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# Using Experimental Archaeology to Answer the Unanswerable: A case study using Roman Dyeing

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*This paper introduces a new approach to understanding the dying industry in Pompeii. This study began with the construction of a full-scale replica dyeing apparatus, copied from remains in Pompeii, to establish the operating parameters of an apparatus. A determination of cycle time, fuel type and requirement was made. The skeletal data of Herculaneum was matched to a modern population and an ergonomic assessment of each dyeing apparatus was made. The replica was amended to allow exploration of the effects of a change in design and ventilation. A computer simulation using Finite Element Analysis was undertaken. The design, cycle times and temperatures were taken from the excavated remains and experimental findings. The FE Analysis allowed the determination of physical changes in materials during heating, the mode of failure of the apparatus and the time span within which this occurred.*

*The approach and findings of this study are both novel and new. The study took a theoretical problem through replicative experimental archaeology into Finite Element modelling. It allowed the problem to be understood and explored by those from differing disciplines. While this study answers specific questions about the size of the dyeing industry, it may be used to illustrate the application of a technique to answer 'unanswerable' questions.*

This study uses experimental archaeology to answer questions posed about the Roman world that until now have been unanswerable. Prior to this study, the understanding of Roman industrial capacity was theoretical and inaccurate, as there was not the means to examine the question fully. This study was the first to use full-scale replicas

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to reconstruct the relevant parts of the industry to understand the capabilities of the apparatus to provide a solid, unequivocal answer to the question of production. Through the application of engineering theory, it has been possible to take these answers and examine the textile manufacturing industry as a whole. This study has also provided a case study of a new approach, the triangulation of differing complimentary disciplines to answer questions in archaeology that have hitherto been deemed 'unanswerable'.

The Roman city of Pompeii is located at the base of the volcano Vesuvius in Italy. Pompeii was destroyed by a volcanic eruption in 79 AD. The buildings were preserved in pumice to the first floor level then encased in a lava flow which prevented taphonomic changes (Capasso 2001; Allison 1992). It is possible to observe industrial artefacts in context, in the settlement they originally supplied. Prior to this destruction Pompeii had been subject to an earthquake in 62 AD. Pompeii was rebuilt, but the upheaval caused much change, both physically and legally. Properties without heir were forfeit to the city. Residential areas were the first to have water reconnected. Dyers relocated to former villas. Pompeii was rediscovered during the 18th century and plundered. Following excavation many of the standing remains were consolidated for preservation. Artefacts were removed. Industrial apparatus were preserved in situ. Some dyeing apparatus were cemented into place. Some lead dyeing kettles remained resting within the apparatus, others were cemented into the apparatus.

To determine the industrial capability of Pompeii would allow an understanding of its size and significance, and its economic, social and political importance. To understand the industrial context it is first necessary to understand the processes within a single industry. The textile manufacturing process is complex as each material used has a differing source and process. For example, woad dye required fermenting, while madder dye required the textile to be pre-mordanted. Dyeing apparatus can survive virtually intact and can be unambiguously identified. To understand the industrial process of Pompeii it is necessary to understand the manufacturing capabilities of the dyeing industry. The structure and function of the economy of Pompeii is beyond the remit of this study as it is a complex undertaking that has yet to reach a final solution.

The size of the dyeing industry of Pompeii is controversial. Previous studies were theoretical and reached no conclusive answer. The most comprehensive study, before the current work, was by Moeller (Moeller 1976). Moeller surveyed the standing remains of the structures associated with the textiles industry, concluding that the dyeing industry was large enough to export. However, Moeller was criticised at the time for reaching unsupported conclusions and publishing insufficient data (Wild 1977). Despite this Moeller's work became the basis for the understanding of the dyeing industry. Jongman used Moeller's data to conclude that the industry was smaller than Moeller had stated, possibly relying on imports (Jongman 1988). Mann concluded that Moeller had over-estimated the size of the dyeing industry and that if Jongman's statistical methods were used correctly and his arguments fully concluded he would have found that the dyeing industry was even larger than Moeller argued (Mann 1994). With a knowledge of the economic framework of Pompeii, Laurence reassessed the findings of Moeller and Jongman, agreeing with Jongman's conclusions (Laurence

1994). Although subsequent authors criticised Moeller's findings, they used Moeller's data. Moeller's survey relied on theoretical assumptions.

Prior to the current study the understanding of how the apparatus worked and its capacity was estimated by applying a theoretical understanding of dyeing gained through post-Roman pre-industrial manufacturing to the superficial measurement of the equipment. This study was the first to realise that an understanding of the operation, internal processes or possible missing parts of the dyeing apparatus was necessary to determine the capabilities of the apparatus. The only way to understand these was to reconstruct a physical replica of an apparatus and determine parameters such as cycle time and the consumables involved. Any unknown problems and considerations in construction would come to light. A preliminary replica was constructed using measurements from a dyeing apparatus in Pompeii and used to replicate the dyeing with wool, madder and alum, the most common materials used in the Roman World (Hopkins 2007). This was the first time such a replica had been reconstructed and the first time operating parameters had been determined. This data was used in the survey of all dyeing apparatus in Pompeii, the most comprehensive ever undertaken. The understanding of the practical necessities of a dyeing apparatus and a dyeing workshop allowed each apparatus and workshop to be examined within the context of a working city for the first time. It was also possible to discern parts of an apparatus or a property that were missing.

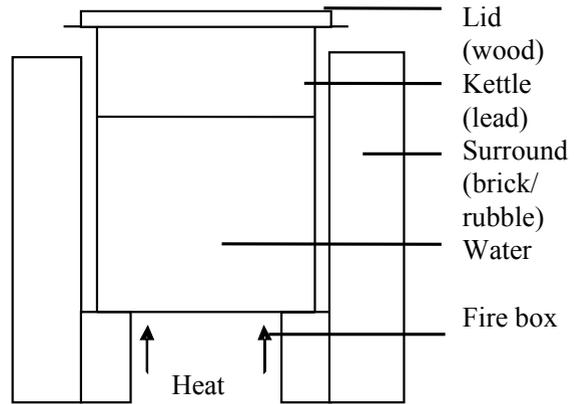
When identifying a 'dye vat' a set of physical attributes, polythetic entities, were used (Robinson pers comm 2005; Clarke 1978). These included:

- Ability to heat the liquid from below
- Operator must be able to reach the base of the water container.
- Kettle must hold at least 90 litres of liquid, the quantity required for a single fleece.
- Adequate ventilation to allow complete combustion.

A list of attributes for a dye property were defined:

- A source of water sufficient to fill each kettle
- Means of disposal of the water
- Adequate storage for consumables and finished items.
- Location and context of the vats. Possible U-shaped plan.
- Sufficient ventilation for complete combustion in all apparatus simultaneously.

Only vats that could satisfy all of these criteria were included in the survey and the subsequent gazetteer. There were 40 dyeing apparatus in six properties. An additional vat identified by Moeller in a seventh property, property I xii 4, was discounted as there was insufficient depth to hold a kettle. The replica apparatus was confirmed as accurate. A complete gazetteer detailing the size, location, preservation and design of each may be found in Hopkins 2007. Alteration or degradation through weathering, vegetation growth or restoration through the application of concrete was also noted. The apparatus were either flued or unflued (Figure 8.1 and Figure 8.2). Flued vats were in relatively enclosed workshops and it was assumed that the flue was necessary to aid



**Figure 8.1** Unflued dyeing apparatus.

*Above:* dyeing apparatus five, property VII ii 11, Pompeii. Vertical measure: 1.0m, horizontal measure: 0.2m.

*Above right:* schematic of unflued dyeing apparatus.

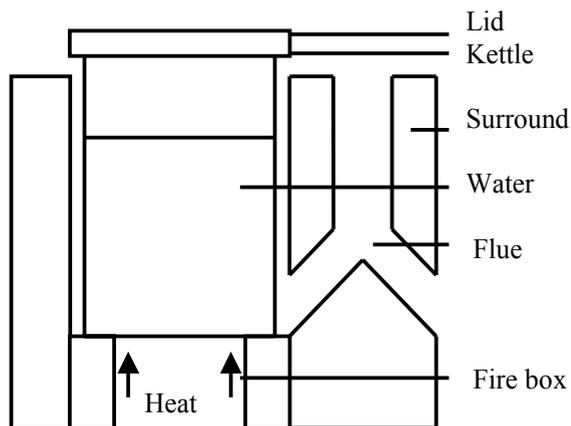
*Right:* replica dyeing apparatus.

Measurements taken from apparatus five, property VII ii 11.



ventilation. Of the lead kettles still present, many had bases that bowed significantly. During comparison of the location of dyeing workshops and reported water sources it was noted that some previous works had been inaccurate. This demonstrated the importance of returning to the evidence and examining the standing remains first-hand.

Use of the replica showed that to empty or clean the kettle it was necessary to reach the base in situ. Although modern individuals could do this, a modern individual could only be used to represent a Roman individual if they matched the Roman individual ergonomically. Ergonomics is the science of understanding the operator – apparatus interface and the efficiency of operation. A number of apparatus had been altered



*Figure 8.2 Flued dyeing apparatus.*

*Above: dyeing apparatus five, property VII xiv 17, Pompeii. Vertical measure: 1.0m, horizontal measure: 0.2m.*

*Above right: schematic of flued dyeing apparatus.*

*Right: replica dyeing apparatus.*

*Measurements taken from apparatus five, property VII xiv 17.*



during restoration giving a false kettle size and output. An ergonomic assessment would allow the correct heights of the apparatus to be discerned.

As skeletons from Pompeii and Herculaneum have survived, an ergonomic assessment is possible. Capasso examined the skeletons from the boathouse in Herculaneum, citing use of an equation by Trotter and Gleser to reconstruct their height (Trotter and Gleser 1958 cited in Capasso 2001). Capasso states that the maximum male height was 174.9cm, the minimum was 148.5cm, the average was 163.8m. The maximum female height was 159.5cm, the minimum was 140.0cm, the average was 151.7cm (Capasso 2001, 926). Ciarallo and Carolis used data from Pompeii taken from all skeletons found in public buildings, streets and villas. They state that the average Roman man in Pompeii was between 157.48cm and 167.64cm tall, with an average of 163.83cm. The average Roman woman in Pompeii was between 147.32cm and 157.48cm with an average of 153.67cm (Ciarello and Carolis 1999, 51). Unfortunately, neither

study accompanied the heights with the measurements of individual bones that would allow calculation of reach.

Roman skeletal measurements cannot be compared with modern measurements without the link of an ergonomic dataset that matches both. The population of the United States between 1900 and 1970 matches the Roman population (Murrell 1957; Dreyfuss 1966). The height of the author is 163.83cm – the height of the average Herculaneum or Pompeii male. The height of the co-builder is 153.67cm – within 1.07cm of the average Roman female. Trotter and Gleser give a range of  $\pm 4.59$ cm when using their height equation (Trotter and Gleser 1958, cited in Bass 1995, 32). This equation is used in modern forensics. The Roman, American and dyeing apparatus operator measurements are within the boundaries allowed. These two individuals both constructed and operated the dyeing apparatus. The author undertook the ergonomic assessment of the apparatus in Pompeii. Each of the apparatus were usable except the three in property IX iii 2 which had been altered. Had these remained unaltered, they too were usable. Some of the apparatus had steps built in to the wall to assist reach.

Following the determination of operating parameters the replica apparatus was amended by the addition of a flue. The resulting vat was a copy of the design of dyeing apparatus five in property VII xiv 17 (Figure 8.2). This did not make any noticeable difference to the consumable requirements or cycle times. However, the flame was easier to control. It was concluded that the apparent lack of difference was due to the through-flow of air to the apparatus – the apparatus was not located in an enclosed area like the original flued apparatus in Pompeii.

### *Preliminary results*

The cycle time of a single dye run required a 24 hour period. It was probable that the dyed fleece was left to cool in the dye liquor overnight and apparatus emptied, cleaned, refilled and reheated for the next dye run the following day. While the output of any apparatus at any time could be zero, it is possible to determine a theoretical maximum. According to modern recipes, the fleece requires 90 litres of water for dyeing (Storey 1978). However, this requirement has been rounded to the modern measure of 90 litres. The quantity of water required must have been approximately 90 litres, as great variation from this would result in there being too little water, which would not have allowed free movement of the fleece, or too much water, which would have made the dye liquor too weak. The actual quantity used by the Romans in their dyeing is unknown, which means that the possible maximum output for each apparatus is a range. Together the maximum daily output across the city is between 154 and 167 fleeces. The number of working days in Pompeii was 318 annually.

Therefore:      Minimum:       $154 \times 318 = 48,972$

                  Maximum:       $167 \times 318 = 53,106$

Between 48,972–53,106 fleeces were dyed annually.

To determine the relative scale, the population of Pompeii must be known. There is debate, but 12,000 is a figure that has been consistently argued (Storey 1997).

Pompeii population: 12,000

$$\frac{48,972}{12,000} = 4.08 \text{ fleeces per person} \quad \frac{53,106}{12,000} = 4.43 \text{ fleeces per person}$$

As a fleece weighs approximately 2kg, it may be seen that:

$$4.08 \times 2\text{kg} = 8.16 \text{ kg} \quad 4.42 \times 2\text{kg} = 8.84 \text{ kg}$$

8.16 - 8.84 kg fleece were dyed annually per person in Pompeii.

The maximum range of dyed fleeces that could be produced per person annually is still relatively small, roughly equivalent to “a (large) washing machine load.” If the population was only 8,000 the range of fleeces dyed per person was between 6.12–6.63 (12.24–13.26 kg). If the population was as great as 20,000 the range of fleeces dyed per person was between 2.45–2.66 (4.9–5.32 kg). The dyeing industry of Pompeii was smaller than Moeller, Jongman, or any subsequent study argued. Not every item was dyed. In the majority of contemporary textiles dyed fabric or yarns were used as decorative features such as *clavi* (lines) and gamma patterns rather than as a main background (Bender Jørgensen and Mannering 2001; Pritchard and Verhecken-Lammens 2001; Cardon 2001). Although fewer soft furnishings have been found, these tend to be uniformly dyed. The Romans tended to re-dye faded material. Over time the amount of undyed fabric would become insignificant in an overall study (Hopkins, 2007).

The picture so far is incomplete. The archaeological presumption that the dyeing cycle operated once a day allows an estimate of the maximum capacity possible. However, while it has been noted that the kettle was lead (Monteix and Pernot 2005), prior to this study no significance has been attached to this.

### *Significance of Lead*

The use of lead for the dyeing apparatus is an unusual choice. Lead was extremely cheap as it was a waste product from silver production. Lead was a brightening mordant, when other metals dulled or altered colour. For these reasons, lead was possibly the only metal that could have been used. However, lead appears unsuitable due to its other properties. Lead is dense, heavy, malleable and weak. Lead has a relatively low melting point (327°C). Lead creeps in hot weather. Creep is time dependent strain on a body subject to constant load or stress. Creep is thermally activated: the higher the temperature the faster it creeps. A dye kettle must support its own weight, the additional weight of 90 litres of water and be subjected to heating above a fire. There is evidence of creep in dyeing kettles in Pompeii: concentric rings in the domed bases of the more complete kettles. It is therefore possible that downtime during dyeing may have been considerable due to the need for repair.

Reynolds wrote against the use of ‘experience’ rather than ‘experiment’ archaeology. He stated that for an experimental replica to actually be a replica it must have been constructed using the same materials as the original. He also stated that for an experiment to be a true experiment there must be a clear aim and the experiment must fulfil this aim (Reynolds, 1999). The aim of the original experimental replica

was to determine the operating parameters of a dyeing apparatus. This included the time taken for the apparatus to heat, the retention of that heat and the loss through dyeing and the amount of fuel that would be required. However, the use of a lead kettle and the original (highly corrosive) lime mortar was vetoed by modern health and safety considerations. Materials had to be substituted. It was necessary to substitute the materials with their thermoconductive equivalents. The replica matched both the design and, in thermodynamic terms, the materials of the original. While aesthetically the materials differed, there was no requirement for an aesthetic match. Therefore the aim of the experiment had been met and the equivalent materials had been used: Reynolds' criticism had been met.

The experiment is a valid archaeological experiment, but through the application of engineering it is possible to see how Reynolds was right. This may be explained through examining how the same words mean different things to archaeologists and engineers. Both wish to understand 'how' an artefact works. In archaeology that means how to operate the artefact and how, at a gross level the artefact responds to the operation. This was Coles' approach: to demonstrate that an artefact may or may not work in a given context to suggest what may have been possible (Coles 1973). However, engineers examine how the materials that make up the artefact respond to the external influence of use. There is little consideration of the complete context of the artefact, including intangible concepts such as the social, economic and religious use. Few studies have attempted to combine both approaches, and these have not often been successful due to a lack of balance. Speth attempted to explain the physics behind the patterns that occurred on struck flints. However, in so doing he divorced the artefact from any social context (Speth 1977). Cotterell and Kamminga examined the physics behind a selection of artefacts, but each exploration was so brief that it was not possible to apply the principles to other artefacts (Cotterell and Kamminga 1990). This study is the first to take a classical question through experimental archaeology into engineering sequentially allowing each part to be fully accessible to each differing background.

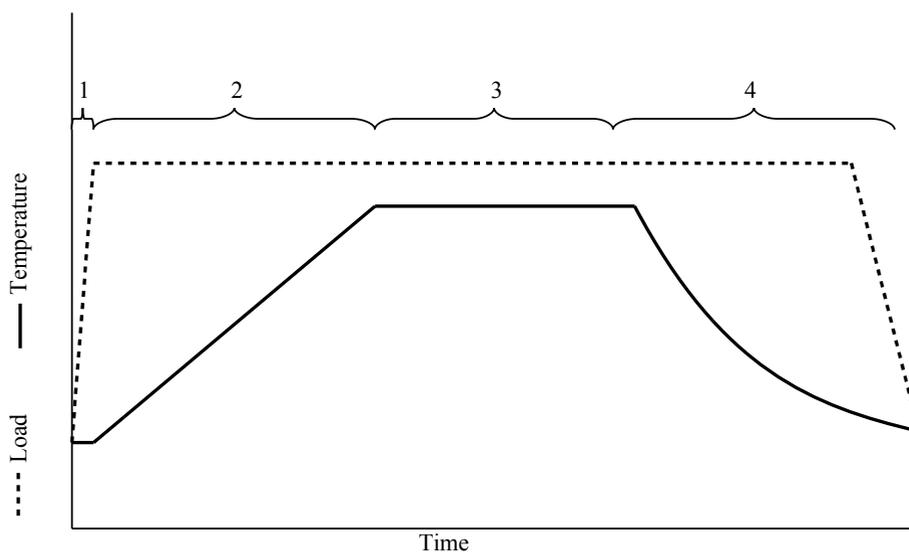
The kettle used in the replica was constructed from stainless steel. Although this had comparable thermoconductivity to lead it did not creep in the same way. The experiment was valid and met Reynolds' criteria, but Reynolds was still right – for a full understanding it was necessary to use the original materials. However, even if health and safety considerations had not prevented the use of a lead kettle, there was still the factor of time. How long the kettle took to bow was still unknown. As each apparatus differed, to understand each would require a reconstruction of all 40 apparatus. The environment in which each apparatus was constructed differed. To construct a replica that allowed for airflow through buildings would have required the construction of parts of the city. The only way each of these criteria could be met was to construct a virtual replica in a virtual environment.

### *Finite Element Analysis*

The apparatus was modelled using Finite Element Analysis software. This software is used extensively in engineering to test a design before it is manufactured (Fagan

1992). Finite element analysis is used to determine changes within a structure when an external influence is applied. The structure is divided into discrete parts, finite elements, each part represented by an equation. Each material has a known set of physical properties and this too is included in the equations. As a force or temperature is applied to one surface or point of the material, its effect continues through the structure. The equations at each point allow the changes to the material to be gauged. The points at which specific changes occur may be located and studied. These calculations are used when exploring the effects of the application of temperature or stress and are used when determining fatigue. The program used, ABAQUS, had been designed to allow the breakdown and understanding of the physical principles within apparatus, specifically creep within metals and the transfer of heat. The dyeing apparatus was deconstructed and coded as part of a system, with inputs, outputs and losses. As coding a dyeing apparatus had not yet been attempted, the code was designed from first principles. This is difficult as archaeological artefacts are not uniform, are incomplete and each has never been deconstructed before.

A computer simulation of the dyeing apparatus consists of two parts in combination: the geometric model and the thermal load (Figure 8.3). The geometric model is the design, measurements and materials used in the apparatus. These were taken from the apparatus in Pompeii and the replica apparatus. Some of the properties of lead

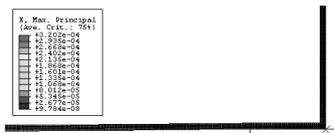


**Figure 8.3** Schematic showing the relation of temperature of the kettle and the load the kettle is subject to during one dye run. The load and temperature are mutually exclusive but change over time as the dye run progresses. The combination of these two factors increases the rate at which the kettle fails.

- 1 The kettle is loaded with water, then the fire is lit
- 2 The load is constant, the temperature rises
- 3 The temperature is held as the dye liquor simmers, the load is constant
- 4 The fire is extinguished and the vat left to cool. As it approaches ambient temperature the fleece may be removed and the kettle emptied.

at higher temperatures were unknown before this study, as lead has limited use in engineering due to its structural properties, so these were determined (for further details, refer to Hopkins 2007). The thermal load was modelled by the inclusion of the temperature profiles gained during experimental use of the replica. The timings of the thermal cycle and the load cycle were determined through the use of the experimental replica. These recordings placed the archaeological experiment of how to physically operate the apparatus into the engineering context by providing the data that allows the movement and transfer of heat. This was the first time these cycles had been determined and this process undertaken.

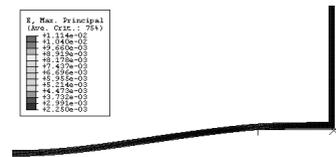
The loaded dyeing apparatus at 20°C may be seen to bow slightly in the centre (Figure 8.4). Following ignition the effect of the heat on the lead kettle may be seen (Figure 8.5). At the end of the first thermal cycle (Figure 8.6) the kettle had bowed



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Self weight + water, plastic material, temp dependent, creep
ODB: vm-160cr-1000sec.odb  ABAQUS/STANDARD Version 6.5-1

Step: Step-1, self weight
Increment: 10, Step Time = 1.000
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+00
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Figure 8.4 Strain of the dye kettle under self-weight and loaded with ninety litres of water at 20°C.



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Self weight + water, plastic material, temp dependent, creep
ODB: vm-160cr-1000sec.odb  ABAQUS/STANDARD Version 6.5-1

Step: Step-2, heat cycle 1
Increment: 20, Step Time = 0.5600
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+00
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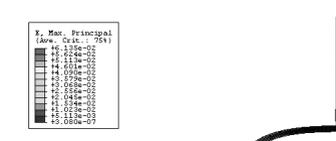
Figure 8.5 Loaded kettle following heating to 120°C over ten minutes during first thermal cycle.



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Self weight + water, plastic material, temp dependent, creep
ODB: vm-160cr-1000sec.odb  ABAQUS/STANDARD Version 6.5-1

Step: Step-2, heat cycle 1
Increment: 20, Step Time = 5.400
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+00
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Figure 8.6 Loaded kettle following cooling during first thermal cycle.



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Self weight + water, plastic material, temp dependent, creep
ODB: vm-160cr-1000sec.odb  ABAQUS/STANDARD Version 6.5-1

Step: Step-3, heat cycle 2
Increment: 24, Step Time = 5.400
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+00
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Figure 8.7 Loaded kettle following cooling during second thermal cycle.

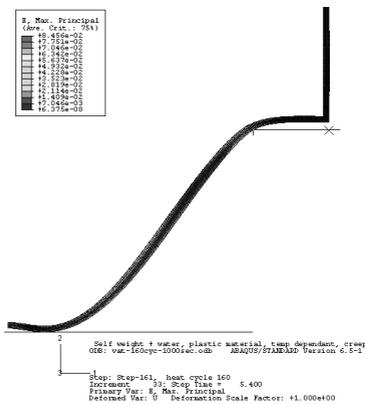


Figure 8.8 The dyeing kettle after 160 thermal cycles, equivalent to six months use.

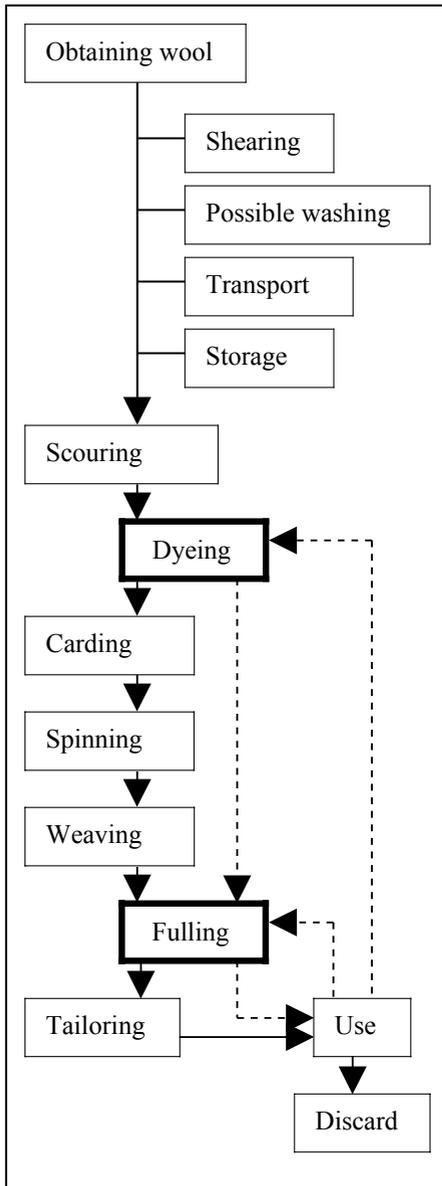
through the effect of creep, but its base does not touch the ground. However, following the second dyeing cycle the base does reach the ground, through the effect of creep (Figure 8.7). This effect was unpredicted, as it was believed that due to the weak nature of lead the base would tear before it was could creep this distance. More surprisingly, although in subsequent dyeing cycles the base began to thin, the creep was not structurally hazardous. After 160 dyeing cycles, approximately 6 months of use, the shape of the base remained the same (Figure 8.8).

If left unchanged the lead base thinning would be the probable cause of failure of the kettle. At present it is not possible to determine the length of time this would take. However, it is likely that at the end of the first dyeing cycle the kettle would have been levered back to its original shape, probably while the lead was still warm. If the kettle continued to fill the firebox it would be extremely difficult to place fuel within it or cause sufficient ventilation for complete combustion.

## Systems theory

This is the first study to apply modern manufacturing systems theory to the ancient world. By considering the system of manufacturing and the processes within it, it is possible to determine the down-time at each stage and within the system overall. While the Romans did not possess the terminology of modern economic theory, they already had an empirical understanding of economic concepts and their application (Edmundson 1989). They had the same approach to manufacturing systems theory. The Romans were effective, efficient engineers (Hodge 1992) and would have empirically determined the most efficient methods to date (Hoffman 1967, 185). However, allowance should be made for intangible endemic entities. These are the factors that are only known to those within a society as they leave no tangible trace (Clarke 1978). The Roman Empire was the most bureaucratic seen before the modern day (Temin, 2001). However, trying to understand the system of the economy has been likened to trying to understand the system of the London Stock Exchange by only reading the Financial Times: day-to-day occurrences are discernible, but not the framework in which it occurred (Temin 2001).

Within Roman manufacturing there was the system and production line within a workshop and the system and production line of the manufacture as a whole (Figure 8.9). Textile manufacturing was linear and broken down horizontally with each workshop being task-specific. There may have been dependence through ownership and economic considerations, pre-requisite processes and the considerations of supply



*Figure 8.9 Stages of textile manufacture using wool, after Moeller, 1976 and Frayn, 1984. Red and green arrows indicate re-dyeing or laundering. Blue indicates unambiguous apparatus found in situ.*

and demand, but these are intangible. The Romans would have ‘balanced’ their production line, arranging it in such a way that delays would not prevent production. Balance was achieved through using parallel workstations, that is different apparatus simultaneously; buffers, storage of finished parts between processes; and dividing work into elements, using separate, independent apparatus (Groover 1987; Muhlemann, *et al.* 1992; Hopp and Spearman 2001). However, the nature of the industry must also be considered. To dye a fleece it must be pre-mordanted (Grierson 1986; Grieve, 1992), but the pre-mordanted fleece must still be damp when dyed (Storey 1978). It was necessary to plan processing in advance to ensure that the entire procedure could be undertaken without interruption. To repair the kettle following failure costs time and money, both to actually repair and in the loss incurred by the halt in manufacturing as the repair took place. To mitigate against these losses repairs and failure had to be planned for and the production line balanced accordingly to mitigate against these losses.

The dyeing process was either Job Shop production or Batch production. In Job Shop production the products are “one-off” or in low volume, requiring highly skilled workers (Groover 1987; Muhlemann, *et al.* 1992). In Batch production the products are manufactured in a medium size load of identical products (thereby more cost-effectively). The production rate exceeds demand and as stock of a particular product is depleted another batch is produced (Groover 1987; Muhlemann, *et al.* 1992).

The size and needs of apparatus could have constrained the lay-out of the workshops. The Roman dyers empirically developed a workshop arrangement and production system similar to Toyota in the modern era. Toyota’s system was state-

of-the-art and other manufacturers attempted to emulate it. The apparatus were positioned in a U-shape, a technique that allows a single dyer to monitor all apparatus simultaneously (Monden 1993). Toyota went further and linked each of the U-shaped sections within the factory. This causes the production process to flow and eliminates isolation, (Japan Management Association 1985; Monden 1993). The Romans did this, but across a city not a factory. The Roman dyers would have had to fit the location and lay-out of their dye works within the pre-existing physical and socio-economic fabric of the city (Hoffman 1967, 185).

Raw materials and consumables required storage. Following shearing a year's worth of storage was required for the fleece, the requirements diminishing as the year progressed. Furthermore, dyes should not be allowed to get damp or to rot while fleeces, once scoured, should not be allowed to become dirty. The type of production determines the storage requirements and allows the demonstration that the Roman dyers had empirically determined Just-In-Time manufacturing, a state-of-the-art system that limits storage requirements and therefore costs and possible losses. In job production, minimal storage was required as each component was brought as needed. In batch production, storage would be required for new batches. This demonstrates the problem of intangible endemic entities within society. As it is not possible to determine the ownership of the consumables at each stage of processing it is not possible to determine the storage requirements and costs. The possible storage requirement for processed textiles depends on their ownership: whether a workshop owned and so stored a batch ready for sale, or whether the owner collected fleeces as they were produced. It is advantageous to store materials and completed products for as little time as possible due to space and money constraints (King-Scott 1971). The ownership at each of production would determine the feedback loop of inspection: Procedure could be different for re-dyeing if the dyer did not own the unsuccessfully dyed fleece.

Dyeing requires precise chemistry and temperature control. This requires training and specialism over time, resulting in more efficient working (Groover 1987). However, if these specialists worked solely with the kettles contemporary records of lead poisoning (Vitruvius) would have mentioned the dyers as being at high risk. Water supplied to the workshops did not contain lead but the kettles were lead. Therefore, it may be supposed that dyers must have been some form of variation of task.

### *Findings*

Two types of findings have resulted from this study: solid and theoretical. The solid findings are those that are tangible or grounded in unarguable data. The survey, the most comprehensive undertaken to date, has provided data for the replica and for future study. The operating parameters of the dyeing apparatus and the times and temperatures involved have now been established. That the lead does not fail and that only lead could have been used for the construction of a dyeing apparatus is also an entirely new finding. It was discovered that the restoration in Pompeii was far more accurate than previously believed.

The theoretical findings are those based on the application of a theory to the solid

data. The application of systems theory allows the inputs, outputs, losses, waste and consumables to be determined. The water supply required, the content of the water and its disposal are better understood. When dyeing using madder and alum, wool was dyed in the fleece, rather than as textile or yarn. With a greater understanding of the economic and social situation of dyers, it is possible to state that they were 'better off' than previously thought as their value gave them importance. It is also possible to state that only two or three were needed to run a dyeworks and that once the apparatus were lit only one was needed to monitor.

Further to the findings relating to Pompeii, the study has successfully proved the combination of previously isolated techniques to answer previously 'unanswerable' questions. This includes a proven link between a modern and ancient population and the ergonomic assessment of apparatus. Finite Element Analysis has not previously been used to examine archaeological apparatus or archaeological artefacts consisting of more than one material. This is the first study to apply modern manufacturing systems theory to the ancient world. This study has paved the way for the development of the use of the techniques involved. Furthermore, this study was sequential, moving from classical, to experimental archaeology, through to engineering principles and finite element analysis through computer modelling. Each of these disciplines is unknown to a practitioner of each other, and so this study took each back to its first principles, providing an illustrated example. This approach made each discipline accessible, enabling the principles to be taken and applied to other archaeological problems.

This study has added greatly to experimental archaeology. The introduction of the engineering definition of 'how', the need to understand the materials that make up the artefact has great potential to answer questions that previously could not even be asked. The use of replicas grounded in the solid evidence from Pompeii to construct previously unknown dyeing cycles is entirely new and with the application of systems theory, a theory new to archaeology, has led to an understanding of the dyeing industry and its place in the economic life of Pompeii. The use of Finite Element Analysis, ergonomics and new approaches is grounded firmly in experimental archaeology, without which the data would have been unobtainable. This study answered the question of the scale of dyeing in Pompeii, but more than this, it provided an example of the great potential that combining disciplines has to answer 'unanswerable' questions anywhere in the archaeological world.

### ***Further Reading***

For a more detailed exploration of this work please refer to Hopkins 2007. Please also refer to Hopkins, *et al.* 2005 and Watling 2004.

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