Investigations into the Dyeing Industry in Pompeii

Experimental Archaeology and Computer Simulation Techniques

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Cover: Replica dyeing apparatus, constructed 2002, based on Vat 5 in Property VII ii 11 then Vat 5 in Property VII xiv 17 in Pompeii. Photograph: author.

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To my family and to my friends, who encouraged and supported me to be whatever I wanted to be.

To everyone who got me through in tempestuous times...
Thank you. I wouldn't be here without you.

'Your years at Bradford will be the most exciting of your life.'
Freshers Guide, 2002.

'The temptation, when a problem arose, was always to reach for the volume of Vitruvius, conveniently to hand, rather than go to the site, often inconveniently distant, to look at the actual remains, much less, to cross the quad to that, psychologically at least, even more distant ultima Thule, the Faculty of Engineering.'

A. Trevor Hodge, 1992.

'If a Stone Age Man could have come to life again and seen the models I made, I expect he would have flung himself down and laughed until he cried. That is why I call it experiment in reconstruction. No one was going to catch me saying that I intend to build a Stone Age house as it really had been, but only as it might have been.

Now here is the problem that I was faced. Try it for yourself before I go on to tell the story of what happened and how I fared.

Figure 2 is an archaeologist's plan of the site on which I based my experiment, and includes information given in his report on his excavations. See if you can reckon from this how the house would have looked, which is what I had to do. Figure 3 shows how I made a model of house B on the site. If you think that you can do better than mine, all right, or if you feel mine are better than yours, I won't quarrel with that either. It will just show how difficult it is to arrive at the truth, or how many possible ways there are of interpreting facts.'

Hans Ole Hansen, *I built a Stone Age house*, 1959.

Archaeological experiments ... 'generate powerful memories and infectious enthusiasm that persists for life'.

Marion Blockley, 1999.

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Acknowledgements to this publication

There are far too many people to thank individually here but a special mention to my husband Christopher.

Preface

The following text constitutes the publication of my PhD thesis, submitted and awarded by the School of Engineering at the University of Bradford in 2007. The PhD expanded from a BSc dissertation that was submitted and awarded by the Department of Archaeology at the University of Bradford in 2002. Following the award of the PhD, research has continued, which has been subsequently published, but this is the first time that the contents of the PhD have been made available. The PhD material includes the previously unpublished full data that formed a basis for further research, such as the gazetteer of the dyeing apparatus and workshops in Pompeii.

Every study is undertaken within a theoretical, cultural and technological context, which influences its approach and findings. This context is intangible and if left unrecorded will become lost over time. To explore and record the context of this thesis, a 'Chapter Zero' has been included in this publication, which follows this preface. This could only be written after time had passed, allowing reflection through hindsight.

Throughout Chapter Zero, there is reference to the 'study' and the 'thesis'. The 'study' is viewed as the whole study, beginning with the BSc, which then expanded into the PhD, then continued through further research until the present. The 'thesis' refers to the PhD only, part of the wider study. The PhD stands alone as a discrete body of work submitted for examination at PhD level in 2007. The thesis refers to itself as the 'thesis' throughout Chapters One-Eight. At the time of writing the PhD (2002-2007), the BSc had been awarded (2002) and an article published from it (2005). It was not known at this time that further research would occur after the PhD was awarded, so reference to the 'study' within the thesis refers to only the BSc and PhD together or the PhD, depending on context.

Heather Hopkins
November 2019

Chapter Zero

Preface to the published thesis

No study stands alone – all are affected by the context in which they are undertaken, which may not be explicitly recorded in the final work. This 'Chapter Zero' aims to give an overview of the context of this study so that these intangible factors that affected its approach and methods do not become lost.

This context shall be explored through:

- Introduction
- How and why the approach of this study differed
- How location and time affected this study
- Overview of the study
- New approaches within this study
- Expansion since the doctorate was awarded

Introduction

In the time that has passed since this thesis was written much has changed, allowing reflection on its findings and its context. This publication gives the opportunity to update it, presenting it with a more modern approach to a new audience who would receive it differently. But that would be a dis-service. This thesis stands as a single discrete body of work, submitted for examination at PhD level. It was written within the wider context of academic knowledge and belief of the time, which it now forms part of. This study's findings withstood scrutiny from three academic fields, when ordinarily it would have been required to withstand only one. Any update now could be disproved in the future, while this study stands as it is, a solid foundation for further work.

Each doctorate should 'add to the body of humanity' through findings and approach – the first question during the viva was whether this study had done that. This study used a new approach triangulated between three academic disciplines to answer a previously unanswerable question, while being undertaken in a university with a unique history from which the study could benefit. This also coincided with an exciting time in the evolution of technology, which included the advance of home computing and the birth of the internet. At the time of writing this thesis, these were ongoing developments with an outcome that was not yet known, so it is only now that it is possible to look back and place the study in the context of the time and place it was undertaken. Without doing this, the wider factors and events that affected the approach and findings would be lost.

This introductory chapter complements the thesis which provides more detailed explanation of term and ideas cited below, and a full list of references.

How and why the approach of this study differed

The study took a new approach, moving from a classical question into archaeology then on into engineering, first theoretically, then literally as the author moved from a Department of Archaeological Science to a School of Engineering. To ensure academic integrity, the study was supervised throughout by academics in Archaeology (experiment and textiles) and Engineering (materials and thermodynamics) both at the University of Bradford, and Classics (Roman Pompeii) at the University of Oxford. After graduating with BSc in Archaeology the author sat modules in engineering and mathematics in the School of Engineering at the beginning of MPhil. Applying experimental archaeology to understand Pompeii's dyeing industry was new, but moving between departments to undertake the study was itself also an experiment. Each part of the study had to be accessible to supervisors with no background in that area, and the author, with no A level mathematics or physics, had to research and write a thesis in engineering. This explains why a thesis that would ordinarily have been five-six chapters in length is eight chapters and five appendices. As this includes the origin of the data used, explanations of engineering equations that are accessible to classicists and a publication of early results, the thesis is a whole greater than the sum of its parts and has been heralded as a good step-by-step introduction for anyone with a phobia to science.

The inclusion of multiple disciplines allowed the study to self-challenge, triangulate and calibrate its data and findings. Early criticism made the study stronger as each was deconstructed and robustly challenged. These diverse inclusions allowed this study to form a robust foundation and springboard for further work, moving in unpredictable ways, continuing to reassess and develop while remaining unsurpassed. The publication of this thesis allowed an opportunity to update the thesis, but it was decided that as it is a discrete body of work forming a single examination piece it should stand unchanged. Instead, this has been taken as an opportunity to explore what has altered within the study and its context.

Experimental archaeology is a discipline in its own right, falling under the umbrella of archaeology.

Previous examples of applying physics to archaeological questions do exist, but the majority are so scattered, specific or dense that they cannot be used or applied to other artefacts. This study provided a broad walkthrough of a worked example that can be applied to other work and during planning of the replica it was discovered how much such examples are needed: participants from the school of engineering had to be informed that cooking potatoes in the firebox was inauthentic as the Romans did not have potatoes, while classicists had to be shown that painting wood to match brick aesthetically does not help find the fuel required to heat brick as wood and brick do not react the same thermally, or to a naked flame. In the School of Engineering, the study has inspired exam questions and dissertations in heat and air flow, as an unseen example that requires application instead of simple recitation from a textbook. The apparatus was found to be 20% efficient – the archaeologists felt this was wonderful, the engineering felt this was shockingly inefficient, showing the difference in viewpoint from different schools of the same finding. Dyeing in Pompeii was 'pre-industrial' but was still an industry, with skilled business professionals operating specific apparatus in dedicated workshops. A paradigm shift allowed archaeology to appreciate the skills involved and engineering the difference in scale.

When Finite Element Analysis was introduced into the study to allow a digital reconstruction of the physical apparatus, the study became too technically complex to be supported in the Department of Archaeological Science and so moved to the School of Engineering. Issues with compartmentalising and publishing are problematic, especially as the first person in a new field has nowhere to publish – the analogy is the Wright brothers' first flight being documented in 'Gleanings in beekeeping'. Moving to engineering allowed an expansion and greater in-depth exploration of technical questions that had an overall impact on the dyeing industry. The linguistic differences between archaeology and engineering, both constructed on empirical science, highlighted differences in approach, method and how comprehensive answers could be: when asked the method of 'How does a car work?' an archaeologist could describe inserting petrol, while an engineer could lift the bonnet and describe the engine. When asked how a dyeing apparatus worked, an experimental archaeologist can add fuel to a replica and watch the heat move through it, while an engineer can see how the heat moves through the lead at a molecular level. This highlights the difference in mindset between understanding and approaching an artefact on the 'macro' (archaeological) or 'micro' (engineering) level. To construct a more complete picture, this study had to explore and combine both. Now it is possible that an experimental archaeologist would also explore an artefact on the micro and macro level, but at the time this study began, moving to engineering was a new idea, part of a change in wider mindset without which experimental archaeology would not view 'engineering' techniques as accessible or normal.

How location and time affected this study

Location

Where a study is undertaken is important. This study was undertaken at the University of Bradford and would not have progressed as it did if it had taken place elsewhere. Ordinarily, the experiment would have been situated on moorland owned by the university, meaning that all participants would require ferrying to site. The author could not drive so the experiment was sited on campus land within the boundaries of the inner city. The first apparatus was constructed in 2001, at the time of the Bradford riots and no objection was made by civil or university authorities to a small, controlled fire within a smokeless zone when the daily news was of other areas within Bradford already being alight. The experiment required full wool fleeces. The Wool Board storage depot of the North of England was on the road running through campus and due to a recent economic downturn they were giving fleeces away. This provided the wool and also meant it was possible to see the size and scale of the storage required for one year's fleeces. Bradford was documented as having the cheapest cost of living in a university town or city in the country which meant that after AHRB (Arts and Humanities Research Board) converted to AHRC (Arts and Humanities Research Council) and cut funding of projects involving experimental archaeology it was possible to continue as a self-funded student. Although distressing at the time, this financial release gave the author freedom to move between academic departments, following the development of the study. Furthermore, the school of engineering specialised in automotive engineering and has existed since the 1960s, an era of change in automotive design, so possessed the original ergonomic data from a demographic match of Pompeii. The presence of the discipline of 'forensic archaeology' also allowed complementary interpretation of skeletal remains.

The only immediate disadvantage with the choice of experiment location was that it was between a children's nursery and a cancer research department, so releasing fumes and steam from chemicals boiled in lead was not feasible. The aim of reconstructing the apparatus was to see how heat transferred through it, so this issue was resolved by using a physical, thermal replica of lead: stainless steel. There was criticism that it was not an aesthetic match, but this was not required as this had no bearing on its physical behaviour. Modern

bricklaying mortar was used instead of lime mortar: this had known properties, was a thermal match to the Roman lime mortar and had the advantage of being less corrosive to skin. Later work, subsequent to the thesis, found that a stainless steel replica could not be used to explore creep or the chemical effect on dyes, but these factors were not part of the original question so the replica was valid when it was constructed. The closest previous reconstructions were by John Edmonds at the Chiltern Open Air Museum who explored dye chemistry and a replica of cooking apparatus from the Mary Rose constructed by the Mary Rose Trust as a public demonstration of cooking methods below decks, to inform and entertain. This study was the first to construct and use a replica dyeing apparatus from Pompeii, and was the first attempt to investigate cycle time: it was discovered that the apparatus could be used once per day, due to it taking at least eight hours to cool, used 7.5kg of pine to heat, and allowed 8.8kg of fleece to be dyed per person annually in Pompeii.

Study in the context of time and technological developments

During the first week of the first year of the undergraduate degree of BSc Archaeology in 1998, the class were taken into the library, sat in front of computers and taught how to write an 'e-mail'. None of us had used 'the internet' before. The author's dissertation, written in 2002, was typed on a word processor and saved on 3.5 inch 1.44mb floppy disk, which unusually for the time were DOS compatible and so could be edited using a computer with Microsoft word. Sat typing at a laptop now, the last twenty years of work is backed up on a 16gb datastick. At the beginning of the undergraduate degree only students of computer science owned computers, but at graduation four years later the author was one of very few to not own one. Private internet use was also still beyond the finances of most students – to use the internet, students went into the library on campus to use the institution's computers and internet connection. The author was ordered to buy a computer before beginning the MPhil in 2002 and bought a 20gb hard drive laptop affectionately called 'Doorstop' as the screen was easier to see – prior to flatscreen monitors this was a serious consideration. It was one of the last laptops to feature an inbuilt floppy disk drive. The author's first data stick was bought in 2006 near the end of the PhD and during the world cup in Germany: after waiting for the technology to stabilise, a spherical football shaped datastick was bought, in the hope it would not get lost.

At the start of this study, the classicists involved were technophobic, distrusting any answer acquired through the aid of computing. This extended to Finite Element Analysis, hence the move to engineering. Now, having presented at conferences, it is possible to see the new generation of classicists, who even the most technophobic of which are used to having emails, facts, photos and answers literally 'to hand' through their phones and who have grown up seeing computer games. These same researchers now value network simulation and visual reconstructions as they have purpose and are familiar. Archaeological Sciences is respected and complements wider scientific disciplines, while experimental archaeology and digital humanities are now taught as disciplines in their own right, so other disciplines, including classics, are more accepting of them. There is still confusion as to the role of physical digital reconstructions, possibly because the extra specialism required still falls within the realm of engineering, not digital arts. There is still a reliance on older theories and the belief that an older answer written in the Victorian era or by Pliny must be right as it is already 'established', regardless of whether it withstands scrutiny, which means that digital studies may still be based on erroneous data. Moving away from physically testing artefacts raises the question of what has been lost and what may be lost in the future.

This study taught to beware of sweeping statements and belief that any finding, method or technology will be the last of its kind. In 2001 Monaghan said that contemporary dyeing recipes had not been found, a statement which may be true at the time, but becomes more unsafe as the internet becomes ubiquitous. This is a mixed blessing as data and publications that were thought to be lost and which were otherwise unavailable can now be uploaded and downloaded to be kept in perpetuity. In 2007, when this PhD was awarded, internet use was in its infancy with national institutions having the same online presence as private individuals writing unfounded opinions as 'fact', so relying on internet sources was an automatic academic fail. In 2017, when studying an unrelated MSc, the roles had reversed so that reliance on books and journals was deemed as failing academically as information gained from the internet can be continually updated and demonstrably linked to authenticated resources. 'Digital' photographs were also in their infancy in 2002, so the survey was recorded digitally and with film. The digital copies were initially allowed for publication but now early digital photographs do not have high enough resolution and instead scans of film photographs are sometimes used. This highlights how unpredictable the future is.

Development of experimental archaeology

True experiments, that seek to prove whether something was physically possible, can fail. In the 1960s the Ra I sank, revealing that the design had not been properly understood – the Ra II voyage was successful. The Sea

Stallion, built in 2008, continued this tradition when it sailed across the Atlantic, finding that although the ship moved at speed it could not stop without resting against a quayside or on a beach as the design meant it would fall over if it moved too slowly. This contrasted with the contemporaneous Matthew, which sailed the Atlantic with great publicity, meeting the Queen when it docked. Public involvement in experiments of such large scale and cost mean that they cannot be allowed to fail, which arguably undermines their experimental quality, turning them into inaccurate replicas. Both ships had to meet modern navigation requirements. The Sea Stallion did this by sailing with a support ship, allowing the replica ship to be authentic. The Matthew, a replica of a 15th century ship, had satellite navigation fitted, which did not alter its handling, storage or living space, and an engine with fuel which did.

Modern experiments must meet modern health and safety requirements, which may limit or alter which experiments can be undertaken. FEA (Finite Element Analysis) allows replicas to be tested, with failure speeded up or slowed down, and poisonous or prohibitively expensive materials to be avoided. During this study it was not possible to make replicas from lead, but it was possible to use thermal replicas to get the data regarding heat transfer then digitally model them to be made from lead. Digitally it was also possible to change the shape and size of the apparatus, alter the ambient and firing temperatures, speed or slow time, then repeat dyeing cycles until the kettle broke, slowing the moment of breakage to understand how it happened. This would not be possible with a physical replica and shows a positive way forward for experiments to develop, allowing greater understanding overall.

When this study was presented at an Experimental workshop in Edinburgh, two railway specialists commented that, 'Lead doesn't act like that.' Their views as experienced craftspersons must be considered, but when asked they could not say how it would act instead. To date, no one has built a physical replica and used it to destruction – that is an experiment yet to be undertaken.

Overview of the study

Background to this study

Prior to this study, all previous understanding of the dyeing industry of Pompeii was based on a single survey undertaken by Moeller, published in 1976. Moeller's conclusion that Pompeii's dyeing industry was large enough to export was immediately challenged by Wild who said that Moeller had not produced the evidence for this. Subsequent studies, such as Jongman, used the same survey evidence to demonstrate that the dyeing industry was so small that Pompeii relied on imports, but each study used the same survey, without challenge or review. Some authors, such as Laurence, side-stepped the issue by focusing on the economic context. The diversity of the findings demonstrated that a significant factor was missing from the wider understanding. This study realised that each author had been attempting to calculate the size and scale of the industry through a purely theoretical understanding of the processes involved applied to a superficial measurement of remains. When this study re-surveyed the remains, it highlighted a further issue of authors not revisiting the site with practical knowledge: Moeller had found 33 dyeing apparatus in 1976, Janaway and Robinson found 40 in 1994, this study found 35 in 2002, not including one that Moeller had erroneously included.

This study began as an undergraduate dissertation, academic year 2001-2, then expanded into MPhil then PhD, awarded December 2007. The original aim of this study was to discover the size of the dyeing industry of Pompeii to allow an understanding of its economic role in Pompeii and Pompeii's role in the wider Roman world. It was realised early on that many influencing factors were intangible and ephemeral, such as laws, economics, customs and social convention, each of which could remain undiscovered or change immediately with a new find. To develop an unchanging answer, a solid foundation, this study decided instead to develop an understanding of the physical capabilities of the apparatus, then define how each tangible or intangible factor could affect it. This study was the first to reconstruct and use a replica of a dyeing apparatus from Pompeii, to see its capabilities, limitations and method of operation. The figures gained, such as fuel required, temperatures reached and time taken, will stand until intangible findings are able to refine them, without time limit. The Romans did not dye whole fleece, use pine offcuts for fuel or dye with modern tap water – these were 'holding values', known analogies to be replaced when the real quantity of wool, calorific value of fuel or content of water were become known. It still is not known if wool was dyed in the fleece, yarn or fabric, or the rate of re-dyeing. The fuel type was believed to be charcoal on economic grounds, but practical experiment and engineering theory independently demonstrated that there was insufficient oxygen to burn it. Understanding the water quantity and type required allowed exploration of the water content, source and storage needs. The recipe was an amalgamation of pre-industrial methods derived from textile finds, texts and practice to dye wool with madder and alum, the most common materials believed to have been used, as discovered through contemporaneously textile finds from across the Roman world. These were deconstructed to find the common activation points – dyeing will not work without the correct time,

temperature, pH, water content or kettle shape. The study began before widespread use of the internet so the author only had access to British publications or selected German or Italian translations. The scale of an industry can only be known from comparing its size to the size of population it supplies. After reviewing contemporary literature, this study based comparison on Pompeii having a population of 12,000 people, despite figures in the academic literature varying between 8000 and 20,000 people. Each new finding meant recalculating the industry, but this just made the study more accurate.

Since completion this work has been presented and published widely. This has highlighted the importance of disseminating work, allowing other disciplines to evaluate it: mysteries have been remedied, mistakes realised and unrecognised assumptions challenged. Presenting has also allowed expansion, making a stronger study with fuller answers. One person's mystery may be another's daily routine, which can bring answers or spark new questions to answer together (see below).

New approaches within this study

Surveying the original apparatus in 2002

Constructing and using a replica based on the 1994 survey gave a practical knowledge and findings that allowed the dyeing apparatus in Pompeii to be re-surveyed in 2002. This formed the basis of expanding the dissertation (2002) into MPhil. The survey included where properties were in the city, the property size and layout, water supply, apparatus number and their location. These were measured accurately, documented in writing and recorded through photographs. If all factors influencing output could be known or allowed for, the process would then only be defined by time. Understanding the apparatus size and dyeing cycle time allowed storage requirements and supply process to both be explored, such as whether the industry relied on 'Just In Time' supply – organisational arrangements that mean only the immediate resources required for a manufacturing process are present, with next resources delivered 'Just in time' to allow the process to continue, meaning that storage requirements for each work station (e.g. dyeing apparatus) are kept to a minimum. Findings indicated that if dyed whole, space would be required for up to 54,000 fleeces annually to supply Pompeii, but in reality only the finer quality parts of fleece were dyed, suggesting storage requirements for a far larger number.

Understanding operating parameters allowed a set of polythetic entities of a dyeing apparatus to be identified. Apparatus were surveyed and ergonomically assessed, which allowed identification of apparatus that were missing features, had additions or had otherwise been amended. All remaining kettles were lead. Dyeing apparatus braziers were either flued or unflued. An apparatus that Moeller identified was discounted as it could not have held a kettle. Three apparatus were found to have been heightened, indicated by a change in cement and a geometry that would have resulted in too high a pressure on the lead kettle during use. Sympathetic conservation was identified where walls had collapsed and kettles cemented into place to prevent their loss.

Pompeii can be compared to a ship wrecked at sea: everything required for it to function had been present – the size and number of dyeing apparatus and workshops present would have been the number the city required, the number altering with economic viability. Archaeology explored the kettle geometry as a complementary interest, while engineering actively sought to understand it. The geometry of the kettles showed that they were of comparable design regardless of size, with comparable pressure on the base when in use. This appeared to be a deliberate design. Prior to inclusion of computer simulation into the study, this was calculated by making paper templates. It is unknown to what extent the dyers knew of creep and whether the chamfered edge of the brick support in some apparatus is an original feature. Later it was noted that the design matched purpose-designed kettle for dyeing yarn, not fleece or fabric – again it is unknown if this was deliberate. Several kettles had taps passing through the brazier which meant that they were emptied, cleaned and filled *in situ*.

The survey in 2002: water supply

Pompeii's water supply is well preserved, resulting in diverse studies, one of which is used (by Hodge) to show the importance of returning to the original remains before reporting findings. Hodge is quoted at the front of this thesis. New findings should challenge or complement existing theory and sometimes there is no apparent alternative. Hodge and the author share learned behaviour that would have made using Pompeii's lead-lined water supply safe: to ensure that the water is flowing fresh from a mains supply before drinking from it by running the lead contaminated water through the pipes first. In Pompeii the water supply was continually flowing, while also cleaning the streets as it overflowed from fountains, two actions that improved the population's safety from lead poisoning and disease. Running the water for long periods before drinking it is a behaviour now lost to a modern generation who view it as wasteful, especially since the advent of water meters, showing how dangerous it is (theoretically and literally) to apply modern squeamishness or values to

an ancient problem and solution. In 2002 during the survey in Pompeii, when faced with a choice of drinking from the flowing lead-piped fountains or the modern supply containing stationary sections and sewage from a recent flood, the author chose to drink from the lead. Like witnessing the birth of the internet, the author has also witnessed the loss of lead use in plumbing and the learned behaviour that made it safe – the author's housemates did not know to run the water in a Victorian house with suspected lead pipes in 2002 and felt it wasteful until they realised.

Originally it was believed that the Roman population were at risk of lead poisoning through their water supply. During the 20th century this was disproved through a better understanding of the water supply, focusing on the use of hard water which coated the lead pipes with cinter. Subsequent excavation in Pompeii and newly available tests undertaken since this thesis was submitted have again disproved this by showing that skeletons in Pompeii did contain lead which is believed to have accumulated before cinter was able to develop after new lead pipes were added to the system (e.g. Keenan-Jones et al, 2011). This does not change the context of Vitruvius' findings: lead workers are notably unwell through working with lead, but dyers are not. It is probable that lead leaching from new sections of pipe into the water supply and being absorbed by the population was at such a low level that its accumulation in the population went unnoticed. It is possible that Pompeii's population may have absorbed lead from other sources.

The survey undertaken in 2002 allowed the location and provision of public fountains to be explored in relation to the location of the dyeing workshops, the water storage requirements and possibilities of workshops to be investigated, and the identification of drainage slots in workshop doors that allowed dye liquor to be disposed of into the streets. The liquor would have been washed away by the fountain overflow. Further mysteries about water supply remain, such as pipework being found below a dyeing workshop (by Borgard): it is not possible to tell where it runs from or to, just that it is present.

The survey in 2002: finding a 'Real Roman'

One criticism levelled at the study was, 'You can build what you like – you can't find a real Roman to use it.' Answering this was irritating at the time, but allowed a better analysis and understanding of the Roman population and the apparatus through an ergonomic assessment, leading to a stronger outcome. Skeletal data from Pompeii and Herculaneum was reviewed and the forensic application of ergonomics was examined. Ergonomic data is not the same as skeletal data – bridging data, that matches the skeletal data but comes from a living population, must be used. Coincidentally, Pompeii and Herculaneum's populations matched the USA population from 1900-1960. In the 1960s, through improved food and lifestyle, the USA population increased in height. This coincided with an increase of women driving and entering the workforce. To cater for this, there was a sudden need for an ergonomic understanding of an increasingly diverging population. One result is that there is now a complete dataset available that can be used to represent Pompeii's population, gathered from car manufacturers, the World Health Organisation (WHO) and the US army.

During the survey of dyeing workshops undertaken in 2002 as part of this study, some of the dyeing apparatus were found to have steps. These could only have been used by children. This finding was rejected for publication (Papers for the Institute of Archaeology in 2013) because it was already assumed that children had been present, so publishing evidence demonstrating that they had was felt to be unnecessary. This shows the need for publication of all findings – such presumptions remain either unwritten or without evidence and unchallenged. This study is the first to identify steps at all, let alone to provide physical evidence of the presence of children. Finding that there had been children in the dye works fits Temin's theory that dyers were released on contract and remained within the workshop – close to their family and prevented from competing. This poses the question of the financial and social value of dyers, and if this was altered by needing additional business skills. An example cited is Pliny's speech writer who although a slave was sent to recuperate from illness at Pliny's country villa – the treatment of a skilled but stained professional slave or freedman is unknown. The skill required to dye accurately without thermometer, pH meter or precision control over the apparatus should not be underestimated – theory changes but the skills required do not. Children born to dyers would grow up within the environment proficient in dyeing, becoming skilled adults.

Saying that a Roman dyer cannot be found but a Roman can sounds reminiscent of Functionalism and Middle Range Theory: assuming that a modern person will respond to a situation with the same logic as someone in the past. This study produced a physical replica of a Roman, not a skills replica. Again, like experimental archaeology overall, it does not show what happened but what could have happened – it gives boundaries to what is physically possible, which the true answer will be contained within. These boundaries should also allow that dyers would have been acclimatised to the dye works and that WHO recommendations may be broken in practice, meaning that dyers may have managed more than theorised possible. But conversely,

dyers may not reach their full genotype height if a reduced dietary intake as a slave stunted their growth and a modern individual may have a more sedentary lifestyle than a Roman dyer or American driver from the 1960s. An allowance for differences in capabilities between individuals must be made.

The survey in 2002: defining 'Recording', 'Conservation', 'Reconstruction'

Undertaking the survey of dyeing workshop in 2002 highlighted a glaring omission: no complete plan of Pompeii existed until 2004. Pompeii is so large that each part had been surveyed individually, but a single detailed plan could not be drawn. In 2004 a satellite photograph and single plan drawn from the photograph were published. It was so large that standard computers of the time would crash when attempting to open it. This study had access to this plan and satellite image, but as this came through the AAPP (Anglo-American Pompeii Project) it no longer does. The new version was accepted at the time unquestioningly – it was forgotten that any new technology is only as accurate as its programming. When comparing the digital plan with the satellite photo and the survey from this study it was found that some walls, doors and windows had been moved, which was problematic for exploring storage space and airflow. This highlighted issues in older plans: maps showed fountains in different locations than where they were in reality and there was no standard way of recording multi-storey buildings or architectural features that had been known to be present but since lost. Today technology has moved further and now plans of this size may be multi-layered and 3-dimensional visual reconstructions may be devised that allow viewers further levels of understanding as they 'walk' through the city, with computers able to support this.

In 2002, this study undertook the last survey of remains. The apparatus were compromised through 'reconstruction' by 2010 when replica kettles were cemented to apparatus walls, altering airflow and heat transfer compared to the original remains. The survey and digital physical reconstruction have allowed the study to fulfil a criteria of UK commercial archaeology, to 'Preserve By Record' (Hopkins 2010). In commercial archaeology the artefacts are faithfully recorded, with the artefact and records going into the national archive where they remain unaltered, but in Pompeii the artefacts remain *in situ,* in their altered state without accompanying explanation, allowing future viewers to be misled into thinking they are seeing unaltered originals. After twenty years of erosion they will appear original or a sympathetic conservation. This does raise the question of how original the remains were when reconstructed in this study, but this was allowed for when examining them.

A wider question posed by the alteration of the apparatus is what 'restoration' is and means. During the 1970s in the UK architectural restoration had to be obvious, to ensure it was not mistaken as original. This leads to examples, such as Tattershall College, where the restored areas are brighter and more robust to erosion than the original, overwhelming it visually. Now reconstruction is more muted, but can be mistaken for the original. Examining the apparatus showed that historic reconstruction was completed by people who did not understand the apparatus but who were sympathetic to the remains and without their work the remains would not have survived well enough to be examined.

'Restoration' overlaps with 'conservation' and 'recording': each may be of questionable accuracy and alter future understanding of remains so are a mixed blessing. The survey required a faithful record and representation of misunderstood remains. Engineering required photographs and a design schematic to record what the apparatus currently looked like, any visible changes and to show how it could have operated, allowing highlight of alterations or missing parts. This was rejected in archaeology where it was felt a drawing of each apparatus would be more accurate and last longer. In addition, the ivy present on the apparatus should be drawn too even though if the apparatus had been used with it present it would have burned instantly. There were similar arguments over whether the apparatus should be painted white – there is no evidence that they were, but Borgard's reconstructions were painted white.

Undertaking the survey and wider research also highlighted recording mysteries that had either been overlooked or presumed endemic knowledge. Borgard speaks of 'The House of the Queen of England' but this was not shown on any plan this author had access to so its location remains a mystery and conclusions made about it unusable. This house may be known by a different name and already included in this study. Borgard also refers to newly discovered pipework which is not on any plan, is of unknown age and flow direction. This demonstrated the need for a single comprehensive map of Pompeii, but highlighted difficulties such as what to include in such a monumental work and how to show features that were known or believed to exist but have been lost. It is not possible to reconstruct a feature that there are insufficient records of and likewise it is not possible to excavate twice to find remains that were removed or discarded in an earlier excavation as unimportant or unrecognised. Differing styles and priorities mean that some evidence or working are not published, just the end result, so data and calculations cannot be checked. This was problematic when reconstructing Pompeii's population through its skeletons during this study and when reviewing Borgard's reconstructions during and after this study. Differing priorities causes

relevant subjects to be excluded as their importance is not understood: Flohr stated (Pers. Comm 2018) that defining the physics of how the apparatus worked was completely irrelevant as it did not show the social issues involved. This assertion missed that other researchers may be studying the physics and that the physics gives a solid framework that intangible, changeable subjects, such as social issues, fit around – only by knowing how a dye works operated is it possible to see how many people would be required.

Redefining 'experiment'

When reconstructing the apparatus, where to place the flue led to a redefining of 'experiment' for this study. The replica was unflued, copying an unflued original apparatus. To replicate a flued apparatus would mean adding a replica flue to the replica apparatus. A matching flued apparatus was found but when reviewing the survey it was discovered that apparatus with flues also had taller fire boxes as part of their overall design. In an unflued apparatus, the exhaust gases rose from the firebox, upwards between the supports holding the kettle aloft, then through the gap between the kettle and the brazier wall, being released at the top under the kettle flange. In the flued apparatus, some exhaust gases were lost this way, but the majority were drawn upwards between the supports holding the kettle aloft then upwards into the opening of the flue, which was at the bottom of the kettle. To add a flue to the unflued apparatus at the correct height but leaving the fire box unaltered would mean the flue would open into the side of the kettle, so could not draw gases into it. The apparatus would not work and it would not replicate the design of an apparatus – the experiment would be void. To alter the firebox before adding the flue would mean making two changes to the apparatus. An experiment only changes one thing at a time – the decision was made to amend the flue height to continue the experiment. The aim of the experiment was to explore the design of the apparatus, so the flue was put at a height to be workable, even though an apparatus has not yet been discovered that matches these dimensions. A matching apparatus may yet be discovered – one third of Pompeii has yet to be excavated and other examples may be found elsewhere in the Roman world. Further experiments could alter the design incrementally allowing changes to be understood. The presence of taller fireboxes on flued apparatus suggests that there had been difficulties with ventilation of the originals. The survey appears to suggest that flued apparatus were in more enclosed environments than unflued apparatus. This issue was presented at ExArc 2008 which has yet to be published. Further works are developing this idea.

Finite Element Analysis

This study constructed the first physical digital model of an archaeological artefact of more than one material and the first to model temperature. FEA had been used only twice before: modelling of strength in chimpanzee wrist bones and modelling pressure fractures in amphorae. Abaqus was the FEA program used to model the dyeing apparatus. This computer program has been used for modelling aircraft wings since 1982, so had a proven record of modelling metal failure. Modelling lead proved problematic as the data required did not exist – a study from 2000 that explored the compression strength of lead was used and data was extracted and inserted into the model by the programmer Mark Robinson.

FEA and a wider understanding of the properties of lead showed that not only had lead been chosen for its chemical properties (see below), but that the wider physical properties protected it. Lead has a different grainsize to other metals, which allows movement during temperature change, meaning that the lead will creep but during cyclical creep/strain it will not break. Instead lead will display a ratchetting effect, demonstrating that the same stress can cause different strain in different metals. If the change in lead doesn't exceed 4% it will not break. The significance of this factor in Roman dyeing is new.

When collecting data from the physical replica to use in the FEA model a counterintuitive change had to be allowed for: as fuel was added the fire initially got colder. This was because the fire decreases as the energy is used to break up the wood releasing new energy. As each dyeing cycle differed slightly, in ambient temperature, fuel size, rate of combustion for example, taking mean temperatures at certain times would not provide an accurate dataset for the model. Instead the data was examined for its activation points – tasks, times and temperatures – and a representative amalgamation was used in the model instead.

Finite Element Analysis is now used widely to test the design of objects before they are constructed physically, avoiding cost, risk and time if they fail. The test can be repeated to see accumulative damage and the object is constructed in a controllable environment, allowing external changes such as ambient temperature to be modelled. This study was able to use the digital physical replica to repeat the dyeing cycle of heating and cooling, within different temperatures of between 20°C to 40°C, mimicking the use of dyeing apparatus in Pompeii. The FEA was judged to be accurate as it replicated changes in the lead and the apparatus discovered in Pompeii.

'Roman' vs 'Modern' manufacturing

Moving to the School of Engineering allowed engineers to explore Pompeii's dyeing industry in new ways. One was to draw back from the apparatus and explore its context within the dyeing workshop and each property

as a whole. It was realised that each workshop was set out as a modern 'U-shaped' layout devised by Toyota in 1985 for vehicle production. This allowed parallel workstations (individual dyeing apparatus) to operate within a single space, while simultaneously under observation by a single person. The quantity of storage at each property suggested the use of 'JIT' (Just-In-Time) delivery and processing. For example, harvesting fleece was an annual occurrence and storing up to 54,000 fleece before use, not counting fleeces that would not have been dyed, would require a larger area than that offered in the city's workshops – they would have been stored elsewhere and brought to the workshops for processing.

Modern manufacturing uses three main methods: continuous, batch and one-off. Continuous was not possible in Roman Pompeii – it is the method by which food is manufactured and packaged on a conveyor belt. 'One-off' specialist craft production may have occurred but not been economically feasible for everyday production, 'Batch' production was most likely to be the method used – manufacturing a quantity together, such as pots within one kiln firing. Defining the method of manufacture is possible from understanding the remains, but ownership of the materials involved at each stage would dictate the rate of dyed material produced. If the dyers owned the material to be dyed, they could dye in batches, restocking as required. This may have allowed for slight variations in dyeing outcome to be acceptable. If private individuals owned the materials and requested specific colours, greater precision may be required from the dyer, otherwise the owner may reject the outcome or require it to be redyed. The question of ownership affects the quantity of material that could be dyed and would need to be answered for the output of the industry to be fully understood but as yet is intangible. This harks back to the aim of the study: to create an objective physical framework that can be used to explore the subjective questions involved.

The use of 'U-shaped' dyeing workshops and 'JIT' manufacturing was called 'old' and 'out of date' by some engineers in 2007. This highlighted again the difference in mindset: it had been forgotten that the Romans had empirically devised a system that it took manufacturers more than 1900 years to devise a second time. Line balancing is used in modern manufacturing and was also used in Pompeii. Line balancing is understanding the time taken for each part of a process, then using parallel workstations to complete tasks that take a longer time, so that no workstation is left idly waiting and the whole manufacturing process is as efficient as possible. Each workshop appears to have had multiple apparatus and specialised in a single task overall, meaning that line balancing occurred not within a single property but between properties across a city. Each workshop would have been linked to the next process, economically or by ownership, each producing, storing and feeding into the next stage. A delay in one workstation would not delay the whole workshop, a delay in one workshop would not delay the whole city as other workshops could supply the next stage. Ownership of materials and workshops would have structured production. This could have increased production making it as efficient as possible.

When dyeing, each stage is dependent on the last. To dye, fleeces should be rinsed after mordanting, but still be damp. Starting up a dyeing cycle requires 1-3 people, depending on size of apparatus and experience, but once all dyeing apparatus are alight only one person is required to watch them. Using the experimental replica suggested that if each apparatus could be used once per day, staggering start up would mean all dyers were at work, able to process each apparatus in turn as it finished, creating most output with fewest labour and people. This raises the question of the role each person took, whether there was a single dyer overseeing a workshop with an assistant and if the dyer simultaneously managed 'front of house', the customer interface and book keeping. Workshops Vi4 and Vi5 were on to the street so the public would meet the dyer, while other workshops were located within properties away from public gaze.

Intangible questions

Economic, social and pragmatic questions about dyeing operations highlight the intangible side of an industry. This study sought to develop a physical framework and understanding, but the industry would have operated in an intangible ever-changing framework of law, economics, material supply, culture, social norms and fashion, each of which will remain unknown or change as new discoveries are made. Only the contemporaneous public and dyers of Pompeii would know these endemic entities and their effect may differ between people and workshops. An example would be the learned behaviour that makes using a lead-containing water supply safe to use. Pompeii's populace did not need to know this, as the water supply of the city was constructed with the behaviour in-built – the water was continually running so was mainly uncontaminated by lead. As discovered by the author, this behaviour is nearly unknown in the modern era, giving an example of how a modern archaeologist may not understand how to use a hazardous artefact is safely, instead coming to an erroneous understanding that cannot be challenged as the knowledge has been lost.

The legal and financial framework of Pompeii will remain broadly unknown. This study had to rely on Diocletian's edict of 301 AD for a basis which could only be used to compare relative prices due to its being written more

than 200 years after Pompeii was buried. Temin likens understanding finance in the Roman world to trying to understand the workings of the London Stock Exchange from reading a single copy of the Financial Times. The Roman civilisation had an empirical understanding of economics without the modern vocabulary to describe it, but much remains lost.

Fashion remains another endemic entity and links to wider economic issues. Fabric was overdyed and redyed but the rate of this was unknown. Dyers were skilled but the rate of failure of dyeing outcome (e.g. ruining the fleece, dyeing an unwanted colour) was unknown. It may be possible to devise a figure from modern historic dyers, but without knowing the ownership of materials in Pompeii the rate will remain unknown. New discoveries that explore empirical entities are welcome, as they may increase, limit or change findings.

Expansion since the doctorate was awarded

This study was presented to three Experimental Archaeology conferences where it was well received. After this it was presented at the first European Textile Forum in 2009, which specialises in presenting new textile-related questions and findings to academics, professional re-enactors and skilled enthusiasts to explore together. The science, archaeology and textiles knowledge were valid, but this study had not included the knowledge, skills and experience of a professional historic dyer. The study had begun before the widespread use of the internet so was built on works published in English available in the UK. The dyer, Sabine Ringenberg, physically demonstrated there and then that with the same equipment but a different method it was possible to produce triple the dyed output. The study had already found demographic Romans that could use the apparatus but now it had found a Roman dyer to use it properly. This demonstrated the importance of including craft knowledge from the beginning of the study, which had not been appreciated before. It showed the importance of presenting to diverse audiences, as one person's mystery or overlooked factor is another's daily routine. Sabine also noted that despite the assertions of the British authors, a professional dyer would not dye the whole fleece, just the best quality parts, which would alter the fleece requirement and quantity of textile produced, especially as soft furnishings were dyed whole while clothing could be undyed with features picked out in dyed wool. Sabine's reaction to the study also showed the importance of presenting before the craftspeople with skills and learned behaviours are lost.

The professional historic dyer noted that the dyeing kettles had been made from lead. During the survey the archaeologists had noted the presence of lead as a curio, the engineers with disbelief and dismissal as lead was so inherently unstable when heated or placed under load. Engineering had no data about the loading properties of lead as there was no modern use for it. Monteix and Pernot had confirmed through analysis that the kettle was lead and the survey in 2002 had found that all surviving kettles had been lead – they kindly sent their unpublished data confirming it. Experiment design and understanding of outcome is affected by background and approach of the designer. This was demonstrated in 2007 when the engineers and archaeologists could not believe lead was used, despite evidence from the survey, contrasting with finding in 2012 that lead was the 'neutral kettle', that reliably would not alter the expected outcome and had actively been sought for use as a kettle. Experiments replicating dyeing in kettles constructed from different metals found that iron and copper resulted in altering the colour outcome, while lead and in particular lead with an oxide layer on the surface, were 'neutral' resulting in a bright colour, the choice of dyers. Lead had been dismissed in 2007 as a horrendous choice due to its physical properties, but in 2012 at European Textile Forum, held as the LEA (Labor für Experimentelle Archäologie) inaugural event in Mayen, lead was found to be the perfect choice chemically. The influence of mordants and dyes had been previously investigated and understood, and although dyeing handbooks (including in the UK) note that use of iron or copper as a mordant would affect dyeing outcome, this study provided exploration of the phenomenon of the difference kettle material made. This appeared to be the first study to focus on the kettle material. Theoretically, premordanted fabric should not be affected by kettle material as only the dye should bind to the mordant, but empirically it does. Findings were published as Kania et al 2014. An addendum took place in 2013 that highlighted the need for reference samples and in 2016 the experiment was repeated broken into stages. This showed that metals absorbed during mordanting, during dyeing, during both procedures when wool is exposed to both, but that most absorption happens during dyeing.[1] LEA is part of RGZM (Römisch-Germanisches Zentralmuseum) and now hosts European Textile Forum annually – these ongoing experiments take place in Germany as part of European Textile Forum so at the time of writing 'Brexit' is causing great interest.

The choice of materials for replicating the apparatus in the laboratory has been queried as brass and other alloys were contemporaneously available in Pompeii but this study used only elements. Elements were chosen as alloys can have an infinite variation of ratios of the constituent metals and would require a correspondingly large group of samples to test the effect of each one. Madder, wool and alum were used as they were the most commonly used materials for

[1] The whole experiment was repeated in stages in 2018, in order to collect fresh samples of each type to allow complete dye analysis.

dyeing in the Roman civilisation contemporaneously to Pompeii, with samples found in Israel and Vindolanda. Further experiments took part with madder and birch, crossing over to birch through changing one variable at a time. Birch showed colour subtleties that madder could not, so was deemed more suitable for experiments investigating the effects on colour variation. Birch has been reliably available to participants in the Textile Forum experiments, allowing consistency. It is arguable that birch was available to Roman dyers – birch was growing in northern Europe – but whether it was available to dyers in Pompeii is more questionable. Like other quantities in this study such as using pine offcuts for fuel, birch gives a 'holding' value to be used until the actual dyes used in Pompeii can be determined and substituted in. Repeating the experiment also highlighted the need for repetition in experiments – each dyeing batch is slightly different as plants contain natural variations depending on many factors, which can lead to very different results and possible misinterpretations. The first experiment using birch resulted in a yellow yarn with a reddish tinge – this tinge has not been replicated since.

The importance of using lead as a kettle would have been unrecognised by the archaeologists without the input of the dyers and professional dyers cannot know every facet of enquiry without archaeologists presenting it. This raises the question of what other influences the dyers and archaeologists do not yet know of and which specialism could reveal yet more about the industry. Currently further experiments and analysis are being undertaken from older samples made in 2012 and fresh samples gained in 2018.

Presentations and publications since this thesis was submitted

Since graduation, this study has formed the basis for further research, presentation and publication. Please note that some items may have similar titles but were rewritten with a new focus for difference audiences. Further information may be viewed at: http://bradford.academia.edu/HeatherHopkins

Publications

Eds: Hopkins, H. J. and Kania, K. 2018. *Ancient Textiles, Modern Science II*. Oxbow.

Hopkins, H. J. and Kania, K. 2018. Introduction. In: *Ancient Textiles, Modern Science II.* Oxbow.

Kania, K., Hopkins, H. J. and Ringenberg, S. 2018. The influence of metal kettle materials on the mordanting and dyeing outcome. In: *Ancient Textiles, Modern Science II.* Oxbow. Chapter 8: pp 99-121.

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Hopkins, H. J. 2013. *Reconstructing the Dyeing Industry of Pompeii: the Importance of Understanding the Dyers' Craft within a Multidisciplinary Approach. Nesat XI The North European Symposium for Archaeological Textiles XI. 10-13 May 2011 in Esslingen am Neckar.* VML Verlag Marie Leidorf GmbH.

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Hopkins, H. J. 2008. Using experimental archaeology to answer the unanswerable: A case study using Roman dyeing. In *Experiencing Archaeology by Experiment.* Proceedings from the Second Conference of Experimental Archaeology. Eds: Heeb, J. Paardekooper, R.Oxbow Book, Oxford. Pp103-118.

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Hopkins Pepper, H. J. The role of interdisciplinary experiments in developing untested theories: The application of engineering and digital approaches in the study of Roman dyeing vats from Pompeii' In: Grana, L., Ivleva, T. and Griffiths, B. (eds.) Forthcoming *A Guide to Roman Experimental Archaeology*. Bloomsbury.

Hopkins, H. J. *Experience versus Experiment: differing disciplines' definitions leading to the answering of 'unanswerable' questions, a case-study using Roman dyeing.* In Proceedings of the Third Conference of Experimental Archaeology, Edinburgh University.

Conferences presentations

Archaeology Sciences UK 2019, 24-26th April 2019:
Vavle, A. Taylor, G. Hopkins Pepper, H. and Kania, K. Presented by Vavle, A. Poster presented: *Micromorphological analysis of textiles fibres from experimental dyeing vats.*

European Textile Forum. Laboratory of Experimental Archaeology, Mayen (part of RGZM Römisch-Germanisches Zentralmuseum, Mainz). 2018:
Paper presented: *Reconstructing dyeing in Pompeii: molecular answers to industrial questions.*

TRACamp 2018. Vindolanda:
Paper presented: *The diverse role of experiments in reconstructing dyeing.*

RAC/TRAC 2018. Edinburgh University. 2018:
Paper presented: *Contrasting the roles of experience, experiment and expertise in experimental archaeology: a case study of reconstructing the dyeing industry of Pompeii*

Tenth Experimental Archaeology Conference EAC 10. ExArc. Leiden University. 2017:
Paper presented**:** *The effect of discipline bias on the accuracy of reconstruction: a case study of dyeing in Pompeii*

Seventh European Textilforum. Laboratory of Experimental Archaeology, Mayen (part of RGZM Römisch-Germanisches Zentralmuseum, Mainz). 2016:

Paper presented: *Potatoes, paint and photographs: why making mistakes is vital to accuracy, a case study of the dyeing industry of Pompeii.*

Sixth European Textilforum. Laboratory of Experimental Archaeology, Mayen (part of RGZM Römisch-Germanisches Zentralmuseum, Mainz). 2015:
Lightening talk: *The supply of water to the dyeing workshops of Pompeii.*
Lightening talk: *Who were the dyers? Populating the dye works according to Strabo.*
Lightening talk: *The camera never lies? Even with modern technology, why it's always best to check things that are 'accurate'.*

Seventh Experimental Archaeology Conference, University of Cardiff, 2013:
Paper presented: *The influence of the dyers' craft on experimental context: investigating the affect of metals in the dyeing industry of Pompeii.*

The Historical Metallurgy Society: Research in Progress 2012. Newcastle University:
Paper presented: *The unforeseen consequences of Roman metal choice: The far-reaching influence on dyeing in Pompeii and modern experimental archaeology.*

Third European Textilforum. Laboratory of Experimental Archaeology, Mayen (part of RGZM Römisch-Germanisches Zentralmuseum, Mainz). 2012:
Paper presented: *An investigation of parameters that would influence the scale of the dyeing industry in Pompeii: Background to the dyeing experiment*. Introduction to experiment undertaken during Textilforum 2012.

Interface 2011. The 3rd International Symposium for Humanities and Technology. University College London, 2011:
Paper presented: *Unlocking the potential of virtual replication in experimental archaeology*

NESAT XI, Esslingen 2011. (North European Symposium for Archaeological Textiles):
Paper presented: *Reconstructing the Dyeing Industry of Pompeii: the Importance of Understanding the Dyers' Craft within a Multidisciplinary Approach* (Presented on my behalf by Katrin Kania).

MRS (Materials Research Society) 2010 Fall Meeting, Boston Mass:
Paper presented: *Reconstructing the past to prevent future loss: the dyeing industry of Pompeii.* (Presented on behalf of H. J. Hopkins by Lesley Frame).

Interface 2010. The 2nd International Symposium for Humanities and Technology. International Digital Laboratory, University of Warwick, 2010:
Paper presented: *Establishing the scale and significance of an industry through physical and virtual reconstruction, a case study using Roman dyeing.*

Experimental Archaeology Workshop. National Museums Scotland, 2009:
Paper presented: *Using experimental archaeology to answer the 'unanswerable': a case study using Roman Dyeing.*

First European Textilforum. Openlucht Museum, Eindhoven, 2009:
Paper presented: *Reconstructing the dyeing industry of Pompeii through experimental archaeology: the challenges and rewards of a new approach.*

Third Experimental Archaeology Conference. University of Edinburgh, 2008:
Paper presented: *Experience versus Experiment: differing disciplines' definitions leading to the answering of 'unanswerable' questions, a case-study using Roman dyeing*.

Fourteenth Annual General Meeting of the European Association of Archaeologists. University of Malta, 2008:
Paper presented: *An investigation of parameters that would influence the scale of the dyeing industry in Pompeii*. (Presented on my behalf by Roeland Paardekooper).

Second Experimental Archaeology Conference. University of Exeter, 2007:
Paper presented: *An investigation of parameters that would influence the scale of the dyeing industry in Pompeii An application of experimental archaeology and computer simulation techniques to investigate the scale of manufacture of the dyeing industry and the factors that influence output.*

AHRB Research Centre for Textile Conservation and Textile Studies First Annual Conference 'Scientific Analysis of Ancient and Historic Textiles: Informing Preservation, Display and Interpretation', Winchester, 2004:
Poster presented: *Understanding the economic influence of the dyeing industry in Pompeii through the application of experimental archaeology and thermodynamics.*

Seminars given

Department of Classics and Ancient History, University of Durham, 2009. *Using experimental archaeology to answer the 'unanswerable': A case study using Roman dyeing How exploring differing disciplines' definitions and 'Experiment versus Experience' lead to the reconstruction of the dyeing industry of Pompeii and its scale of manufacture*.

Department of Archaeology, University of Reading, 2009. *Using experimental archaeology to answer the 'unanswerable': a case study using Roman Dyeing.*