (CIMS) and the professors therein; Dr. Stephen Fai, and Dr. Mario Santana. My first brush with heritage documentation occurred when Dr. Santana, invited a team of architecture/engineering conservation students to a documentation workshop in Guadalajara Mexico. I was fortunate enough to be a part of the workshop with local Mexican students. The purpose of this workshop was to gather emerging professionals in a learning environment; documenting the local architectural heritage using digital and manual surveying technologies. I knew site documentation was an important step in a conservation project, but what I experienced there was something that transcends the x,y,z,r,g,b values of heritage.

The ignition of this thesis was born of the work from *Digitally Assisted Stone Carving.* I admired my colleagues' work in augmenting traditional crafts skills. They were working on finding an intersection of digital scanning/carving tools with traditional stone carving tools in collaboration with the Dominion Sculptor of Canada. Figure 1 shows the dominion sculptor's restoration work overtop the milled foam as-found geometry. I was driven to emulate a similar workflow but in the timber/wood conservation field.

Figure 1. Detail of CNC-milled polyurethane foam maquette of relief sculpture with modelling clay applied (Hayes et al., 2015)

I was curious to see how other researchers in the heritage conservation/documentation field were using digital scanning/fabrication tools to augment traditional crafts and craftsmen. I reviewed the literature regarding scanning, fabrication, heritage, and repair/restoration; it seems that most of the published research in this area does not include a keeper of past practical knowledge skills.

And so I did 2 internships as part of my studies. The first at Factum-Arte in Madrid, Spain; developing new high-resolution photoscanning techniques. The second internship was at Discovery Dream Homes in Peterborough, Ontario; experiencing the CNC Timber framing process. These internships started shaping my research question into finding an intersection between high-resolution scanning and timber framing.

After approaching Algonquin College Heritage Carpentry professors Jack Hollinger and Andrew Pamenter, they invited me to participate in their window restoration course. I was then interacting with the carpentry students there while trying to find an intersection of digital and traditional technologies/techniques.

The case of the Red House Timber Frame came up as a possible project for digital scanning and fabrication repair. One of the original ideas was to try and use the robotic arms—from CIMS' digitally assisted fabrication—to mill timber repair joints with possibly complex interfaces built from photogrammetry.

Like the barn beam reclaimers, the rough-hewn surface caught my attention, especially since most timber framers today are far from hand hewing their own timbers. What kind of historical craft knowledge has been lost since relying solely on large scale timber sawmills?

2 Chapter: LITERATURE REVIEW

The literature review of this thesis covers a broad range of topics—from axes to engineering craft. Initially, chapter 2.1 describes the multiple aspects of reverse engineering, then relates them to similar fields in experimental archeology and craft science. By bridging these fields, we recover a sort of traditional engineering. Chapter 2.2 brings the discussion closer to (timber) conservation principles set out by international and national conservation bodies. Then I outline the inconsistencies and gaps between different timber conservation approaches. Chapter 2.3 contains documentation and categorization of relevant axe types used in the conversion of logs into timber while chapter 2.4 focuses more on the timber conversion and construction process. The hewing process is reconstructed in this chapter based on a craftsman's perspective, textual accounts, and photographic evidence. Chapter 2.5 looks at defining and recognizing different features on timber surfaces, specifically, the features created by the timber conversion process. Additionally, I consider the particular features of axe marks on timber. Then, in chapter 2.6, the literature review is shifted back to conservation and the different types of survey on a conservation project. This chapter then focuses on photogrammetry—its metrics and underlying algorithms. Photogrammetry is documented to be a powerful and versatile tool in conservation projects.

2.1 Reverse Engineering

Well, may it be asked, what is a sapper? This versatile genius is, as Shakespeare has already answered,—

"not one but all mankind's epitome,"

Condensing the whole system of military engineering and all that is useful and practical under one red jacket. He is a man of all work of the army and the public: astronomer, geologist, surveyor, draftsman, artist, architect, traveler, explorer, antiquary, mechanic, diver, soldier and sailor; ready to do anything or go anywhere; in short, he is a sapper.

Capt T.W.J. Connolly, Royal Engineer Historian (1815-1885)

Head (1869) writes, in *The Royal Engineer, about the* importance of enlisting military [applied] scientists, military engineers, or 'sappers'. He quotes, Capt T.W.J. Connolly on what it is to be an engineer, specifically the original engineer; a military engineer. Sappers had the capability to complete their work themselves if need be, this supports the meme that engineers had their origins in the trades. Conversely, this isn't quite true for civil engineers—civilian engineers—in early Canada.

White (2000) argues that civil engineering did not have its origins in the trades, due to many of the early civil engineers in

Canada being highly educated, upper/middle class, ‘gentlemen’, who were not from a family of tradesmen. However, White (2000) does admit:

> *True, civil engineers had to be familiar with construction trades like carpentry and masonry, as well as with surveying and earthmoving—all of which they gained in their apprenticeships—but they needed this knowledge in order to understand the work they supervised. They did not do the work themselves. (pp 85-86)*

Even though this familial origin did not exist for civil engineers, they still require an understanding of the trades. The fullest understanding can be obtained via physical imitation. Remnants of these ideas of reconstructive imitation can be found in the processes of reverse engineering.

Reverse engineering is a process, fundamental to the field of engineering itself. At Carleton University, all first-year engineering students participate in a reverse engineering project. In this project, students choose any physical product, reverse engineer it, improve it, and then fabricate a prototype. Reverse engineering has its origins in mechanical engineering, but its formal research is also developed in relation to software engineering. Similar processes also existing in heritage studies and archaeology fields; however, they are still relevant to the architectural conservation engineer.

2.1.1 Reverse Engineering

Reverse engineering is a process of deconstructing a complex, man-made object, in order to generate specific knowledge of its design. The process is completed by another designer, without the original designs. It originates from the analysis of hardware, where the design understanding is obtained from the analysis of a finished product. This process is most used in competitive imitation, where a company will seek to understand its competitor’s product and design. Additionally, reverse engineering can be used to obtain an understanding of a product for its maintenance; since, those who maintain, are usually not the original designers. Traditionally in hardware reverse engineering, the goal is a full duplication of the product; whereas in software, the goal is to obtain working knowledge (Chikofsky & Cross 1990).

Chikofsky & Cross (1990) define several processes related to reverse engineering methods, including forward engineering, redocumentation, design recovery, restructuring, and re-engineering. Each of these subprocesses are illustrated in relation to each other by figure 2. Forward engineering is, of course, the traditional engineering process; starting with high-level abstractions, applied to specific conditions, thus creating a ‘design’ and resulting in an implementation. Re-engineering and design recovery are the most relevant for this thesis. Re-engineering combines both forward and reverse engineering processes resulting in a sort of renovation or reclamation of a product’s design. Based on the reconstructed design (reverse engineering), changes may be made to fit new requirements for a new product (forward engineering). More interestingly, design recovery is a subset of reverse engineering in which domain knowledge external information and deduction or fuzzy logic are applied to the observations obtained from reverse engineering. The design that is recovered is constrained by a broad range of information sourced from related designs, existing documentation, personal experience, and general knowledge that lie outside the product of interest (Chikofsky & Cross 1990).

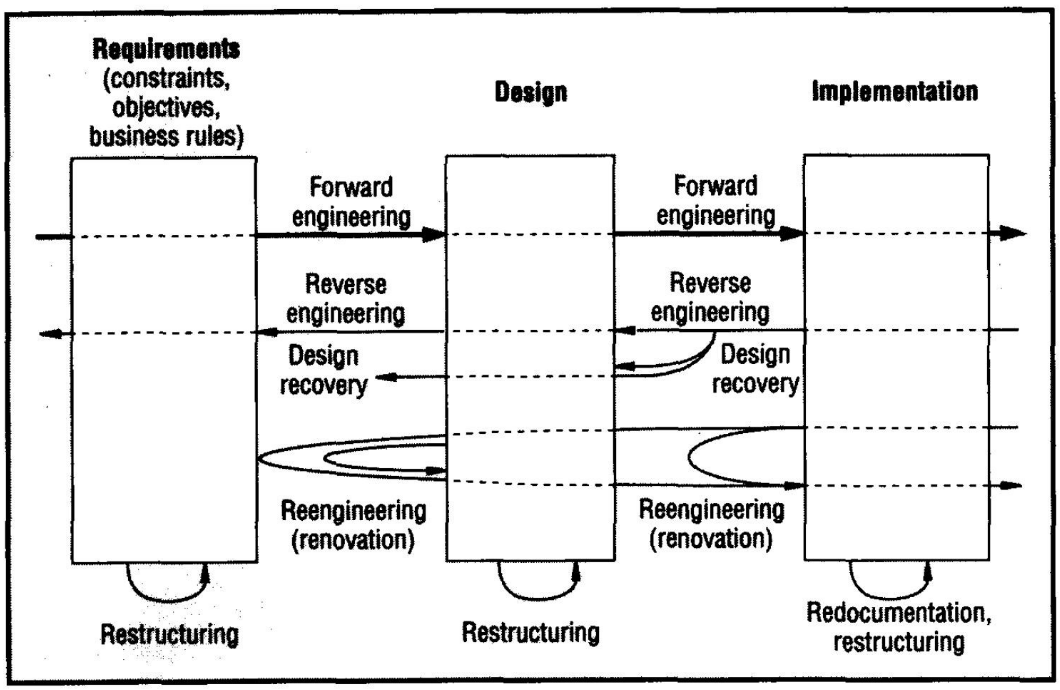

Figure 2. Reverse engineering and related processes are transformations between or within abstraction levels, represented here in terms of lifecycle phases (Chikofsky & Cross 1990).

An entire field of re-engineering exists from the need to adapt old and outdated software to new software architecture and platforms. This is motivated by the time and cost savings of reusing parts of the outdated systems along with the developed maintenance techniques. Majthoub et al. (2018) describe some situations in which software re-engineering is needed which include when: code may no longer have a clear and logical structure, documentation may no longer exist, hardware and/or software support is outdated, developers of legacy systems are not available for consultation, or when legacy systems with years of modifications become difficult or risky or expensive to change.

Reverse engineering is generally used within software engineering and more traditionally mechanical engineering. Even with these software and mechanical fields containing such explicit information, through a product's evolution, design information is inevitably lost. Reverse engineering and more specifically, design recovery aim to recover this information. Biggerstaff (1989) elaborates on design recovery; specifically, for maintenance and reuse of software systems. He states that if we are to harvest, reuse and maintain components of software systems, we must analyze and reconstruct the software's design; unfortunately, the source code material does not contain very much information of the original design; only the most subtle clues that remain unseen by the untrained eye. According to Biggerstaff (1989) and previously (Chikofsky & Cross 1990), "Design recovery recreates design abstractions from a combination of code, existing documentation (if available), person experience, and general knowledge about problem and application domains” (p. 1) (p. 15).

Mechanical reverse engineering has one distinct advantage over software reverse engineering; mechanical reverse engineering can involve the reconstruction of the original product. However, the most recent research is at the abstracted computer modelling level.

It is evident that reverse engineering is typically referred to in recovering mechanical and software designs; when reverse engineering is referred to in architectural conservation applications, it is typically only at an abstract level. Buildings are reverse engineered almost exclusively using surveying, modelling, and sometimes rapid prototyping techniques. Martin & Wood (2013) mention reverse engineering in English Heritage’s major book *Conservation Basics* from their practical conservation series. Reverse engineering appears in their overview of metric survey techniques and their uses; specifically, reverse engineering via laser scanning and photogrammetry. Luca et al. (2006) also refer to the “architectural surveying process [as] reverse [engineering] process which, starting from the real object, rebuilds a digital model and interprets the idea upstream of its realization.” (p. 3) The understanding they are trying to achieve through their hybrid architectural modelling approach is purely geometric, aiming to extract, formalize and translate drawing rules for a semantic-based template library. Furthermore, Dore & Murphy (2018) relate reverse engineering to the scan-to-BIM process; which is using a survey to capture as-built geometric data for the creation of a historic building information model (HBIM). They point out how long the process is of creating a BIM, and the need for automatic generation of BIM components. When considering the original purpose of reverse engineering, the automation of the process starts to seem counterproductive.

In addition to architectural surveying, workflows in digital scanning to digital fabrication are popular in the heritage conservation field especially as a 'new paradigm' for heritage conservation. This type of reverse engineering is consistent with current methods of mechanical and architectural reverse engineering, where the focus is on geometric understanding. Weigert et al. (2019) summarize many of the publications with this type of reverse engineering, where conservators are using scanning and prototyping for repair purposes.

The original purpose of reverse engineering was to recover the design or high-level understanding of a product. If we automate this process, we are not doing a lot of understanding. The (original) reverse engineering of traditional structures is left to other fields like experimental archaeology. Many archaeologists and architectural historians reverse engineer ancient buildings and building methods by studying archaeological material, integrating domain knowledge, and use personal experience with reconstruction efforts.

2.1.2 Experimental Archeology & Craft Science

"Archeology is the study of man's past activities and includes the examination and assessment of all his requirements for living." (Coles, 1979) These studied requirements may include, but are not limited to, hunting & farming land selection, shelter provision, tools & weapons provision, and satisfaction of community spiritual needs. Most archaeologists are concerned with only studying the archaeological material and its analysis in the lab. Many others engage in the study of the topological arrangement of artefacts while pursuing the discovery and excavation of ancient settlements or cemeteries. By studying these details of archaeological remains, some archaeologists build models or theories of their ancient societies (Coles, 1979). Coles (1973) describes a field designed to test these theories built on archaeological remains:

> *The term experimental archaeology is a convenient way of describing the collection of facts, theories and fiction that has been assembled through a century of interest in the reconstruction and function of ancient remains. By definition the words suggest a trial, a test a means of judging a theory or an idea, and this is exactly so; experimental archeology provides a way, one way, of examining archaeological thoughts about human behaviour in the past.*

Experimental Archeology, as a subdiscipline of archaeology, expands archaeological knowledge analogous to how design recovery and re-engineering expands knowledge relative to reverse engineering. Both reverse engineering, and experimental archaeology are exclusively concerned with the deconstruction and study of the material—the matter. Experimental archaeology experiments have common features that address problems in the archaeological material. This may include incomplete survival of archaeological material or a loss in the understanding of archaeological material.

All these experiments begin with a reconstruction and a test for function and suitability (Coles, 1973).

Figure 3. A replica of the Gokstad Viking boat, moored at the Great Exhibition in Chicago (Coles, 1979)

One of the most remarkable experimental archaeology projects is the excavation and reconstruction of the Gokstad Ship in Norway. This 1000-year-old Viking ship was discovered and excavated from the Oslo Fjord in Norway in 1880. From the archaeological study of the ship's remains, the theory was that the ship was designed for long open sea voyages. What was the best way to verify this hypothesis? In 1893, a replica of the Gokstad Ship was built, and an experiment was devised to test its open water seafaring capabilities. In this experiment, the Gokstad Ship was successfully sailed from Norway to New York in 27 days (Coles, 1979). Figure 3 shows the Gokstad ship moored in Chicago, after its hypothesis proving voyage.

2.1.3 Applied Craft Science

Recent research in experimental archaeology—under the name of craft science—explicitly puts the researcher in the inside perspective of the experiment. One of the leaders in this field is The Craft Laboratory at the University of Gothenburg; they take a craft science approach in researching, recovering, preserving, educating, and disseminating traditional crafts. As of 2020, the craft science anthology includes carpentry, ceramics, culinary crafts, gardening, boat building, blacksmithing, weaving, textile, conservation, building conservation, traditional painting & furniture design (Westerlund et al., 2019).

Another major distinction, in this line of research, can be understood through the difference between science and engineering.

On a surface level, science and engineering look the same, but their differences are subtle and hypersensitive. Bulleit et al. (2014) look to distinguish the two fields, while noting their overlapping domains. Science is more generally concerned with necessity, certainty, universality, and abstractness; conversely, engineering is more concerned with contingency, probability, particularity, and concreteness. Science pursues knowledge and engineering looks for useful change. Therefore, applied science—in an engineering context—can be considered the application of scientific knowledge for useful change. Applied craft science, therefore, is the type of knowledge obtained from craft science experiments applied to engineering projects (Bulleit et al., 2014).

A superb example of applied craft science is the *Reconstruction in the Ashes of the Medieval Wooden Church of Södra Råda.* In this project, Almevik & Melin (2015) describe their reconstructive experiments aimed at rebuilding Södra Råda, which burnt down in 2001. Their experiments are based on previous documentation of Södra Råda, preserved similar medieval churches, deposited building materials, historic tools, and interpretation of tool marks and craftsmanship. They were even able to find medieval documentation of woodworking techniques; depicted in figure 4. By conducting the imitative experiments, they embody skills that allow for revelation of historical working procedures, intentions, and affordances.

Figure 4. Medieval examples of timber cleaving (Antonius 2008)(left), (Acoma, 2011)(right)

A specific carpentry process Melin (2017) reconstructed was the *Techniques of Cleaving Wood with an Axe and Mallet*. The technique—illustrated in figure 5—was used to create boards from logs, using an axe, wood wedges, and a wooden mallet. They reconstructed the cleaving techniques based on historical records of cleaving and recent interviews with craftsmen—refined by practical experiments. An interesting assertion from (Almevik & Melin 2015) states: "One undisputed fact is that cleaved boards are stronger than sawed boards since the fibres are whole and not cut." (p.90)

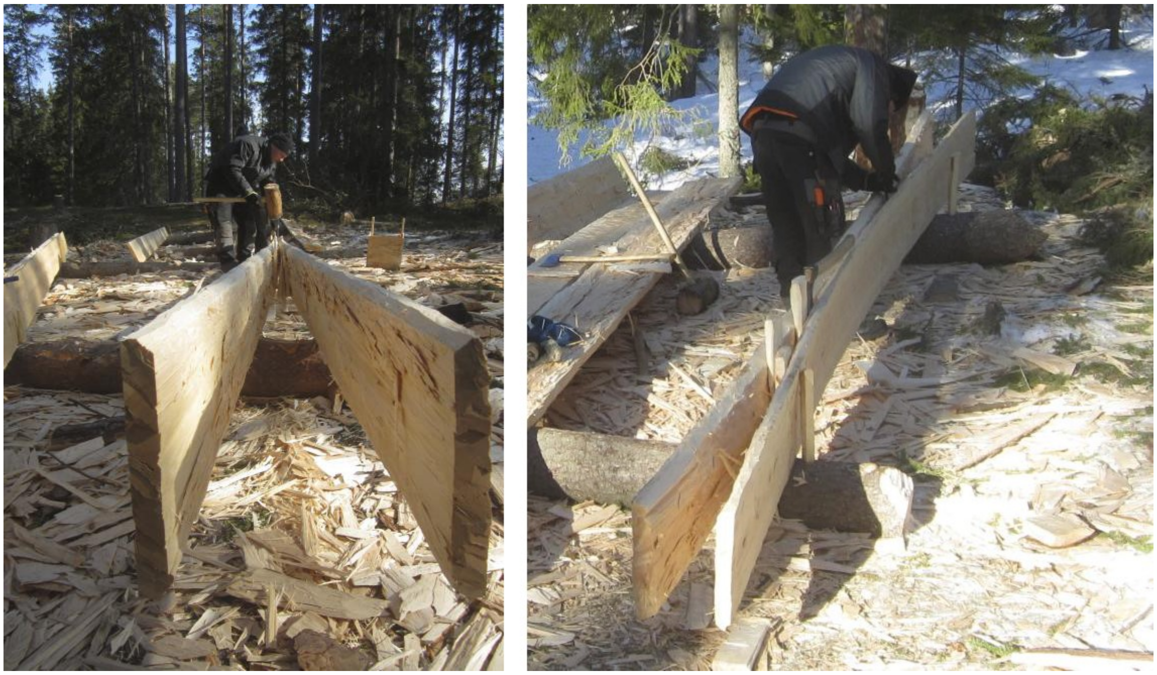

Figure 5. Cleaving reconstruction (Melin, 2017)

Another good example is the recovery of the sprett-telgjing or bounce-whittling technique of dressing timber in Norway and Sweden. This type of finish can be seen on the sill beam in figure 6. The technique produced a desirably smooth and undulating timber surface; unfortunately, knowledge of sprett-telgjing was lost during the Black Death Plague. Many medieval churches and barns featured tool marks left from this unknown method, and in the early 1990s, Norwegian and Swedish carpenters attempted to replicate the methods and marks. They found they were not able to perfectly reconstruct the surfaces and proceeded to question the tools they were using. The initiation of the Russian Glasnost opened access to Northern Russia, where the sprett-telgjing technique was still alive. This new access between Northern Russia, Sweden, and Norway, allowed the Scandinavians to learn and recover their shared traditions. The revival of this technique allowed Scandinavia to replicate these timbers in order to conserve their valued medieval building stock.

Figure 6. A sill beam prepared using sprett-telgjing (Larsen, 2000)

In *"Håndverkerens redskapskasse"* Høgseth (2007) intensively develops theory and practice in craft science. He divides the contents of the craftsman's theoretical and methodical toolbox into four categories: materiality, bodily knowledge, cognitive aspects, and cultural communities. The implements of materiality deal with the materials, tools, and tool tracks (facets). The physical knowledge of the craftsman encompasses movement, rhythm, patterns of action, the sense of sight, hearing, smell, and taste, and perception of shape, size, softness, and hardness. The craftsman's cognitive aspects entail spatial awareness, material sense, feeling for tools, sense of intended form, craft ethics, the recognition of the unknown and unique, and the reflection of methods and theories. The cultural community tools of the craftsman include interaction, learning, language, subjective expression, economics, production resources, labour, logistics, laws, and conventions. Although these are separate categories, they all interwoven.

Høgseth (2007) relates the knowledge obtained from archaeological sources material to the bodily and cognitive knowledge of the craftsman. Most importantly from a craft science perspective, he argues that gaining a broad understanding of craftsmanship must be done without the separation of theoretical abstract thinking from bodily practical work.

2.2 Wood Conservation Repair

Based on the International Council on Monuments and Sites' (ICOMOS), International Wood Committee's (IWC) (2017) *Principles for the Conservation of Wooden Built Heritage*, the same type of wood should be used—when possible—in the replacement/restoration/repair of historic timber. This includes the same/similar species, grain orientation. Additionally, the same tools and techniques should be used to convert, dress, and assemble the timbers. However, their approach remains centred around material conservation: "The primary aim of conservation is to maintain the authenticity of the historic fabric." (IWC, 2017, p.

2). They do; however, explicitly recognize that the conservation of character defining features—aspects of historic fabric—may compromise the traditions and techniques.

The idea of craft skills conservation is expanded on by the ICOMOS endorsed book: *Conservation of Historic Timber Structures – An ecological approach* (free to download from ICOMOS website). In this book, Larsen & Marstein (2000), look at timber conservation, specifically the balance of the preservation of the timber material and the preservation of the craft knowledge. Their approach—based on the International Wood Committee's (1999) *Principles for the Preservation of Historic Timber Structures*—of duplicating the choices of previous generations, is out of respect for their insight, wisdom, and knowledge. By using the preserved wisdom of our forefathers, we can faithfully preserve our timber structures.

Their approach extends all the way and starts in the preservation of forests, creating a relationship between the timber structures and their material origin. The craft knowledge in the use of the forest and timber can provide insight in making durable structures. Along with the International Wood Committee's Principles, Larsen & Marstein (2000) also highlight the use of preventative conservation, as a first policy in conservation projects. They stress limiting the use of toxic substances used for the preservation of wood from its decay. If a timber is compromised past its ability to be preserved, then a minimum intervention repair is appropriate; even then toxic materials, like epoxy are not recommended. At the centre of heritage timber conservation, is the traditional knowledge of timber acquisition, processing, construction, maintenance, and repair.

These ideas of maintenance, structural preservation, minimum intervention, then repair and replacement are also echoed in our local philosophies from the Parks Canada's *Standards and Guidelines for the Conservation of Historic Places in Canada.* This document—also endorsed by ICOMOS as a pan-Canadian conservation benchmark—focuses almost exclusively on the conservation of building material as opposed to building techniques. Their approach is based around the heritage value contained in the character-defining elements. There are 14 standards the first 9 of which deal with general preservation and should be applied to any conservation project. The other standards deal with cases of rehabilitation then restoration—entailing repair, and/or replacement.

Unfortunately, their standards in repair and replacement only focus on matching forms, materials, and detailing; not methods. Ironically, Parks Canada (2010) even has an example of replacing hewn timber in a log home, but the timber is hewn to conserve the look of the timber. There is still hope; Standard 11 b) comes closest to suggesting the conservation of traditional craft skills. It requires physical compatibility with new additions to a heritage structure, this includes, compatible materials, assemblies, and construction methods. Additionally, Parks Canada (2010) also states "The use of traditional methods and techniques should be encouraged, where possible, in a restoration project." (p. 17), this would lead us to believe they support the conservation of traditional craft skills. Paradoxically, when addressing repair and replacement, they state that "Reconstruction, or reconstitution of a disappeared historic place, is not considered conservation and is therefore not addressed in this document" (p. 15). This reveals the greatest discrepancy in the conservation approach between Parks Canada's (2010) material focus and Larsen & Marstein (2000) craft skills focus. Although Larsen & Marstein (2000) centre their approach around the conservation of the traditional techniques, they do not discount the conservation of material.

Larsen & Marstein (2000), are also clear to say that their book is not a handbook and specific repair techniques must be adapted from local conditions and resources. Most countries have their own documents outlining specific conservation and repair techniques. Larsen & Marstein (2000) just so happened to use British and American resources to illustrate this point. They cite English Heritage for their Practical Building Conservation series and Association Preservation Technology (APT) for their publications in Canada and the USA. Both resources are relevant to this thesis. APT does not have a consolidated document on timber conservation, but they do have a few articles published specifically on the conservation of hewn timber structures.

In English Heritage's Practical Building Conservation: Conservation basic, Martin & Wood (2013) detail repairs from the perspective of the roles and responsibilities of each of the parties involved with the conservation project. Within these roles and responsibilities, they highlight the need for traditional building craft skills. English Heritage also has a very in-depth timber conservation book—*Practical Building Conservation: Timber* by McCaig & Ridout (2012). It may be more specific to conservation of English structures; however, it maybe a useful adaptation. There is an entire chapter dedicated to the history and use of the timber building material; specifically, timber biology & properties, conversion & seasoning, water & dimensional stability, and traditional tools & working methods. In their repair in treatment chapter, they describe specific methods of repairing, replacing, and restoring timber structures. They also describe that the new timber should match the excising timber "as closely as possible in every way: species, grain orientation, moisture content, growth characteristics, and section orientation." (p. 293). They address that traditional methods may be used to repair timber; but, it will result in the loss of the heritage fabric.

Considering all these different approaches from national and international conservation bodies, figure 7 organizes them into a matrix. The final thing detailed about each source, is whether their conservation is centred around material conservation or craft skills conservation, additionally, how are they treated as a secondary approach to conservation.

Timber Conservation Approaches from International and National Timber Conservation Documents			
Source	Compatibile Material	Compatible Tools/Techniques	Aim
ICOMOS - Principles for the Conervation of Wooden Built Heritage	In replacement, repair, and restoration	In replacement, repair, and restoration	Conservation of material then skills
Conservation of Historic Timber Structures	Compatility from repair detailing to heritage forest use	Compatility from repair detailing to heritage forest use	Conservation of skills resulting in conservation of material
Parks Canada - Standards and Guildlines for the Conservation of Historic Place in Canada	In replacement, repair, and restoration	Replacements, repairs and restorations should support traditional practices, but not necessarily conserve craft skills	Conservation of material and sometimes conservation of skills
English Heritage - Practical Building Conservation: Basics & Timber	In replacement, repair, and restoration	In replacement, repair, and restoration	Sometimes conservation of material sometimes conservation of skills.

Figure 7. Matrix of timber conservation approaches of international and national sources.

In addition to direct approaches to timber conservation and repair, the IWC also has many other principles in their Doctrinal Texts—relating to inspection, survey & research (principles 1-4), analysis & evaluation (5-6), interventions (7-22), present-day materials & technologies (23-26), recording & documentation (27-28), monitoring & maintenance (29-31), historic forest reserves (32-33), and education & training (32-36). The most relevant principles to this thesis are:

Inspection, Survey & Research

1) The condition of the structure and its components, including previous works, should be carefully recorded before considering any action.

2) A thorough and accurate diagnosis should precede any intervention. This should be accompanied by an understanding and analysis of the construction and structural system . . . The diagnosis must be based on documentary evidence, physical inspection, and analysis and, if necessary, measurements of physical conditions using non-destructive testing (NDT). . .

4) "Invisible" (hidden) marks on old wooden parts must also be recorded. "Invisible" marks refers to features such as scribe marks, level and other marks used by carpenters in setting out the work (or in subsequent works or repairs) and which were not intended to be visible features of the structure.

Interventions

10) Interventions may take the form of:
   a) Simple repairs using simple repairs using either traditional carpentry techniques or compatible modern fasteners;
   b) the strengthening of the structure using traditional or compatible materials and techniques;

11) Interventions should preferably:
   a) follow traditional practices

14) Any replacement timber should preferably:
   a) be of the same species as the original;
   b) match the original in moisture content;
   c) have similar characteristics of grain where it will be visible;
   d) be worked using similar craft methods and tools as the original.

Education and Training

34) It is essential to record, preserve and recover the traditional knowledge and skills used in constructing historic wooden architecture.

(IWC, 2017, pp. 2-5)

The research in this thesis develops a method addressing the inspection, survey & research principles. Specifically, chapter 3.2 describes a photogrammetric method of documenting the building fabric, which augments the analysis & understanding of the construction system. The described techniques are also specifically used for recording the hidden tool marks on historic timbers in chapters 3.3.4, 3.3.5, 3.4. 3.5.2, and 3.6. Finally, chapters 3.3.2, and 3.3.5 deal with the recording, preserving, and recovering of traditional craft skills.

2.3 Axes

"If a hierarchy of woodworking tools were established, it is quite probable that the axe would head the list." (Kauffman, 1972, p. 1). The axe was the first and remained the only woodworking tool for many years. The first axe, around 6000 B.C., was fashioned with roughly chipped stones fitted to wooden shafts. Over the millennia, the axe remained a valuable tool while undergoing many evolutions; from stone, to bronze, to iron, and to steel.

They reached their highest functional development during the settlement of America. The development of the American axe occurred as a result of two main factors. First, the Europeans were not versed in working the huge virgin American timbers; their tools were not satisfactory for the job, especially with the impending harsh winter season. Second, the settlers were detached from their homeland and would have to solve many of their problems on their own (Kauffman, 1972). With the immigration of millions of European settlers, the axe also allowed for the transformation of millions of acres of eastern North American forests into farmland (French, 2010).

2.3.1 Axe Typologies

The most common image of an American axe is that of the great felling axes; either single or double bit. These axes were developed up until the 21st century to efficiently fell trees. Other types of axes smithed for several different wood processing functions; splitting, cleaving, hewing, chopping, carving, etc. Each profession had its own variation of similar axes in lumbering, timber framing, shipbuilding, coopering (barrel making), etc. Each of these types of axes will have many variations depending on the geographic and ethnic region. French (2010) organizes the terms used to describe these variations with three levels of axe characterization: type, form, and pattern. The axe 'type' refers to its function, 'form' refers to its typical national style, and 'pattern' refers to its minor geographic style. For example, a hewing axe made in Ottawa would be a broad type, North America form, Canada pattern axe.

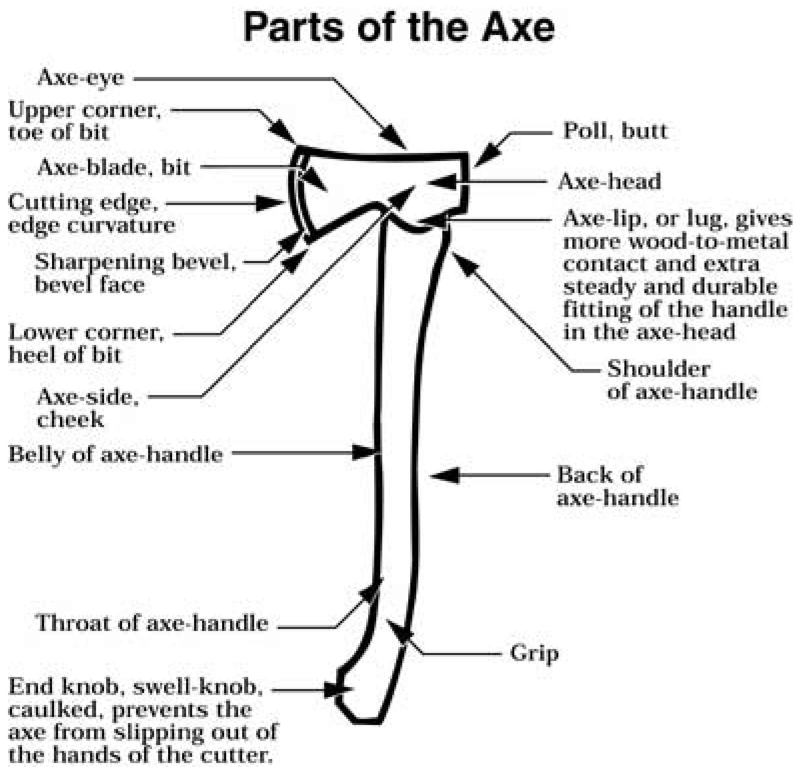

Figure 8. Anatomy of an axe (Weisgerber, 1999)

The parts of an axe—labelled in figure 8—also have their own names and are used to describe the variations among different types, forms, and patterns. The Canadian pattern broad axe has a broad/wide bit, with one tapered cheek and one cambered planar cheek. This diagram of the anatomy of an axe can also be referenced in the glossary.

Many local variations on the same type of axe were developed throughout America; these regional variations are known as the axes' pattern. Particularly with felling axes, the names were given to each of their patterns usually represent their geographic origin, but they are also sometimes named related to their use.

2.3.2 The Broad Axe

The broad axe (hewing axe or side axe), is a specific form of axe used to efficiently and precisely remove thin layers of wood from timber—or dress the timber. One of the earliest broad axes found in America is the goose wing style brought to Pennsylvania by the Germans (Kauffman, 1972), (Weisgerber, 1999). An example of a particular goose wing is shown in figure 9. The goose wing broad axes were also manufactured in America for a period, but it would soon be replaced by its American successor. Contrary to the regular chopping axe which has two ground bevels, the goose wing broad axe has only one ground bevel like a chisel; angled on one side and flat on the other. English and German type broad axes generally have single bevels while other European type broad axes are fashioned with a double bevel. Goose wings featured canted eye socket so that their handles would be angled away from the blade, preventing the user from scraping their knuckles during use. This creates the need for right and left-handed axes.

Figure 9. Corey Pool's right-handed goose wing pattern broad axe

The main reason the American form broad axe was developed was like that of the American felling axe, for working large, clear grain, almost knot-free pine. The British form and German form broad axes were less than ideal to handle the American timber; however, they would have had some influence on the construction of the American broad axe. Local American blacksmiths developed their own broad axe patterns mainly in the 18th century and the early 19th century. These pattern characterizations were assimilated as early as 1865 as seen in the tool catalogues; specifically, the Russell and Erwin American Hardware catalogue. Generally, the American broad axe did not feature a canted eye; therefore, with a new handle, one broad axe could be converted from right-handed to left-handed (Kauffman, 1972). This did require the handle to be bent instead, to continue protecting the users' knuckles. American broad axes—excluding those used for ship work and forming railway ties—also featured a single-bevel, chisel edge (Kauffman 1972).

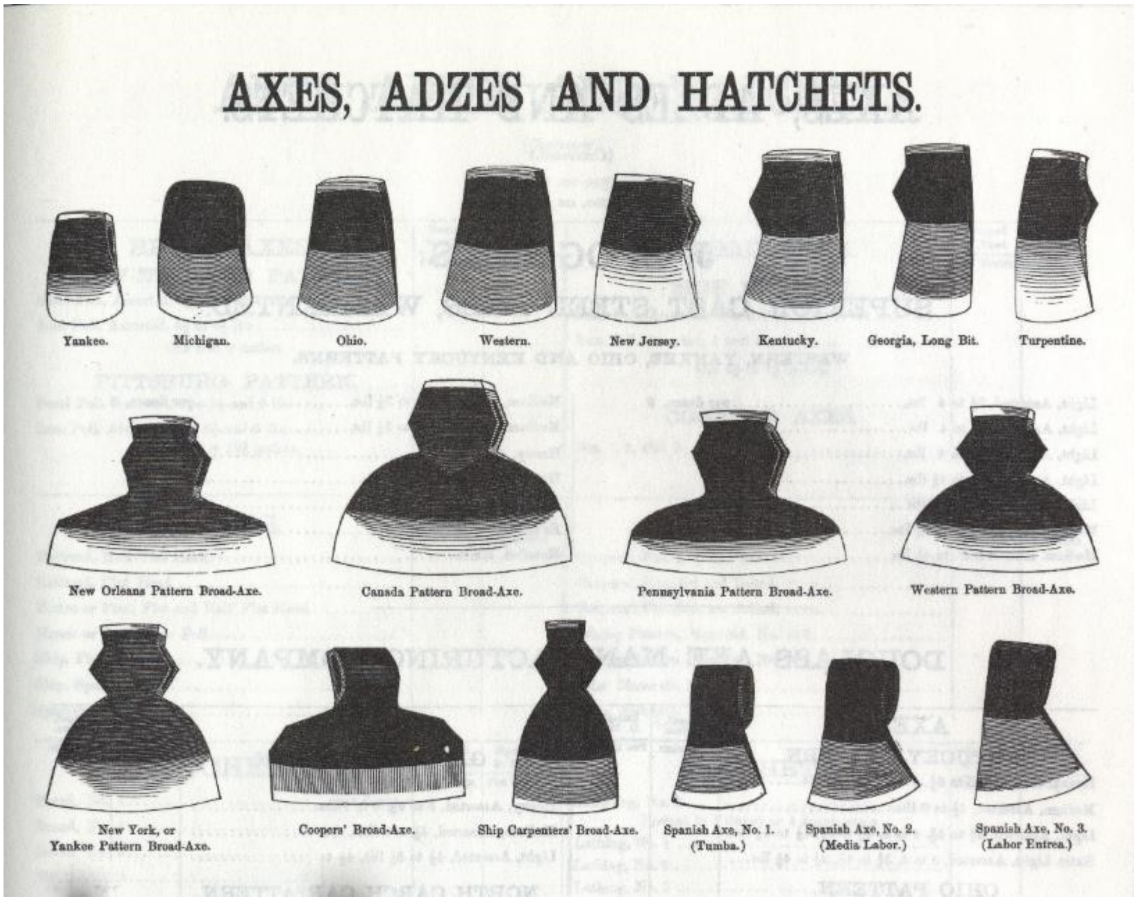

Figure 10. Broad axe patterns from the 1865 Russell and Erwin American Hardware catalogue (Russel & Erwin, 1865)

Even in the tool catalogues—figure 10 for example—there are many names for different patterns, originally given based on their geographic origin. Canadian, New Orleans, Pennsylvania/Pittsburgh, Western, New York/Yankee, or Ohio are most of the pattern names found in tool catalogues. The Canadian pattern broad axe is the most distinguishable; all the largest broad axes are Canadian patterned, and it is the only pattern that lacks a necked poll. Some Canadian broad axes weighed up to 12lbs. and had blade widths up to 15½ inches; there are of course small Canadian broad axes as well. These massive Canadian broad axes were usually smithed in the Ottawa Valley, French (2010) refers to these as Ottawa pattern broad axes. Another distinguishable hewing type axe used for shipbuilding was the ship carpenters/builders' broad axe or mast axe, which was usually a tall and narrow version of a broad axe featuring a double bevel.

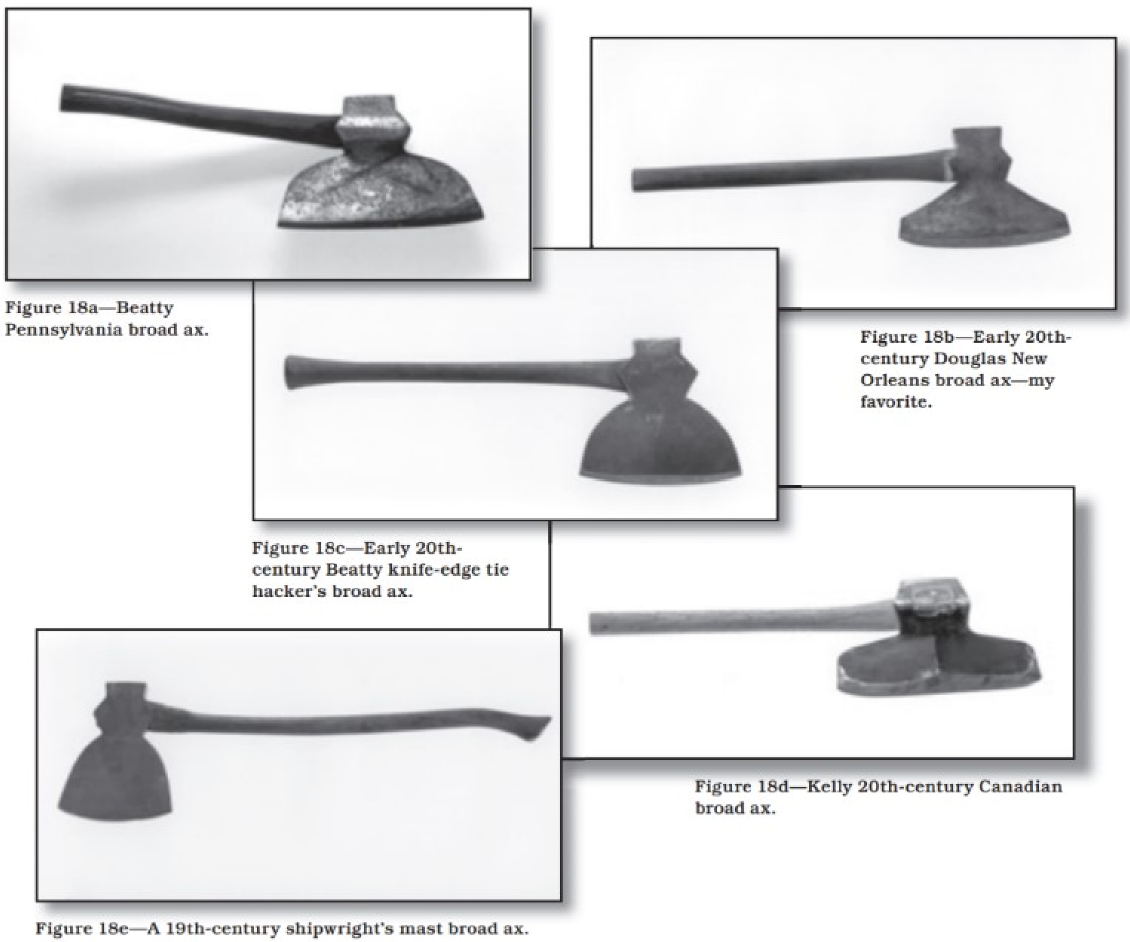

Figure 11. North American broad axe patterns (Weisgerber, 1999)

This categorization seen in the tool catalogues is still used in recent documentation illustrated in figure 11. *An Ax to Grind: A Practical Manual*—published by the United States Department of

Agriculture Forest Service—depicts the same categorization of North American broad axes. This depiction is in image form as opposed to illustrative prints.

French (2010) also details the patterns of broad axes that were found across Ontario, which are typically either Canadian pattern or New York pattern. Most broad axes from Eastern Ontario are Canadian pattern and most broad axes from central or Western Ontario are either Canadian or New York pattern. French (2010) states that "The further west in Ontario one moves, the more likely it is that the axe is New York pattern rather than Canadian pattern and the smaller and lighter the axe is likely to be." (p. 31). Aside from the pacific forests' trees, the largest accessible trees were found in the Ottawa Valley, which is where the larges broad axes are found.

2.4 Timber Framing

2.4.1 Timber Framing

A Timber frame is a method of construction, characterized by joined wood structural members. In North America, timber framing refers to large solid timbers (over 5"x5" size section) joined with traditional wooden joinery (Beemer, 2016).

The timber framing process can be split into multiple steps typically ranging from design to raising. Descriptions of the timber framing process can be found in major timber books including *Building the Timber Frame* by Benson and Gruber (1980) and *Learn to*

Timber Frame by Beamer (2016). The general steps in timber framing are typical as follows: design, timber acquisition, layout, cutting, and raising. The finishing processes are not necessarily exclusive to timber framing, they can be enclosed using conventional stick framing or structural insulated panels (SIPs).

Traditional timber framers would also personally select, acquire, and convert timber—sourced from local forests. This process is not included in major timber framing books. For a traditional view of this process, we must investigate the documentation on log home construction; another type of timber construction in which walls are built up using horizontally placed logs or timber.

2.4.2 Hewing

Hewing is the process of converting a round log into a square timber—using an axe. When hewing a log, it is natural to follow the grain of the timber, contrasting sawing techniques that cut across the grain and any defects. As a result, produce less waste and may produce a stronger timber than sawing, for the same timber cross-section (McCaig & Ridout, 2012). Hewn timber was typically used for log house building, timber frame construction, railway ties, and shipbuilding. Even after the construction of sawmills in an area, timber was hewn to avoid transportation to the sawmills since this process could be done right where the tree falls. Hewing technique often has regional differences that may depend on the timber size/species, local axe construction, and intended construction product. Even then, people still argue over 'the correct way' to hew timber. The following is the hewing technique described and demonstrated by local preservation carpenter Corey Pool.

The hewing process can also be divided into three major steps preparing, scoring, and hewing. Preparing the log usually involves peeling the bark, either the entire log or just along the approximate snapped lines. To secure the log in place, log dogs (long metal spikes) are driven into the log and its perpendicular supporting logs. The desired dimensions are then marked as a rectangle on each end of the timber using a level and/or plumb. Then the corners are connected via chalk/charcoal line—vertically snapped along the length of the timber. This snapped line is used as a reference for setting the depth of wood for hewing.

Figure 12. Notching timber

Scoring the timber is achieved by notching and blocking the timber roughly to the chalk line. With a felling type axe, a notch is chopped out every one-to-four feet along the timber—the interval depending on the size of the timber and the skill of the man. Figure 12 shows the notching step on a large white pine timber, while figure 13 shows an alternative method of notching with axes.

Figure 13. Alternative Notching (The Norwegian Forest Museum Foundation, 2017).

Some may stand atop the log or behind the log—depending on log height and size—while chopping the notches from above. One notching technique documented with European hewers utilizes two men standing 45° to a log at about hip-level, alternating strikes down on the timber face closest to them.

Figure 14. Hacking the blocks

On larger timbers, the blocks created between each notch are hacked off, ideally with one—strong but accurate—swing of the felling axe. If looking closely, notice the large block removed in figure 14. With smaller timbers people may go straight to using a broad axe for hacking the blocks; some simply with a swing of a broad axe and some may pound their broad axe with a large wooden mallet to cleave off the blocks.

Figure 15. Scoring

In photo and video documentation of present-day lay-hewers, the scoring step is usually skipped over; however, it does appear in written documents like *A Hundred Years A-Fellin'* (Whitton, 1942). This discrepancy may be due to those photographers/cinematographers confusing ‘scoring’ with what was previously described as ‘notching’. When scoring would take place, it was completed with a felling type axe as shown in figure 15.

Figure 16. High hewing

A broad axe is used to dress or hew the timber by methodically slicing thin strips of wood, millimetres from the finished timber surface.

Figure 17. Low hewing (Weisgerber, 1999)

The height at which the timber is hewn will determine subtle variation in the hewing technique. The timber height may depend on the size of the timber and weather the hewing is taking place in the bush or a construction camp. Low hewing (figure 17) usually takes place with the timber resting on perpendicular logs, whereas high hewing (figure 16) utilizes trestles to raise the timber to waist height and above.

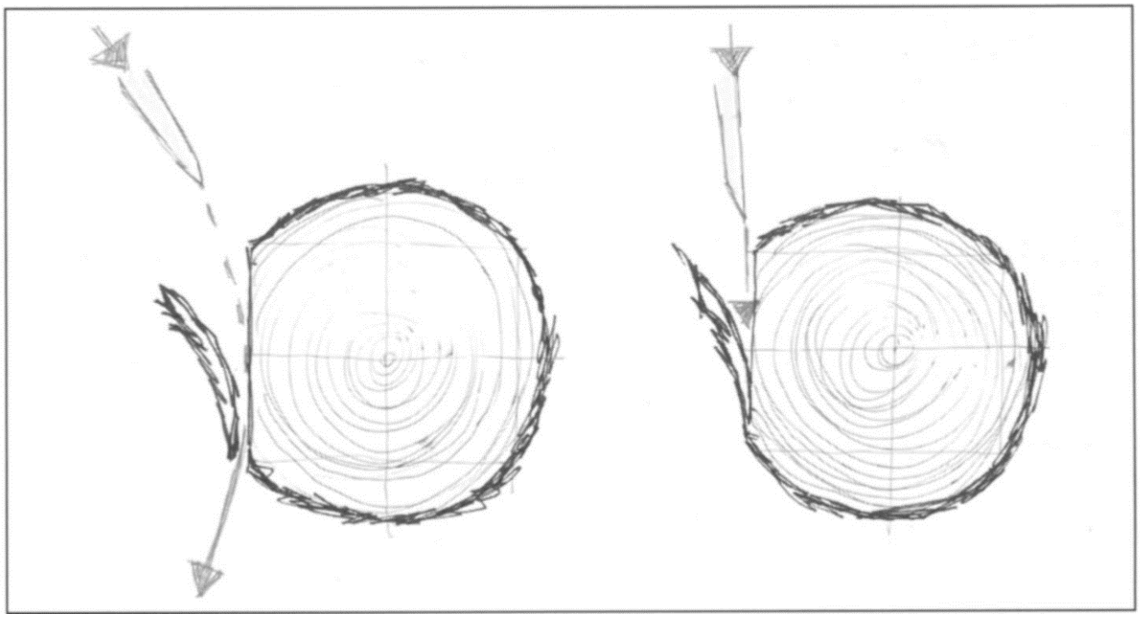

Figure 18. Double-bevel (left) VS single-bevel (right) hewing technique differences (Drdácký et al., 2004)

One of the most significant factors in the hewing technique is the type of broad axe in use: a (chisel grind) single-bevel axe or a (knife grind) double bevel. Since a single-bevel broad axe has one large flat face, the axe swings are essentially plumb with the desired finished timber surface. With a double-bevel broad axe the technique requires a more swing with more lateral momentum, that glances the axes off the finished timber surface. Drdácký et al. (2004) illustrate—in figure 18—the difference in technique looking down the length of the log/timber.

2.4.3 Hewing in the Ottawa Valley

> *Square timber was rafted out of The Valley for a century, and, though the high mark of its glory was probably from 1861 to 1891, never were the clean white timbers cribbed nor ever the great sticks driven down a stream that colour and romance, daring, high adventure and brave and careless living were not there. For square timber was of the very heart of our early forest story and the square timber of the Ottawa was of the very fibre and soul of that rich and long lost day. (p. 109) (Whitton, 1942)*

The best-written record of the hewing process in the Ottawa Valley comes from Whitton (1942) in *A Hundred Years A-Fellin'.* He provides a record of the phases and people involved in lumbering in the Ottawa Valley from 1842 to 1942 as a Gillies Brothers, Limited (Ottawa lumbering company), anniversary volume.

In the earlier days, settlers would cut timber on their own land, also possibly floating and rafting the timber themselves. This also allowed for the clearing of farmland. As the timber stands were progressively cut, the market increased giving birth to more organized operations (Whitton, 1942).

Before a company bid on a timber stand, a 'cruiser' would survey the timbers. The survey cruise was preferably in the winter, in March when bare trees could easily be seen, and the ice was still good for toboggans to travel uninterrupted by bodies of water. Cruisers were the woodsmen-brothers to the surveyor, estimating timber stands and values in bounded areas. At the same time, they were identifying timber stand configurations, potentially floatable streams, potential dam, camp, and road sites. After a site was acquired, a second special cruise was initiated to provide a confirmed thorough and detailed estimate. The timber was indicated based on their proximity to the best cuts, slopes for roads, sites for skids, and routes of floatable streams with camps. Out of all the species in the Ottawa Valley—maple, elm, basswood, paper birch, beech, red oak, yellow birch, ash, balm of gilead, white pine, red pine, hemlock, balsam, white spruce, white cedar, and tamarac—they sought only the white pine. Following the cruise, advance gangs would follow the blazed trails to set up camps at the designated sites. In late autumn—before snowfall—men, oxen, horses, food, and equipment would find their way up the valley to the camps.

Timbering began with teams of about 5 men, setting out in the winter to fall, buck, and square the previously surveyed timber. A 'liner' would go ahead on the cruised and blazed trails to assess, pick, and mark specific timber for felling. Then the 'scorers', armed with felling/chopping/scoring axes, began by felling trees using a series of notches in the trunk bases to aim the fall direction. The trees were precisely aimed to rest on cross logs, allowing the timber to be raised for hewing. The older, more skilled scorers carried six to seven-pound axes with 48" handles. Typical felling axes today are closer to five pounds with 36” handles. Crosscut saws were not used to fell timber until 1875. Once felled, a liner would identify and measure out lengths of quality wood to cut. He selected lengths for their straightness, soundness, and quality—free of knots and blemishes. Once marked, the liner would scrape the bark from the timber to reveal a smooth surface. With this white, smooth surface exposed, the line then snapped a chalk line to create a downline and thus a reference face for the finished square timber face. The liner snapped the line for both sides of the timber. Looking closely at figure 20, one can see the snapped chalk line on the bare timber.

Figure 19. Blocking, hacking and hewing a square log, Muskoka District (Notman, 1873)

The scorers then mounted the timber, chopping notches to the depth of the downline. They created the notches every four feet along the liner’s downline (figure 19 & 20). Blocks of wood between the notches could easily be knocked off by the scorers, this method allowed for efficient removal of large amounts of material with just an axe; however, it left a rough surface that required a finish dressing.

Figure 20. Blocking, hacking and hewing a square log, Muskoka District (Notman, 1873)

Figure 21. Booth lumber camp Aylen Lake Ontario ca 1895. Scoring a timber where it fell in the woods. (Unknown, 1895)

The scorers then prepared the surface for the 'hewers' by using their axes to score the timber precisely to the downline, this step is evident in figure 21. These scores created vertical cuts across the entire grain of the timber surface every four inches along the timber length. The scoring set the depth for the finished hewn surface. This was an important step; cut too shallow and leave a heavy task for the hewer, cut too deep and risk scarring the finished timber face. The timber was scored on both sides so they could be finished by the skilled hewers simultaneously.

Figure 22. Hewing Felled Timber, operations of McFadden & Gillies, Jocko River (Watt, 1913)

The hewers swung razor-sharp, ten to twelve-pound broad axes; shaving the timber to a satin sheen smooth finish. Once both sides were finished, the timber was rotated 90° and the other surfaces were hewn by the liner, scorers, and hewers, using the same process. Once the timber was fully hewn, the hewers would sign their initials into their respective finished surfaces. Figure 22 shows two hewers, swinging large Canadian pattern broad axes. Each of the steps of hewing timber can also be referenced in the glossary.

Most of the square timber in the Ottawa Valley was bound for export; however, we would expect the same hewing techniques to be used for local timber structures. Most of the lumbermen in the lumber camping making square timber were farmers, and so they would likely have the knowledge to be able to square their own timber for their timber frames and log houses.

2.5 Traceology

2.5.1 Traceology

Traceology is illustrated by Bláha (2013), as an intersection between criminalistic and historic construction and reconstruction. The criminologist uses techniques like dactyloscopy, graphology, odorology, and terminal ballistic analysis in order to study the ‘footsteps’ left at the crime scene by the perpetrator. Conversely, the building historian may use stratigraphy, paleographyology, use-wear analysis, and experimental archaeology to understand the ‘footsteps’ of the craftsman. These two spheres overlap (figure 23) when the investigators are examining tool marks and analyzing morphologies.

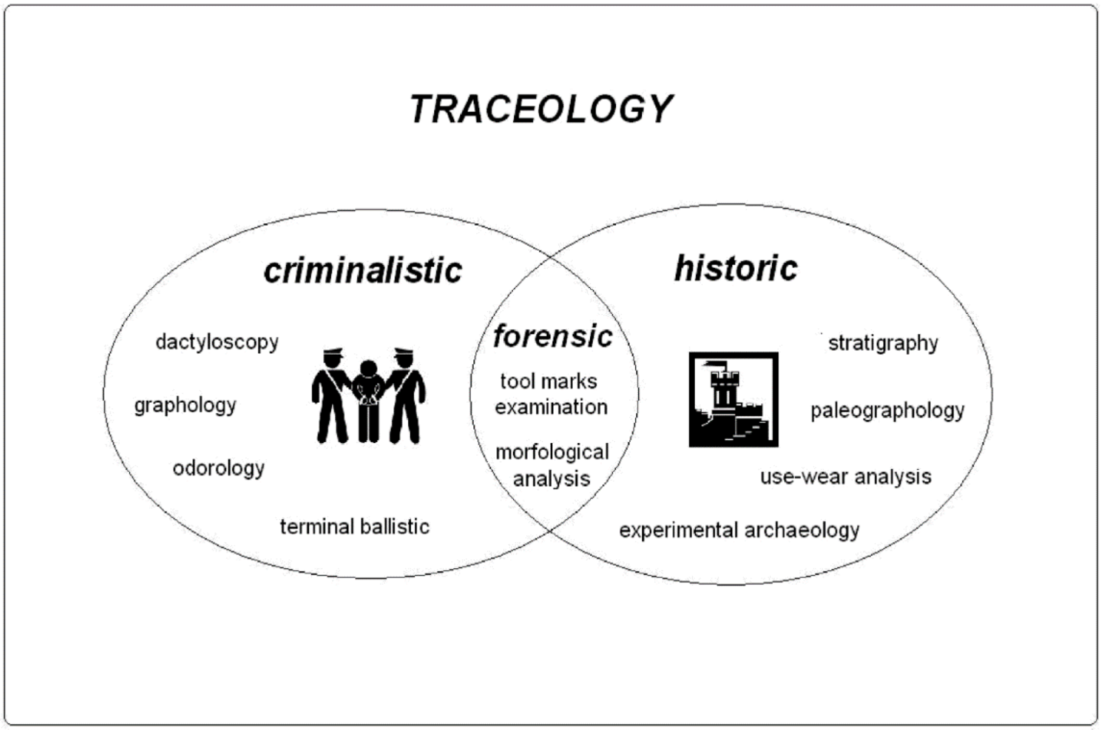

Figure 23. Main fields of traceology and their sub-methods (Bláha 2013)

The trace marks of tools are particularly important to conservators that are trying to understand the history and construction of a building. These trace marks can also help us understand the forgotten or lost practices in building crafts. With traceology in traditional building crafts, we may identify many different types of trace marks:

> *"According to their origin they can be divided into several groups including traces of the transportation or other manipulation during construction; geometric schedules, height and direction lines, auxiliary design sketches; signs of wear and natural aging of materials; structural*

> *failures and impact of natural disasters; traces of subsequent additional modifications or conservation interventions; small epigraphical relics such as inscriptions, datings, the names of artisans or craftsmen, various graffiti etc." (Bláha, 2013)*

Conversly, Høgseth (2013) argues that reading tool marks is more akin to recognizing a face as opposed to calculating fingerprints. The tool marks from one edge tool may change over time analogous to how the human face ages with its wrinkles and furrows. The human face ages but remains recognizable. As an edge tool ages, it gradually collects new damage like notches, breakage, bulges, etc (Høgseth 2013).

2.5.2 Timber Conversion Traceology

Working with existing timber frames and using timber framing tools is the best way to acquire the ability to identify signature tool marks. Many trace marks may be present on the surface of a timber.

In *The Conversion of Structural Timbers,* Thompson (2017) documents the historical and modern techniques used to turn round logs into timber, in the United Kingdom. For this article, in the *Building Conservation Directory, photographer* Tim Walton produced a series of images depicting the tool marks left by their respective conversion technique/tool. Thompson and Walton reveal the surface textures using raking lighting photography; this allows them to read the surface of the timber and determine the conversion technology. There are three major methods carpenters have used to convert timbers: cleaving, hewing, and sawing.

Figure 24. Cleft surface: torn grain with distinctive, slightly, ridged surface © Joe Thompson (Thompson, 2017)

Cleaving timber—an ancient technique used by the Anglo-Saxon and Norman forbears of England—is achieved by splitting a log along its grain. A series of splitting axes, steel splitting wedges, and wood wedges are used to tear the grain along the length of a log. This process leaves a distinctive slightly ridged surface finish; depicted in figure 24. Cleaving is generally suited for hardwoods and can also produce several other wood products including panelling, boards, shingles, laths, staves, and pins (Thompson, 2017).

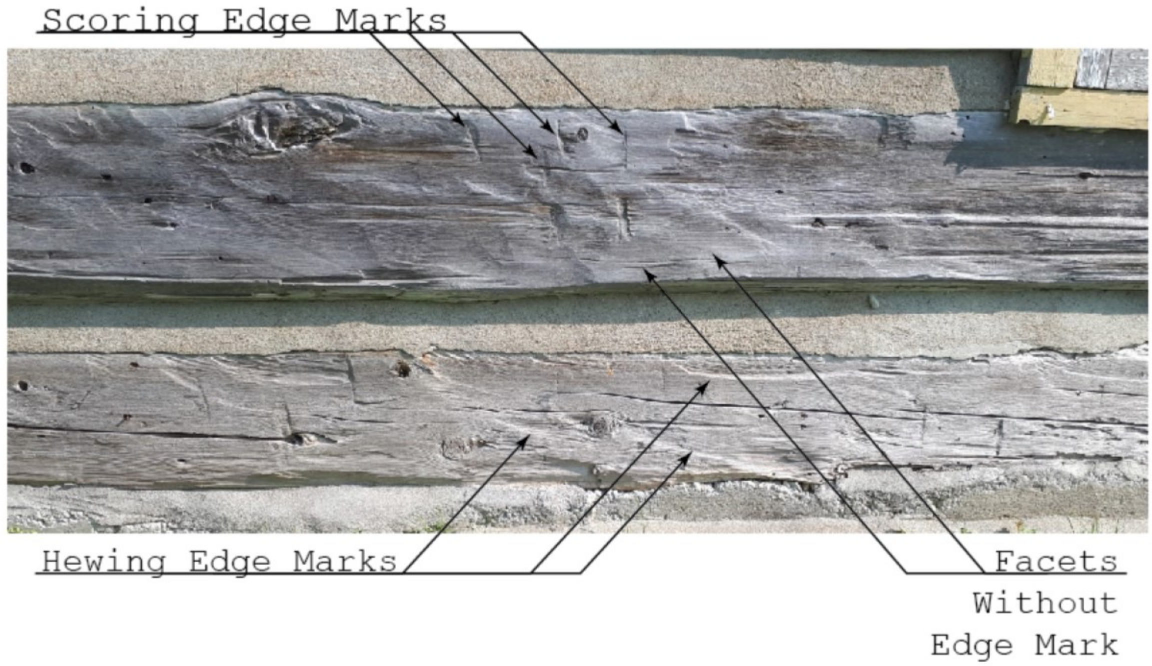

Figure 25. Hewn surface: vertical scoring cuts, large axe bites, and shallow faceted undulating surface

Hewing—the process described in the previous chapter—generally leaves 3 types of marks. The more obvious vertical marks are left from the scoring process. When the scorer would sink his axe too deep past the snapped line, the wood tears out and cannot be cleaned up from hewing any further than the snapped line. The second and third marks are left by the hewer and are harder to spot; usually only in raking light. Depending on his skill, the hewer will either have his swing cleanly slice and glance off the timber or his axe will bite and stop into the timber. The clean slice creates a facet tool mark without the edge mark, while the biting axe creates a tool mark with a facet and an edge mark. Each of these tool marks are shown in the raking lighting of figure 25—these terms can also be referenced in the glossary.

Ideally, a hewn surface would have no hard marks only shallow undulating facets left from the skilled broad-axeman. Thompson (2017) Reports that hewing is slower than cleaving but quicker than [pit] sawing.

Figure 26. See-sawn surface © Joe Thompson

Sawing timber has the largest variation of techniques, and therefore a large variation of tool marks. English timber sawing technology started in the late 12th century with the use of man-powered saws. The first technique was 'see-sawing', in which a hewn timber is supported near its centre on a single trestle. The timber—propped at an angle—was then sawn along its length until stopping at the trestle and pivoting the timber; like a children's see-saw. The process leaves a small equilateral triangular area unsawn and consequently cleft off (figure 26). See-saw marks are irregular and typically at an angle of 50-70° to the length of the timber (Thompson, 2017).

Figure 27. Pit sawn surface: saw-marks at about 75-85° to the length of the timber and a cleave-off at one end in the shape of an irregular triangle © Joe Thompson

Pit sawing in England gradually became adopted between the late 14th and mid 16th centuries. They were also initially used in the Ottawa Valley from around the year 1800; however, they were slowly phased out when mill saws were introduced around 1850 (Dunfield, 2002).

Pit sawing involves a hewn timber supported horizontally high on a frame or over a pit in which a sawyer would stand atop and below the timber, sawing along its length. In the end, a small irregular triangle is left unsawn and is cleft off (figure 27). Pit sawing can also be identified by its irregular saw marks at about 75-85° to the length of the timber (Thompson, 2017).

Figure 28. Reciprocating sawn surface: saw marks closely and evenly spaced at about 90° to the length of the timber © Joe Thompson

Early sawmills used (sometimes multiple) reciprocating blades powered by water or wind to rip timber along its length. Reciprocating sawn timber in England dates from the 17th century onwards. These saws in Canada existed in early, cheaply built, smaller sawmills, but were eventually replaced by circular sawmills (Wynn 2006). Reciprocating sawn timber can be recognized by saw marks that are at 90° to the length of the timber with a close and evenly spaced pattern (figure 28) (Thompson, 2017).

Figure 29. Circular sawn surface: very distinctive, large, curved saw marks © Joe Thompson (Thompson, 2017)

Circular sawn timber arrived in the late 18^{th} to early 19^{th} century in England, and around the mid 19^{th} century in Canada (Wynn 2006). Both eventually established by the advent of steam power; typically, fueled by the sawmill waste. Circular sawn timber is the most easily distinguished by its large, curved radiating saw marks (figure 29)(Thompson, 2017).

Figure 30. Bandsawn surface: very distinctive and widely spaced saw marks that are at 90° to the length of the timber © Joe Thompson (Thompson, 2017)

Bandsawn timber also dates from the mid 19th century in England, and largely replaced the circular saw after 1890 (Wynne, 2006). Most modern sawmills operate with a bandsaw or multiple bandsaws. Additionally, there are even consumer-grade portable bandsaws that offer individuals to mill their own timber/lumber. Bandsawn timber can be identified by their distinct, widely spaced 90° marks (figure 30) (Thompson, 2017).

Figure 31. Scrub planed surface (left) scrub plane (right) ©LeeValley 2019 (Valley, 2020)

English heritage recognizes the importance of traditionally converted timber but understands it is not always economically viable in heritage repair. To preserve the overall architectural aesthetic of hand-hewn timber, they recommend texturing sawn timber with a scrub plane (figure 31). This is easily distinguishable from hewn timber by any carpenter worth his salt (McCaig & Ridout, 2012). A scrub plane is like any hand plane except for its cambered edge, designed for major stock removal. This creates long shallow grooves in the planed wood. Lee Valley Ltd. sells scrub planes and recommends planning at an angle of 30° or more to the grain direction (Valley, 2019).

Apart from the lumbering industry, there is a lot of information online on how to make timber look as if it was hand-hewn. People then proceed to install these faux-timber beams in their stick-framed two-by-four construction house. This indicates that people appreciate and value the aesthetic of the hand/hewn timber look, but this does not quite hit the mark. Benson (1980) even documents this phenomenon in 1980—this is nothing new.

2.5.3 Axe/Hewing Traceology

There are many ways to hew timber and therefore there are multiple patterns and sizes of hewing trace marks left on timbers. The foundation of axe traceology is laid by Sands (1997) with his work on documenting and analyzing bronze and iron age tool marks preserved in waterlogged timber. He defines each tool mark with three principal characteristics: the jamb curve (edge mark), the waves (facet curvature), and the signatures. The edge marks are created by the axe biting or stopping in the wood, leaving (part of) the profile of the axe edge. Tool marks may also have side features created from the heel and/or toe of the axe tracking through the length of the cut. These marks are illustrated in figure 32 and can also be referenced in the glossary.

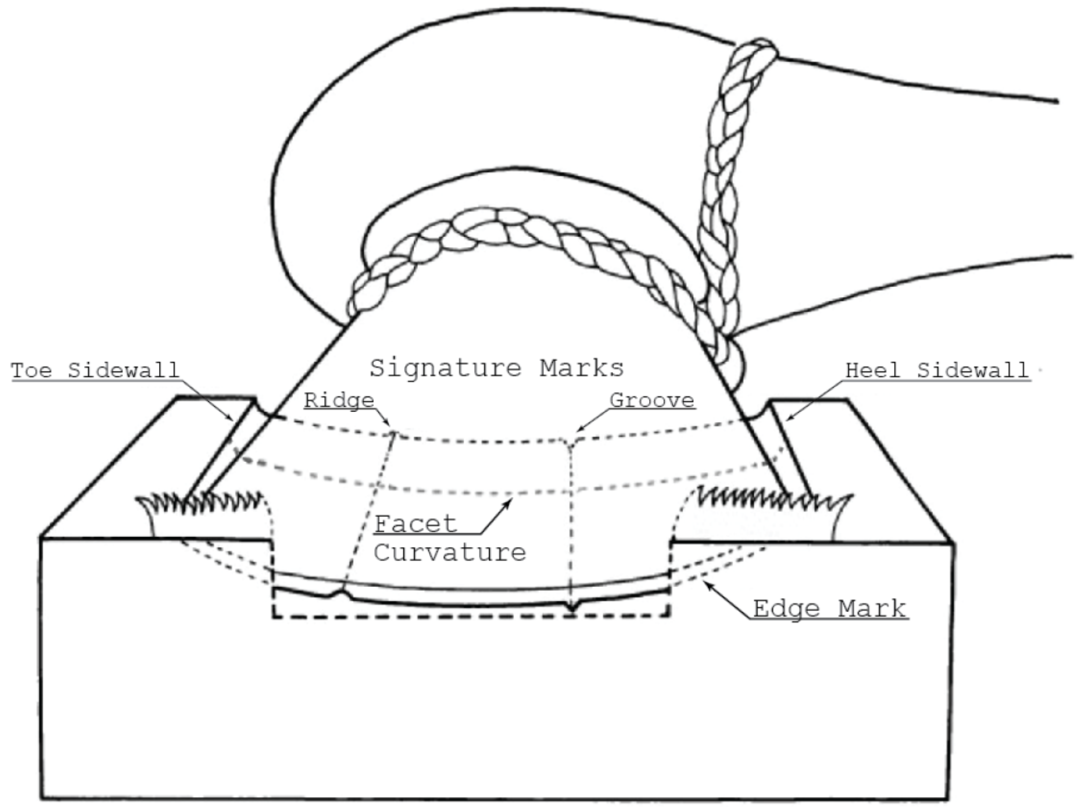

Figure 32. The features of a tool mark (Sands, 1997)

Sands (1997) measures and matches the signature marks to find associations between multiple pieces of hand-worked wood. More specific aspects of the reconstructed ancient processes include identifying structural construction patterns, building phases, associations between structure and stratigraphy, subtle aspects of production sequences, verifying dendrochronology, stratigraphic relationships, reconstructing blade size, blade shape, functional types of tools, fitting tool marks to known tool styles, suggesting the number of people/axes on a construction project, and workforce organization.

Sands' (1997) measured signature marks via raking lighting photography, distilled down to a 2D discrete curve. The camera recorded the light intensities (in grayscale) for each pixel of an image. The camera was oriented in a way that the signature axe marks were top to bottom in the image, with perpendicular raking lighting. Then an area in the image must be cropped to only contain the grooves and ridges of the signatures. Once an area is isolated, the image is smoothed to account for vertical inconsistencies like damage or wood grain features. The vertical columns of the digital image are then averaged down to one value; these values across the width of the image, represent a signature profile. This creates a metric representation for the pattern of grooves and ridges in an axe (figure 33).

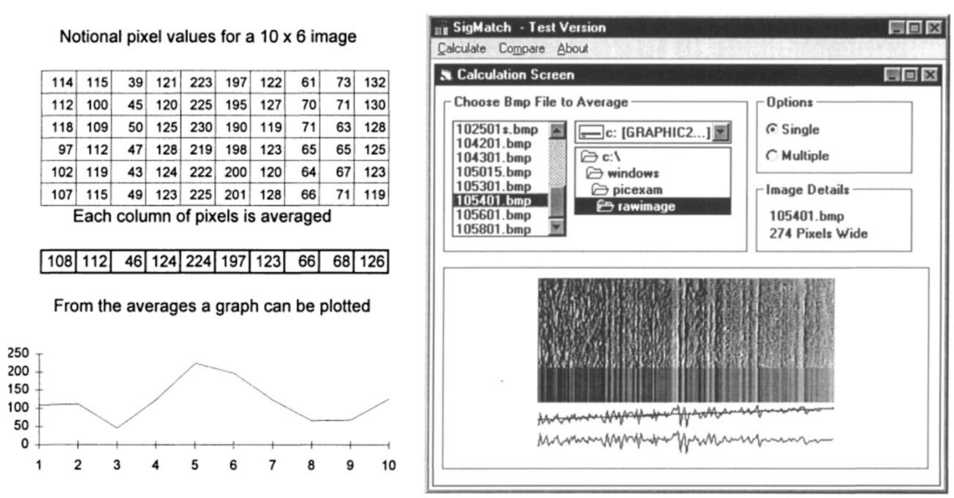

Figure 33. Signature profile calculation visualization

Through the signature combinations and edge mark registrations, Sands (1997) illustrates that the original blade shape can be accurately reconstructed from multiple fragments of tool marks. In terms of the blade camber curvature reconstruction, he reiterates that they are difficult and unnecessary to record. He only recorded the cross-section curvature using qualitative measures—flat, slightly concave, or concave. He also used the edge mark widths and edge mark curvatures to match with existing databases of axes. The widths are a measurement from axe heel to toe and the edge curvatures were calculated with the edge width/depth ratio, as depicted in figure 34.

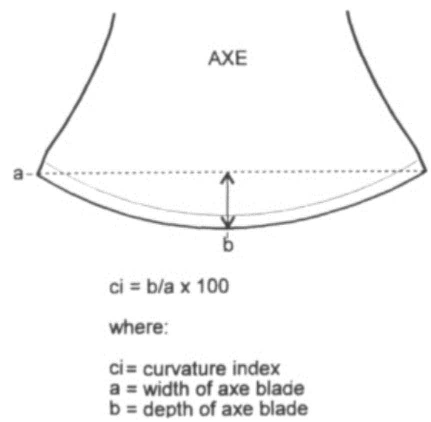

Figure 34. Calculating the curvature index (Sands, 1997)

The work of Sands (1997) is extended by Høgseth (2007) in his doctoral thesis *"Håndverkerens redskapskasse".* He also uses casts and scans for the analysis of historic timber surfaces. In his pursuit to reconstruct the cognitive and physical aspects behind the creation of tool tracks, Høgseth examines many factors:

1. "What tools are used?
    a. Length measurements, widths, and cross-sections

b. Special characteristics for forming a three-dimensional understanding

c. Tool sidewalls, direction of attack, signatures, edge curvature

d. How is the tool sharpened, how is the tool skewed?

   i. Analysis of the stopping point ratio, front/back edge, signatures

   ii. Are both sides of the axe edge used in the process?

2. What is the pattern of movement of the tool track?

   a. What is the front and back of the tool track?

   b. The pattern of movement in each tool track:

      i. The signature pattern

      ii. The relationship between the front/back edge of the tool track and the signatures

      iii. The relationship between the tool's stopping point, front/rear edge, and signatures

      iv. The rhythm and flow of work

3. How can the work processes/procedures take place?

   a. Investigations of impact direction, curvature, and signatures

      i. Which side was the carpenter working on?

      ii. How is the log rotated/turned and how many times?

      iii. How many times did the carpenter change sides?

   b. The order/series of cuts, which tool tracks came first/lest?

   c. Which side of the log was the carpenter working on?

   d. The relationship between a series of tool tracks

4. The performance of work technique, posture, movement pattern, rhythm, flow, the different tools and the peculiarities of materials, different craftsmanship dialects (techniques) are tested by analyzing and comparing its source material with practical, experimental experiments” (pp. 236-237)

One of the most interesting aspects from his craft process documentation is how Høgseth (2007) borrows from standard dance notations. Using his developed notation for bodily movements, he records the reconstructed craft processes for dissemination and replication (figure 35).

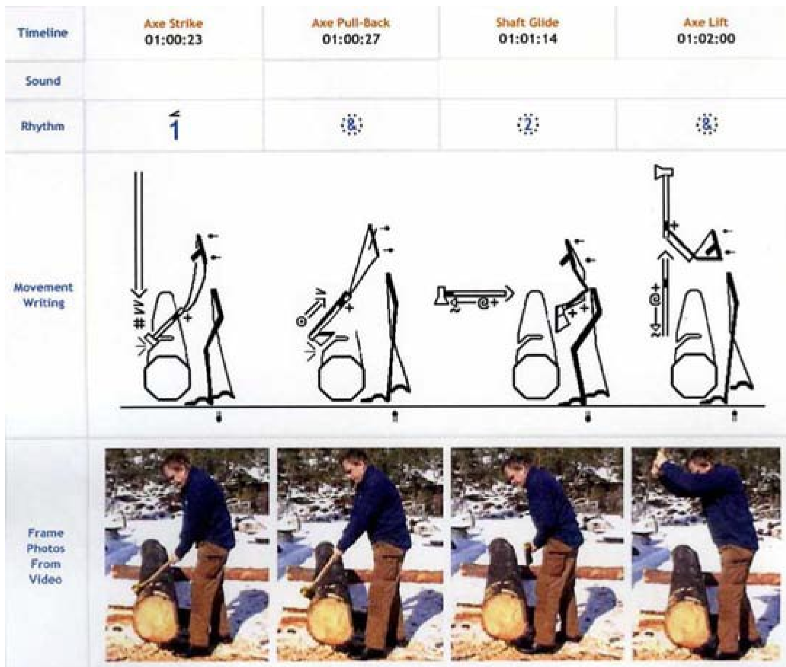

Figure 35. Axe craft process notation (Høgseth, 2007)

In another Scandinavian project—the reconstruction of the Medieval Wooden Church of Södra Råda—Almevik & Melin (2015) document their analysis of hewn and cleaved timbers from similar medieval churches. They use the simple, but effective raking lighting technique to highlight and shadow the axe tool marks on medieval timbers.

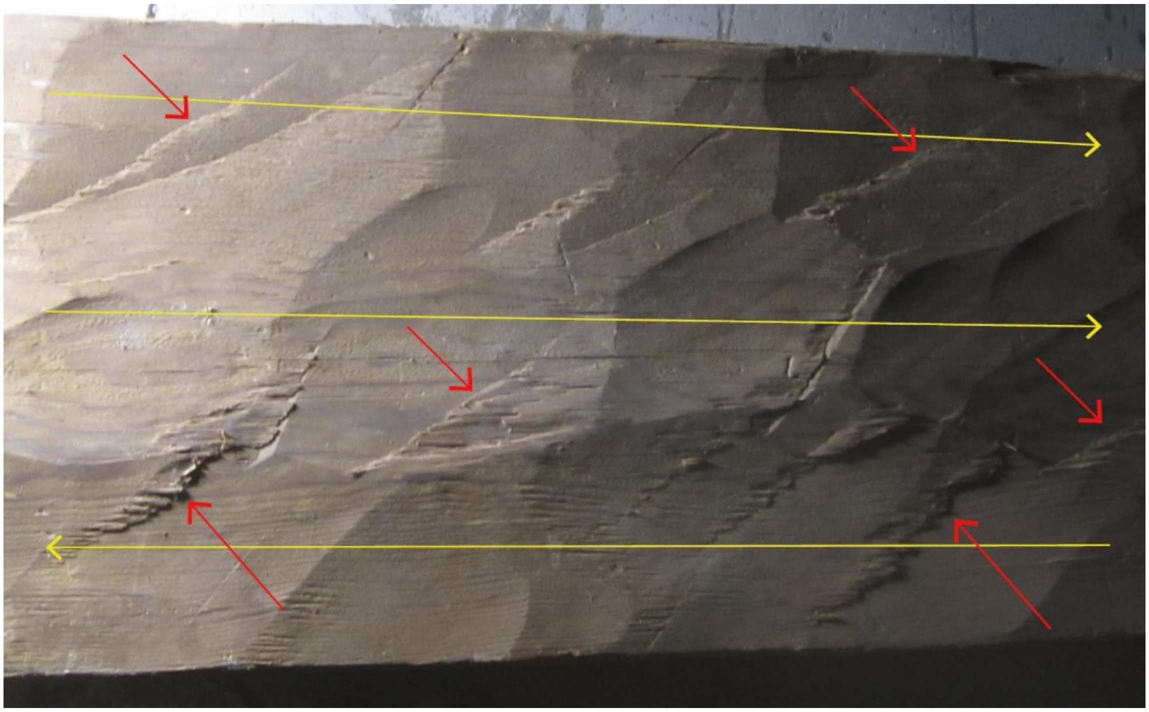

Figure 36. Board with traces of sprätthuggning [Hewing] (Almevik & Melin, 2015)

In figure 36, they read the direction of the edge marks on the timber to discover the first two rows were hewn, the log was flipped 180°, then the third row was hewn. In figure 37, Almevik & Melin (2015) analyze the tool marks and methods for a cleaved board. They signify the marks each time the axe was driven down, with the depth of the interface of the hewing-refinished split grain.

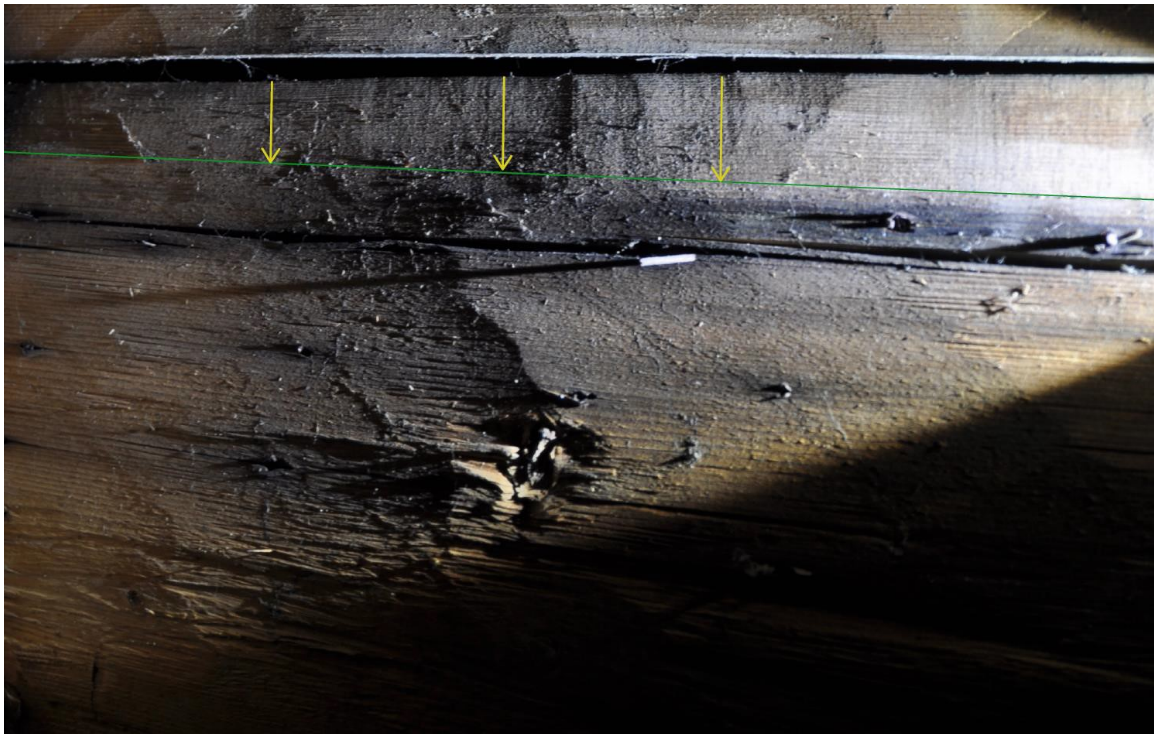

Figure 37. Board with traces of spårning [cleaving] (Almevik & Melin, 2015)

Drdacky et al. (2004) contribute to hewing traceology by analyzing the log hewing heights based on their tool mark angles. The height of the hewing setup typically depends on the size of the log, the situation the log is in—whether in a forest or camp, or the style of hewing axe in use. Their findings conclude that hewing at a low height with the log below the waist, results in the axe edge marks occurring at 20-50° below horizontal. With hewing at a higher height with the log above the waist, the axe edge marks occur at 10-40° above horizontal. In figure 38, Drdacky et al. (2004) show their recreation of high and low hewing, while in figure 39, they describe the relationship between edge mark angles and their respective splintering angles. The hour hands representing the edge marks and the minute hands represent the splinter mark lines.

Figure 38. Recreation of low hewing and high hewing (Drdacky et al., 2004)

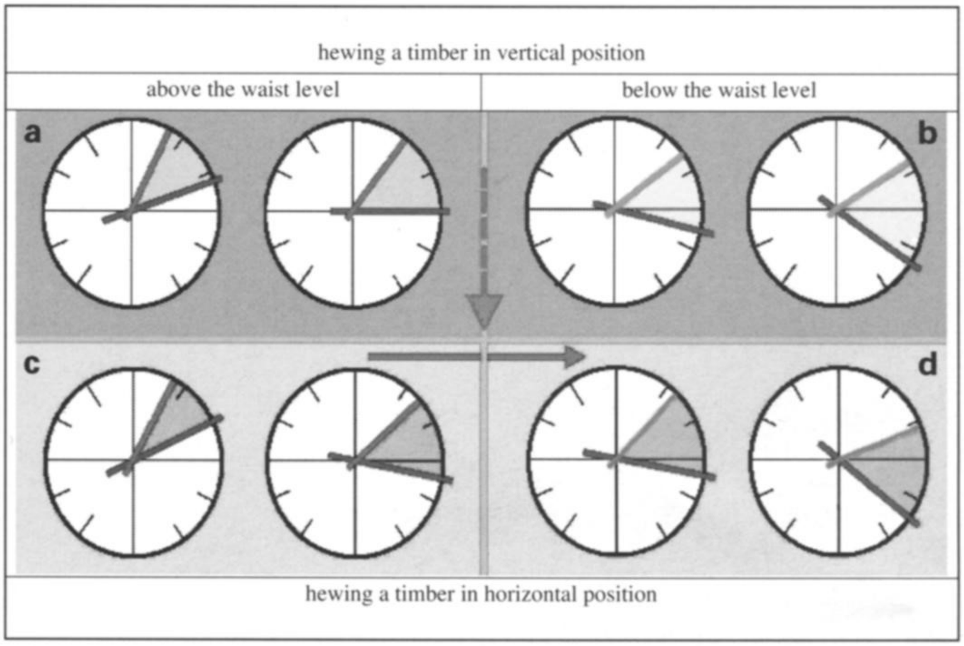

Figure 39. Hewing axe and splinter marks depending on log height (Drdacky et al., 2004)

2.6 Historic Documentation & Metric Survey

Heritage projects are multidisciplinary endeavours, requiring historians, conservators, archaeologists, engineers, craftsmen, and architects. Each of these professionals brings their specific ‘filters’ to read and understand the heritage site. The first step in any conservation project is to understand the heritage site; its origins, evolution, contextual association, current use, and management. This can be accomplished through surveys and investigative methods. According to Martin & Wood (2013), there are three broad categories of surveys: historical Survey, morphological survey, and metric survey.

The historical survey aims to understand a site’s history, evolution, and significance via background documentary research, structural archaeology, and specialist investigations. The morphological survey aims to understand the construction, condition, and behaviour of a site via (periodic) condition assessments, structural surveys, environmental/ecological surveys, diagnostic investigations, and material analysis/characterization. The metric survey is the graphic basis for the recording, analysis, and communication of information.

2.6.1 Historical Survey

Background documentary research, structural archaeology, and specialist investigations are typically involved in the historical survey. According to Martin & Wood (2013), background documentary research should be conducted before any onsite investigative work. This research aims to learn about the site’s history by gathering relevant existing data which is ideally in the form of a designation document; however, they do not always exist. Historical information can otherwise be gathered from multiple sources. Historic maps and toponomy—the geography of places and past land use—can be valuable resources. Additional information can be deduced from photographs, drawings, paintings, construction manuals, and the local planning authorities’ record of past interventions. Building owners and/or custodians can provide insight with their oral history, record drawings, specifications, estimates, accounts, contract documents, maintenance logbook, and/or record archives. The relevant data may be scattered and elusive with gaps and contradictions, but it can still inform conservation decisions. Gaps in the documentation can be filled in later in the project as new information may be revealed. This is a time and labour-intensive process and so it is often under-resourced or skipped entirely Martin & Wood (2013).

"Documentary records seldom provide information about how a building was put together: construction details were usually left to the craftsman to resolve and even where working drawings exist, the building fabric may tell a different story." (Martin & Wood, 2013, p. 159) In the structural archaeological survey, the structure or fabric is closely studied as a primary resource to reveal historical and evolutionary information; specifically, information on the building assembly. Some constructions are simple and standardized, and therefore, easy to read. Other structural assemblies are more complex with many additions to the building fabric which require a more in-depth investigation from a diverse team of professionals. Survey the structural archaeology usually should start with a visual surface analysis, aiming to determine characterization, description of uses, plan form, layout, construction, development, and alterations. Once a visual survey is complete, then gaps in knowledge can be filled with further existing documentation and (semi)destructive building analysis; disassembling specific areas of the fabric. Dendrochronology is another supporting investigation that dates timber or wood based on the patterns of their growth rings. Other supporting investigations may include radiocarbon dating, thermoluminescent dating, mortar stratigraphy, paint stratigraphy, and wallpaper stratigraphy.

2.6.2 Metric Survey

The metric survey serves as an aid to understanding, managing, maintaining, and recording of sites; it is the platform that is built upon by every team in the project. The metric survey must balance precision, time, cost, technical factors, and intended survey use. The creation of line drawings from the survey allows for the understanding of special relationships of the site and archaeological evidence.

Martin & Wood (2013) divides metric survey techniques into two categories: direct survey techniques and indirect survey techniques. Direct surveys include total station, GPS, and hand techniques; techniques calling on the surveyors' skills and observational abilities. These pin-point techniques are rapid and driven by information selection; therefore, requiring minimal post-processing. The nature of direct techniques makes them application rigid and domain-specific. Indirect techniques on the other hand are non-selective, and capture extensively, with less surveyor interpretation. They are quick to capture large amounts of data, requiring more postprocessing time. Indirect survey techniques include rectified photography, photogrammetry, orthophotography, and laser scanning.

INDIRECT METRIC SURVEY TECHNIQUES					
TYPE		USES	SCALE	RANGE	REQUIREMENTS
RECTIFIED PHOTOGRAPHY					
2D	SCALED IMAGES	Condition recording and assessment Works scheduling	1:20 to 1:50	2m to 50m	Metric or non-metric camera Precise control data or scaling information Rectification software
PHOTOGRAMMETRY					
3D	STEREO PAIRS	Recording Condition monitoring	1:20 to 1:200	2m to 100m	Calibrated camera Scaling or precise 3D control data
	LINE DRAWINGS, CAD	Architectural 'stone by stone' drawings Topographic surveys Condition recording Works Scheduling	1:20 to 1:200	2m to 100m	Photogrammetric plotting machine/software: analytical or digital
	ORTHOPHOTOS	Conservation plans Landscape survey Condition recording Condition assessment Works scheduling	1:20 to 1:200	2m to 100m	Operator experienced in stereo-viewing and image interpretation
	DIGITAL ELEVATION MODELS (DEM)	Condition monitoring Surface and 3D modelling Reverse engineering Visualisations	1:5 to 1:50	2m to 100m	Image processing CAD and 3D-modelling software
LASER SCANNING					
3D	TERRESTRIAL SCANNER Point clouds, meshed surface models	Surface and 3D modelling Record drawings Visualisations Reverse engineering	1:20 to 1:100	5m to 500 m	Scanner Post-processing software 3D-modelling software
	CLOSE-RANGE 'ARTEFACT' SCANNER Point clouds, meshed surface models	Condition monitoring	Actual size to 1:10	0m to 5m	Scanner Post-processing software 3D-modelling software

Figure 40. Comparison of indirect metric survey techniques (Martin & Wood 2013)

DIRECT METRIC SURVEY TECHNIQUES					
TYPE		USES	SCALE	RANGE	REQUIREMENTS
DRAWING					
2D	SKETCHES	Diagnostics	1:20 to 1:50	0m to 30m	Trained draftsman CAD skills
	MEASURED DRAWINGS	Plans Sections Elevations	1:20 to 1:50	0m to 30m	Trained draftsman CAD skills
TOTAL STATION/REDM					
3D	POINT DATA	Terrain models	1:50	5m to 100m	EDM set CAD unit CAD skills
	WIRE-FRAME CAD DRAWINGS	Plans Sections Elevations	1:50	5m to 100m	EDM set CAD unit CAD skills
	CONTROL DATA	Monitoring Metric data integration	1:20 to 1:500	5m to 100m	EDM set Specialist survey skills
GPS					
	POINT DATA	Terrain models	1:100	20m to 500m	GPS set Specialist survey skills Open sky Height precision
	WIRE-FRAME CAD DRAWINGS	Control data Site plans Landscape survey	1:100	20m to 500m	GPS set Specialist survey skills Open sky Height precision

Figure 41. Comparison of direct metric survey techniques (Martin & Wood 2013)

In figures 40 and 41, Martin & Wood (2013) summarize the nature of indirect and direct survey techniques including their typical applications, useful scale, reliable range, and technical requirements. This comparisons can help determine which documentation technique is most suitable to the conservation project at hand.

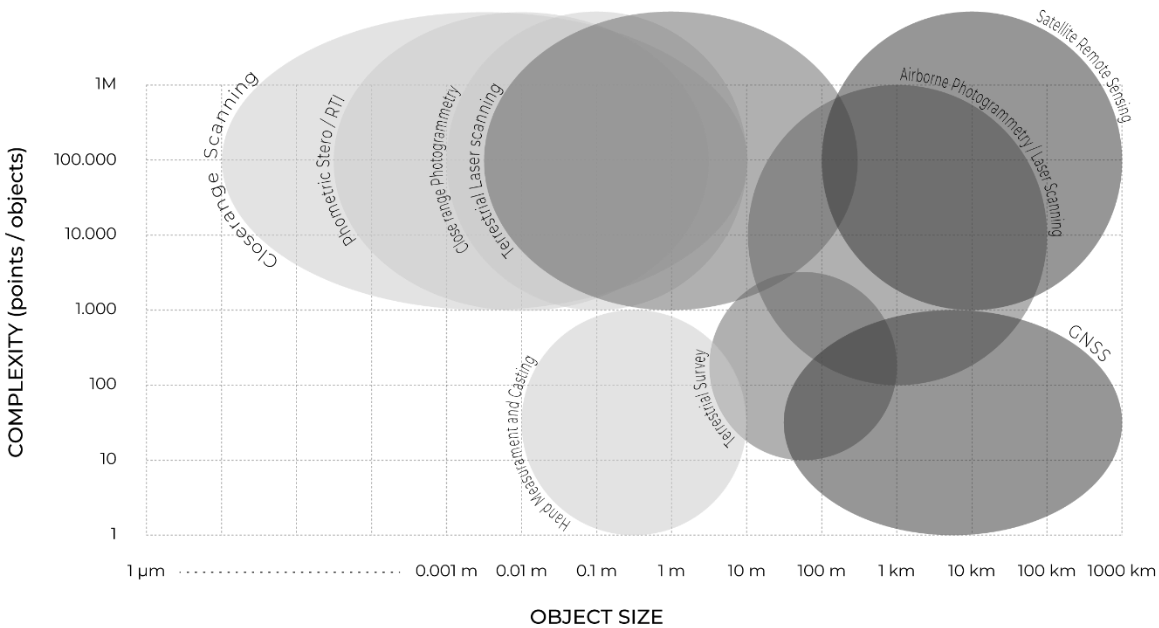

Figure 42. Suitable surveying methods considering object size and object complexity (Boehler & Heinz 1999) adapted by Miquel Reina Ortiz.

Figure 42 expands on the suitability of each surveying technique by visualizing the relationship between object size (to be surveyed) and object complexity. This figure is adapted by many heritage documentation researchers; Miquel Reina Ortiz expanded the diagram to include close-range techniques including, close-range laser scanning, photometric stereo, RTI, and close-range photogrammetry. Photometric stereo and RTI are both emerging image-based scanning techniques that are not considered by Martin & Wood (2013). These scanning techniques require a DSLR camera, a light source, and software; they are used to record surface details on cultural heritage artefacts.

2.6.3 Photogrammetry

The invention of photogrammetry is credited to two people: Aime Laussedat and Albrecht Meydenbauer; however, Meydenbauer coined the term "photogrammetrie"—measurements by photographic images. In 1851, Aime Laussedat created a method to generate topographic maps from aerial photography. Subsequently, Albrecht Meydenbauer further refined the techniques for the application of building surveys (Burtch, 2005). A near-death experience triggered him to search for a safer way of conducting metric surveys. In 1858, Meydenbauer was surveying the Cathedral of Wetzlar; he almost fell to his death from the side-aisle of the cathedral. This incident motivated him to find a better method of measuring buildings using indirect measurements in photographs; thus, architectural photogrammetry was born.

The French Cathedral in Berlin was among the many buildings sustaining heavy damage in World War II; fortunately, Meydenbauer had surveyed the cathedral in 1882. Between 1977 and 1982 his photogrammetric evidence was to reconstruct the French Cathedral in Berlin. Between 1885 and 1920, The Royal Prussian Photogrammetric Institute with Meydenbauer recorded about 2,600 cultural objects totalling about 20,000 photogrammetric images (Albertz, 2007).

Since Meydenbauer, the technology of photogrammetry underwent several evolutionary cycles: plane table photogrammetry (1850-1900), analogue photogrammetry (1900-1960), analytical photogrammetry (1960-present), and presently digital photogrammetry (Burtch, 2005). Several digital photogrammetry software are freely and commercially available. The most popular commercial software includes Agisoft PhotoScan (now Agisoft Metashape), Pix4D mapper, 3DF Zephyr, and RealityCapture. For digital cultural heritage, PhotoScan is the most popular, due to its reliability and reproducibility in digital reconstructions. Compared to its competitor, RealityCapture by Capturing Reality, PhotoScan is much slower to process; however, PhotoScan has lower manual processing times, greater user control, and the ability to process models in separate chunks. Processing photogrammetry in chunks is key in allowing the user to capture the underside of an object by flipping it (causes a change in the photogrammetric environment) (Kingsland, 2019).

2.6.4 Photogrammetry Metrics

When planning or analysing a photogrammetric reconstruction we can estimate the resolution using a ground sample distance (GSD) calculation. GSD is a term originating from aerial surveying and so 'ground' in GSD refers to the measured surface. GSD—in equation 2.1—relates the surface measurement resolution with the camera pixel size, ps, the camera-to-surface distance, D, and the camera lens focal length, f (Stylianidis et al., 2016).

$$\frac{GSD}{ps} = \frac{D}{f} \tag{2.1}$$

Figure 43 illustrates the relationship of the camera parameters to the surface resolution. This relationship can be used in planning a photogrammetric acquisition by specifying a required GSD, obtaining your cameras pixel size, intuiting a focal length (zoom), then calculating the resulting camera-to-surface distance. If the resulting distance is too close or too far—typically due to physical space or camera constraints—each of the other factors can be adjusted to fit the distance and GSD requirements. Stylianidis et al. (2016) give a practical rule of thumb for specifying a desired GSD: "The GSD should be at least 2–3 times smaller than the smallest geometric detail to be captured and digitised as the smallest image element (pixel) is normally not sufficient to reconstruct entirely and correctly an object's detail." (p. 268). Conversely, we can estimate the GSD of a given dataset, if we know its pixel size, the camera-to-surface distance, and the focal length.

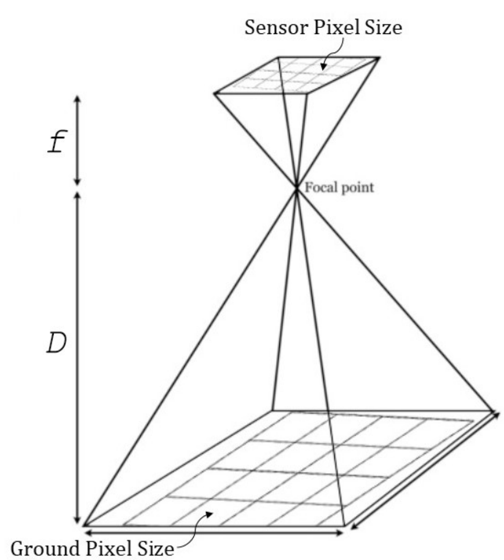

Figure 43. Ground sample (pixel) distance diagram (Humboldt, 2017)

PhotoScan calculates and error for each scale bar, this error would be based on the difference between the calculated distance between points and the input distance between the points. Since the length scale bar applied and the width scale bar is left unapplied, we can use it as a measure for a photogrammetric reconstruction accuracy. If both scale bars were applied, then the error would bias towards the width scale bar; the width error would decrease but the length error would increase. The width scale bar is ideal for an error check because it is perpendicular to the length scale bar and it is a shorter measurement. Longer measurements are better for scaling since it minimizes the amplification of human error. Having a perpendicular error check is important since it accounts for multiple dimensions of accuracy. An example of the resulting scale error is shown in figure 44.

Scale Bars	Distance (m)	Error (m)
point 1_point 2	3.378200	-0.000000
point 3_point 4	0.428625	-0.000767
Total Error		
Control scale bars		0.000000
Check scale bars		0.000767

Figure 44. Scale bar error check for the hewn log photogrammetry

2.6.5 Photogrammetry Algorithms (PhotoScan)

Naturally, commercial photogrammetry software is proprietary, and therefore, typically regarded as ‘black box’. Most research in commercial photogrammetry for cultural heritage focuses on evaluating the input data, user settings, and output data. Agisoft has released a broad overview of PhotoScan’s algorithms used in their digital photogrammetric pipeline, allowing for a greater understanding of the inner workings. These inner algorithms are also reflected in PhotoScan’s user interface (UI); a user can customize settings in each of the major algorithmic steps:

1. Align Photos (Tie Points)
2. Build Dense Cloud
3. Build Mesh
4. Build Texture

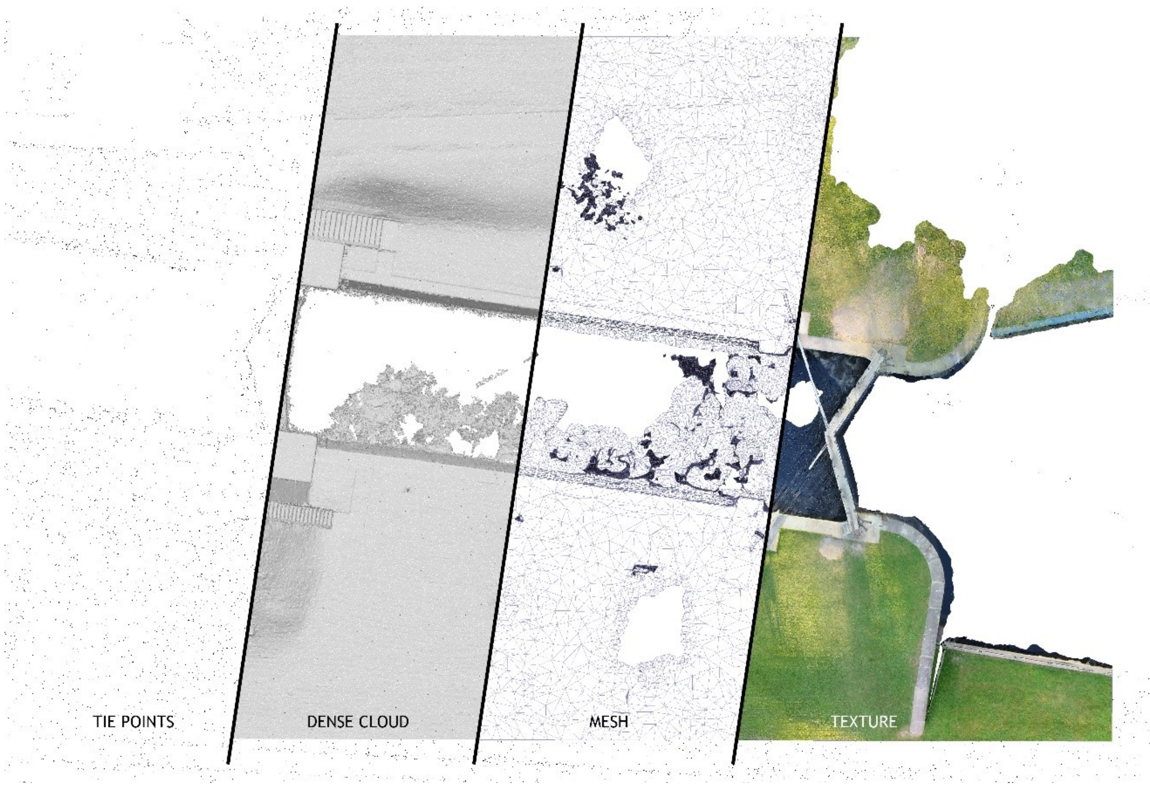

Figure 45. PhotoScan’s UI photogrammetric process

2.6.5.1 *Image Feature Matching*

In order to align photos, PhotoScan photogrammetry generates and matches features across the input set of photos. PhotoScan detects these features that are stable under viewpoint and lighting variations, then generates a descriptor based on the point's local neighbourhood of pixels for each image. The generated descriptors are then used for detecting correspondences within the image set; this image feature matching step is the first part of PhotoScan's The PhotoScan process of matching image features is similar to the computer vision algorithm known as the scale-invariant feature transform (SIFT) approach (Semyonov, 2011).

According to Lowe (2004), the SIFT algorithm can be completed in four major steps. The first step of SIFT is a scale-space extrema detection, which is a type of scale-space filtering—filtering in the sense of a pixel-wise neighbourhood computation of an image. Scale-space filtering using can be achieved with a Laplacian of Gaussian (LoG) filter that acts as a sort of blob detection. The Laplacian filter of an image will render high contrast areas like points or edges; however, it is susceptible to image noise. The LoG filter will first smooth the image—reducing the noise—using a Gaussian (G) filter:

$$G(x,y,\sigma) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \qquad 2.1$$

Where x,y are the horizontal and vertical components of the image, respectively, and σ is the standard deviation.

Unfortunately, the LoG filter is a costly computation; however, the filter can be approximated using a difference of Gaussian (DoG) filter with a scaled (k) standard deviation values (σ) at a coordinate x, y.

$$DoG(x, y, \sigma) = G(x, y, k\sigma) - G(x, y, \sigma) \tag{2.2}$$

DoG operations are completed in a series of images with an increasing scale k; the series of operations is called an octave. Once an octave is complete, the image is downsampled by a factor of 2, and the process is repeated over the next octave. This successive Gaussian filtering and octave scaling is also known as a Gaussian pyramid. Each completed octave, the Gaussian images from the top of the octave stack are resampled. The sampled points are then compared to eight of its neighbouring pixels and nine of its neighbouring pixels from the images above and below in its octave (figure 46). If any of the neighbouring pixels are a greater value, then the sample point is discarded. This accomplishes the search for local extrema—or potential keypoints—across scale and space (Lowe, 2004).

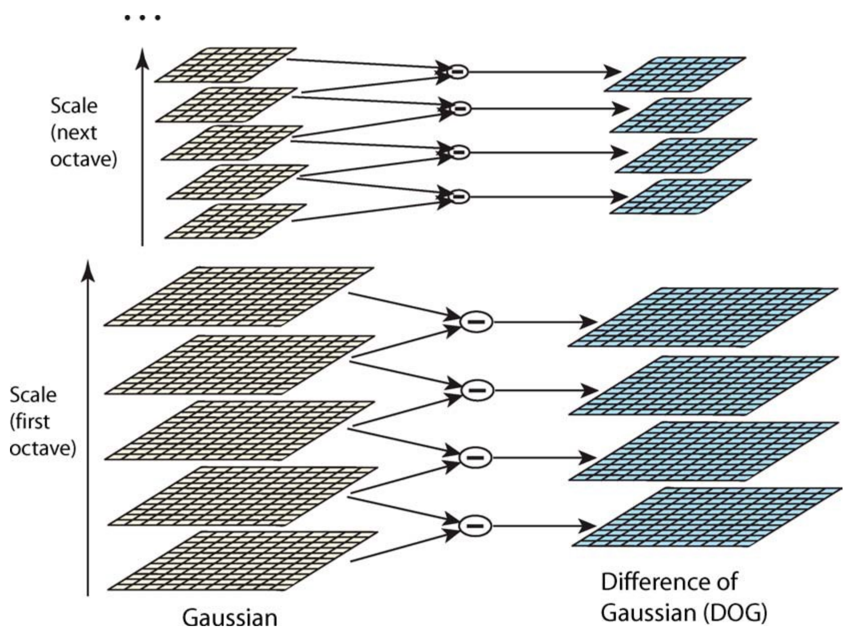

Figure 46. Series of DoG operations with scaling image size and standard deviation (Lowe, 2004)

The second step in SIFT is the keypoint localization in which the set of potential key points are refined. This starts with a Taylor expansion of scale-space that yields a more accurate location of extrema while discarding keypoints if their intensity is below a threshold. The next part of the keypoint localization deals with the high occurrence of potential keypoints along edges caused by the DoG filtering. We can remove these poor key points by considering their principle curvature; key points from edges have a large principal curvature in the edge direction but a small principal curvature in the perpendicular direction. Lowe (2004) uses a 2 x 2 Hessian matrix to compute the principal curvature of each key point. Since the Hessian matrix eigenvalues are proportional to the principal curvatures of the keypoint, a threshold of the principal curvatures’ ratio can eliminate the edge keypoints.

The third step of SIFT is the orientation assignment, where each keypoint is assigned an orientation to account for rotation between images. The orientation is prepared by creating a keypoint neighbourhood histogram; which contains 36 bins, covering 360° of possible orientations. Neighbourhood samples are weighted by gradient magnitude and gaussian-weighted circular window with σ equal to 1.5 times the scale of keypoint. Then each weighted sample is added to the histogram. Only the highest 80% of histogram peaks are taken for each keypoint orientation calculation. A parabola is used to fit a curve to the 3 histogram values closest to each peak; this allows for the interpolation of a more accurate peak location (Lowe, 2004).

These previously calculated keypoint locations, scales, and orientations are used to create keypoint descriptors—the fourth step in the SIFT algorithm. Another neighbourhood of 16 x 16 is created around each keypoint; within the neighbourhood, 16 4x4 sub-blocks are isolated, each with an 8 bin orientation histogram. The descriptors are first generated by calculating the gradient magnitude and orientation for each neighbourhood location, then they are weighted by a Gaussian window with σ equal to one half the width of the descriptor window. This neighbourhood smoothing is to avoid sudden changes in the descriptor while removing the effects of large, but distant gradients. The smoothed keypoint image gradients are then amalgamated in their respective 4 x 4 histograms of 8 orientation bins. Each keypoint descriptor culminates in a 4 x 4 x 8 = 128 element feature vector; figure 47 illustrates a scaled-down version of this process (Lowe, 2004).

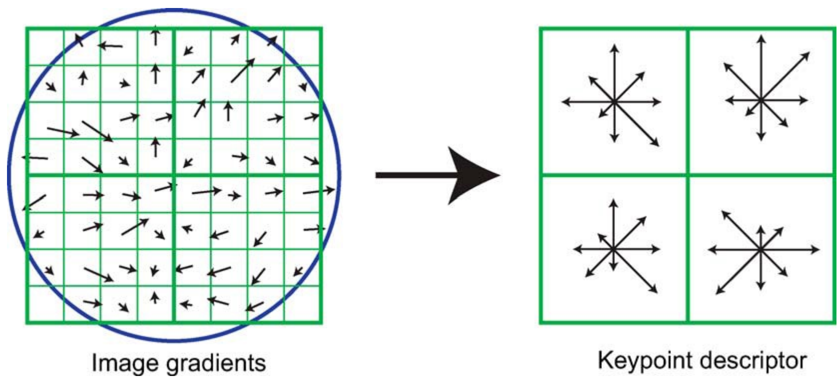

Figure 47. Keypoint descriptor generation representation with 8 x 8 neighbourhood and 2 x 2 descriptor array (Lowe, 2004)

The SIFT algorithm is completed with the computed keypoint descriptors; however, the keypoints still need to be matched across a set of images to achieve a camera alignment. The nearest neighbours—keypoint descriptor vectors with the minimum Euclidean distance—are identified for keypoint matching. For error minimization, the ratio of the first and second closest neighbourhood distances are considered; they are rejected if their ratio is over 0.8 (Lowe, 2004).

PhotoScan completes this matching process over the entire image set but will down sample the images based on the user input accuracy settings. A pair preselection option in PhotoScan's alignment settings also allows for a low-resolution realignment before the main higher resolution camera alignment. This can offer a faster alignment since the matches do not have to be completed over the entire set of high-resolution images.

2.6.5.2 *Solving Camera Orientation Parameters*

After the image matching step, the intrinsic and extrinsic camera orientation parameters are solved. PhotoScan solves these orientation parameters in two steps. Initially, a greedy algorithm is used to find camera parameters quickly, but roughly—for each image. Finally, a bundle adjustment is used to refine the camera parameters (figure 48)(Semyonov, 2011).

Before digital photogrammetry, metric cameras with known internal orientation parameters were used with the bundle adjustment. This bundle adjustment uses input control points, matched tie points, and the interior orientation parameters in order to solve for all the tie point coordinates and therefore each camera's exterior orientation parameters (Stylianidis et al., 2016).

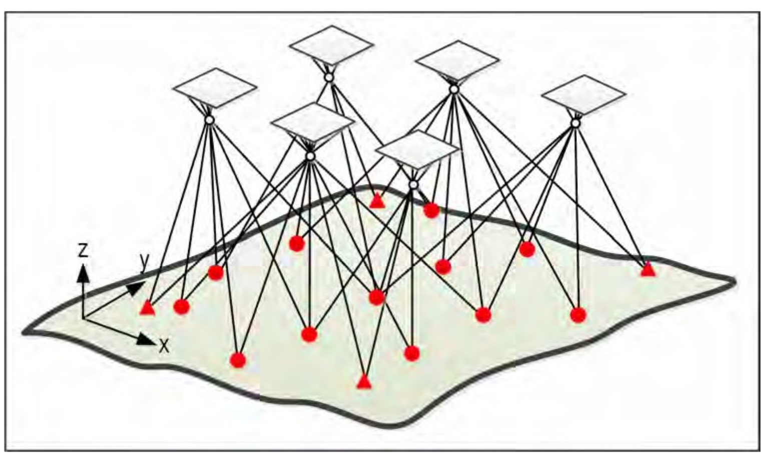

Figure 48. Bundle adjustment (Stylianidis et al., 2016)

With consumer cameras—lacking pre-calibrated internal orientation parameters—structure from motion (SfM) photogrammetry software, like PhotoScan, is used to simultaneously solve the external and internal camera orientation parameters. This is the self-calibrating bundle adjustment (Stylianidis et al., 2016).

Once the camera orientation parameters are solved, the PhotoScan Align Photos step is completed; the resulting alignment is represented by a sparse point cloud of 3D matched points (Agisoft, 2018).

2.6.5.3 Dense Surface Reconstruction

Before PhotoScan 1.0, the *Build Dense Cloud* and *Build Mesh* steps were not separate steps; they were conjoined as the *Build Geometry* step. Several *Build Geometry* user options were available: *Arbitrary-Smooth*, *Arbitrary-Sharp*, *Height Field-Smooth*, and *Height Field-Sharp* methods (Agisoft, 2012). Each of these methods of building mesh geometry is based on pair-wise depth map computation. PhotoScan also has a *Fast* method of building geometry straight from the alignment sparse point cloud; this method is based on a multiview approach (Semyonov, 2011).

The pair-wise (stereo-pairs) and multiview stereo computations are both examples of dense image matching (DIM) operations that generate a dense set of image correspondences. DIM processes produce depth maps—digital images with pixel values corresponding to depth values. Depth maps can be projected into a point cloud with the camera calibration parameters obtained from the camera alignment. Stereo imagery is based on the parallax theory of a stereo pair; parallax being the visual displacement of objects produced from the shift between a stereo pair. Parallax, as shown in figure 49, has two components P_x and P_y. P_x is directly proportional to the distance, *D*; with a greater *D*, a greater P_x is required to maintain a certain parallax. P_y should be minimized or else it can reduce the relative parallax in the stereo pair (Stylianidis, Georgopoulos, & Remondino, 2016).

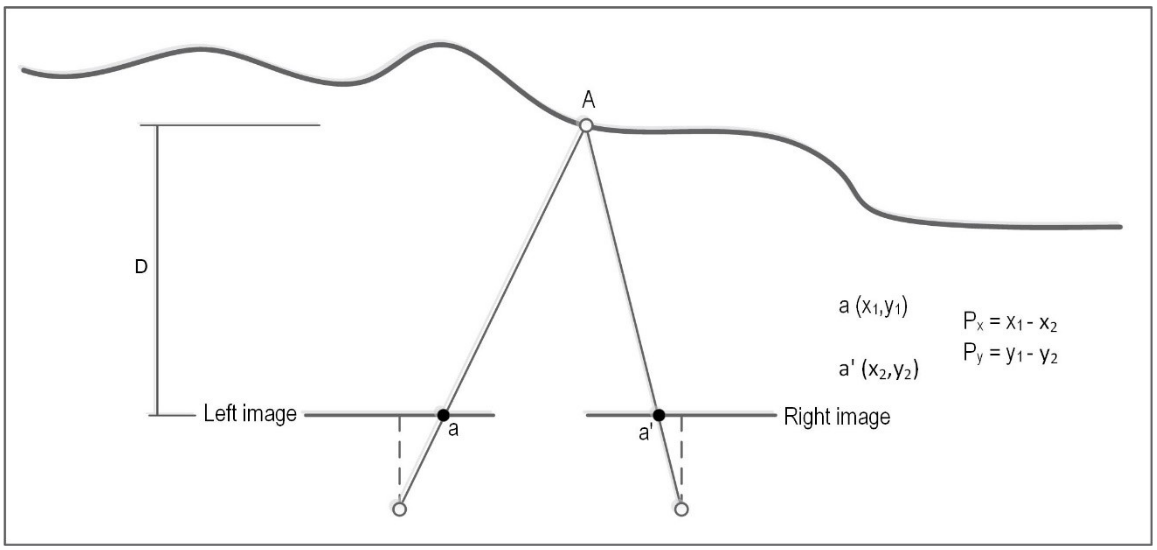

Figure 49. Stereo parallax in an image pair (Stylianidis et al., 2016)

3D points in the stereo pairs can be determined by searching corresponding points along their epipolar lines; then, by intersecting the matched pairs of 3D rays. Photogrammetric projection parameters allow for the generation of each 3D point based on their matched 3D rays (Stylianidis et al., 2016).

A digital elevation map (DEM) or mesh can also be generated from the DIM process. Since PhotoScan 1.0 and after has separated the *Build Dense Cloud* and *Build Mesh* step, it is likely that PhotoScan (1.0 and after) triangulates the point cloud to generate a mesh. For mesh generation, Delaunay triangulation is one of the most popular techniques; it's more of a condition yielding a specific type of triangulation. De Berg et al. (2013) proves and defines the Delaunay triangulation theorem: "Let *P* be a set of points in the plane. Any angle-optimal triangulation of *P* is a Delaunay triangulation of *P*. Furthermore, any Delaunay triangulation of *P* maximizes the minimum angle overall triangulation of *P*."

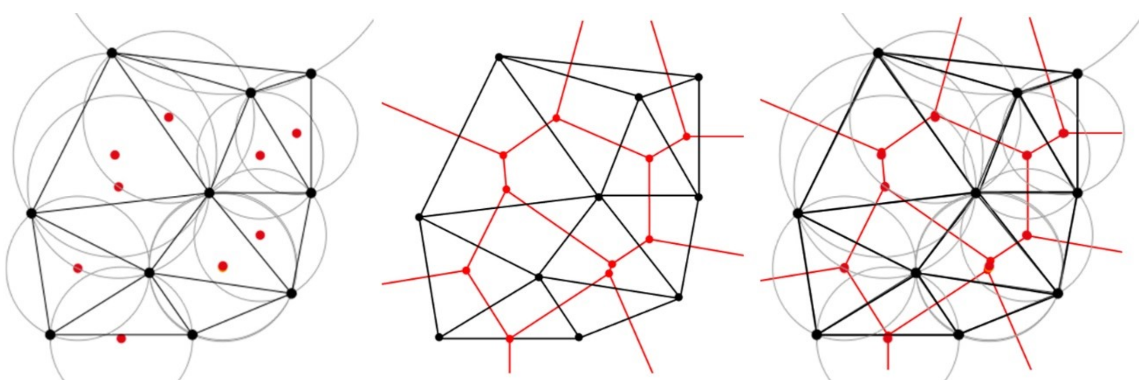

Figure 50. Delaunay triangulation with circumcircles (left), resulting Voronoi diagram (centre), and Delaunay triangulation with Voronoi diagram superimposed Voronoi (right)(Nü es, 2011)

One way to achieve this is by generating a Voronoi diagram from the point set; the Voronoi diagram is dual to the Delaunay Graph Figure 50 illustrates this relationship. The Delaunay triangulation—or mesh—can be obtained from the Delaunay Graph by triangulating the faces with more than three vertices (de Berg et al., 2013).

2.6.5.4 *Texture Mapping*

Once a mesh is generated, PhotoScan parameterizes the mesh—typically piecewise—by mapping the mesh surface to a 2D image (Semyonov, 2011). Mapping a triangle of vertices [(x_i, y_i, z_i), (x_j, y_j, z_j), (x_k, y_k, z_k)] in 3D space to the triangle of vertices [(u_i, v_i), (u_j, v_j), (u_k, v_k)] in 2D space (parameter space) can be given by the equation:

$$\mathbf{x}(u,v) = \alpha\mathbf{p}_i + \beta\mathbf{p}_j + \gamma\mathbf{p}_k \qquad 2.3$$

Where (i, j, k) indexes the triangle vertices, and (α, β, γ) denote the barycentric coordinates at point (u, v). In order to parameterize an entire triangulated mesh surface, the set of coordinates (u, v) in parameter space must be determined for each vertex in 3D space. The most common method of mesh parameterization is Barycentric mapping, which is based on Tutte’s barycentric mapping theorem from graph theory:

> *Given a triangulated surface homeomorphic to a disk, if the (u, v) coordinates at the boundary vertices lie on a convex polygon, and if the coordinates of the internal vertices are a convex combination of their neighbors, then the (u, v) coordinates form a valid parameterization (without self-intersections) (Botsch, 2011, p. 67)*

The second condition of this theorem is represented in the following equation:

$$\forall_i \in \{1, \dots, n_{in}\}: -a_{i,i}\begin{pmatrix} u_i \\ v_i \end{pmatrix} = \sum_{j \neq 1} a_{i,j}\begin{pmatrix} u_j \\ v_j \end{pmatrix} \qquad 2.4$$

$$\begin{cases} a_{i,j} > 0, & \text{if } i \text{ and } j \text{ are connected by an edge} \\ a_{i,i} = \sum_{j \neq 1} a_{i,j} & \\ a_{i,j} = 0, & otherwise \end{cases}$$

where $\forall_i \in \{1, \dots, n_{in}\}$ are the interior mesh vertex indices, $\forall_i \in \{n_{in} + 1, \dots, n\}$ are the interior mesh vertex indices, and coefficients $a_{i,j}$ are such that $\forall_i \in \{1, \dots, n\}$. Using Floater's method—constructing the parameterization—fixes the mesh boundary vertices to a convex polygon—illustrated in figure 51.

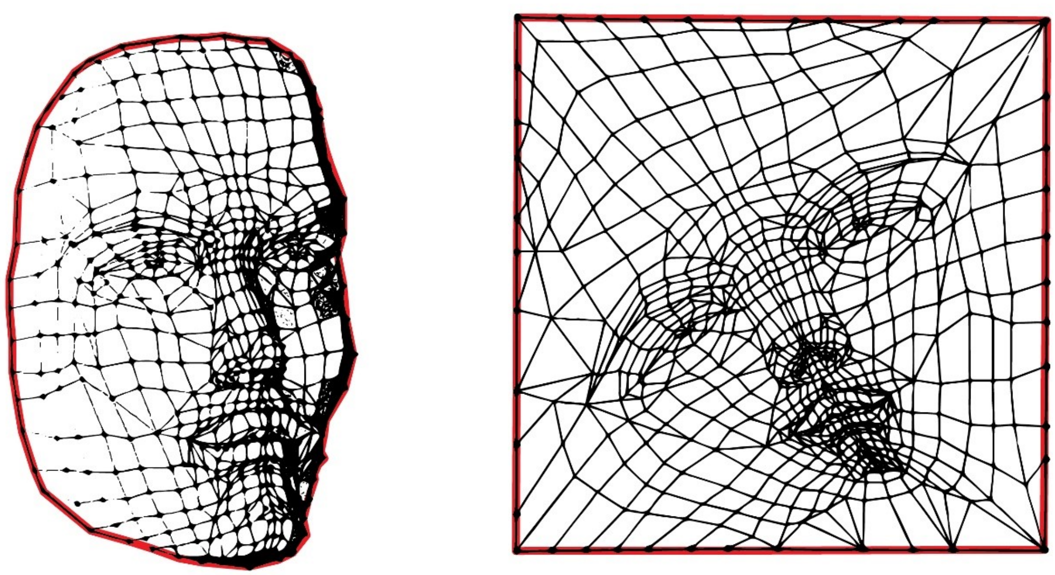

Figure 51. Parameterization with Floater's method of Tutte Embedding (Botsch, 2011)

Internal vertices are determined by solving two linear systems:

$$\begin{aligned} Au &= \bar{u} \\ Av &= \bar{v} \end{aligned} \qquad 2.5$$

where A is a matrix of weights, $a_{i,j}$, from equation 2.4, vectors u and v are coordinates of internal vertices and vectors $\bar{u}$ and $\bar{v}$ are weighted boundary vertex coordinates generated by:

$$\forall_{\mathrm{i}} \in \{1, \ldots, \mathrm{n_{in}}\}: \begin{cases} \sum_{j=1}^{\mathrm{n_{in}}} a_{i,j} u_j = \bar{u}_i = -\sum_{j=\mathrm{n_{in}}+1}^{n} a_{i,j} u_j \\ \sum_{j=1}^{\mathrm{n_{in}}} a_{i,j} v_j = \bar{v}_i = -\sum_{j=\mathrm{n_{in}}+1}^{n} a_{i,j} v_j \end{cases} \qquad 2.6$$

This parameterization process can also be modified for different purposes: uniform mapping (uniform Laplacian), geometric adaptation (Laplace-Beltrami), and one-to-one mapping (mean value) (Botsch, 2011).

Following the (typically piece-wise) mesh parameterization, PhotoScan blends the original input images into the texture atlas that corresponds to the mesh surface (Semyonov, 2011).

2.6.6 Photometric Stereo and RTI

Photometric stereo is an imaging technique—similar to photogrammetry—for scanning object surfaces. This ‘shape from shade’ technique that was introduced by Woodham (1980), reconstructs geometry based on its surface reflectance. Instead of taking multiple overlapping photos by moving the camera [like in photogrammetry], photometric stereo uses multiple photos taken from the same position while raking light. Through the highlights and shadows created from the raking lighting, the surface orientation (surface normal) can be determined at each pixel.

In the heritage conservation field, reflectance transformation imaging (RTI) is a well-known version of photometric stereo. RTI also requires an image set with constant camera location and variable raking lighting; however, the aim of RTI is optimized relighting, whereas the goal of photometric stereo is accurate normals and metric surface reconstruction (Dhanda, 2019). RTI is both a photometric stereo acquisition technique and a dynamic relighting visualization tool.

Conservators, historians, and other heritage professionals use RTI to reveal textural details of heritage paintings and surfaces. Reina Ortiz et al. (2019) integrate RTI images, condition assessments, terrestrial photogrammetry, aerial photogrammetry, laser scans, and perspective matched photographs into one 3D database—a building information model (BIM). This project was for the conservation of Buddhist temple wall paintings in Bagan, Myanmar. The RTI images—as shown in figures 52 & 53—can be used to reveal textural details in these wall paintings to inform their conservation techniques.

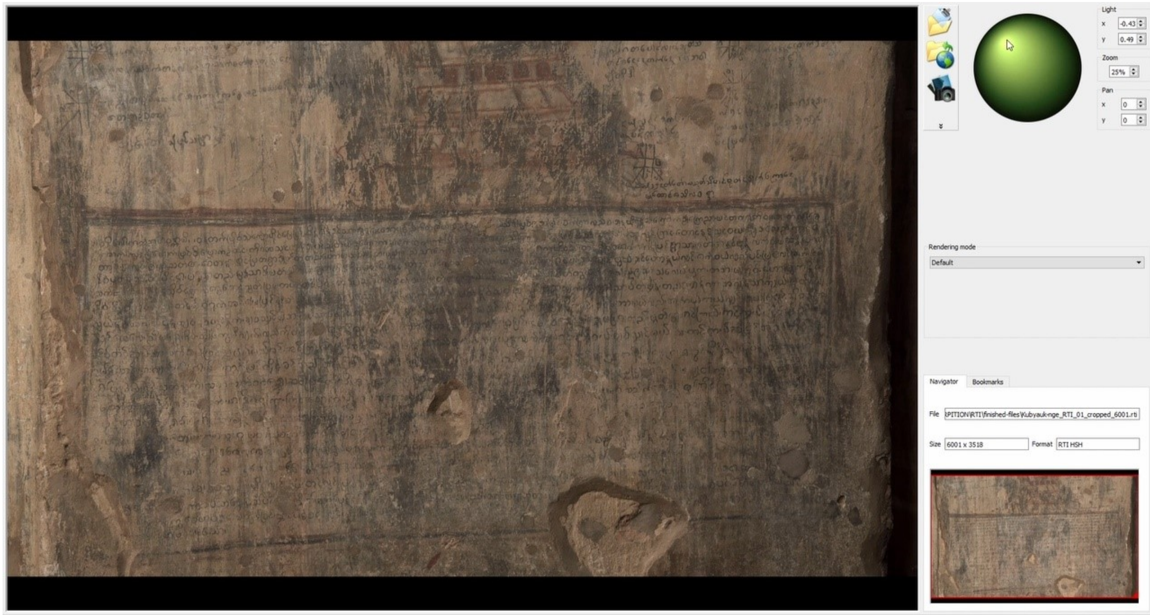

Figure 52. RTI viewer of Burmese temple wall painting—lighting from top left (Reina Ortiz et al., 2019)

Figure 53. RTI viewer of Burmese temple wall painting—lighting from bottom right with specular enhancement (Reina Ortiz et al., 2019)

Recently Dhanda (2019) built a photometric stereo dome rig for *The Geometric Documentation of Painted Surfaces* (figure 54). He combines the high-fidelity surface measurements with the accuracy obtained from photogrammetric imaging. This work is also motivated by analyzing the complex layers of historic surfaces.

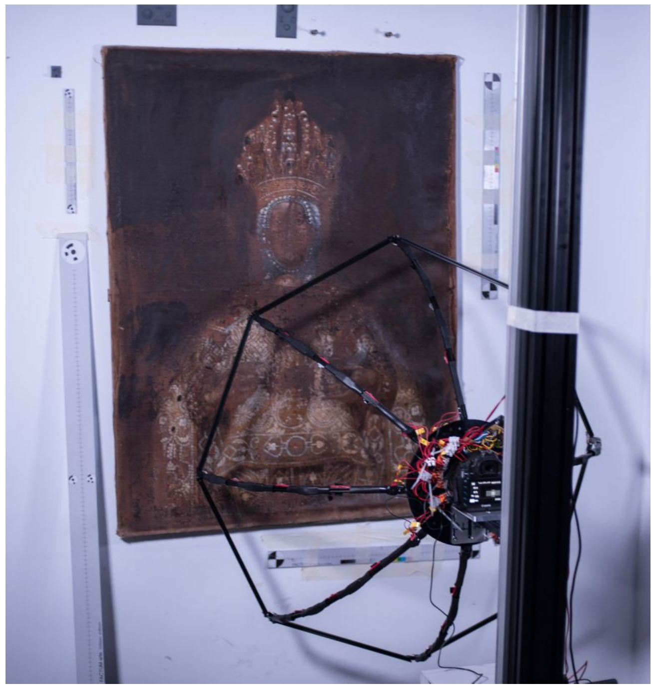

Figure 54. The photometric stereo documentation of the painting of the Virgin Mary © Osama Dawod for the Factum Foundation for Digital Technology in Conservation (Dhanda, 2019)

3 Chapter: PRACTICE

The previous chapter containing the literature review, contains existing research and knowledge that supports this third chapter. Here, I put into practice, the previously described knowledge—with new information—for the conservation of wooden built heritage. Chapter 3.1 describes the case study timber frame, with its history and eventual repair and reconstruction. Early analysis of the timber frame leads to some understanding of its construction; specifically, the timbers were converted by hewing logs. Chapter 3.2 describes the photogrammetric process for documenting the tool marks on timbers, while documenting broad axes that were once used to hew timber. Chapter 3.3 describes experiments that recreate and document timber hewing that allow for further understanding the mechanisms that cause distinctive marks on timbers. Chapter 3.4-3.6 builds on chapter 3.3 by using the timber photogrammetry to augment the process of reading and analyzing the tool marks. By reading the tool marks, hewing tools and techniques can be reconstructed.

3.1 Case: The Red House Timber Frame

The Red House—built in 1816 at 55 Craig Street—is one of the oldest houses in Perth. It was constructed by Lieut. John Adamson and served as a tavern, school, church, public house, masonic lodge, and printing office. A fire damaged the house in the mid-

1900s, and subsequently painted red; however, the red paint only lasted for about 30 years. Ironically, the Red House has been painted white ever since.

Figure 55. The Red House 1907 (Bromley, 2015)

The Red House is a log house; meaning it is constructed with overlapping horizontal logs or timbers. This log house is clad in wood clapboard, painted red, and later painted white (Bromley, 2015). The historic 1907 postcard in figure 55, housed at the Perth Museum, shows The Red House accompanied by another wooden structure to the west. This additional structure is a timber frame. Compared to a log building, a timber frame is constructed of a series of joined timber vertical columns, horizontal beams, sills, and joists, and diagonal rafters. Looking at the images available on *Google Street View* (figure 56), the more recent records show from

2009-2018 The Perth Timber Frame is in an increasing state of disrepair. Additionally, these records show the timber frame significantly shortened.

Figure 56. 1907 Red House (left) (Bromley, 2015) vs 2014 Red House (right) (© Google 2020)

Upon closer inspection of the timber frame, there is other evidence of missing and/or removed timber elements. In the case of the image of figure 57, there are empty joist pockets on the east side of the timber frame—closest to the Red House. The tie beams that run the length of the timber frame, from east to west, are also sawn off on the east side of the timber frame.

Figure 57. The Perth timber frame beam pockets

The Perth Timber Frame was eventually dismantled and donated to the Algonquin College Perth Campus Heritage Institute, as part of their timber frame conservation class. The class was active in the timber frame’s documentation, labelling, disassembly, and repair of deteriorated members.

The hypothesis is that these timbers were converted using the axe-based hewing technique described in chapter 2.4.2 and 2.4.3. Through digital documentation, consultation with craftsmen, and imitative reconstruction—more details can be revealed on the particulars of the employed hewing process.

3.2 Photogrammetry Documentation Workflow

3.2.1 Axe Photogrammetry

The family of the late Dr. Joseph Foohey of Pembroke wanted to honour his interest in local logging history. They donated a large collection of antique tools; specifically, axes; specifically, North American broad axes, to the Algonquin College Heritage Institute. With the support of CIMS, 42 of the broad axes were photoscanned to create digital 3D models; a select few of the broad axes are displayed in figure 58. The photogrammetry of these axes can be publicly viewed on the CIMS page of the Sketchfab website. The techniques developed to rapidly and accurately scan these axes were also used off-site to scan additional broad axes from the Bytown Museum and Corey Pool’s personal broad axes. From these 3D scans, subtle 3D geometries can be compared between the axes and their corresponding marks. Conducting such a study was also an initial familiarization of the types of axes that could have been used to build the Red House Timber Frame.

Figure 58. Photoscans of select Foohey-Algonquin collection broad axes by Sarah St. Cyr and Raphael Mabalot

3.2.1.1 Setup

Scanning axes is a challenging endeavour; for one, they can be razor-sharp, and therefore must be handled with care. You know what they say: "Safety third!" (Rowe, 2020). Additionally, they are objects with simple but awkward geometry, while being heavy and flat. This makes it challenging to capture the entire object with photogrammetry. Photogrammetry of an entire object typically requires at least two image capturing environments—each time the object moves in relation to its surroundings, this can be considered a new environment. Each of these photogrammetric environments is processed separately and combined in a later state. With typical photogrammetry setups there are only two environmental configurations that can—safely—occur with axes, each with one axe cheek facing down.

Several initial photogrammetry configurations were devised to try and get around these difficulties; however, the finalized setup consisted of a fixed camera on a tripod, a bamboo IKEA lazy Susan turntable, and a green screen. The axe was placed—each cheek down—on the turntable while spinning it after every captured image. The photogrammetry 'rig' was fixed with PhotoScan-produced-targets that are automatically detected by the software. These targets were calibrated with a calliper to the 0.0001 m. This setup proved to be efficient and portable, as it could be set up anywhere from a cold war bunker to a farm (figure 59).

Figure 59. Axe photogrammetry at Cumberland Village Museum (left) and the Diefenbunker (right)

After the photogrammetry rig was set up, adjustments were made to the camera's exposure settings; the shutter speed, aperture, and ISO. Typically the ISO was set as low as possible—around 100—to minimize noise, then the aperture was set around f-8 or f-9 to balance sharpness and depth of field, finally, the shutter speed was adjusted to obtain adequate exposure. In some cases with low lighting conditions, external lights, or strobe/flashes were used to increase scene exposure. File types were always set to record in the camera's native RAW format; .NEF for Nikon and .CR2 for Canon (instead of JPEG). Once the exposure was set, a colour correction image was taken by photographing the scene with a colour profile checker card.

3.2.1.2 Image Acquisition

Image acquisition was completed using a remote to trigger the camera's shutter—after each image capture, the turntable was manually rotated, while being careful not to move the axe in relation to the turntable and its calibrated targets. The manual rotations were by an intuitively approximated angle while ensuring a 60-80% overlap between images. Once a full turntable 360° rotation was complete, the camera was raised or lowered in relation to the axe while keeping the same distance. The manual rotation imaging process was repeated for each camera height; this would create a dome-like network of images around the axe (figure 60).

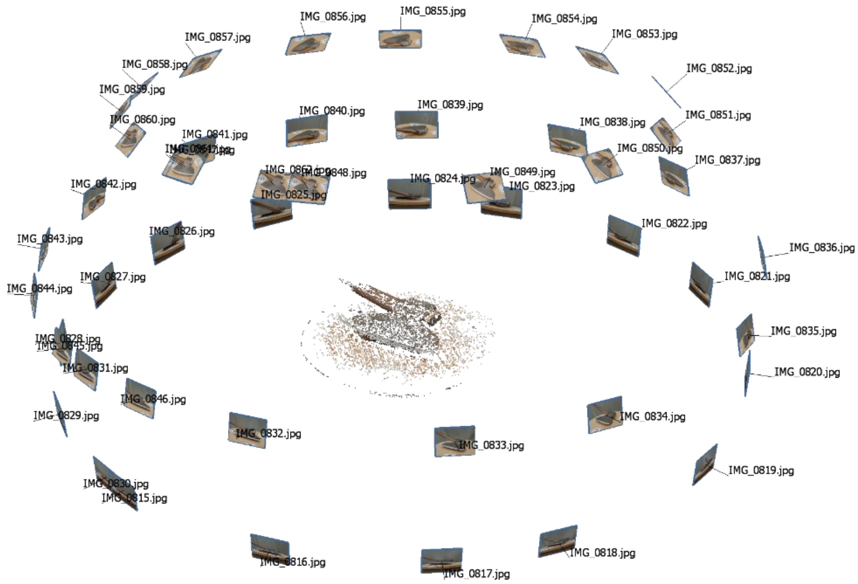

Figure 60. Photogrammetric network of one side of an axe head

Since the geometry of the axe heads were of specific interest, the initial two acquisition batches—one for each axe side—were framed to focus on the heads and not the handles. In order to include the handles, two more batches were completed where the entire axe in within the camera frame. These four batches are illustrated by the four camera-axe orientations in figure 61. Usually, in photogrammetric acquisition planning, the ground sample distance (GSD) is specified, then the camera-to-object distance is calculated and implemented in the setup. With this axe photogrammetry, the GSD was maximized by filling the camera frame to include as much of the axe head and turntable photogrammetry targets.

Figure 61. Four axe configurations for four photogrammetric chunks

3.2.1.3 Image Pre-Processing

Following photo acquisition, the images need pre-processing before PhotoScan processing. Since the images were taken in a raw format, they contain more scene information, allowing for a high degree of versatility in image modification. In Adobe Photoshop's Camera Raw plug-in, modifications were made to the images. These modifications include colour correction, equalizing exposure across images, and flatting exposure within an image. The colour correction was implemented using Camera RAW's W*hite Balance Tool* to select the first patch on the colour checker passport. This colour correction was then applied to the entire set of images. The exposure across photos was approximately equalized by adjusting the Camera Raw exposure slider in each image until they looked to have similar exposure. Within each image, the exposure was flattened by removing the major shadows and highlights with Camera Raw's *Shadows* and *Highlights* tools.

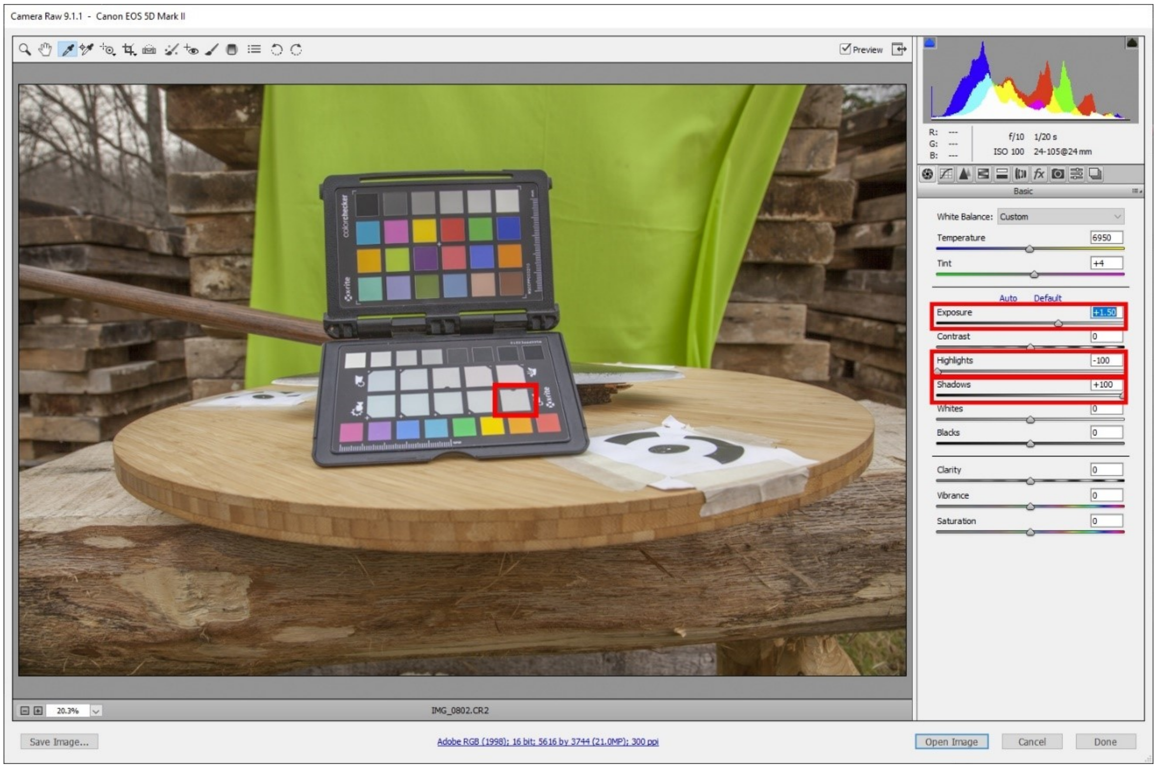

Figure 62. Camera Raw for colour balance and exposure adjustments

Photoshop was also used to automatically generate masks based on the background greenscreens—allowing for the isolation of the moving axe and turntable from the background. Masks were stored in a JPEG format containing only two pixel values; black pixels for areas to be blocked and white pixels for desired areas. The colour correction and exposure must be adjusted before generating the masks, or else Photoshop will not be able to properly recognize the green; resulting in a noisy mask. Once the masks were generated, the green colours were desaturated from all the images. One issue with using a green screen in certain situations is colour leakage. Especially with their reflective surface, the green colour would show on the axes, caused by their reflection to the green screen. By desaturating the green, potential colour accuracy may be lost; however, it looks better and it won't affect the geometric accuracy. These three sets of images are depicted in figure 63.

Figure 63. Colour corrected raw (left) masked (centre) desaturated green (right)

3.2.1.4 Photogrammetry Processing Method 1

Once the image pre-processing is complete, the exported JPEGs and corresponding masks were imported into a PhotoScan project. PhotoScan has a unique feature allowing a project to be separated into chunks, that can be processed simultaneously but independently. In the case for one axe, four batches were created—one for each photogrammetric setup. A batch process was set up to align all the chunks, with an alignment parameter set to 'High' accuracy—this results in a sparse 3D point cloud representing the image tie points. By masking in the images, the photogrammetric key/tie point search was limited to the unmasked areas (figure 64).

Figure 64. Masked images with identified key points and tie points

If some cameras failed to align, they were reset, then realigned to the existing alignment. If they still failed to align, or an overly large number of photos failed to align, 'natural' control points were added and identified across the photos. The natural points are precise points occurring at sharp corners formed by the object. Identifying the natural points between images can aid PhotoScan's alignment, by providing an initial reference for image matching. In only one of the alignment batches, the targets were auto-recognized from the turntable PhotoScan Targets. The 3D coordinates of each target were input based on their relative distances—this applies an absolute scale to the model. Before generating the dense point cloud from each alignment, PhotoScan's bounding box was adjusted to exclusively encapsulate the axe head.

Only geometry within the bounding box will be considered by PhotoScan when processing—by disregarding the turntable from the calculations, the dense cloud processing time was noticeably reduced. The geometry of the turntable was also not desired in the final 3D model. Another batch process was then set up to process the dense cloud—generating a dense point cloud for each chunk. The dense clouds were also processed with the 'High' quality setting. Once the dense clouds were complete, stray false points were deleted, and all the chunks could be aligned into one. To align all the four chunks, natural targets were created on common points between the chunks, then the chunks were aligned and merged based on their shared natural targets. After all the chunks were aligned into one, the mesh and texture could be built. Thus, a photogrammetric model of an axe was complete.

3.2.1.5 Photogrammetry Processing Method 2

One major change was made to this process; specifically, how the multiple chunks were aligned. As described in the previous paragraph, the chunks were processed to the dense point cloud, then aligned using natural points. This 'manual' alignment caused some anomalies in the seams between aligned chunks, especially along the axes' edge—as shown in figure 65. These messy seams were most likely caused due to the quality of photogrammetric reconstruction at the boundary of a captured area. The boundaries of the photogrammetric reconstruction areas tend to fray with inaccurate noisy points. This is why documents like *Photogrammetric Applications for Cultural Heritage* by English Heritage recommend extending the image acquisition area past the areas of interest (Historic England, 2017).

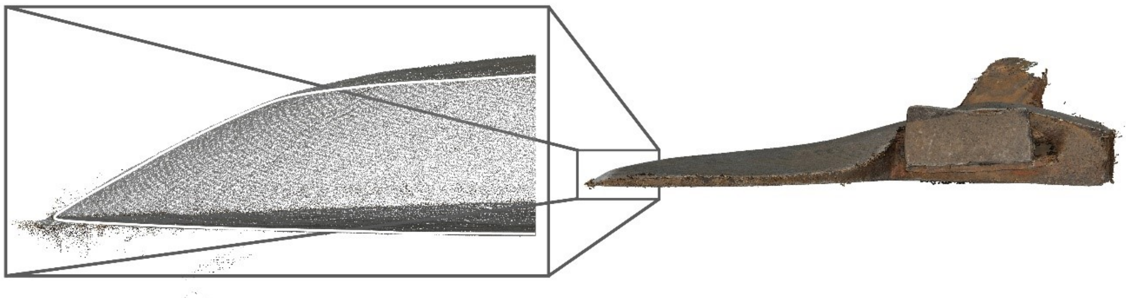

Figure 65. Seam noise in the dense cloud on the overlapping edge

To combat this seam issue, the entire set of images could be aligned at once; that way, photogrammetric alignment is used over a manual alignment. There was still the challenge of the varying environments between chunks—the axes were moved in relation to the turntable for each chunk. This was solved by masking everything in the scene except the axe; which would be a long process if there was no way to automate it. This photogrammetric method 2 was essentially the same as the previously described method 1: import images/masks, batch align images, adjust bounding boxes, build dense cloud. Then instead of aligning chunks, they are batch-processed to the mesh at medium quality. PhotoScan's tool, *Import Masks>From File*, can generate masks for each image based on the constructed mesh geometry in the scene. Figure 66 shows an axe image, with its corresponding mask applied based on the 3D model.

Figure 66. Greenscreen masking vs model-based masking

Since the axes were already isolated via bounding boxes, it was easy to automatically create masks that isolated the axe in each image. Once all of the images were automatically masked—with some manual intervention of course—they were merged into one chunk. Then the images were re-aligned with the accuracy set to *High*. Again, in some cases, some images failed to align; therefore they were selected, reset, and realigned to the rest of the aligned images. Using method 2 would still sometimes produce intersecting geometry at the edge of the axes. This was usually resolved by using the *Optimize Camera Alignment* tool, then rebuilding dense cloud, mesh, and texture. The final photogrammetric model may look like that in figure 67.

Figure 67. Textured mesh from photogrammetry of Corey Pool’s Higgins-made Canadian Pattern broad axe

3.2.2 Timbers

The photogrammetry methodology for timbers was developed similarly to method 2 for axe photogrammetry; however, green screens were not utilized. Since the entire timber was rotated to capture all sides, the photogrammetric project was split into chunks to obtain their model-based masks, then merged and reprocessed together.

The first timber scanned was from the Perth Timber Frame. The timber frame had already been dismantled, labelled, and stored on the Algonquin College Perth campus. This is where the timber photogrammetry acquisition took place. This level of photogrammetry was much easier while the timbers were dismantled; the camera could be moved around the entire timber relatively unobstructed. The timbers—being more than 100 years old were dry and lightweight—they could be lifted by a more serious Sunday weightlifter. The timbers were set on timber framing trestles, which are designed to support the timbers at an exact height for cutting timber frame joints. Conveniently, the timber framing trestles were also the perfect height to support timbers for photogrammetry.

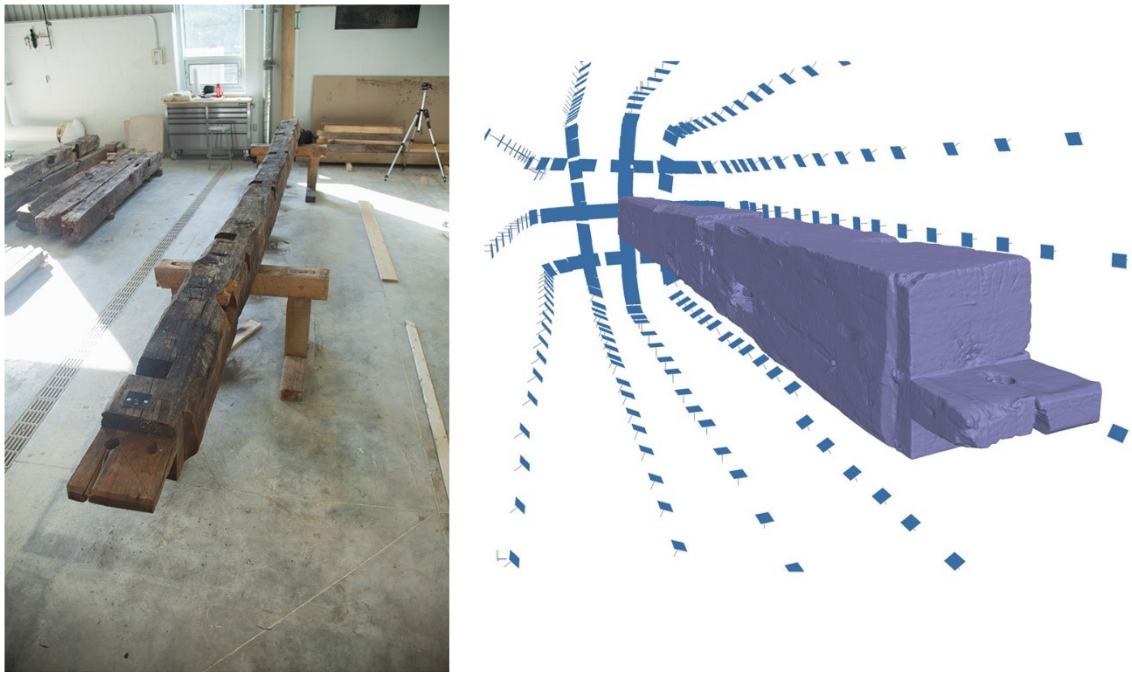

Figure 68. Timber trestle (right) and typical photogrammetric network for timbers (right)

To obtain a consistent GSD, lines were marked out on the ground around the timber for reference when shifting over the camera. Analogous to method 2, the exposure was set by adjusting the camera’s shutter speed, aperture, and ISO. Then images were captured while moving the camera and tripod around the timber while keeping a 60-80% overlap between photos. The grid in the camera viewfinder could be used as a reference to approximate the overlap between photos. At least four loops of photos were captured around each timber; two loops orthogonal to the faces, and two loops each about 45° to the faces. This photogrammetric setup and resulting network are depicted in figure 68. Then measurements were taken across the length and the width of the timber.

After the image acquisition, the similar photogrammetric processing was executed: pre-processing, mask and image import, batch organization, batch alignment, batch dense cloud generation, batch mesh generation, mask generation from models, batch merging, realignment, target import, dense cloud generation, mesh generation, and finally texture mesh building. By generating the photogrammetry of the old timbers, the geometry can be isolated, and the tool marks can be revealed more easily.

3.3 Hewing Recreation

3.3.1 The Craftsman

Figure 69. Hewers in the Ottawa Valley with scoring crew behind (LAC C75265).

Corey Pool is a preservation carpenter and works mostly in the restoration of historic timber structures. He focuses not only on the preservation of historic buildings but also on the preservation of the traditional skills required to work the materials. His focus on preserving the intangible cultural heritage resides mainly in the recovery and preservation of hewing techniques; specifically in hewing in the Ottawa Valley. Corey has been reconstructing and refining the hewing techniques through experimental archaeology types of processes. He has been analyzing historic photographs of 19^{th}-century loggers in Ontario, while also analyzing and reading the tool marks left on the historic timber structures in his restoration projects. He reconstructs the hewing techniques by imitating the old logger's body posture's while aiming to recreate the same kinds of tool marks on his timbers.

Corey's working knowledge of these hewing techniques has provided vital insights into the work in this thesis; specifically, styles of broad axes, broad axe edge geometry, local hewing techniques, and reading tool marks. Conversely, the work in this thesis has provided Corey with a sort of mirror to his work; allowing him to look at his technique reconstructions in a particular light.

Without Corey's embodied knowledge, this thesis would not be anywhere near where it is. The axes and timbers could be scanned and catalogued to the micron, but the information is useless without the received knowledge of what to look for.

Joyfully, the collaboration with Corey Pool resulted in a CBC Ottawa article: https://www.cbc.ca/news/canada/ottawa/tools-antique-heritage-culture-hewing-1.5380861.

3.3.2 Making New Tool Marks

The first reconstruction experiment I conducted was to study Corey Pool's hewing technique with a large Canadian pattern broad axe. By documenting this process, an explicit connection was made between specific tools, specific techniques, and their respective tool marks. The hewing process was recorded with video, high-speed video, and time-lapse video; and the hewing results were recorded with photogrammetry. This experiment took place at the Cumberland Village Heritage Museum; where they have set up a hewing demonstration station, in front of their circular sawmill and shingle mill.

3.3.3 Video Documentation with Time Variation

During the recording of Corey Pool’s hewing processes, I set up three video cameras—each recording video at a different time scale; slow time, standard time, and fast time. By compressing and stretching time, aspects of the hewing process and the techniques could be isolated. This leads to an understanding of the process at different levels; especially for the layman. A highspeed camera—the *Sony DSC-RX10III Cyber-Shot*—was used to record at a high frame rate, thus allowing for the hewing to be viewed in slow motion. The Cyber-Shot can record up to 1000fps; however, recording with a higher frame rate, this camera sacrifices recording time and video quality. The standard speed video and audio was recorded with a *Canon 5D Mark II*. A Nikon D5200 was used to record the hewing by taking an image every 5 seconds—the images were compiled into a video making a time-lapse. A time-lapse video speeds up the video playback, which makes Corey’s work look real quick.

When reviewing the hewing time-lapse, the first evident thing is how fast one can understand the overall process of hewing; the preparation, the notching, the blocking, the scoring, and the final broad axe hewing. A specific technique of the broad axe hewing is revealed in the time-lapse. I realized that Corey has naturally found it to be best to hew the timber in a series of 'sweeps', keeping the hewing interface at an angle to the length of the log (figure 70).

Figure 70. Corey's sweeping hewing interface technique

One can also see how Corey took more time and care when scoring and hewing around knots. He typically scores with his felling axe right on the knot, just in front of the knot, and just behind the knot. This breaks up the hardened wood grain around the knot, making it easier on the broad axe hewing.

Standard time video is most vital to the conservation of the intangible aspects of hewing and timber framing. Out of the three different time scales of video documentation, it is the best for dissemination—for others to watch and recreate the techniques. By watching this type of video one can easily imagine themselves recreating the movements in real-time. The audio also makes a large impact on a viewer’s understanding of the process. The effectiveness of each axe stroke can be related to the sound it makes—whether the axe chop bites deep or shallow, or whether the broad axe bites or slices. These types of videos with no speaking—only the sights and sounds of the tools—are so powerful, they can grab an audience's attention during a presentation, and cause them to ignore the presenter.

The high-speed video revealed subtle details of the hewing technique; most importantly it can clearly show the mechanics of each type of broad axe mark. Generally, two different types of marks are left by the broad axe. When the axe cleanly and completely slices though the wood it only leaves a subtle concave facet. This faceting is very challenging and requires precise axe work. The other mark that is left from the broad axe occurs when it ‘bites’ into the wood and stops without completing the axe stroke of the swing. These phenomena of different broad axe tool marks is consistent with the hewing traceology described in chapter 2.5.3. Looking at the video documentation, multiple bites occur before completely removing a layer of wood from the timber.

Although the Canadian broad axe is flat on one side with an edge bevel on the other, the flat face has a significant camber from heel to toe. This camber typically causes the centre of the axe edge to contact the wood. The resulting axe mark only has edge marks, facets, and signatures, without any heel/toe side features. One of these edge marks is compared with its corresponding broad axe in figure 71.

Figure 71. Canadian broad axe with a corresponding edge mark

While reviewing the high-speed footage taken from above Corey while hewing, I realized one of my conceptions of hewing was not quite right. Since the one face of the broad axe is flat, I expected that each axe stroke would be exactly vertical; however, this is not the case. Most single bevel broad axes do have a subtle amount of curvature from poll to edge; however, this can range from entirely flat to more pronounced camber. The subtle amount of camber in the Canadian broad axe allows the hewer to take a subtle lateral glance with each stroke; most likely lowering the chance of the edge biting. Of course, Corey already knew this was the case. The slight lateral component of the axe stroke is evident in the overhead high-speed footage. Figure 73 shows the lateral swing from the video while, figure 72 shows the filming perspective.

Figure 72. Filming overhead of the broad axe hewing

Figure 73. Angled axe at top of axe stroke (top) and parallel axe at bottom of axe stroke (bottom)

3.3.4 Photogrammetry of Hewing Results

Once the hewing experiment was completed, I photoscanned the log’s hewn surface along with the hewing axe. This can contribute to developing a geometric relationship between an axe mark and its known corresponding axe. At this point, I set up the axe photogrammetry rig in front of a barn-like structure. The Higgins Canadian pattern broad axe photogrammetry was processed as described in chapter 3.2.1; in fact, it was the axe used to illustrate the process.

Photogrammetry of the hewn log followed a similar process as described in chapter 3.2.2; however, no timber rotation was necessary. This made the photogrammetric processing less complicated since no masking and realigning were required. The photogrammetric image set is seen in figure 74.

Figure 74. Photogrammetric image set for the hewn log

To scale the log photogrammetry, I took one measurement across the length of the log, and the other across the width. The measurement start and endpoints were located and documented at natural targets on the log. These natural points were input to PhotoScan and scale bars were created between the points (figure 75). The recorded measurements were applied to the scale bars and only the length scale bar applied to scale the photogrammetric model—the width scale bar was kept unapplied to use as an error check.

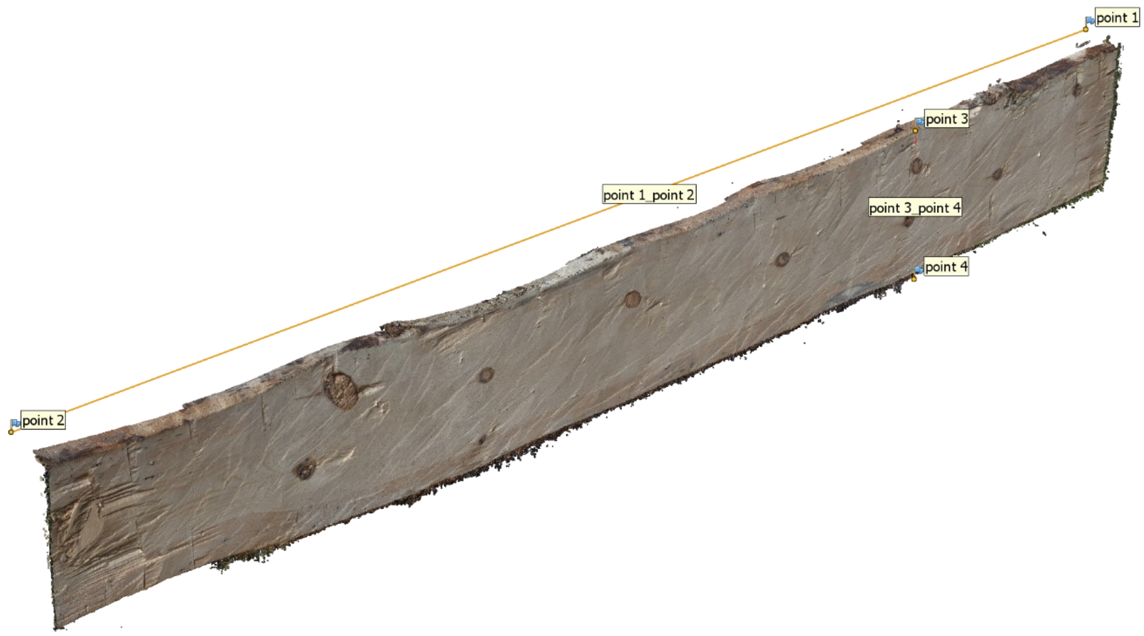

Figure 75. Scale bars along the length and width of the log

3.3.5 Documentation with Axe Variation

In the next experiment I documented tool mark variations of different North American broad axes. The log hewed in the previous experiment was only hewed on one face with the 10¾" (273 mm) Higgins Canadian pattern broad axe; later on, Corey hewed a log with a 9⅛" (233 mm) Campbell Bros (Nova Scotia) shipbuilders single bevel broad axe. This axe is smaller and lighter while having a more pronounced camber; both from toe to heel and edge to poll. With these differences between broad axes, it is likely to see differences in their tool marks. Specifically, I was expecting to see shorter edge marks and facets with a higher curvature.

Figure 76. Corey Pool’s shipbuilders’ broad axe and hewn timber

Naturally, the finished hewn timber and the shipbuilder’s broad axe were scanned using the photogrammetric process described in the previous chapters.

3.4 Analysis

3.4.1 Survey of Basic Axe Geometry

In *Axe Making in Ontario During the Settlement Period,* French (2010) displays a photographic collection of mainly broad axes. When it is available, he also records a few other details about each axe; description, maker’s mark, location, width, height, and weight—width being the toe-to-heel distance and height being the edge to poll distance. While scanning the 42 broad axes from the Algonquin-Foohey collection, the pattern, width, and weight were also recorded. Figure 77 plots the relationship between the blade width and weight; of axes combined from the Algonquin-Foohey collection and French's (2010) photographic collection. In this case, 'Canadian pattern' refers to a broad axe without a necked poll and 'Pennsylvania' refers to a broad axe with a necked poll. From this survey, all the largest and heaviest broad axes are a Canadian pattern—as seen in figure 77. Conversely, the larger a broad axe mark is, the more likely it is made a Canadian pattern broad axe. This is a good confirmation of French's (2010) statement:" it was markedly heavier (and therefore larger) than other options."

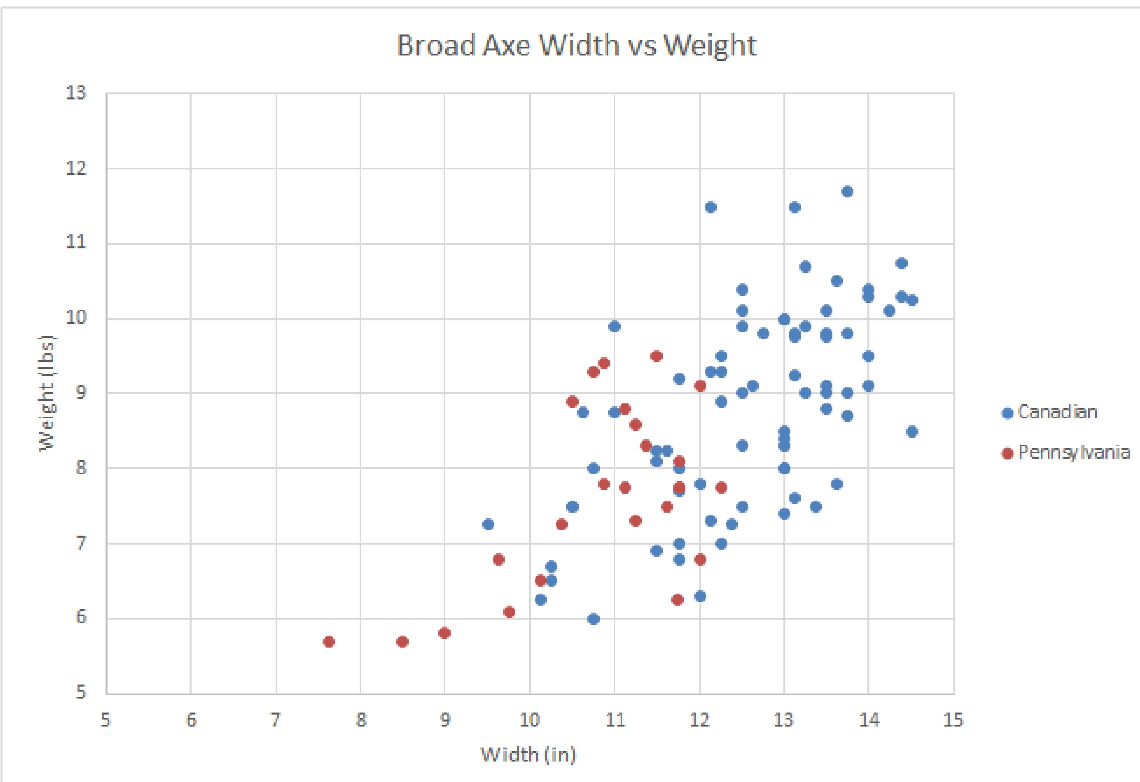

Figure 77. Canadian and Pennsylvania pattern broad axe blade width vs weight

3.4.2 Tracing Tool Marks

In an initial tool traceology test, I manually traced identified axe edge mark profiles from the initial hewing reconstruction experiment. Timber conversion marks can be identified with the patterns described in chapter 2.5.2 & 2.5.3. The tracing is an attempt to find a metric relationship between the axe edge width and the edge marks. This tracing was completed in the 3D computer-aided design (CAD) software Rhino(cerous) 6. Rhino is a powerful CAD tool, that supports 2D and 3D linework, 3D modelling, and most importantly triangle meshes. Within the Rhino environment, the user has the option to work in a perspective or orthographic view independently or simultaneously (figure 78).

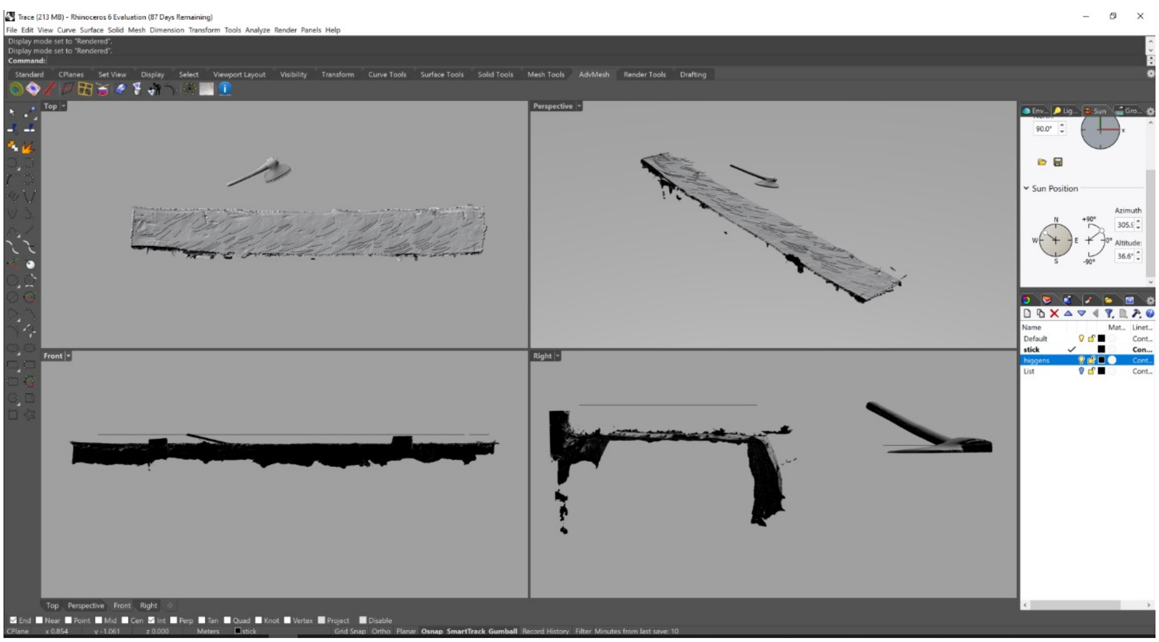

Figure 78. Working in Rhino 6 CAD software.

I was able to import the photogrammetric mesh of the log and axe into Rhino and roughly align them to the orthographic top view.

This way, all the tracing could be completed in the orthographic work plane—figure 79 shows an example of tracing edge marks on a timber. Using a CAD program like Rhino, stores each of the traced profiles as vectors; therefore, it is easy to complete calculations over the entire set of identified profiles. Aligning the face of the timber to the top view is important for virtual raking lighting, using Rhino’s sun analysis tools.

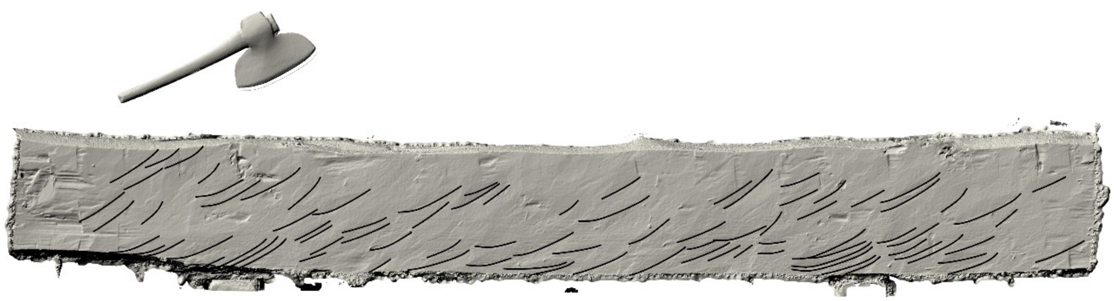

Figure 79. Tracing tool marks over mesh with axe as reference

By selecting all the traced lines, the *Export Selected* command can be used to export the attributes—including length—to a comma-separated value (CSV) text file. The CSV file can be opened in Microsoft Excel where a statistical analysis of the mark widths can be conducted.

Assuming a normal distribution the mean and standard deviation of the traced lines can be found with equation 3.1 and 3.2 respectively. Where $\bar{x}$ is the mean, σ is the standard deviation, n is the population size, and x_i is each sample value. It is important to note that the edge width that was calculated here was along the profile of the blade, not the straight distance from axe heel to toe.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad 3.1$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad 3.2$$

The resulting traced axe width mean value was 0.155 m or about $6\frac{1}{8}$″ and the standard deviation was 0.049 m or about $1^{15}/_{16}$″. This means that 68.2% of the measured edge marks range from about $4^{3}/_{16}$″ to 8″. The mean value of $6\frac{1}{8}$″ is only 55.6% of the true edge width of 0.279 m or about 11″. In the case where the only the timber with its axe marks survive, the axe width could be estimated using this method of scaling the average using the factor of 1.8 based on the 55.6%. However, this may not be a reliable measure. Assuming the normal distribution does not help us in estimating the real axe edge width—figure 80 even shows the distribution of the Higgins axe marks, skewing away from the real axe length.

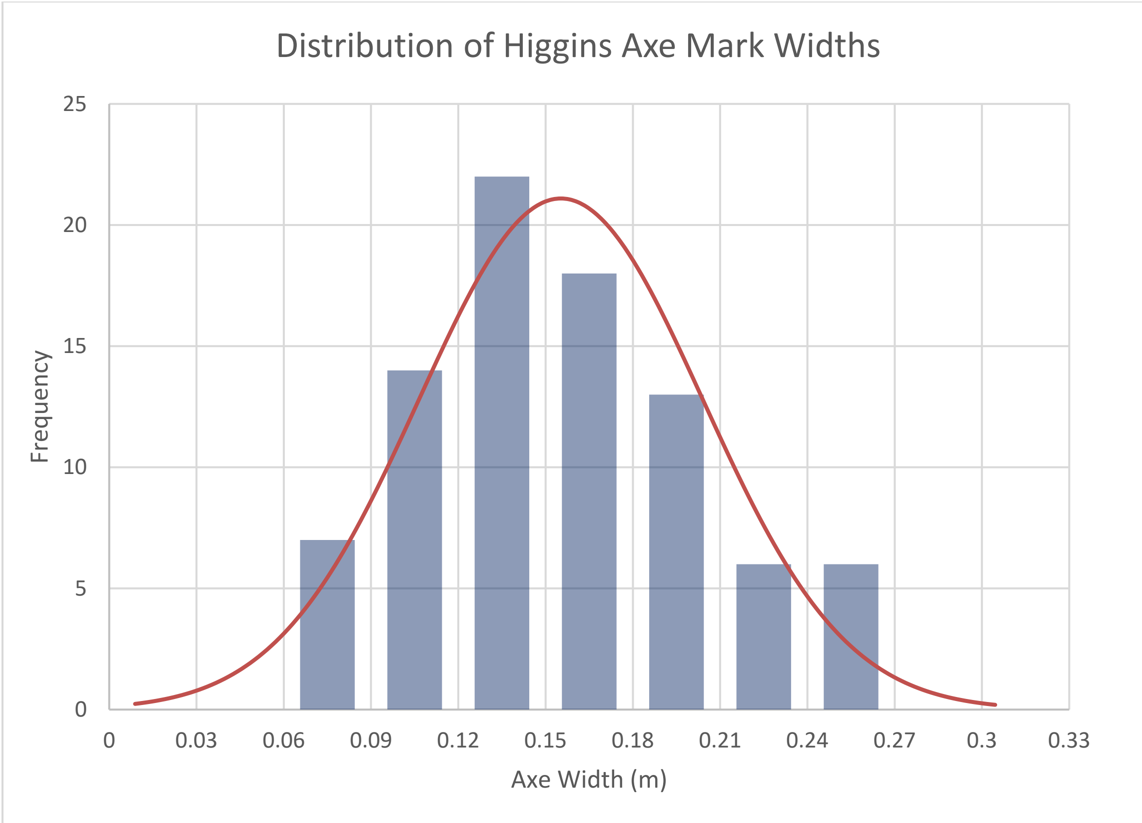

Figure 80. Histogram of Higgins axe mark widths with fit normal distribution

Another way to estimate the axe edge width is by only considering the widest recorded trace mark. In this case, the longest trace was 0.267 m or about 10½″ which is only 95.6% of actual axe width.

By organizing all the traced tool marks by width (figure 81), it seems the traced profiles cover the entire axe profile even though they are fragmented into multiple traces. This suggests that—although North American single bevel broad axes have a cambered cutting surface—the entire profile of the axe can be found on a timber. The best way of reconstructing multiple tool traces is by matching through signature profiles as described by Sands (1997). Unfortunately, the resolution of the photogrammetry acquisition did not allow for the required precision of the subtle signature marks.

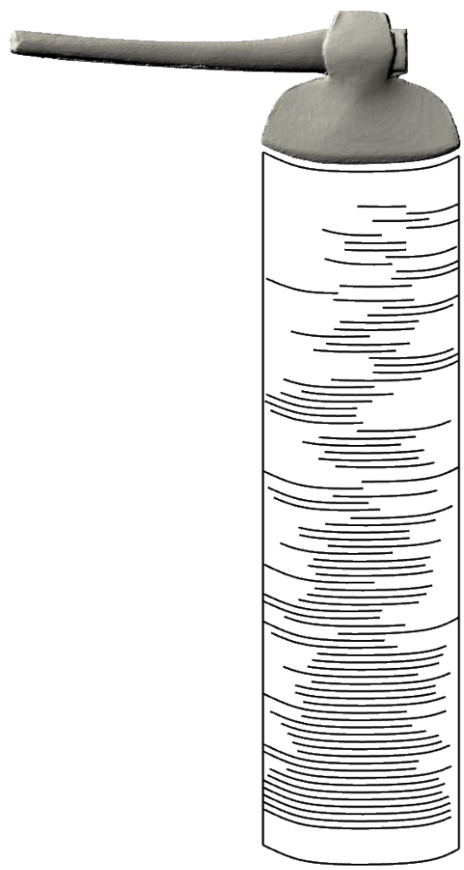

Figure 81. All traced tool marks organized by length

Each axe stroke leaves a facet, sometimes followed by the edge mark. The curvature of these facets was captured by drawing a straight line from the start to finish of the widest identified edge mark, then the line was projected over the facet in the mesh.

The curvature measure of the facet was determined with a method used by Sands (1997)—shown in figure 82—to measure the curvature of an axe blade. This measure is simply the ratio of the depth and width of the curve.

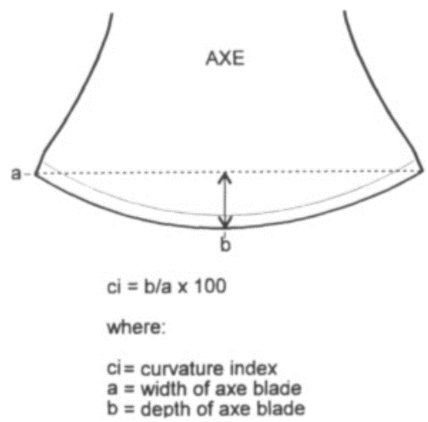

Figure 82. Calculating the curvature index (Sands 1997)

The measured depth, b, of this facet was 1.3 mm and the width, a, was 285.6 mm. Calculating the curvature index is given by:

$$ci = 100\left(\frac{b}{a}\right) \tag{3.3}$$

$$ci = 100\left(\frac{1.3\ mm}{285.6\ mm}\right)$$

$$ci = 0.46$$

When measuring the curvature index for the corresponding broad axe, it must be from the profile of the edge and not just a straight line from heel to toe; illustrated in figure 83.

Figure 83. Traced profile and camber of the Higgins broad axe

The traced profile on the Higgins broad axe edge yielded the actual curvature index. With the measured depth, was 1.4 mm and the width was 274.7 mm. Calculating the curvature index of the Higgins broad axe is given by:

$$ci = 100\left(\frac{1.4\,mm}{274.4\,mm}\right)$$

$$ci = 0.51$$

The curvature index for the measured timber facet at significantly close to the index of the axe. This makes it seem like it has the potential for a reliable axe geometry reconstruction.

3.4.3 Axe Variation

The statistical methods of axe width variation were also tested on another axe and log. This was the second experiment described in chapter 3.3.5. The Campbell Bros ship builder's broad axe, yielded interesting results, most likely due to its aggressive camber. This timber was also hewn by Corey Pool. With the timber photoscanned and imported into Rhino, I manually traced each hewing axe mark (figure 84 & 85).

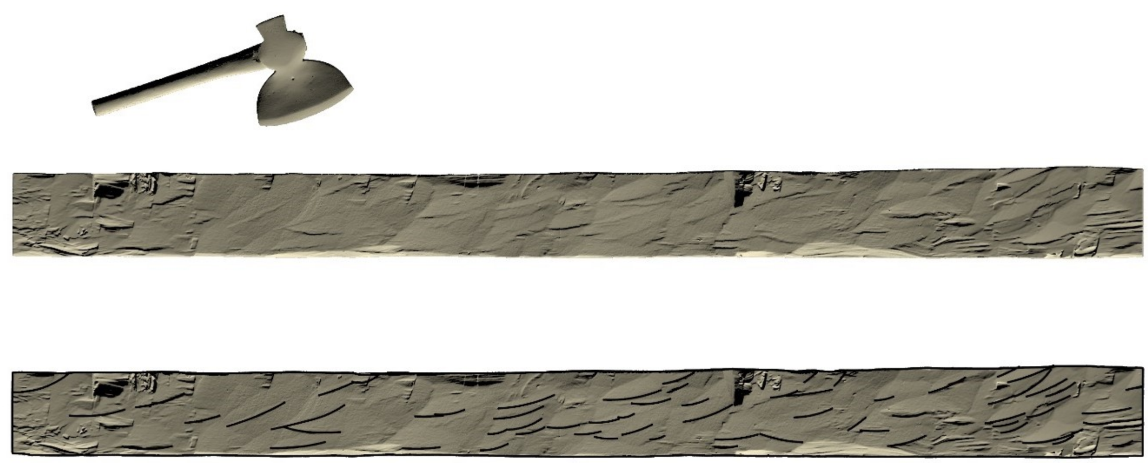

Figure 84. Campbell Bros hewn timber with traces

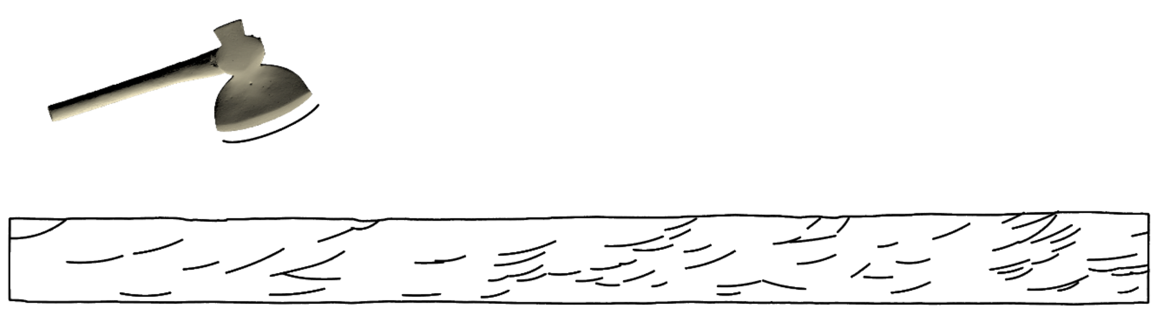

Figure 85. Timber traces

From these traces, the mean width was 0.081 or about $3^{3}/_{16}$", and the standard deviation was 0.032 m or about $1^{1}/_{4}$". So 68.2% of the traces range from about $1^{15}/_{16}$" to about $4^{7}/_{16}$". Compared to the axes actual $9^{7}/_{16}$", the average traced mark is only about 34%. The widest trace recorded was 0.178 m or about 7", which is about 74% of the actual width. This major underestimation of the edge width is most likely due to the aggressive curvature of the axe, causing only a small width of the edge to bite into the wood. This is also consistent with the plotted histogram and fit normal distribution in figure 86; the measurements seem to skew even more heavily away from the real axe width—roughly compared with the Higgins measured width distribution.

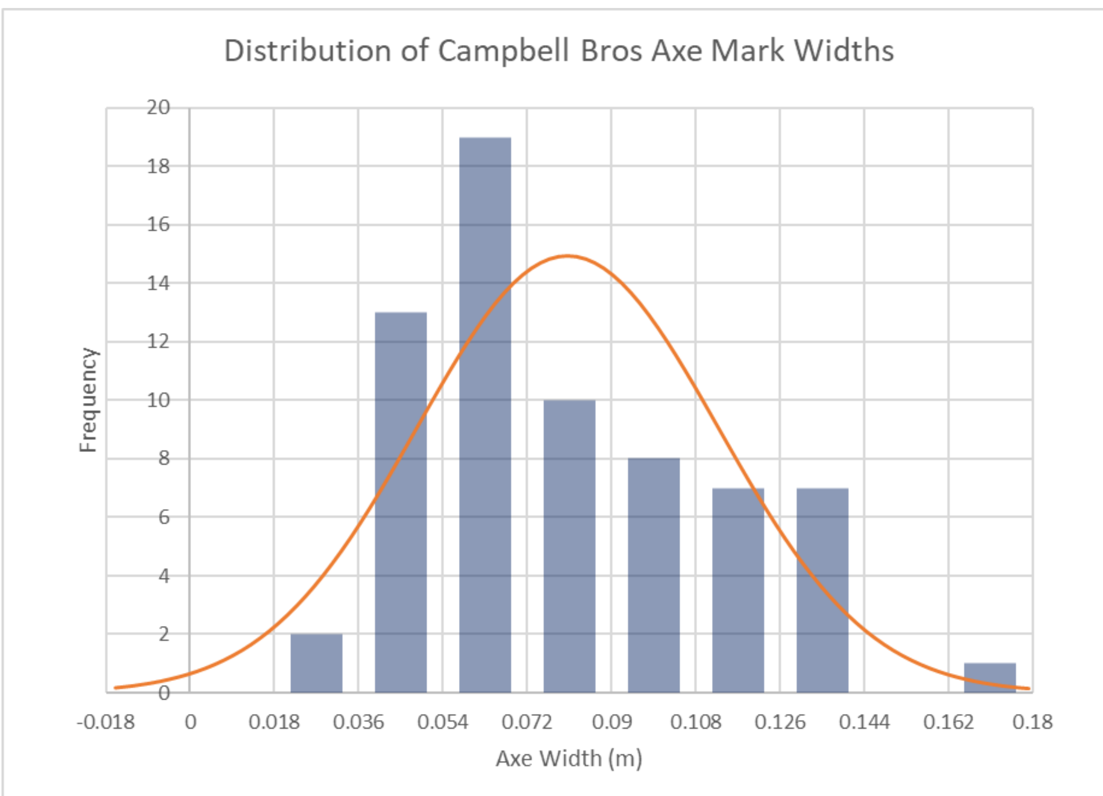

Figure 86. Histogram of Campbell Bros axe mark widths with fit normal distribution

Of course, the curvature is likely to be reflected in the facets above the edge marks. Again, a majorly intact edge mark and facet were selected on this timber, then I was able to project a line onto the mesh in this area as per figure 87.

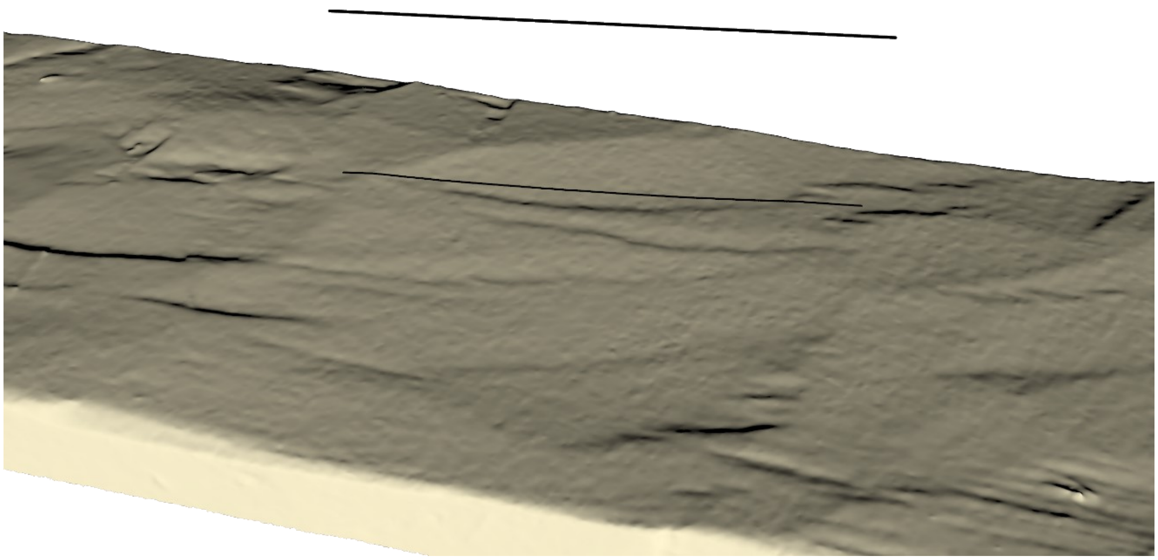

Figure 87. Line projected over facet in mesh

With the measured depth, b, of this facet was 1.6 mm and the width was 147.0 mm. Calculating the curvature index of the Higgins broad axe is given by:

$$ci = 100\left(\frac{1.6\,mm}{147.0\,mm}\right)$$

$$ci = 1.1$$

For the curvature of the Campbell Bros broad axe, the measured depth was 2.9 mm and the width was 230.7 mm. Calculating the curvature index is given by:

$$ci = 100\left(\frac{2.9\ mm}{230.7\ mm}\right)$$

$$ci = 1.3$$

This consistency between axe and facet curvature indices displays how reliable of a measurement it is, even with the more aggressively cambered axe.

Figure 88 summarizes the edge widths, curvatures, and errors between the Higgins hewn timer and the Campbell Bros hewn timber.

Higgins Axe and Timber						
	Mean traced width (mm)	Max traced width (mm)	Real traced width (mm)		Traced curvature	Real curvature
Value	155	267	279		0.46	0.51
% Error	44	4			10	
Campbell Bros Axe and Timber						
	Mean traced width (mm)	Max traced width (mm)	Real traced width (mm)		Traced curvature	Real curvature
Value	81	178	240		1.1	1.3
% Error	66	26			15	

Figure 88. Table summarizing edge widths, curvatures, and errors

3.4.4 Hewing Height Estimation

One of the other aspects of Rhino(cerous) 6 that makes it such a powerful CAD program is its ability to active daylighting analysis. With Rhino's *Sun* tool, I can numerically specify a sun angle relative to the horizon (altitude) and relative to North (azimuth). Combined with a high-resolution photogrammetric mesh, this feature simulates the type of active relighting in RTI, described in chapter 2.6.5.

Since it is a sun angle relative to Rhino's xy plane, the surface of interest must be aligned to the ground xy plane. The longitudinal axis of the timber was also aligned to the x-axis in Rhino. This allows for the calculation of the (sun) light angle relative to the longitudinal axis of the timber. Especially with the heavily weathered timber, the colour texture was removed from the mesh to exclusively reveal the geometry. To estimate and angle of the axe marks, the altitude was adjusted to a low angle relative to the ground and timber surface, then the azimuth was adjusted until all the hewing marks disappear. This gives a good intuitive measure of the angle of the axe during hewing. Figure 89 shows how adjusting the light angle to be parallel and perpendicular to the edge marks with hide and reveal them.

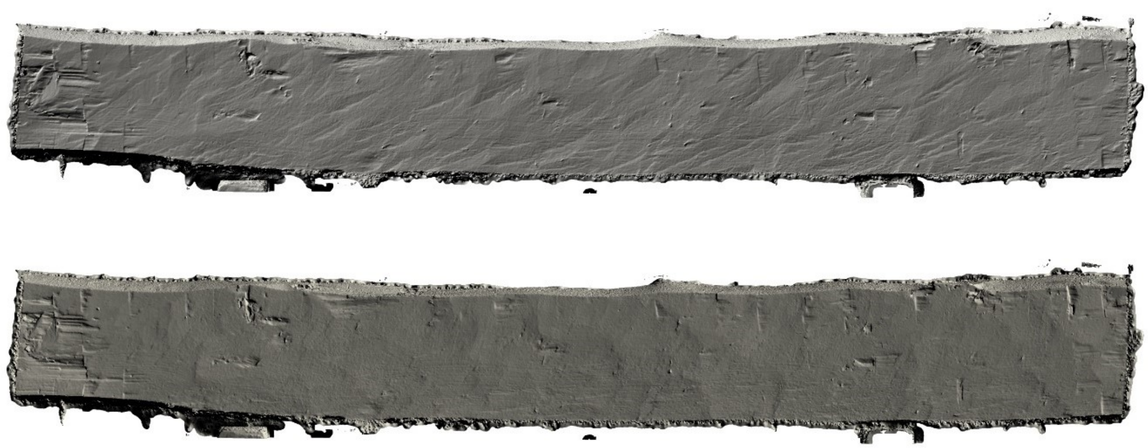

Figure 89. Light perpendicular to edge marks (top) and light parallel to jam curves (bottom)

In this case, the edge marks indicate the axe at either 23° or 203° to the timber's longitudinal axe—depending on if the timber was hewn above or below the waist—assuming that is unknown. To delineate whether the log was hewn low or high, I considered the angle of the tool marks relative to their height on the timber. The edge marks were at a steeper angle at the top of the timber while they were closer to horizontal at the bottom of the timber. This suggests that the bottom of the timber was close to the hewer's waist and the top of the timber. This becomes evident while varying the sunlight; a steeper azimuth of about 38° aligns with the higher marks, while a shallower azimuth around 18° aligns with the lower marks. If the timber was hewn below the waist, then the shallow marks would be at the top of the timber and the steep marks would be at the bottom of the timber. Figure 90 shows how the variation in hewing edge mark angles are revealed with different lighting angles.

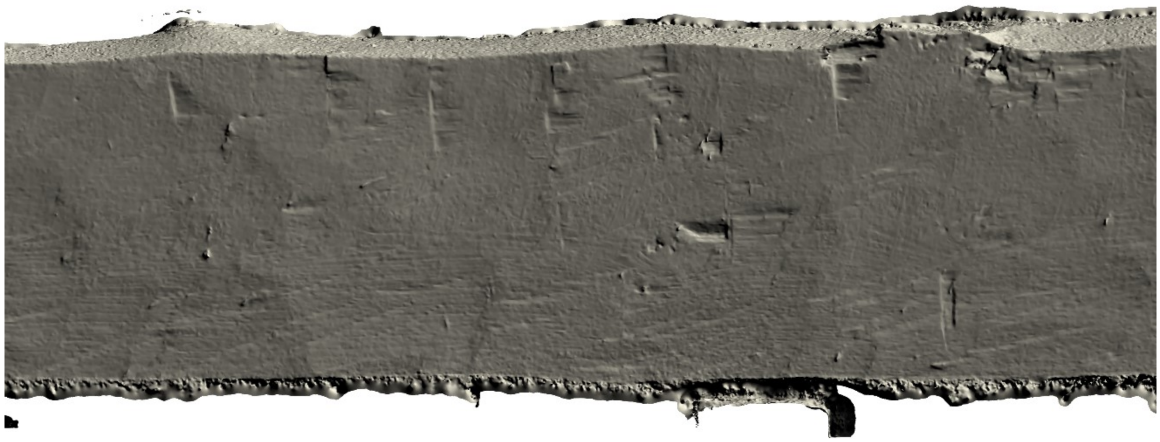

Figure 90. Steep lighting aligned to higher marks (top) shallow lighting aligned to lower marks (bottom)

There are a few reasons why it is advantageous to use digital relighting as opposed to raking lighting photography. For one, the photogrammetry allows for the rectification of the timber surface, as opposed to the camera's perspective distortion from raking lighting. The photogrammetric analysis also allows for easy viewing of the entire timber, instead of a small area. Another important aspect includes the digital sun's parallel light rays all cast at the same specified angle contrasting how raking lighting is with a point light source—radiating its light rays. Radiating light rays cause inconsistent shadows; whereas the parallel light rays will correspond with the sun angle. This gives the sun lighting tool a metric and intuitive method for axe mark angle analysis.

3.5 Red House Timber Frame Analysis

For the analysis of the Red House timber frame, I used the timber labelled B2S was used as a specific case (Figure 91). The label B2S refers to a location in the timber frame—bent #2, south side.

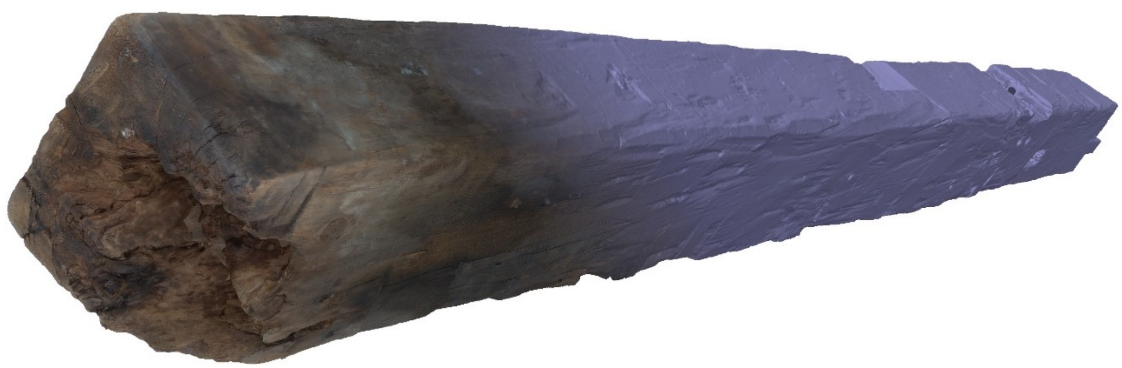

Figure 91. Photogrammetric textured mesh of timber B2S

The first question to answer was: how was it converted from a log to a timber? By studying the surface of the timber, with reference to the conversion traceology in chapter 2.5.2, the distinctive hewing marks became apparent. The timber featured the two types of axe marks typically seen on a hewn timber; the score marks perpendicular to the timber and the large subtle broad axe facets and edge marks. This is labelled in figure 92. It was much more challenging to see these marks on a heavily weathered wood surface. When isolating and relighting the photogrammetric geometry of the timber, these marks are much easier to see. Therefore, the timbers were converted via hewing.

Figure 92. Trace marks on B2S timber under raking lighting

The next question was: what kind of broad axe was used to hew the timber? Based on French's (2010) research in *Axe Making in Ontario*, he states that "The further west in Ontario one moves, the more likely it is that the axe is New York pattern rather than Canadian pattern and the smaller and lighter the axe is likely to be." (p. 31). Since this timber frame is located in Perth, it is in eastern Ontario, and the broad axes made in this area were likely large heavy Canadian pattern broad axes.

3.5.1 Axe Mark Tracing

Due to its weathered nature, the B2S timber was much more challenging to trace for tool marks—less marks were visible; however, all four sides were traced (Figure 93).

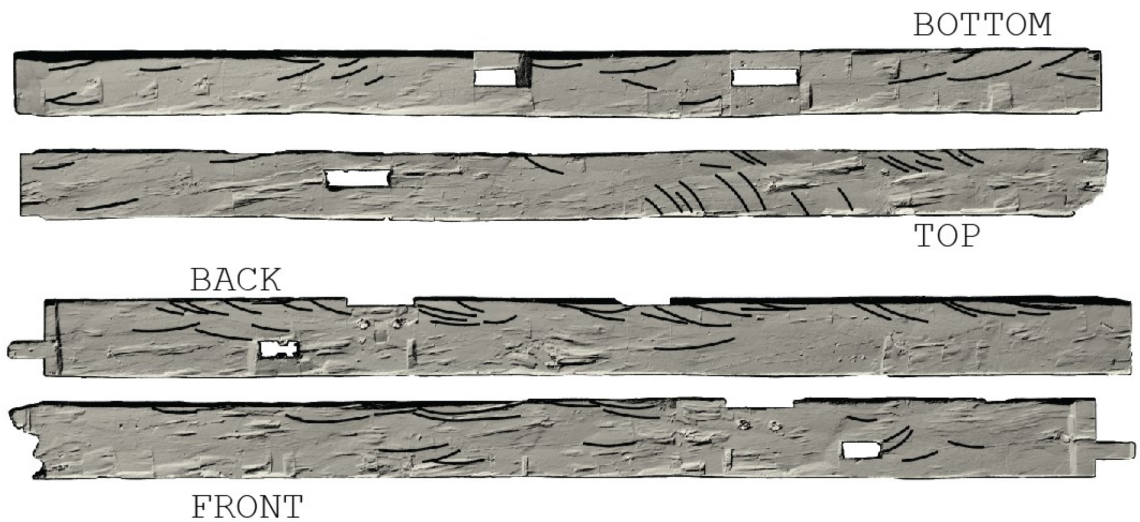

Figure 93. Traced sides of timber B2S

Using all the traced edge marks the mean value was 0.132 m or about $5^{3}/_{16}$″ and the standard deviation was $2^{1}/_{8}$″, while the largest edge mark measurement was 0.321 m or about $12^{5}/_{8}$″. Measuring the facet curvature yields an unexpectedly large curvature index of 1.1. This could be why there is such a large standard deviation.

3.5.2 Hewing Processes

The height of the timber was the most challenging to determine due to the sparsity of the edge marks, the variation in the angles in the edge marks, and the edge marks being localized towards the tops of the hewing surfaces. In general, most of the edge marks were around a shallow angle of 10°. Since these shallow angled edge marks are close to the top of the hewing surface, I expected that the timber was just at or below the waist while hewing.

Based on the angle of edge marks on the opposite sides of the timber, it seems that the timber was hewn down one side with a right-handed broad axe and the other side with a left-handed broad axe (figure 94). This is also consistent with the techniques used by the hewing teams back in the day. This is depicted in the figure 22 in chapter 3.3.1. Since there were two axes used, this will throw off the edge width estimate, but it is still likely that large Canadian pattern broad axes were used to hew this timber.

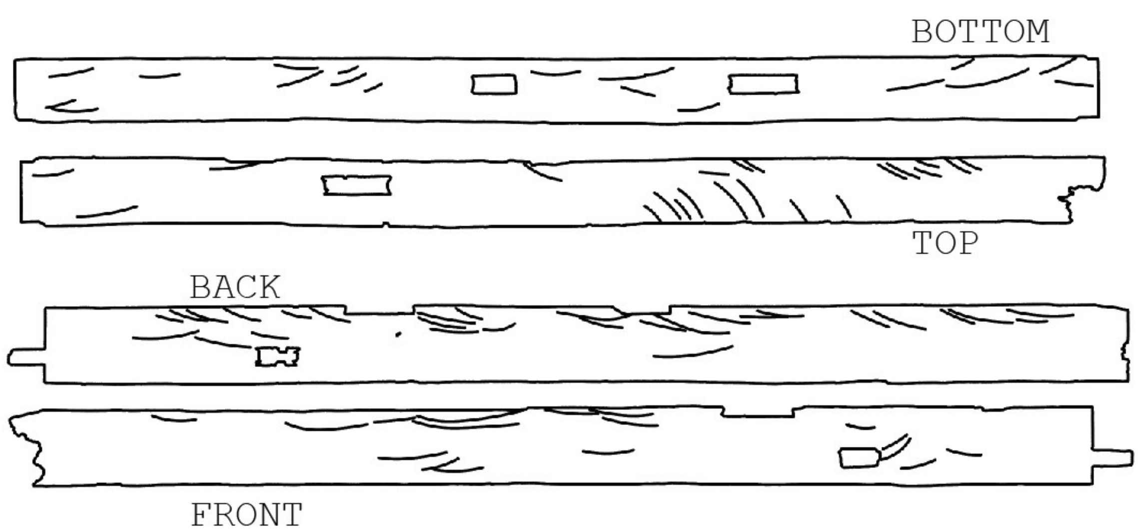

Figure 94. B2S trace depicting hewing with left-handed axe (back and top) and with right-handed axe (front and bottom)

Another interesting aspect of this timber was on the top face. With closer inspection, it is evident that the timber was mostly hewn from one side; however, there are some edge marks that are upside down. This suggests that the timber was flipped upside down and hewn in that orientation. This is also seen in the change in direction of the faceting in the timber from the axe’s camber. These edge marks also have a very steep angle toward the top of the timber surface. This suggests that when the timber was flipped, it was hewn at high above the waist. The alternating tool marks are traced in figure 95.

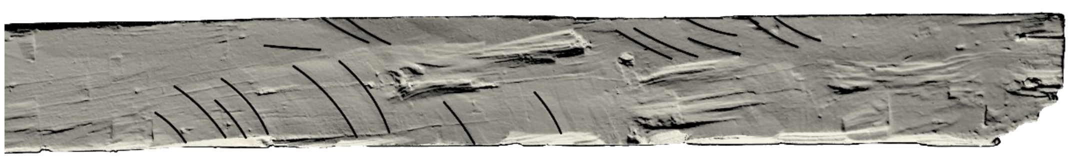

Figure 95. B2S timber top face with alternating hewing direction

3.6 Axe Signatures

The best way of reconstructing axe edge profiles is described in the matching process of axe signature profiles by Sands (1997). Photogrammetry may be a good tool to measure these groove and ridges in the wood created by the folds and chips in the axe edge. I conducted a preliminary test to see if photogrammetry has the precision to be able to recognize these axe signatures in a hewn oak log. For this experiment, I restored a Canadian pattern broad axe with an unknown maker. Most second-hand broad axes are found in a state of rusty disrepair, with rotted handles, and multiple chips on a dull edge. Figure 96 shows the partially restored axe—with a handle that was based off the photogrammetry of Corey Pool's Campbell Bros. shipbuilders broad axe.

Figure 96. Unknown broad axe with a partially finished new handle

After hanging a newly carved handle on the cleaned unknown broad axe, I sharpened the edge with a bastard file, a mill file, then an oil stone. It was only sharpened until it was sharp across the majority of the edge; most of the edge defects were left to accentuate the signatures. Then, I hewed an oak log using the techniques described in chapters 2.4.2 and 2.4.3. The unknown broad axe was used for the final hewing step—figure 97 shows the finished hewn log.

Figure 97. Oak log hewn with highlighted signature marks

After hewing the one face of the oak log, I selected a section to be captured with photogrammetry. The resulting photogrammetry and corresponding photo network is shown in figure 98.

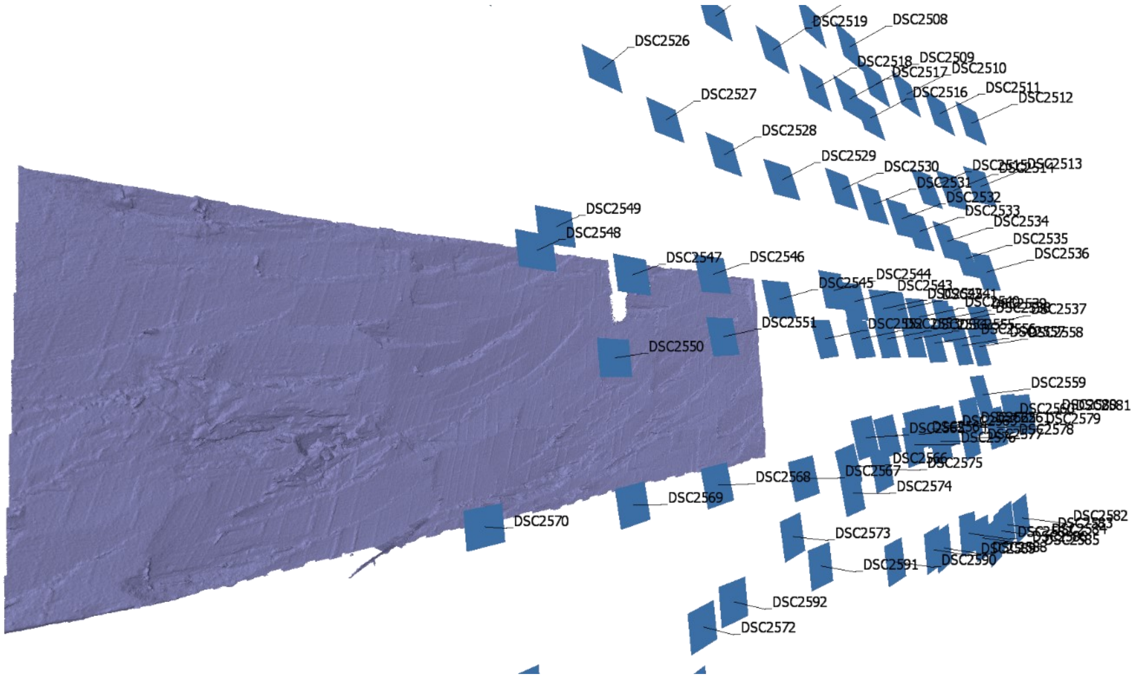

Figure 98. Photogrammetry of a section of the hewn oak log

By inserting the mesh into Rhino, lines were projected over the mesh, creating a profile of the signature marks. Figure 99 shows the profile projected on the mesh, while figure 100 shows the profile of a signature marks.

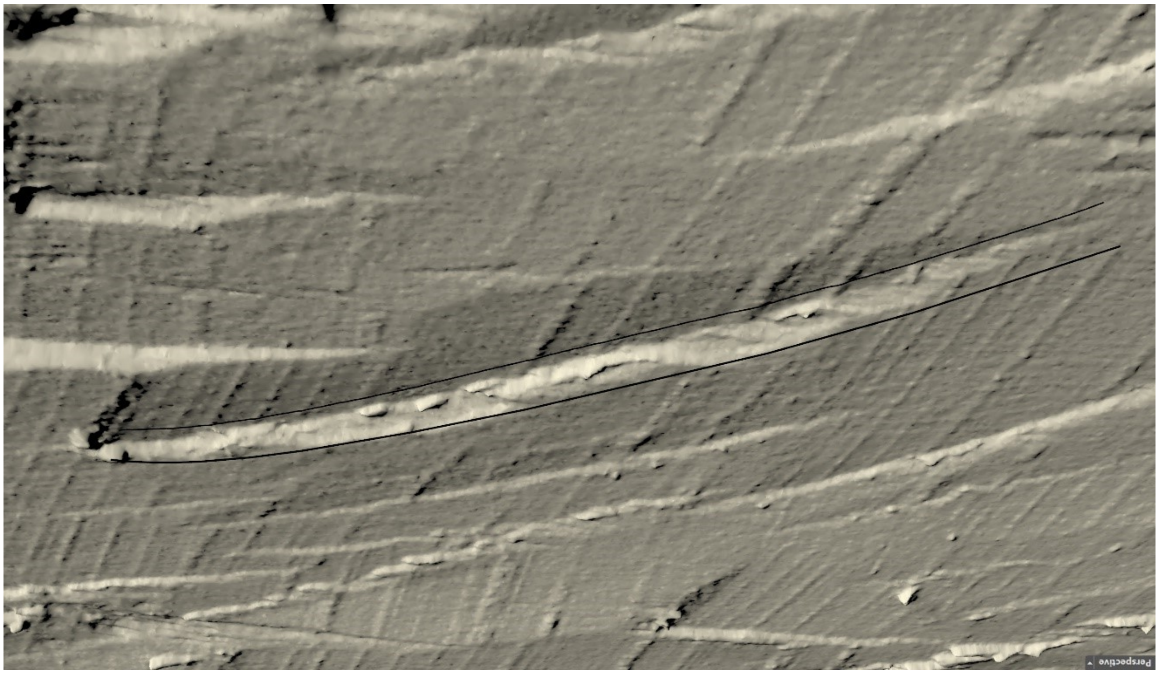

Figure 99. Traced axe mark with signatures in Rhino

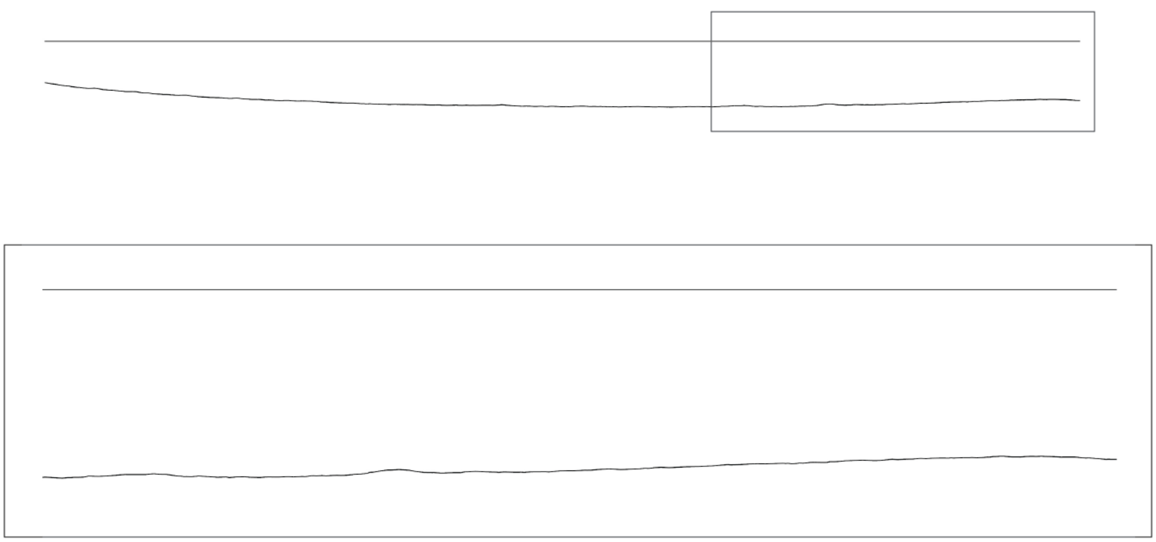

Figure 100. Projected signature profile

This work shows that capturing axe signatures can be done using photometric techniques. This experiment should be extended to make geometric comparisons with the axe edge while trying to precisely reconstruct the geometry of the axe.

This last experiment is the best illustration of the importance of craft knowledge to the conservation engineer/metrologist/surveyor. When initially scanning the timbers for tool marks, I had minimal knowledge of timber tool marks—how they were made and how to recognize them. I merely used photogrammetry to scan timbers to see what I could get. It is important to know what to measure before measuring it. This became clear during the collaboration with Algonquin College and Corey Pool, while personally practicing the timber fabrication process. The initial statistical methods of edge reconstruction were not good enough, I knew this due to my craft understanding of hewing—axe mark shape, direction, variation, etc. Then by shifting to a more appropriate tool—reconstruction via signature marks—we may achieve a reconstruction of axe geometry. This application of craft in science leads to the ability to accurately conserve our heritage—accurate in the both the metric sense and the historical sense.

4 Chapter: Conclusion

4.1 Conclusion

This thesis looks to the guidance international principles in repairing historic timber structures—supporting both tangible and intangible aspects of timber conservation. Using the repair of the Perth Red House Timber Frame as a case study, I hit three main points from the ICOMOS International Wood Council's *Principles for the Conservation of Wooden Built Heritage*:

3) "Invisible" (hidden) marks on old wooden parts must also be recorded. "Invisible" marks refers to features such as scribe marks, level and other marks used by carpenters in setting out the work (or in subsequent works or repairs) and which were not intended to be visible features of the structure.
Interventions

14) Any replacement timber should preferably: a) be of the same species as the original; b) match the original in moisture content; c) have similar characteristics of grain where it will be visible; d) be worked using similar craft methods and tools as the original.

34) It is essential to record, preserve and recover the traditional knowledge and skills used in constructing historic wooden architecture.
(IWC, 2017, pp. 2-5)

I address principle 3, by developing a photogrammetric workflow for documenting timber surfaces, at variable resolutions. The photogrammetry is used to augment the process of metrically reverse engineer the craft methods and tools used to work the timber. This allows for the future repair of the structure to be completed as per principle 14. In addition to recording the tools and tool marks, a recreation of the craft process is recorded at multiple time scales—allowing for the (principle 14) preservation and recovery of traditional knowledge and skills.

4.2 Future Work

4.2.1 Variation of Tool Marks

The one thing these experiments need is more data and variation of the data. Particularly variation on sizes, shapes, and regional differences of broad axes, variation of hewing height, hewing direction, left vs right-hand hewing, and timber size. These can help paint a broader picture of the idiosyncrasies of different broad axe marks.

4.2.2 Axe Signature Matching

In this thesis so far, axe signature marks were only shown to be captured using photogrammetry. There is greater potential for using the signature marks in matching the edge marks for reconstructing the edge profiles. This seems more promising that the statistical methods used to estimate the edge width.

4.2.3 Automated Tool Mark Recognition

The previously described method of manually tracing tool marks is prone to human error, and a more computerized method may offer a more robust method of finding tool marks. Initially, with automated recognition in mind, one super hot method—at this time in history—is machine learning.

Kovács & Hanke (2013) have already attempting to address the issue of tool mark recognition using GIS watershed analysis. Inspired by their work, a topography Rhino plug-in was used in some preliminary tests, on a segment of a photogrammetric mesh. The challenge was to avoid pooling in the mesh noise which causes a multiplicity of watershed areas.

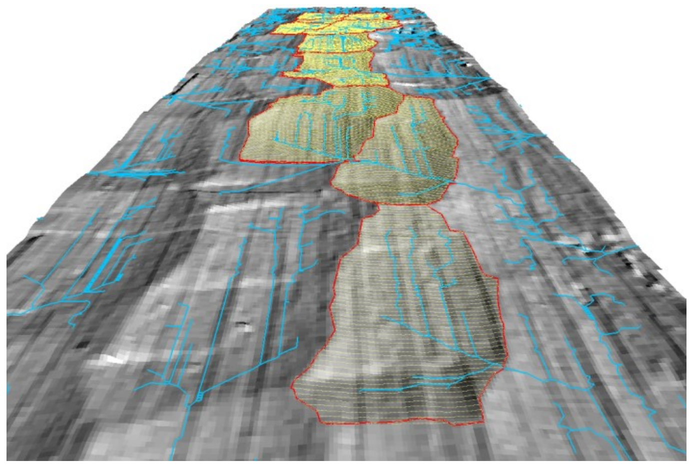

Figure 101. Visualisation of the selected tool marks in 3D GIS environment - blue lines: calculated stream network; red lines: the facets, the boundaries of the predefined polygons; yellow lines: the extracted cross-sections (Kovács & Hanke, 2013)

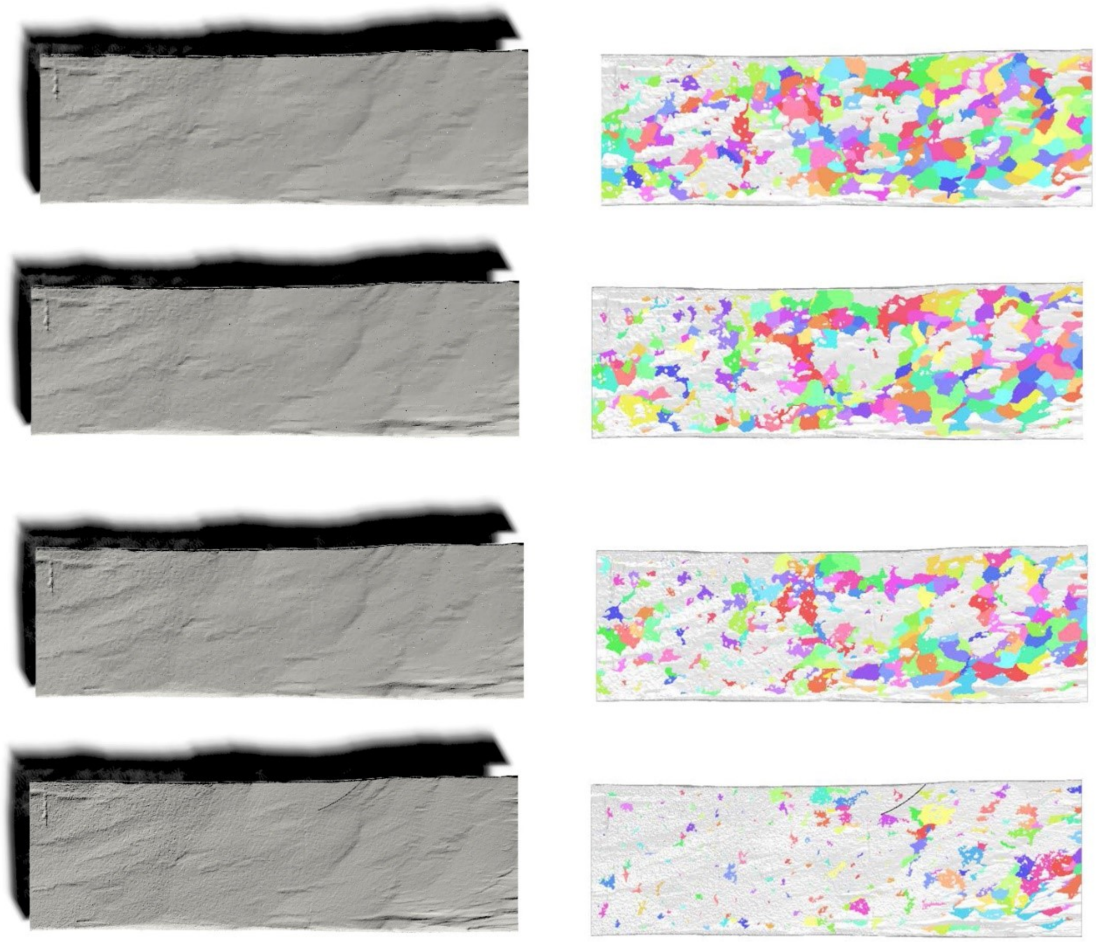

Figure 102. Watershed analysis on photogrammetry of tool marks with varying mesh smoothing

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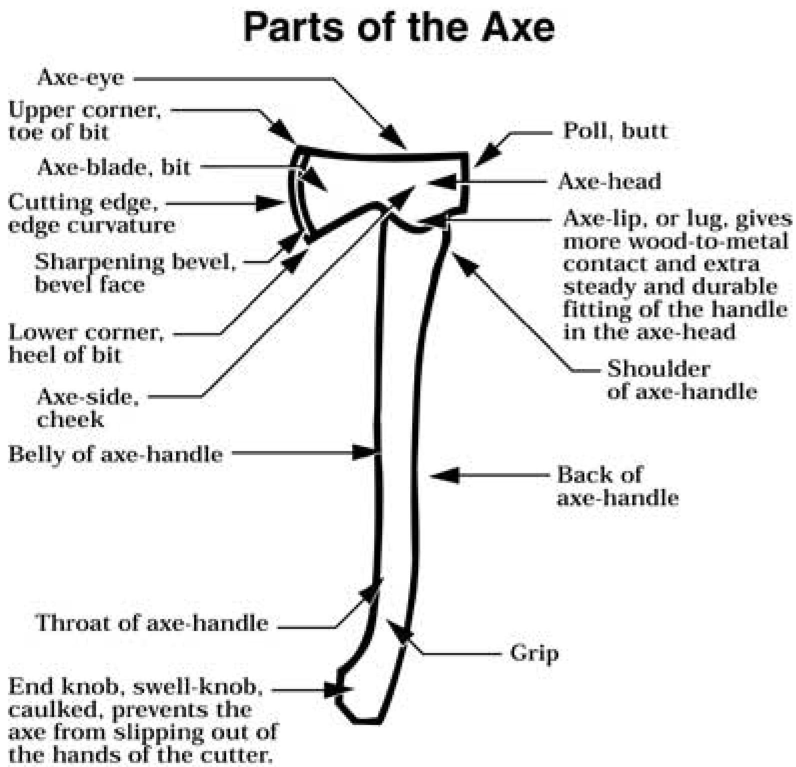
GLOSSARY OF ILLUSTRATED TERMS

G 1.   Notching timber in hewing process

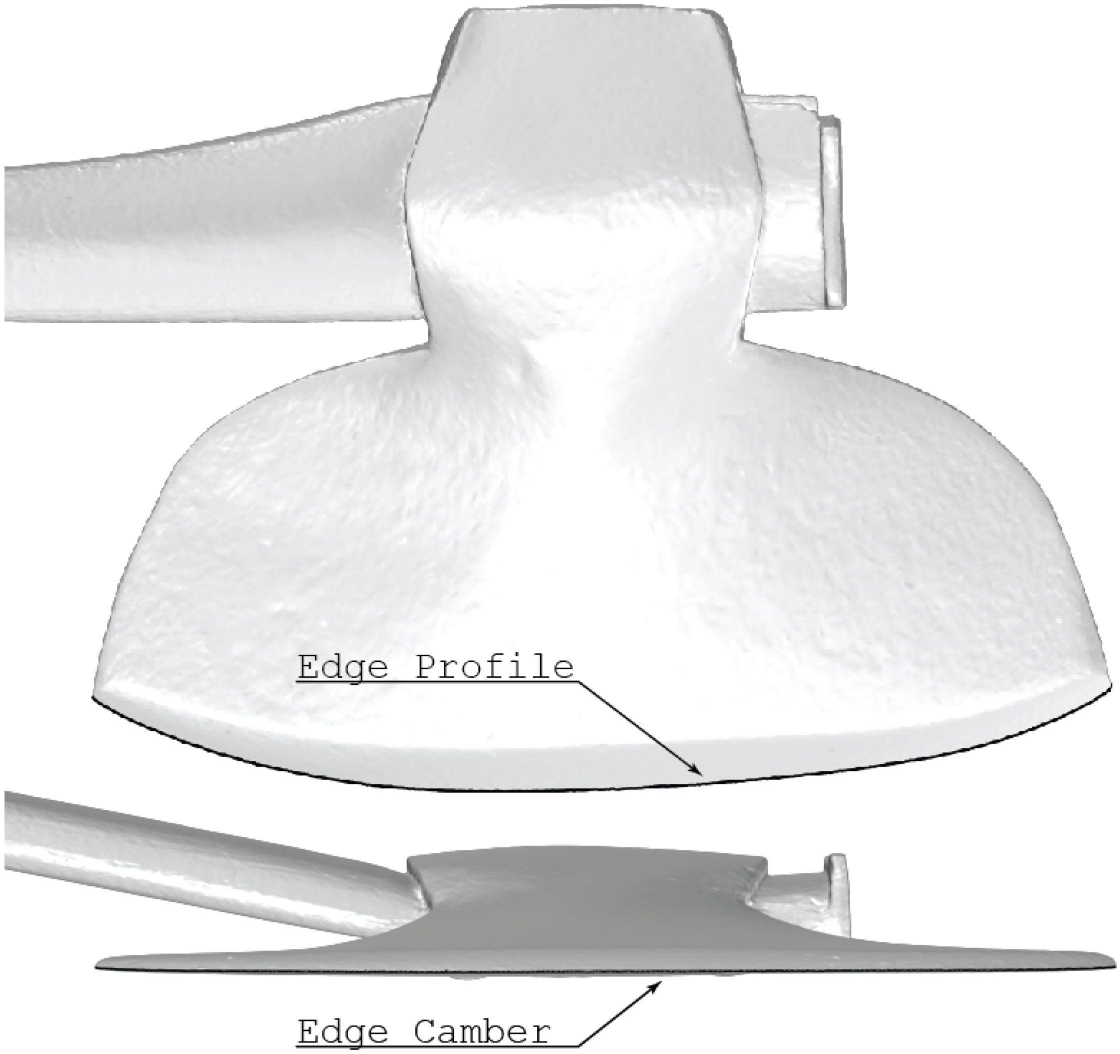
G 2.   Hacking blocks/removing waste in hewing process

G 3.   Scoring timber in the hewing process

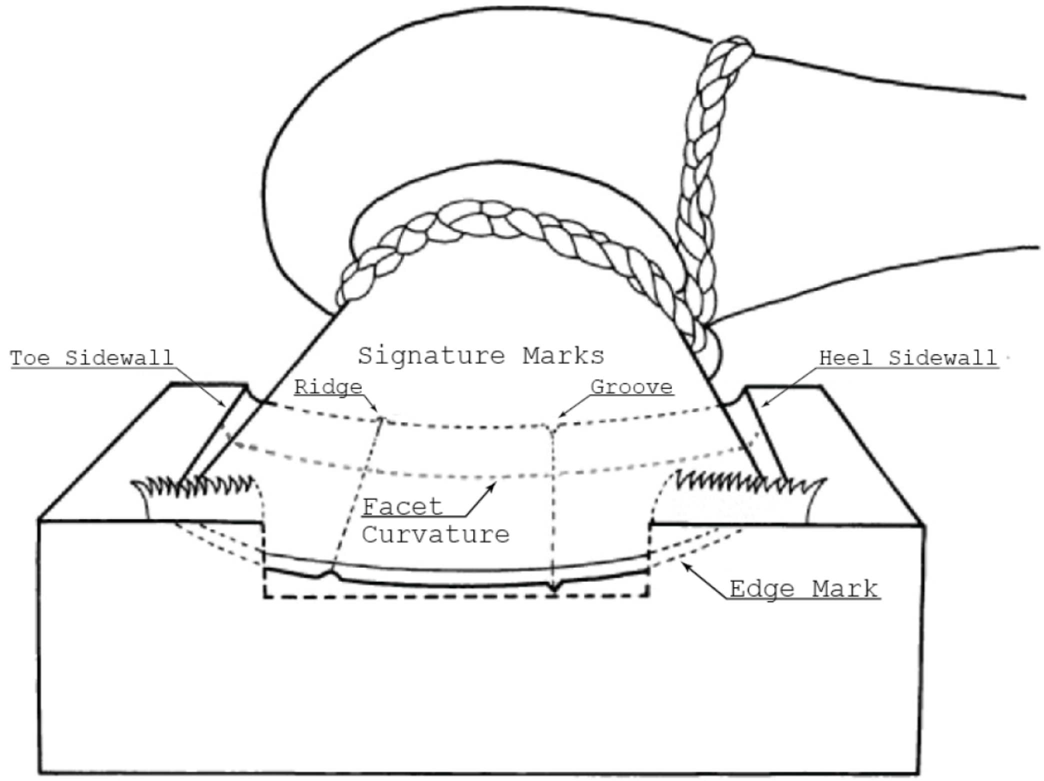
G 4.   Hewing timber in the hewing process



G 5. Anatomy of an axe (Weisgerber, 1999)



G 6.   Broad axe edge terminology



G 7. Anatomy of an axe mark (Sands, 1997)

G 8. Recognizing hewn timber