Innovation and Society in the Roman World

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Abstract and Keywords

This article assesses the impact of innovation on Roman society. It starts from a critical engagement with past debate about technological progress, which over the past decades has been too strongly focused on economic growth, and a re-appreciation of the literary evidence for innovation, which points to a culture in which technological knowledge and invention were thought to matter. Then, it highlights two areas where the uptake of technology had a direct impact on everyday life: material culture, where the emergence of glass-blowing, a proliferation of metal-working, and innovation in pottery-production changed the nature and amount of artefacts by which people surrounded themselves, and construction, where building techniques using opus caementicium, arches and standardized building materials revolutionized urban and rural landscapes. A concluding discussion highlights the role of integration of the Mediterranean under Roman rule in making innovation possible, and the role of consumer demand in bringing it about.

Keywords: Innovation, Technology, Glass-Blowing, Roman Economy, Roman Architecture, Metal-working, Terra Sigillata, Roman construction technology, Standardization, Arch (construction)

One of the most eye-catching tombs along the Via Appia stands some four miles outside the city, close to the Villa dei Quintili, on the east side of the road. Essentially, what remains of it is just an enormous mass of concrete, meticulously deprived of its stone facing at some point between antiquity and modernity. Its construction date is unknown, but to judge from its size and its use of concrete, it is probably early imperial, perhaps Julio–Claudian or Augustan. It is a large example of the monumental Roman tomb architecture that emerged in the late republic and of which the development cannot be seen apart from the development and spread of *opus caementicium*, which made it possible to construct larger, architectonically more daring monuments at a reasonable price, making them available to much larger groups of people—as the first miles of the Via Appia attest (Fig. 1). Not far from the tomb is the point where there was, in antiquity, a good view from the Via Appia over two aqueduct bridges that were built to cross the plain between the Alban Hills and Rome. The lower of the two aqueduct bridges dates to the second century BC. It was built for the Aqua Marcia but had the Aqua Tepula and the Aqua Iulia superimposed on it later.[1] It was made of tufa and had low, wide arches. The higher, more monumental aqueduct bridge stood out with its elegant, high arches in tufa. It was built between AD 38 and AD 52 and carried the Aqua Claudia and the Anio Novus.[2] Critical to both aqueducts is the arch, an innovation that became increasingly widespread from the second century BC onward.[3] At the time they were constructed, both aqueducts presented a clear innovation in hydraulic engineering: the Aqua Marcia was the first Roman aqueduct with such a long section above the ground, and the Aqua Claudia was unparalleled in its height. Obviously, the Via Appia itself also presented an innovation when it was constructed in the late fourth century BC in the way it was imposed on the landscape, running in an almost perfectly straight line between Rome and Terracina, with the exception of a short section near Ariccia, where it had to divert in order to successfully cross the southern part of the Alban Hills.[4] What for modern viewers might look like a landscape of memory may very well have looked differently through Roman eyes: as an environment, the Via Appia, in the early imperial period, was not a romantic relic of a faraway past but a clear manifestation of Roman achievement. Especially in the first century AD, it was a landscape of innovation at least as much as a landscape of memory.

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Fig. 1. Early imperial tombs along the Via Appia. Photo: Miko Flohr.

The Via Appia was no exception: Roman construction and engineering technology had a deep impact on landscapes throughout the Roman Empire. Indeed, in the very place where it started, Rome, the widespread application of the same new building technologies created private architecture of dimensions hitherto unknown, resulting in an urbanism of a completely new category. Outside Rome, increasingly advanced engineering enabled the Romans in the first century AD to dig the tunnels and canals necessary to drain parts of the Fucine Lake, not only creating more agricultural land but also transforming the entire Fucine region, as indeed had been done before with the plain of Rieti and, earlier still, with the plain of Ariccia on the Via Appia in the Alban Hills.[5] Perhaps the most dramatic impact of innovation on the landscape is to be found in Asturia in northwest Spain, where the Romans in gold mining applied a practice they called *ruina montium*, which meant that they exposed mountains to high quantities of water, leading to collapse and to the liberation of gold-rich sediments, which then could be further processed.[6] The environmental effects of this practice are still clearly visible, especially at the site of Las Medulas.[7]

In many places, and in many ways, the Roman world looked like no world had done before; and to a considerable extent, this was due to innovation—the emergence and spread of new ways of doing things.[8] The present article highlights this societal impact of innovation in the Roman world, particularly focusing on the changes it brought to the direct living environment of people. After two introductory sections on the history of the debate about innovation in the Roman world and the wider culture of innovation in the late republican and early imperial periods, two key aspects of this will be discussed. Firstly, there were innovations in the manufacturing of everyday consumer goods that changed the material culture with which people throughout the Roman Empire surrounded themselves. Secondly, there is the emergence of advanced construction techniques that redefined the physical environment in which everyday life took place, in cities and, to some extent, the countryside. While the theme of innovation is, of course, broader than these two issues, other aspects have been covered rather well in recent contributions to the debate, as will be highlighted in the next section; and their omission does not affect the overall argument made here, which is that technological innovation was fundamental to the historical development of everyday life in the Roman world from the second century BC until well into the second century AD.

Debating Innovation in the Roman World

Classical scholars of the nineteenth and twentieth centuries have often discussed innovation with a particular emphasis on invention and technological development, and Roman and Greek technology have often been approached together: until the late twentieth century, the topic was mostly referred to as “ancient technology,” with little formal distinction between the Greek, Hellenistic, Roman, and late antique realms; and even today, there is a certain tendency to discuss antiquity as one undifferentiated whole, much to the detriment of our understanding of both Greek and Roman technological histories and their relation to the social, political, and economic developments specific to these particular periods.[9] The earliest approaches to ancient technology primarily aimed at collecting relevant sources—textual and material—and reconstructing technological knowledge and practice; particularly influential was Hugo Blümner’s *Technologie und Terminologie der Gewerbe und Künste bei den Griechen und den Römern*, which brought together a lot of references from the works of classical authors, illustrated—to some extent—by recent archaeological discoveries.[10] Blümner's work set a standard for approaches to ancient technology in the encyclopedias, handbooks, and specialist studies of the first half of the twentieth century and beyond.[11] Yet while this antiquarian approach produced gold mines of information on technological specifics, it actually had little to offer on the *history* of ancient technology in general and on the relation between technology and society. More relevant here, therefore, is a second tradition that, within the field of classics, more or less started in 1914 with Hermann Diels's *Antike Technik*, a booklet of six lectures discussing ancient technology with an eye on the bigger historical questions of his time.[12] Unsurprisingly for someone writing in the middle of the second Industrial Revolution, many of the historical issues raised by Diels had to do with the fact that the Greeks and Romans, despite their cultural achievements, never came close to anything comparable to the Industrial Revolution that had been unfolding in Europe and North America since the early nineteenth century.[13] Diels provided two key explanations for the absence of a technological revolution in antiquity: the aristocratic mentality of the elite and its low esteem of technological accomplishments as well as slavery, which meant that there was little incentive for alternatives to manual labor.[14] Scholars of the interbellum, such as Lombroso-Ferrero, Rostovtzeff, and Lefebvre des Noëttes started from similar questions; and while their answers differed to some extent from those of Diels and from each other, they were in the same broad range: technological progress was prevented or cut short by the structures that shaped economy and society.[15] While there had been a highly polarized debate concerning the nature of the ancient economy since the late nineteenth century, there was much more agreement on the issue of technical progress—or, rather, on its absence.[16]

This status quo continued, for quite some time, after the Second World War. Indeed, Finley's 1965 article in the *Economic History Review*, which has become the standard reference for the "stagnationist" take on ancient technological progress, incorporated a lot of ideas that had been circulating since the time of Diels.[17] Finley claimed that it made no sense to discuss the history of ancient technological innovation separately from the economic history of the ancient world and, though acknowledging that there was some technological progress in antiquity, thought it of little or no value: it never significantly increased productivity so that there were no other ways to counter demographic growth than migration to underpopulated territories or conquering and taxing other areas. For Finley, key reasons for this technological stagnation were the easy availability of cheap (servile) labor and the absence of an economic rationalism that would foster elites to maximize returns on investment. Other scholars of this period, particularly Pleket and White, ventured similar views, particularly stressing the role of ancient mentalities.[18]

It was only toward the end of the twentieth century that scholars, particularly archaeologists, began to express views that were more favorable to the socioeconomic impact of ancient technological achievement. Embracing the idea that the ancient world was a preindustrial society, they considered it less urgent to point to the failure of the Greeks and Romans to unchain an industrial revolution and more interesting to focus on the developments that *did* take place.[19] In a 2000 article in the *Economic History Review*, Kevin Greene published a lengthy deconstruction of Finley's article that had appeared 37 years earlier in the same journal.[20] Greene suggested that the Greco–Roman world should be seen not as a period of stagnation but rather as the "maturing of the European iron age" in which the proliferation of iron changed everyday socioeconomic processes, making agriculture more productive and allowing for the emergence of large-scale buildings.[21] The "stagnationist" view was attacked even more vehemently by Andrew Wilson in a 2002 article in the *Journal of Roman Studies*, in which he argued that, particularly for the Roman period, there was substantial per capita economic growth based on significant technological progress in agricultural technology, in water technology, and in several other areas.[22]

As a result of this, the pessimistic view on the impact of ancient technology has lost considerable ground since the turn of the millennium. Lo Cascio's 2006a volume on technological innovation and economic progress in the Roman world perhaps best captured the new optimism.[23] In the introduction, Lo Cascio argued at length that what he called the "Finleyan model" suffered an existential crisis and was vulnerable on a theoretical level and a methodological level, as well as on the level of actual historical evidence.[24] Many of the subsequent chapters echoed this view, particularly concerning the impact of technological change on the agricultural economy and on construction practice.[25] Serafina Cuomo's 2007 book on technology and culture in the ancient world, though not so much focusing on the relation between technological change and economic history, also explicitly criticized the stagnationist take on ancient technology.[26] Similarly, many of the contributions to the 2008 *Oxford Handbook on Engineering and Technology in the Classical World* suggest that, as the editor notes, "the classical world was marked by remarkable technological advances in many areas."[27] Few scholars have stood up to defend the traditional model, and many have acknowledged that there was more technological progress, with more impact on Greco–Roman economies than past orthodoxy had allowed for, though some, particularly Scheidel, have questioned the extent of Roman innovation, arguing that the Romans mostly absorbed and spread the technological culture of the Hellenistic East and that this was not enough to allow for sustained per capita economic growth.[28]

However, though the pessimistic interpretation of innovation in the ancient world has lost ground, it may be argued that the tradition that produced it still defines the terms of the debate. Indeed, while Finley complained, almost 60 years ago, that there was too little interaction between those studying ancient technology and those studying the ancient economy, the reverse has been true since: a key feature of almost all recent approaches to Greek and Roman technology has been that they have focused almost exclusively on the relation between technological change and economic growth, particularly on forms of economic growth that made it possible to feed more people.[29] This is to some extent understandable as the limited elasticity of the Malthusian ceiling—already alluded to by Finley—is an undeniable and defining aspect of the Greco–Roman demographic regime.[30] However, at the same time, there is more to the impact of (technological) innovations than just per capita growth. In the ancient as well as the modern world, new technologies or practices may have an impact that does not translate itself into measurable growth and does not affect the Malthusian ceiling, while fundamentally changing the way people live and what their everyday world looks like. These technologies and practices, too, need to be part of the history of innovation in the Roman world, but recent scholarship has tended to marginalize them in favor of innovations with a potentially high impact on the economy and on demography.

A Culture of Innovation

Key to any understanding of the history of innovation in the Roman world is the fact that the Romans established an infrastructure of knowledge on a scale that had not existed before in Europe and the Mediterranean: expansion of Roman political power beyond Italy into Punic territories and the Greek world and the subsequent conquest of the Near East, Egypt, and Europe integrated theoretical insights, technical know-how, and everyday practices of widely varying origins into one big network, in which knowledge could circulate easily. It is also clear that the Roman elite, at least from the second century onward, actively invested in making themselves familiar with the technological know-how of others and in making this know-how accessible to a wider public. As Pliny narrates, the work of the Carthaginian agricultural writer Mago was not only taken to Rome after the destruction of Carthage but also translated into Latin at the orders of the Senate—despite the fact that Cato had just written his book on agriculture.[31] The Carthaginian travelogues of Hanno and Himilcar were also used by the Romans, as were, of course, the many writings of Greek and Hellenistic authors on all matters related to technology, architecture, and agriculture. Roman elite authors of the first century BC, like Cicero, Varro, and Vitruvius, compiled large, multivolume treatises on practical and theoretical fields of knowledge, establishing a tradition of “scientific” literature in the Latin language that would form the basis upon which Pliny would build his *Naturalis Historia*. In 39 BC, Asinius Pollio used spoils from a successful campaign in Illyria for the construction of the first major public library in Rome, close to the Forum Romanum, an example that was quickly followed by several others in the Augustan period; and by AD 14, Rome had surpassed established Hellenistic centers of knowledge like Pergamum and Alexandria.[32] The first-century AD encyclopedia of the elder Pliny exemplifies how not only knowledge itself but also its history became a central part of Roman society and how this knowledge extended far beyond the theoretical realm of philosophy, mathematics, and mechanics into the practical world of applied chemistry, medicine, crafts, and agriculture. The list of sources in the preamble to the *Naturalis Historia* and the list of inventors of all kinds of everyday procedures at the end of the seventh book highlight the varied and multicultural roots of Roman knowledge.[33]

It is true that most of the knowledge brought together in Rome's public libraries found little or no practical application in everyday life and that the scientific works of Pliny and others were aimed at an elite audience rather than the general public, but the practical nature of a considerable proportion of Roman scientific literature and the active role of the late Republican elite in fostering a public culture of knowledge exchange so close to the seat of power suggests that they felt there was more to knowledge than just prestige and fun—as indeed is already suggested by the explicit interest of the Romans in the agricultural treatise of Mago: knowledge was something that could be of use. Moreover, a considerable amount of practical, technical knowledge did not need the imperial elite or literary texts to spread itself: it just circulated, and with the growth and intensification of the Roman Mediterranean network, it began to circulate faster and over much larger distances. In the early Roman Empire, the possibilities for intercultural cross-fertilization and hybridization in all cultural fields were larger than they had been ever before, and the effects of this are clearly visible in, for instance, the religious history of the Roman world. Technological history expresses itself differently in our sources and is less visible in iconography and epigraphy, but in terms of circulation, there was no fundamental difference: the Roman world was uniquely well-equipped to exploit the technological potential of the ancient world to its maximum and to combine practices and ideas of distant origin into a new technological vocabulary.

To some extent, there also appears to have emerged a culture in which practically applicable invention and innovation were thought to *matter*. Two anecdotes from—not coincidentally—the first century AD are relevant to discuss. The first is the famous story of the unbreakable glass that was presented to Tiberius by its inventor, who immediately was executed on the orders of the emperor because the invention was thought to threaten the price of gold, silver, and copper.[34] Finley used the anecdote as an example of the negative attitude of the Roman elite toward invention, but this makes it difficult to explain why the inventor would have thought it worth going to the emperor to present his invention in the first place: key to the story is the fact that the inventor expected reward but did not get it. Moreover, the reason Tiberius executed the poor inventor was not that he did not understand the potential value of inventions but rather that he understood it all too well and thought it was not in his (or Rome's) interest to let this knowledge become public. Both elements can only be understood in a culture where innovation could lead to reward and were known to be able to have significant societal or economic impact.[35] The second anecdote is told by Suetonius in his account of the life of Vespasian.[36] It concerns the invention (apparently) of some mechanism to transport large and heavy columns easily up the Capitoline hill. In this case, Suetonius reports that the invention was rewarded but not used because the emperor preferred to employ people who would otherwise have no income. Again, twentieth-century commentators, most prominently Finley and Pleket, focused on the decision of Vespasian not to use the invention and neglected the fact that it was precisely this unexpected decision that made the story worth telling: rather than profiting from the invention that—again—was *offered* to him with the idea that it would be of use, Vespasian appreciated the intelligence behind it and spent his money on giving some people a bit of work.[37] Vespasian—if Suetonius is right—used the situation to play his role as a generous emperor, at once rewarding innovation and protecting the people who were to make a living from carrying the columns uphill. In other words, rather than reflecting negative attitudes toward innovation, both anecdotes suggest that first-century AD Roman Italy was a society that could be rather open to practically applicable inventions.

There is also evidence—written and archaeological—for the emergence and spread of several new practices in the period between the emergence of Rome as a Mediterranean superpower and the early Empire. One example concerns aquaculture. Pliny mentions how between the early and the mid-first century BC, Romans invented several ways to cultivate oysters and marine fish. This began around the Bay of Naples with Sergius Orata building commercial oyster beds; around the same time, Licinius Murena built saltwater fishponds that were so successful that others followed his example.[38] Pliny leaves no doubt that the innovation brought enormous profit: the villa of Caius Hirrus Postumius is thought to have been sold for four million sesterces because of the value of the stock ponds; likewise, Licinius Lucullus owned fishponds whose contents after his death were reportedly sold for the same sum. Even if these fishponds did not provide large amounts of food to the masses, they presented an innovation that had a clear impact on Roman elite cuisine; and, as Marzano has rightly emphasized, their construction must be seen as a form of commercial investment.[39] Another example concerns the gradual improvement of winepresses, which traditionally had been operated mainly by muscular force. Pliny discusses two developments.[40] First, the screw was invented, according to Pliny less than a century before his writing in the AD 70s. This made it much easier to operate the lever. Subsequently, in the mid-first century AD, a new improvement led to a smaller, more powerful type of press without a lever. While few screw-driven winepresses of the first century AD have been securely identified in the archaeological record, the technologies described by Pliny can be seen in the wooden press found in Herculaneum and in the cloth press depicted in paintings in a Pompeian fullery (Fig. 2).[41] This shows how the invention of the screw had, within a couple of decades, found its way to the everyday lives of craftspeople in the wealthier urban communities in Roman Italy.[42]

Click to view larger

Fig. 2. Depiction of cloth press with screws from Pompeii, AD 60s or 70s. Photo: Miko Flohr.

It appears that the literary evidence for innovation and change is hard to reconcile with a model in which the Roman world of the late republic and early empire was technologically stagnant. However, written evidence for a more optimistic scenario is neither overwhelming: it does not go much beyond the examples highlighted here. This can be explained, of course: Roman authors had—geographically, chronologically, and socially—a limited view of what was happening in their own world and literary agendas that fostered them to highlight some, but not necessarily all, inventions and innovations they knew of; their impressionistic way of writing about technology makes it very hard to understand to what extent innovations actually spread over the empire and beyond elite circles. As suggested by Greene and Wilson, part of the problem of twentieth-century debates about Roman technology was that they were guided too much by the literary evidence and too little by archaeology. Indeed, Greene's rebuttal of Finley was predominantly based on archaeological evidence that "Finley did not know about," while much of Wilson's argument about the impact of technological innovation on the Roman economy was built around material evidence for the use of water power in milling grain and in mining.[43] The contributions to Lo Cascio's edited volume on technological innovation and to the *Oxford Handbook of Engineering and Technology* also are to a large extent based on material evidence.[44] In what follows, there will be an equally strong focus on the archaeological record.

Material Culture

It is clear from excavated grave goods, production waste, and in-use assemblages that the material world in which early imperial Romans lived had undergone significant changes compared to the late republic and the Hellenistic period. Whereas the Greek and Hellenistic worlds had been dominated by pottery, wood, and textiles, Roman material culture was considerably more varied; and this was at least to some extent facilitated by improved production technologies that made the end products better, cheaper, and more affordable to a larger group of people, even fostering the emergence of forms of consumption that some have, in recent years, characterized as "consumerism."[45] Three developments are worth highlighting here: the emergence of blown glass, an increase in the use of metal objects, and changes in the nature of everyday pottery.

Glass

Glass had been known since approximately 1500 BC, but for a long period it was a rather marginal phenomenon in ancient material culture: making objects with the aid of molds was labor-intensive and required trained skills, so glass vessels were rare and expensive items.[46] Glass was mostly used in colored form and predominantly for open shapes that could be easily produced by means of molds: colorless, transparent glass was extremely rare. This changed dramatically once, in the early first century BC, it was discovered—probably in Syria or Judea—that glass could be easily blown into shape by means of a pipe. This revolutionized the entire glass industry and the technique, and glass spread quickly over the entire Roman Empire, first to Italy, where it was perfected, and then to Africa, Gaul, and Germany: by the middle of the first century AD, evidence for glassblowing is attested throughout the Roman world.[47] Moreover, glass quickly became available to a broad audience, as is attested by the proliferation of glass objects in Pompeian households of all social classes: by the late first century AD, blown glass had become an affordable consumer good in the cities of the Roman Empire.[48] The same picture emerges from first-century AD glass finds from the Roman provinces.[49] Indeed, while we might want to think of Trimalchio's description of glass as "too cheap" for his taste as snobbery, there is more than a pinch of truth in the underlying idea that it had become widely available at the time of Petronius's writing.[50]

The proliferation of glass changed the culture of drinking as much as the Roman culture of storage: unlike pottery and metal, glass does not have a smell of its own; and while clay is relatively hard to shape, glass can easily be blown into every imaginable shape, for example, by using a mold (Fig. 3).[51] This made it, for instance, much easier to produce rectangular bottles that could be stored more efficiently than traditional round vases or long and narrow flasks from which it was easy to distribute small quantities of, e.g., perfume. Moreover, from the mid-first century AD onward Romans were also able to liquify glass and to shape it into flat plates that could be used for windows.[52] The first examples of small-plaque window glass can be found in Pompeii and Herculaneum, but the technique was subsequently developed further, making it possible to construct larger windows and thus to make buildings lighter without exposing their users directly to the elements.[53]

Click to view larger

Fig. 3. Second-century AD Gallo–Roman glass jugs. Reims, Musée Saint-Remi.

Metals

Arguably, (blown) glass was the key innovation in the material culture of the Roman Empire, but it was not the only one. The Roman world saw an explosion in the consumption of metal objects, particularly tableware and oil lamps.[54] While tableware and oil lamps of bronze already existed in the Hellenistic period, they became increasingly common from the first century AD onward.[55] Moreover, besides bronze, other alloys also emerged, such as pewter and brass, and there was a proliferation of silverware.[56] This “metalization” of Roman material culture cannot easily be traced back to any clear technological developments in manufacturing: the standard technologies to make cups, plates, and lamps already were widely known; and while they may have been improved a bit, they do not seem to have become significantly less labor-intensive (Fig. 4). What did change, however, was the availability of raw materials; and here, as has been argued by Wilson and several others before, technological developments played a key role: innovations in mining technology, particularly through the application of Hellenistic water-lifting technologies, made it possible to reach layers that could not be reached earlier and thus to extract more ores at a lower cost.[57] Admittedly, innovative technology is not the only factor at stake here: access to mines also mattered, and the spread of Roman power meant that more mines came under Roman control. Often, conquest led to immediate exploration or, in the case of existing mines with rich deposits, intensification.[58] This is certainly the case in the Iberian Peninsula and in Dacia, and Pliny notes how in his time, some two decades after the conquest of Britain, lead production had boomed to the extent that laws were made to prevent the market from being flooded with the silver extracted from it.[59]

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Fig. 4. Roman bronzeware. Leiden, Rijksmuseum voor Oudheden, no. 134133.

Perhaps initially a by-product of the explosion of mining activity was the proliferation of lead. After glass, lead is the second major Roman addition to the material spectrum of the ancient world: even if the Greeks mined certain quantities of it at the silver mines at Laurion, they do not really seem to have used it in its pure form except as writing material.[60] The Romans, however, began to use it for all kinds of utilitarian purposes, particularly—as is well known—for pressurized water pipes but also for weights, cauldrons, and sarcophagi; and the evidence suggests that lead ingots were commercially traded (Fig. 5).[61] The easy availability of lead and its malleable nature made it easier, for instance, to build complex water systems and large cauldrons for industrial purposes. The increased use of lead must be seen as an important innovation with significant impact throughout the Roman world.[62]

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Fig. 5. Roman lead bar. London, British Museum, inv. no. 1856.0626.1.

Terra Sigillata

The basic technologies for making fine, high-quality pottery did not develop spectacularly between the early Hellenistic period and late antiquity: key procedures were already known throughout the Mediterranean. They had been known for quite some time and were improved only to a limited extent. Innovation, as far as pottery production is concerned, rather lies in the way commonly known technologies were used. For instance, the emergence of relatively simple tableware with mold-formed rather than painted decoration in the later Hellenistic period had profound effects on the economics of pottery workshops and on the labor costs involved in the production of cups, bowls, and plates.[63] The same is true for the standardization of forms in Italian black gloss production in the same period, which in the case of open forms also significantly reduced transport costs and perhaps even transport risks: these were changes in strategy rather than radical innovations, but they paved the way for the late republican and Augustan boom of the Italian *terra sigillata* industry and for the first-century AD Gaulish pottery boom.[64]

Innovations, as far as the Roman world is concerned, seem to have been related to two issues: firing and slip preparation. It has been argued that the red slip that characterizes the large majority of Roman fine ware pottery depended on the use of a new kind of kiln that used clay pipes to protect the products against direct heat and smoke from the fire so that they got a homogeneous red color and a gloss and a new firing procedure that consisted of one instead of three phases.[65] Moreover, the maximum size of kilns seems to have increased, which, combined with the simpler firing procedure, may have slightly lowered production costs. A recent comparison between Italian and Gaulish *terra sigillata* strongly suggests that potters in Gaul had further improved upon the model that Italy initially provided to them and were able to fire their pottery at a substantially higher temperature. At the same time, the Gaulish potters began to artificially lower the amount of magnesium in the clay. Together, this meant that the slip became redder and glossier and adhered much better to the body than was the case in the established *terra sigillata* industries of Italy (Fig. 6).[66]

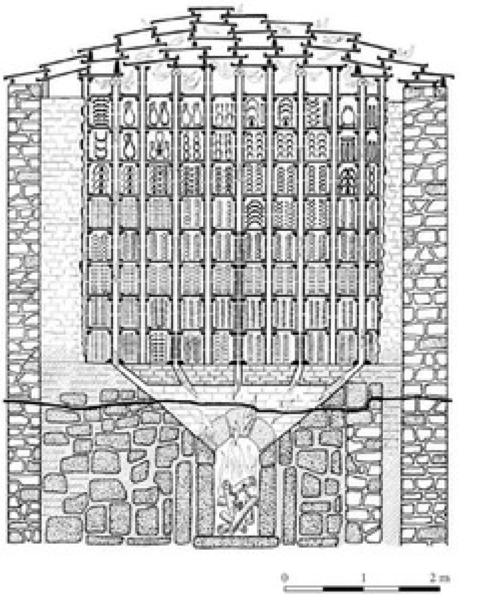

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Fig. 6. Reconstruction of the great kiln at La Graufesenque. Vernhet (1981: fig. 10).

In other words, even if the shapes and decorations of Roman *terra sigillata* present a new commercial strategy rather than a technological innovation, the color, the gloss, and the durability of the slip were improved by employing new techniques in slip preparation and firing. Indeed, the emergence of *terra sigillata* may be seen in a wider context of experimentation with slips and glazes: in the eastern part of the empire, potters of the late republic experimented with techniques to give pots a lead glaze, leading to glossy green pots that, even though the technique eventually spread over the entire Roman world, never became very popular.[67]

Innovation and the Consumer Goods Economy

Thus, three key sectors of the consumer goods economy, and the three sectors from which most products have been preserved, show clear signs of innovation and change, though in different ways and on a different level. For other branches of the manufacturing economy, the situation is less straightforward because there is much less evidence or the evidence has been less well investigated. It is possible that innovation was the norm throughout the manufacturing economy, but it is also possible that some sectors did not change in a way that affected the nature of the products bought by consumers. For instance, textile manufacturing—not the smallest sector of the manufacturing economy, nor the least visible—appears a beacon of stability until late antiquity: there are several changes in the organization and scale of the textile economy, but these do not seem to have affected the quality and price of textiles as the basic procedures that cost the most time remained fundamentally unaltered.[68] The supposed replacement of the warp-weighted loom by the two-beam loom in the first century AD, which is attested in the material remains of Pompeii and Herculaneum, does not seem to have had a dramatic effect on productivity or on clothes design.[69] It is possible that in late antiquity the technologically more advanced horizontal loom was introduced, but arguments in favor of that innovation rest on woven fabric rather than on direct evidence for such looms and remain conjectural.[70] It is also possible that dyeing technology improved so that the world of dress became more colorful, but scholars studying Roman dyeing practices have thus far not addressed the technological development of the industry.[71] However, whatever the amount of innovation in the textile industry or any other, this would qualify rather than undermine the picture of change visible in the manufacturing of glass, metal artifacts, and pottery.

Construction Techniques

If the nature and quality of several classes of Roman consumer goods were decisively affected by several technological changes and innovations, this is even more true for the built environment, in both cities and the countryside, as was already highlighted by the example of the Via Appia at the start of this article. The invention of concrete, the introduction of the arch and vault as common elements in public and private architecture, and the increased use of standardized building materials decisively lowered the (minimum) costs of building projects and gave architects more freedom in designing complex structures on a large scale and in improving key aspects of urban infrastructure (Fig. 7). The standardization of building materials behind construction techniques like *opus reticulatum* and *opus latericium* reveals a rationalization of the building process that not only brought down labor costs but also lowered the level of skill needed to build walls. As Wilson has argued, the modularity of large-scale public building projects based on concrete further added to this.[72] The question remains, however, what the actual effects were on the (urban) environment and what implications these had for the social functioning of communities.

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Fig. 7. Rome, basilica of Maxentius. Photo: Miko Flohr.

Opus Caementicium

Opus caementicium belongs to the most famous inventions of the Romans, but actually the early history of its development and use is far from clear. Until recently, most scholars assumed that it was introduced somewhere in the third century BC, when Rome was establishing its power over Roman Italy.[73] A recent article by Marcello Mogetta has, however, provided strong arguments in favor of a later date—around the middle of the second century BC.[74] Rather than belonging to the Italocentric Roman world of the middle republic, *opus caementicium* thus is more likely to have emerged in the thoroughly Hellenized realm of late republican Rome. Mogetta links the emergence of concrete with developments in the elite housing market, suggesting that the construction technique became popular as a way to make the most of demolition or quarrying waste, which would have been easily available in this period. It is, however, also possible (and perhaps more likely) that the use of concrete proliferated simply because of the enormous and continuous demand for new buildings in a century in which Rome was quickly transforming itself from a big Italian city to a massive Mediterranean metropolis and is commonly believed to have at least quadrupled its population.[75] *Opus caementicium* made it possible to build big, multistory buildings very quickly and, thus, to make more money in less time.

The effect of concrete on the Roman world can hardly be overestimated. Architectural historians might be tempted to emphasize the liberating flexibility of concrete, which facilitated the introduction of many round forms, including the cupola, to the architectural repertoire; but as calculations by DeLaine suggest, the strength of concrete structures and their relatively low construction costs compared to ashlar actually may have been much more fundamental.[76] In and around the Roman metropolis, concrete made it possible to construct multistory apartment buildings, without which the city of Rome could never have housed as many people as it did within the area later surrounded by the Aurelian walls: had Rome consisted of buildings with only one or two upper floors, it would have needed a vast urban area that probably would have made it too big to function properly as a city given the constraints on movement and transport in a society where most people were dependent on walking. In the case of Ostia and Puteoli, a city without *insulae* would even have needed more space than actually was available within the boundaries imposed on these cities by nature.[77]

Concrete thus facilitated the most extreme forms of urbanization in the Roman world. Besides that, concrete also played a crucial role in leveling uneven areas, in building platforms on which temples and other public monuments could be constructed, and in the architecture of spectacle buildings such as theaters and amphitheaters. The construction of the large public baths of the imperial period would also have been impossible—or at least considerably more expensive—without concrete. In infrastructure, concrete played a crucial role in the construction of artificial harbors, which became increasingly common in the Roman Mediterranean. Besides the obvious example of the moles of the harbor of Claudius at Ostia and those of the harbors at Puteoli and Alexandria, there is the Severan harbor at Lepcis Magna and the harbor of Caesarea Maritima in Judea, which appears to have been built with skills and materials from Roman Italy.[78] In a world in which long-distance trade was dominated by maritime transport, the possibility of constructing big and well-protected harbors in areas where good natural harbors were scarce was of crucial importance.[79]

Arch and Vault

However, besides concrete, the importance of arch and vault should not be underestimated. The origins of the arch are unclear, and while it has been attested for the Greek and Hellenistic world, especially in funerary architecture, it never was a common element in architecture before its adaptation by the Romans.[80] The earliest, and by far the most important, application of the arch was in bridges and, thus, in the network of Roman roads that from the mid-republic onward began to facilitate traffic, communication, and transport in Italy and beyond.[81] While there were alternatives to the stone bridges that were built along these roads, structures of stone were stronger—allowing for more weight passing over—and more durable than wooden alternatives, as well as more reliable than fords.[82] As an indispensable part of the Roman road network, the arch played a crucial role in the improvement of connections overland that is a defining characteristic of the Roman world.[83] However, from early on, arches also were used in urban architecture, particularly in wall circuits—a very early example being the city gate at Falerii Novi, dated to the later third century BC (Fig. 8).[84] From the early first century BC onward, arches are commonly applied in public and private architecture in Roman Italy.

Click to view larger

Fig. 8. Falerii Novi, Porta di Giove, arch, second century BC. Photo: Miko Flohr.

Arch and vault were key elements in the construction of late republican and early imperial spectacle buildings, such as the theaters of Marcellus and Pompeius in Rome and, of course, the Colosseum. These buildings have an ashlar facade with arches and concrete vaults underneath the *cavea*. This made it possible to build large structures of a relatively low weight that not only were stable but also used less building materials and were therefore cheaper—even if it requires a bit more skill to build a facade with arches than it requires to build a closed wall. Thus, without arch and vault the proliferation of free-standing theaters and amphitheaters in the western part of the Roman Empire would probably have been less straightforward: spectacle buildings would, as indeed they had been in the Greek world, have been restricted to places with natural relief, or their construction would have been considerably more laborious, as indeed is likely to have been true for the amphitheater that was constructed in the early first century BC at Pompeii, which did not have the Colosseum-style layout based on arches and vaults but a much simpler design based on filling the space underneath the *cavea* with enormous quantities of earth and building a massive retaining wall around it (Fig. 9).[85]

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Fig. 9. Santa Maria Capua Vetere, amphitheater. Photo: Miko Flohr.

Initially developed in ashlar-based constructions, the arch also became common in concrete-based architecture of the late republic and the early empire, which made extensive use of (flat) lintel arches above doors and windows. As a lintel arch could span a considerably longer distance and bear considerably more weight than a lintel of wood or stone, its invention made it possible to construct larger windows so that large rooms and halls could be made to receive more daylight—a development neatly paralleled by the development of window glass discussed above.[86] Moreover, in the monumental architecture of the imperial period, relieving arches made of *bipedales* played a key role in massive walls of *opus latericium*, making it possible to construct heavier buildings: monuments like the Pantheon and the Baths of Caracalla would have been impossible to construct without the stability provided by the arches in the walls, and the same is true for many bath complexes and temples of the imperial period (Fig. 10).[87]

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Fig. 10. Ostia, Caseggiato del Serapide (III × 3), eastern outer wall, relieving arches. Photo: Miko Flohr.

Standardization of Building Materials

A third key element in the development of construction practice in the Roman period is the increasing use of prefabricated building materials of standardized dimensions, which substantially brought down production costs.[88] This seems to begin in the late second century BC but on a relatively small scale, with limited use of (round) bricks in columns and quoins, for example, in the basilica at Pompeii, which was constructed around 120 BC.[89] With the appearance of *opus reticulatum* and *opus vittatum* (*simplex*, and later *mixtum*) in the first century BC, the use of standardized materials starts to become increasingly common, first in the facing of massive concrete structures and in quoins and doorposts and later in free-standing walls.[90] By the first century AD, *opus reticulatum* and *opus vittatum* had become the norm in public as well as private architecture in Pompeii and Herculaneum (Fig. 11).[91]

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Fig. 11. Opus reticulatum, Ostia, Taberne Repubblicane (I × 1). Photo: Miko Flohr.

Alongside these building techniques, there also appears to have been an increasing tendency toward using standardized, prefabricated elements of terra cotta, particularly floor tiles and pipes. The replacement, in hypocaust construction, of the *tegulae mammatae* by *tubuli* in the first century AD highlights how better elements drove their predecessors from the market: *tubuli* were easier to produce, easier to transport, easier to handle on-site, and easier to fix to the wall than the oddly shaped, large, and heavy *tegulae mammatae*.[92] In Britain, Roman builders even invented rounded voussoirs that could be used for the continuation of the hypocaust in the vault of the *caldarium* in a way that was both effective and affordable.[93]

The first century AD saw the emergence of brick as a leading building material.[94] Brick had been used with some frequency for quoins from the late second or early first century BC onward, but it is not until the first century AD that it becomes widely used. The increased popularity of brick is clearly visible at Pompeii and Herculaneum in the building techniques used in repairs necessitated by seismic activity in the decades preceding the AD 79 eruption.[95] Much more frequently than ever before in the Bay of Naples region, these repairs used bricks, especially in the form of *opus vittatum mixtum* and *opus latericium*.[96] It has to be noted, however, that the real proliferation of brick in the Roman metropolis and in Ostia only started in the second century AD: most public architecture from the Julio–Claudian and Flavian periods used tufa ashlar rather than *opus latericium* in the outer parts of the building, perhaps, as DeLaine suggested, for reasons of prestige.[97] From the reign of Trajan onward, *opus latericium* became a key building technique in the Roman metropolitan region, but the second-century building boom in Ostia and Portus was almost completely dominated by *opus mixtum*, which combined *opus reticulatum* with *opus latericium*. Only later in the second century AD did plain *opus latericium* become the preferred building technique in Rome, Ostia, and Portus.[98]

Besides the standardized materials used in walls, floors too were increasingly paved with prefabricated stones of standardized dimensions. A key innovation in this respect is the *opus spicatum* technique, in which floors were made of small, standard-size bricks laid out in a herringbone pattern.[99] *Opus spicatum* was barely found at Pompeii or Herculaneum, while 200 kilometers north in Ostia and Rome just a couple of decades later it had become the standard way of paving floors in rooms of a less representative character, such as corridors, shops, and workshops. Moreover, *opus spicatum*, more than any of the other techniques discussed here, found its way to the countryside, where it has been found in the courtyards and corridors of farmsteads and villas from Istria to Sicily and in field surveys throughout the Italian peninsula. It appears to have been a relatively quick and simple way to construct durable, waterproof floors (Fig. 12).

Click to view larger

Fig. 12. Opus spicatum floor, Lucus Feronia, Villa of the Volusii Saturnini. Photo: Miko Flohr.

The problem with our understanding of the Roman use of standardized materials is that there is a relative lack of scholarship on the history and spread of specific techniques: many scholars have commented on the qualities of *opus reticulatum* and *opus latericium* and on their efficiency in the construction process, but there has been little debate about their diffusion, though several scholars have observed that *opus reticulatum* was rarely used outside Italy.[100] The same is, to a much stronger extent, true for *opus spicatum*, though this technique appears to have been rather more widespread. Moreover, there also is little scholarship on the production of brick and *tesserae*, perhaps with the exception of the Tiber valley brick industry.[101] It may be suggested that, generally, investment in the production of these materials only made sense when there were economies of scale, so a certain amount of ongoing or expected building activity was needed for these building techniques to emerge, which makes them especially useful in the context of large-scale public building and less so in private contexts, except for in large urban centers with a substantial structural demand for *lateres* and *tesserae*, as happens to be true for second-century AD Ostia and for Pompeii after the seismic upheaval of the early AD 60s. In these contexts, the use of *opus reticulatum* and *opus latericium* was extremely profitable, especially in the larger building projects.

Diffusion

The emergence of new construction techniques and the new strategies embraced by Roman builders were a major innovation and one that left a deep impact on Roman social, economic, and cultural history. A key question, however, concerns the diffusion of the innovation, both spatially and socially. It is clear that, alongside the new techniques developed in Rome and Latium, traditional building practices continued to exist: even at Pompeii, there are late first-century AD walls in *opus craticium* and *opus incertum* remained the dominant building technique in private architecture. This is to a much stronger extent the case in other cities of Roman Italy, with the exception of the Roman metropolis and its harbor cities; outside Italy, even in other densely urbanized regions like Africa and Asia Minor, locally rooted building techniques seem to have remained the norm in public architecture: ashlar in Asia, *opus africanum* in Roman North Africa.[102] Moreover, while concrete was used throughout the empire, as were arches and vaults, it is, for the reasons outlined above, legitimate to ask how common they were outside major public monuments and other building projects initiated by the state or by the elite. Yet even if there were limits to the diffusion of innovations in urban construction, it is still beyond doubt that these innovations had a deep impact on the Roman imperial network of transport and communication, on the public landscape of Roman cities, and indirectly on the social lives of urban communities throughout the Roman world.

Innovation and Its Societal Impact

When discussing technological innovation in the Roman world it is essential to move beyond the narrow economic history agenda outlined by Finley, in which innovation is relevant only when it succeeds in heightening the Malthusian ceiling: this is too modern and too teleological a perspective to make sense of technological development in a preindustrial society. Besides the economic or demographic impact, the societal impact of innovation matters too—as, indeed, it does in the modern world. In the Roman world, technological changes in the manufacturing of everyday consumer goods and innovations in construction techniques had a deep impact on the daily lives of people in the cities and in the countryside and changed the way the world looked, both spatially and socially. In terms of technological history, the first centuries of Roman hegemony over the Mediterranean must indeed be seen as dynamic rather than as static: Romans integrated technological insights and practices from an array of origins into one huge knowledge framework and saw the emergence of a culture in which innovation was valued positively if it made life easier and better, as well as several clear innovations that directly impacted everyday practice within and outside elite circles.

The Roman imperial way of life, which depended on public facilities like aqueduct water, spectacle buildings, roads, and harbors, would have been less easily affordable for urban communities without the innovations and technologies that made large-scale building projects cheaper. Indeed, it must be emphasized that Roman urban landscapes, with their massive public buildings, were something completely new in the history of the Mediterranean; and the legacy of this architecture defines the way in which contemporary scholars, as well as the general public, look at and think about the Roman world: to a considerable extent, the modern, visual image of the Roman world rests upon Rome's innovations in building practice and architecture. This is perhaps less obvious in the case of everyday consumer goods, but on a different spatial scale—that of the room, not that of the street—the impact of changes in everyday material culture is likely to have been as profound as that of the changes in the built environment: innovations in manufacturing technology made everyday domestic life quite a bit more comfortable for a significant number of consumers.

The question remains what brought these changes about. Walter Scheidel has, some years ago, suggested that most innovations of the Roman period actually originated in the Hellenistic eastern Mediterranean, proposing a model in which the Roman world just diffused practices developed in the Hellenistic East over a large area, rather than being innovative itself.[103] However, the innovations discussed here are geographically rather varied in their origin. The new Roman construction techniques all appear to have been pioneered in Rome or on the Bay of Naples. The first mass-produced *terra sigillata* came from the Italian peninsula, while the technique was further perfected in Gaul, in workshops producing for the European market. Advanced drainage technologies were based on Hellenistic knowledge but first applied underground in the mines of Roman Spain. In Roman Britain, the hypocaust system was perfected in a way not seen elsewhere in the empire. Of the innovations discussed in this article, only glassblowing unequivocally came from the (very late) Hellenistic East; but even this technology is thought to have been perfected in Italy. Chronologically, the innovations were also rather evenly spread over the period between, roughly, 150 BC and AD 150, continuing until well into the imperial era.

Thus, what was happening in the Roman world was considerably more complex than a simple transfer of technology from a developed East toward an underdeveloped West. Rather, it may be argued that the integration of the Mediterranean under Roman rule marks the start of a period of empire-wide innovation and cross-fertilization that, basically, lasts until the period in which the empire reaches its demographic and economic peak. Yet while the unification of the Mediterranean created ideal circumstances for exchange of knowledge, cross-fertilization, and innovation, the crucial factor in the spread of newly developed techniques and strategies was the fact that they made desirable products more affordable and, thus, made it easier to satisfy consumer demand. For innovations in the production of glass, metal, and ceramic artifacts, the demand potential of private consumers must have been leading. For innovations in construction techniques, interest of the political elite in public architecture is likely to have played a significant role, perhaps in places like Rome and Ostia alongside a more widespread demand for affordable living space. Especially in Italy, the profits of conquest and the influx of taxes levied from the provinces generated a culture of private consumption and public expenditure that fostered the spread of innovations; when, in the course of the second century AD, this consumer demand began to falter, perhaps due to demographic developments, innovation in building and manufacturing also slowed down.[104] In the meantime, however, innovation had turned the Roman world into a fundamentally different place with a material culture more varied than ever before and with human-made landscapes that, in the city as well as the countryside, sometimes must have presented a quite radical breach with how the world had looked before.

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Notes:

([1]) Aicher (1995, 98–102).

([2]) Aicher (1995, 97–98).

([3]) On arches, see Adam (1984, 173–178). See also below.

([4]) On the Via Appia, see Quilici (2008, 553–558).

([5]) On the drainage of the Fucine Lake, see Grewe (2008, 327); Pliny, *NH*, 36.124. The drainage tunnels of the Alban Hills are undated, but it is believed that they were built with Etruscan technology. Cf. Grewe (2008, 326–327).

([6]) *Ruina montium* is described in some detail by Pliny, *NH*, 33.21. On its actual application in Spain, see Domergue (1990).

([7]) On Las Medulas, see Domergue (1987, 297–310).

([8]) See, on the definition of “innovation” and its relation to “invention” and “diffusion,” Greene (2008a, 77–79), with references.

([9]) See, e.g., Greene (2000b), Cuomo (2007), and Oleson (2008).

([10]) Blümner (1875–1886).

([11]) E.g., Forbes (1955–1964).

([12]) Diels (1914).

([13]) Diels emphasized how this failure affected the standing of *Altphilologie* as a discipline. See Diels (1914, 5–6): “Der Kampf der modernen Technik und Naturwissenschaft gegen die Antike.”

([14]) Diels (1920, 31–32). This section misses in Diels (1914).

([15]) Lombroso-Ferrero (1920), Rostovtzeff (1957), and Lefebvre des Noëttes (1924). Cf. Schneider (1992, 23–24).

([16]) On the history of the debate about the ancient economy between the late nineteenth century and the Second World War, see Flohr and Wilson (2016).

([17]) Finley (1965). See also Finley (1959).

([18]) Pleket (1967, 1973) and White (1959). White, however, would later offer a more positive interpretation of ancient technological history based on a reassessment of the archaeological evidence (1984, esp. 172–173).

([19]) Schneider (1992, 29).

([20]) Greene (2000b).

([21]) Ibid., 55. See also Greene (2000a).

([22]) Wilson (2002).

([23]) Lo Cascio (2006a).

([24]) Lo Cascio (2006b).

([25]) On agriculture see Brun (2006), Foraboschi (2006), Forni (2006), and Marcone (2006). On construction, see Wilson (2006) and DeLaine (2006).

([26]) Cuomo (2007, 3–5).

([27]) Oleson (2008, 6).

([28]) See, e.g., Scheidel (2009) and Wilson (2009). See also Saller (2002) and Pleket (2006).

([29]) Cuomo (2007) is a notable exception.

([30]) Finley (1965, 45).

([31]) Pliny, *NH*, 18.5.

([32]) On the libraries of Rome, see *LTUR*, 1:196–197.

([33]) Pliny, *NH*, 7.57.

([34]) The story is narrated by Petronius, Pliny, and Cassius Dio: Petr. *Sat.*, 51; Pliny, *NH*, 36.66; Cassius Dio, 57.21.

([35]) *Contra* Finley (1965, 41). Finley’s interpretation was already criticized by Greene (2000b, 46-47), who deemed the story an “urban myth.”

([36]) Suet., *Vesp.*, 18.

([37]) Finley (1965, 42–43) and Pleket (1973, 10). See also Greene (2000a, 49–50) and Wilson (2002, 4).

([38]) Pliny, *NH*, 7.79–81. Murena, of course, was nicknamed after the fish that flourished in his ponds.

([39]) See also Marzano (2013, 212).

([40]) Pliny, *NH*, 18.74.112.

([41]) See Brun (2004) for some examples of screw-driven presses in the archaeological record, e.g., at the villa at Russi near Ravenna (49) and at Salamis in Cyprus (98–100). For the press at Herculaneum, see Monteix (2010, 205–216). For textile presses, see Flohr (2013, 145–148).

([42]) On the dissemination of the screw press, see also Schneider (2007, 157–158).

([43]) Greene (2000a, 29–30) and Wilson (2002).

([44]) Lo Cascio (2006a) and Oleson (2008).

([45]) On consumption and "consumerism" in the Roman world, see Ray (2006), Greene (2008b), and Van Driel-Murray (2016).

([46]) On pre-Roman glass, see Stern and Schlick Nolte (1994).

([47]) Stern (1995, 34–44). Glass already features in second-style wall decoration in Rome and Pompeii. Cf. Naumann-Steckner (1991).

([48]) De Carolis has even argued that glass was more widespread among lower social classes (2004, 74–79).

([49]) To my knowledge, there is no thorough study of glass consumption in the Roman world, but see, for instance, Isings (1971), Czurda-Ruth (1979), Biaggio Simona (1991), and the papers in Arveiller and Cabart (2012), esp. Brüggler (2012).

([50]) Petr., *Sat.*, 50.

([51]) Price (2005, 167) and De Carolis (2004, 71); Petr., *Sat.*, 50.

([52]) Stern (1995).

([53]) On the history of Roman window glass, see also Dell'Acqua (2004).

([54]) Cf. Harris (2007).

([55]) Cf. Wallace-Hadrill (2008).

([56]) On pewter, see Beagrie (1989). Brass appeared in the first century BC. See Bayley (1990).

([57]) Wilson (2002, 20–21), cf. Domergue (2008, 120–128). For general reference on mining, see also Greene (1986, 144–148).

([58]) Compare maps 2 and 3 in Domergue (2008, 18–21) to get an impression of the sharp increase in mining in the Roman world.

([59]) Pliny, *NH*, 34.49.

([60]) Interestingly, the isotope signal of lead from Laurion is barely detectable in Greenland ice cores, whereas Roman-period mining sites have been successfully identified. Rosman et al. (1999, 3415).

([61]) On trade in lead ingots, see, e.g., Monteix (2004, 369–371) and Trincherini et al. (2009).

([62]) I am not referring to lead poisoning. See Hodge (1981, 491).

([63]) On the “megarian bowl” as a key step in the development of mold-formed pottery, see Rotroff (2006).

([64]) On changes in the later Hellenistic black gloss economy, see Morel (1981). For recent criticism, see Roth (2007, 48–63) and Di Giuseppe (2012, 29–32).

([65]) Vernhet (1981). Cf. Leon et al. (2015, 658) and Jackson and Greene (2008, 505–506).

([66]) Leon et al. (2015, 664).

([67]) Greene (2007).

([68]) On the Roman textile economy, see Flohr (2014).

([69]) Monteix (2010, 176–184) and Wild (1970, 61–75).

([70]) Wild (1987). See also Wild (1970, 75–80).

([71]) See especially Borgard and Puybaret (2004). Columella (7.2.3) suggests that in his time white wool from Gallia Cisalpina became more popular, also because it could be dyed much more easily. This may suggest an increased popularity of dyeing wool, which could have been fostered by technological innovation.

([72]) Wilson (2006).

([73]) See especially Coarelli (1977) and Lugli (1957).

([74]) Mogetta (2015).

([75]) On second-century BC Rome, see, among others, Coarelli (1977) and Hopkins (1978, 96–98).

([76]) DeLaine (2001, 245). Cf. Wilson (2006).

([77]) The size of Ostia was restricted in the east by the salt marshes; Puteoli already seems to have been struggling with the limits imposed by the slopes of the Solfatara volcano.

([78]) For a good overview, see Oleson (2014). See also Brandon et al. (2014).

([79]) On the costs of transport, see Adams (2012) and Morley (2007).

([80]) See Galliazzo (1995, 388–391) for the Greek world.

([81]) See Quilici (2008, 569–573) and Galliazzo (1995, 393–447).

([82]) On the alternatives to stone bridges, see Galliazzo (1995, 157–177).

([83]) On the Roman road network, see Quilici (2008). On land transport, see Greene (1986, 35–42) and Raepsaet (2002, 2008).

([84]) See Adam (1984, 177) for a list of arches before the construction of the Tabularium at Rome in 78 BC.

([85]) On early amphitheaters, see Welch (2007).

([86]) On the lintel arch, see DeLaine (1990, 410–417), also noting the continuation of elements developed in ashlar construction in concrete-based architecture. See, for some earlier examples from the Vesuvian region, also Adam (1984, 187–188).

([87]) On the relieving arches in the main drum of the Pantheon, see MacDonald (1982, 107–108); on relieving arches in the Baths of Caracalla, see DeLaine (1997, 151–153) and Taylor (2003, 106–111).

([88]) On this issue, see Wilson (2006, 226–229).

([89]) On the basilica at Pompeii, see Ohr (1991).

([90]) On the emergence of *opus reticulatum*, see Lancaster and Ulrich (2014, 165) and Adam (1984, 142–147). See also Coarelli (1977).

([91]) For Pompeii, see Adam (2007, 107–108). For Herculaneum, see Monteix (2010, 250–252), but cf. Ganschow (1989, 135–136).

([92]) On the change from *tegulae mammatae* to *tubuli*, see the comment by Seneca, Ep., 90.25; cf. Lancaster (2012, 419).

([93]) Lancaster (2012). As Lancaster noted, the invention seems to have taken place in a civilian context, not in an army context, and does not seem to spread to the mainland.

([94]) Cf. Lancaster (2008, 264–265).

([95]) Traditional scholarship refers to an earthquake in AD 62 or 63, but it is likely that there were more earthquakes in the period between the early AD 60s and the eruption of AD 79.

([96]) See Adam (2007, 108–109).

([97]) DeLaine (2001, 245).

([98]) *Opus reticulatum* essentially seems to disappear after the Hadrianic period. See DeLaine (2001, 244).

([99]) *Opus spicatum* has received remarkably little attention from scholars. No specialist studies have been devoted to it, and it is mentioned only in passing in the relevant handbooks. See Adam (1984, 252–253).

([100]) E.g., Lancaster (2008, 262–263).

([101]) On the production of *tesserae* in Ostia, see DeLaine (2001). On the Tiber valley brick industry, see Graham (2006).

([102]) Lancaster and Ulrich (2014, 186–190).

([103]) Scheidel (2009, 69).

([104]) On the end of growth in the Roman world, see Scheidel (2009) and Wilson (2009). It would be misleading to suggest that late antiquity as a period was completely stagnant. See on this period, the papers in Lavan, Zanini, and Sarantis (2007). See also Ritti, Grewe, and Kessener (2007) on the water-powered stone-saw mill depicted on a sarcophagus at Hierapolis in Phrygia.

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