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A reverse engineering analysis of iron finds from the Roman Age in Valle Camonica (Italy)

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ABSTRACT

Two iron objects, found during the excavation of a rural settlement in Ono San Pietro (Valle Camonica – Italy), dating back to the I-IV century CE, were interpreted as parts of a wagon wheel. A reverse engineering procedure was followed to support this hypothesis. The objects were digitalised by laser-scanning technique, to obtain virtual models that could be easily analysed and measured. Comparing the shape and the size of the objects with those of other finds of the Roman Age, the hypothesis that they were parts of a wheel appeared the most likely. In particular, one could be the external ring mounted at the hub ends; the other one could be a bushing to be mounted in the internal hub cavity to prevent wear of the wooden parts. Starting from the size of the finds, a possible wheel to which they could belong was reconstructed, taking as reference the proportions of some Roman wheels found elsewhere. Subsequently, the whole axle was reconstructed following the same concept. The load capacity of the axle was determined by means of Finite Element analyses, which revealed it was suitable for heavy load transportation. These results contributed to depict the scenario of the discovered settlement, which appeared in continuity with the pre-Roman indigenous culture.

1. Introduction

The Romans developed a sophisticated transportation system, integrating maritime, riverine and land transport (Adams, 2012). In particular, they realized over time a complex road system to connect the various regions of the empire. These roads were built initially for military and domination purpose, but all the economy took advantage of them. (Rossi et al., 2016)(Božič, 2005; Curle, 1911; Keppie, 2002; McCormick, 1968; Torrado Alonso, 2015; Visy, 2008).

The Valle Camonica, an Italian Alpine valley located at the centre of the Rhaetic Alps, was annexed by the Romans at the end of the 1st century CE. At that time, it was inhabited by the *Camunni*, an indigenous people with similarity with the Rhaetian culture but having original and distinct cultural traits (Marzatico and Solano, 2022). They are best known for leaving an endless number of rock engravings, nowadays included in an UNESCO World Heritage site. The annexation of Valle Camonica was bloodless, appearing rather as a voluntary submission to the Roman empire, which was already exerting a strong cultural influence on the indigenous people (Solano, 2017a). The Romans, according to their common practice in newly annexed lands, constructed the main communication route. Many archaeological sites were found on both sides of Valle Camonica: settlements and, most importantly, necropolis with funeral fences (in *Civitas Camunnorum*, Breno, Borno and Lovere), which, as known, in the Roman world were built along the routes. These finds witness that the main communication route likely was a winding road halfway crossing the valley, on both sides, along the north–south direction. The road connected the Valle Camonica to the Trentino region across the Tonale Pass, where, at 1800 m.a.s.l., significant remains of the probable Roman track were found (see Fig. 1) (Solano, 2017b).

In this context, the coexistence and the integration between the indigenous and conquerors peoples was possible. The Romanity appeared especially in the monumental area of *Civitas Camunnorum*, the Roman capital of Valle Camonica, where impressive buildings such as the theatre, the amphitheatre, the forum and the sanctuary dedicated to Minerva are still visible. A different scenario appeared in the peripheral areas of Valle Camonica from the numerous studies conducted by the ex-Archaeological Superintendence of Lombardy since the end of the nineties of the last century. A picture of small villages scattered along the whole valley was painted, with settlements on the sunny slopes (such as Pescarzo di Capo di Ponte and Berzo Demo), on the valley floor along the road tracks (such as Temù and Darfo Boario Terme), and, in some cases, at high altitudes to exploit the mountain resources (such as Cevo-

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Fig. 1. Remains of the ancient Roman road at Tonale Pass (Italy).

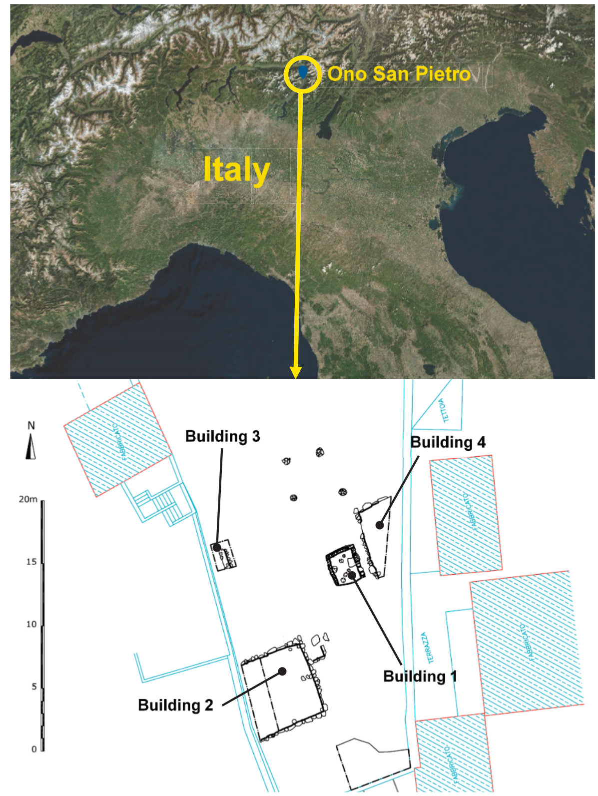

Fig. 2. Location of Ono San Pietro and plan of the Roman Age site.

Dos Curù at 2000 m.a.s.l.).

Proofs of craft activities, mining and metallurgy were found (Mills, 2023). The houses architecture reflected the indigenous tradition, having quadrangular plan with a stone basement surrounding the house. The structure of the houses was generally realized in perishable material, typically wood, by means of vertical poles fixed to the soil inside the surrounding basement (Solano, 2023).

The extraordinary case of the *Camunni* house of Pescarzo di Capo di Ponte is among the most important discoveries: it was destroyed by a violent fire that caused the sudden collapse of its structure, at the same time sealing up and preserving the inside of the house and its inhabitants under a thick layer of coal and ash and giving back an extraordinary glimpse into the daily life of that land between the II and I century BCE (Rossi et al., 1999; Solano, 2017a).

One of the found villages is Ono San Pietro, where in 2019 a small settlement dating back to Roman Age (between the I and the IV century CE) was found (see Fig. 2). The excavation identified and partially unearthed at least six buildings, as a part of a village that certainly, in origin, was larger, likely spreading in the area presently occupied by the historic centre of the modern municipality. The ancient village, which also had open spaces dedicated to production activities, occupied a multiple-level terraced slope, facing east, similarly to the nearby site of Pescarzo di Capo di Ponte.

The houses have structures similarly oriented, perpendicular to the line of the slope terraces, with an overall organization regularity comparable to what emerged in Berzo Demo and in various pre-alpine and alpine settlements of the second Iron Age and Roman Age where a topographic and organization planning was found. Some of these villages are Fai della Paganella (Marzatico, 1999) and Sanzeno (Marzatico, 1993) in Trentino region, Montereale Valcellina and Castelvecchio di Flagogna (Corazza and Vitri, 1999) in Friuli Venezia Giulia region, Trissino (Ruta Serafini et al., 1999) in Veneto region, Waldmatte (Paccolat and Wiblé, 1999) in the canton of Valais (Switzerland), and Parre (Poggiani Keller, 1999) in Lombardy region. The houses are all recessed into the ground along the four sides, with a digging depth up to 1.45 m (at least) in the Building 2, with a stone basement and a structure that should be totally or mostly in perishable material. In addition, on the north side, four large holes, arranged to track a squared space of about 12 sqm, were found: they probably held a wooden structure or fence, maybe a barn or a small warehouse.

Many finds giving information about the daily life were found, among which significant bone remains, belonging to swine, ovine, caprine, poultry, and cattle. Concerning the latter, the analysis of the bones suggested that they were used mainly for the secondary uses, such as milk production and workforce, rather than for meat production. In the Building 1 two iron objects were found (see Fig. 3): a closed thin ring, whose diameter was about 16–17 cm, and an open ring, with diameter of about 12 cm, higher and thicker than the previous one, with a longitudinal cut along the whole height. The archaeological interpretation of these object was that they belonged to a wheel (Cioffi, 2023), based on the comparison with the cited similar finds of other European sites. In particular, the closed ring with larger diameter was interpreted as a reinforcement ring to be mounted externally on the hub; the open ring with smaller diameter was interpreted as a bushing to be mounted internally in the hub hole.

The archaeological interpretation can be supported by archaeoengineering, which takes advantage of the modern engineering tools to provide quantitative data on the investigated finds. In particular, reverse engineering is a systematic approach aimed at comprehending the functionality of a pre-existing device, process or system by employing deductive reasoning. The insights derived from reverse engineering

Fig. 3. Excavation of Building 1 with one of the iron rings emerging from the ground (left-hand); the two iron rings after restoration (right-hand).

applied to archaeology are valuable for gaining a deeper understanding of the inner workings, concepts, and technologies behind the realization of the finds. Previous examples of reverse engineering applied to vehicles are some studies on ancient chariots, with particular emphasis of the Egyptian ones (Rovetta et al., 2000; Sandor, 2012, 2004a, 2004b): they allowed understanding the high technological knowledge and specialization the workers should have to produce such advanced vehicles. Other reverse engineering studies were conducted to investigate structural and technological issues of a Bronze Age chariot wheel (Mazzù et al., 2017), as well as to compare the performances of different typologies of ancient war chariots (Mazzù et al., 2021, Mazzù et al., 2018). From both studies, novel hypotheses on the function of the vehicle components, as well as on the concept behind their configuration, were inferred based on quantitative data. Outside the field of vehicles, reverse engineering was applied, for example, to study ceramic artifacts (Bustamante et al., 2021), to reconstruct collapsed buildings (Erdogmus et al., 2021), to study the production technology of everyday goods such as glass sheets (McArthur and Vandiver, 2017), and to recognise and reproduce inscriptions on historical artifacts (Morar and Popescu, 2012). In this paper, first an investigation of the two iron finds of Ono San Pietro was carried out by laser-scanner acquisition, digitalization, and analysis to reconstruct the original shape of the artifacts. Subsequently, a reconstruction of the possible wheel which the finds could belong to, as well as of the complete axle, was done based on size and shape comparison with objects found in excavations or documented in artistic representations. Finally, finite element structural analyses were done to validate the reconstruction and determine the axle load capacity. This approach shows the great possibilities offered by reverse engineering: by means of quantitative data provided by measurements and calculations, the reconstruction of ancient vehicles can be founded on a solid basis. Combining these results with the information coming from other finds of the same site, a light can be spread on the everyday life of the humble people of the time, usually neglected by written documents and artistic objects.

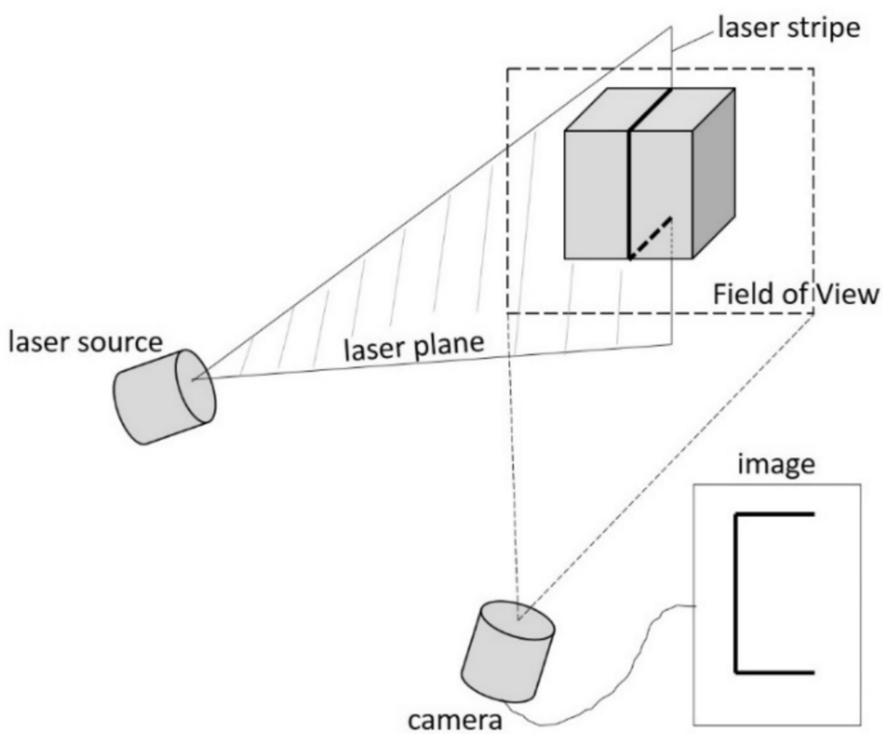

Fig. 4. Schematic of the acquisition setup: the laser source projects a light stripe on the target object and is swept along a direction; the camera acquires the images of the light stripe as projected on the object during sweeping and, after elaboration, the shape of the enlightened surface is obtained.

2. Digitalisation and analysis of the iron finds

2.1. Digitalisation

The crux of reverse engineering lies in acquiring accurate shape data from the physical object, which serves as the foundation for creating a digital representation of the original part's geometry, to be handled in subsequent measurements and elaboration. In this work, the two iron finds of Ono San Pietro were digitalised by laser-scanner technology, which uses lasers to capture the geometry of an object by measuring the distance to its surface.

To acquire the point data, a scanning laser system, the VIVID 910, was employed (see Fig. 4). It uses laser triangulation as its fundamental operational principle. A laser light plane, expanded by a cylindrical lens, emanating from the VIVID's source aperture onto the Field of View (FOV) scans the object under consideration. This light plane is dynamically swept across the field of view through a precisely controlled galvanometer-actuated mirror. The laser light, upon striking the object's surface, is reflected, and each resultant scan stripe is captured by a Charge-Coupled Device (CCD) camera. The elaboration of the acquired light stripe allows evaluating the 3D coordinates of the points illuminated by the stripe; by scanning the FOV, the whole object is acquired, producing the so-called "point cloud". The laser scanner is equipped with three lenses, with different measurement range, FOV size and accuracy; in this work, the measurements were performed with very high accuracy: from $\pm$ 0.1 mm to $\pm$ 0.22 mm, depending on the optics. The findings were very fragile and could not be handled: therefore, the optics were selected depending on the required level of accuracy, and the equipment position changed thanks to its handling ease.

Given the hollow shape of the findings, they could not be acquired in a single scanning, because of the shadows projected on the surfaces. Therefore, the surfaces were subdivided into various zones and a scanning process was conducted for each one of them. The acquired data underwent subsequent processing by the PolyWorks MS software, which involved two fundamental steps. First, all redundant points, such as noise and potential points from objects unrelated to the analysed one (like the scanning base) were eliminated. Subsequently, a software function was employed to merge two distinct point clouds. To achieve this, three points, representing the same feature/area of the object, were manually identified for each view; then the software iteratively overlaid the two views, minimizing distances between all points. This process was iterated for each scan, up to obtain the comprehensive set of points representing the scanned object. In Fig. 5 the sequence of the elaboration phases is shown for the internal open ring.

Subsequently, a 3D model was generated by transforming the point cloud into a triangle mesh based on the topological connection of simple geometrical elements, which tessellate the shapes. The polygon model was edited to decrease the noise influence, optimize the mesh, extract point-to-point distances and sections, extract diameters, and render the 3D representation. Finally, the 3D model was compressed into smaller data files (STL files).

The obtained STL files had defects and issues due to their inherent definition: first, the mesh contained errors such as holes or undefined points external to the object; second, the obtained object was hollow inside. To address these challenges, the STL file was post-processed by the Autodesk Meshmixer software to repair the external surface and convert the objects into solid, by filling the volume enclosed by the surfaces. An example of the STL reparation and conversion to solid is shown in Fig. 6 for the external closed ring; the final models obtained are shown in Fig. 7.

2.2. Elaboration

After obtaining the current geometry and dimensions of the artifacts, their original dimensions during their operational phase were reconstructed through the Autodesk Inventor CAD software, transitioning from the original representations as obtained after the digitalization, which were inherently flawed due to centuries of neglection and oxidation, to a representation in CAD formats that would more faithfully reflect the dimensions these objects should have during their use in Roman times.

The primary obstacle to understanding the original dimensions and shape of the artifacts stemmed from the alterations, both in terms of dimensions and form, resulting from corrosion and oxidation. Conducting destructive tests on the artifacts to analyse the characteristic oxide type on the surfaces and construct a model estimating the corrosion suffered was not feasible. However, studies of the corrosion on archaeological finds showed that this is a complex process including both growth of oxides on the free surfaces of the objects and loss of material due to the detachment of corroded particles (Gerwin and Baumhauer, 2000; Grevey et al., 2020). In particular, (Fell et al., 2006) showed that, in general, the grown volume exceeds the lost one. However, in the present study, in the impossibility of quantifying the lost and grown volume, it was deemed acceptable to equate the current volume of the find (along with its oxide layer) to the original volume of the object, supposing that the grown oxide volume approximately compensated the material volume lost by corrosion. The possible error of some millimetres in the rings' thickness introduced with this approximation is supposed to have negligible consequences in the information obtained, because, as shown in the following sections, the

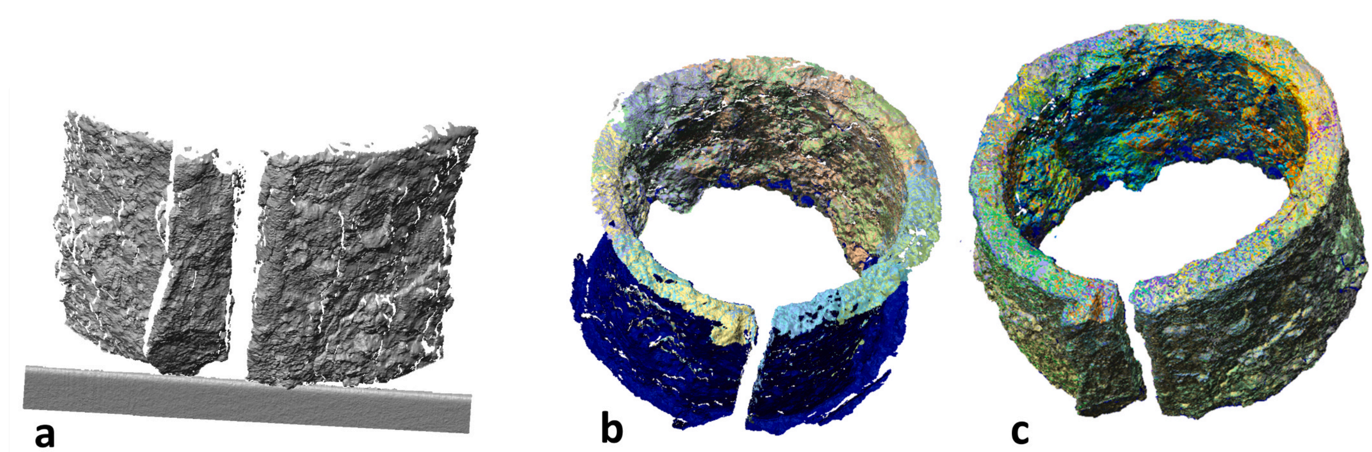

Fig. 5. Phases of point cloud construction for the internal open ring: a) a single point cloud reproducing a part of the surface of the object is obtained after each scanning operation; b) multiple point clouds are cleaned from holes and irregularities and aligned to compose a more extended part of the surface; c) the final point cloud of the find is obtained by joining all the surface parts.

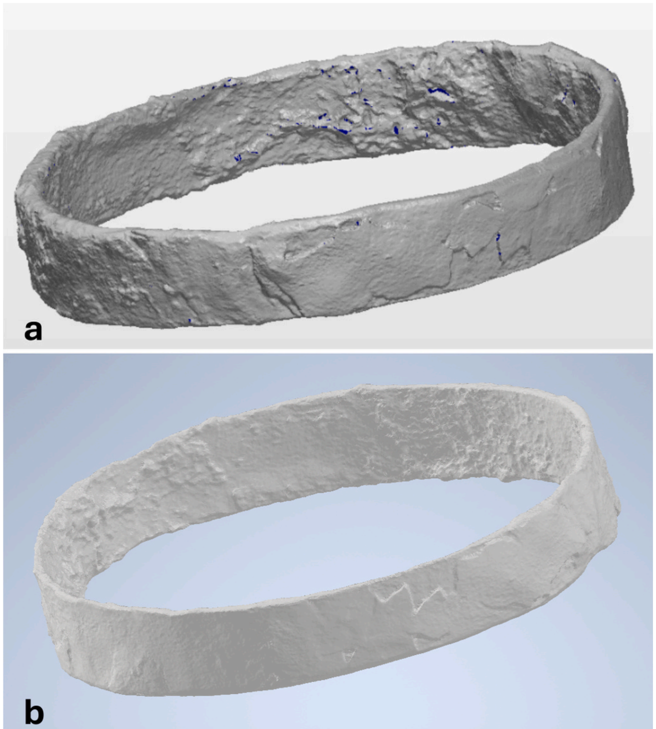

Fig. 6. STL file post-processing of the external closed ring: a) an STL file is obtained after connecting with triangles the point of the acquired cloud (meshing); the blue dots are defects and holes in the external surface; b) the STL file is repaired closing the holes and converted into a 3D model after virtually filling the internal cavity of the surface.

obtained size is comparable with those of other finds and compatible with the required function.

To reconstruct the original shape of the artifact, considering the complex surfaces and compound curves of the two objects, smoothed cross-sections of the rings were then utilized as templates to generate spline contours for the solid model. The resultant objects were further analysed, by systematically adjusting the dimensions of the sections to achieve convergence between the volume of the reconstructed object and that obtained from the digitalisation. A comparison of the digitalised finds with the reconstructed objects is shown in Fig. 8.

The dimension analysis of the reconstructed artifacts allowed finding some irregularities in their geometry. The internal open ring has an average thickness of about 10.6 mm and an average height of about 59.5 mm. Its profile along the tangential direction is ovalized, whereas the inner and outer surfaces show a slight conicity. For these reasons, it is not possible to univocally define the diameter; however, an average internal diameter of about 92.4 mm was estimated. The external closed ring has an average thickness of 5.2 mm, an average height of 27.6 mm, and an average internal diameter of 156.4 mm; again, an ovalized profile was observed.

To produce models suitable for Finite Element simulations, the reconstructed geometry was simplified, referring to the average dimensions; in particular, the height and the thickness were assumed constant, and the profile perfectly circular. A superposition of the reconstructed and simplified geometries is shown in Fig. 9.

3. Discussion on the reconstructed iron finds

Once all pertinent information concerning the iron finds were collected, the initial hypothesis about the function of the two objects was examined by comparison with objects from the literature that have been confirmed to have such function.

In the Roman world a wide variety of vehicles was available for various purposes (Rossi et al., 2016), which can be grouped into three families: race or parade two-wheeled vehicles (*currus*); heavy-haul transportation vehicles (*plaustrum*, *serracum*, *carrus*); travel vehicles (*cisium*, *carpetum*, *raeda*, *pilentum*). They could be pulled by various animals (horses, oxen, donkeys, camels), depending on the load and the road. The spoked wheel was, in general, the preferred type for all vehicles, as witnessed by many illustrations and finds. In many cases, iron elements were found as complementary parts of the wheels: tires placed around the rim to protect the wooden felloes and hold together the wheel elements, as well as rings to reinforce the external and internal surfaces of the hubs (Božič, 2005; Curle, 1911; Keppie, 2002; McCormick, 1968; Torrado Alonso, 2015; Visy, 2008).

The hub reinforcement rings are relatively common finds due to their metallic nature, which, unlike wood, tends to preserve for a longer duration. As exemplified by the remnants of Roman Age wagons in

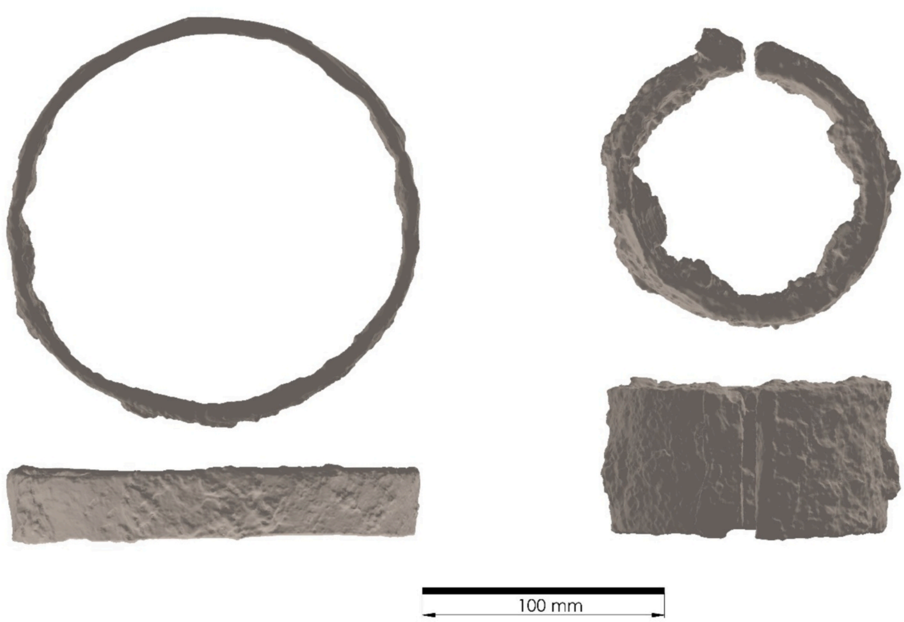

Fig. 7. Final solid models of the iron finds.

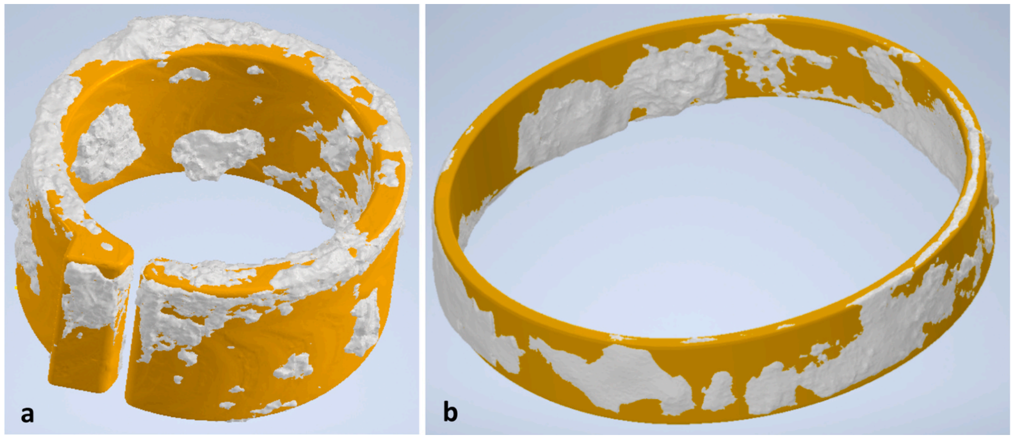

Fig. 8. Comparison of the digitalised finds with the reconstructed smoothed models, where the formers are coloured in grey and the latters in gold: a) internal open ring; b) external closed ring.

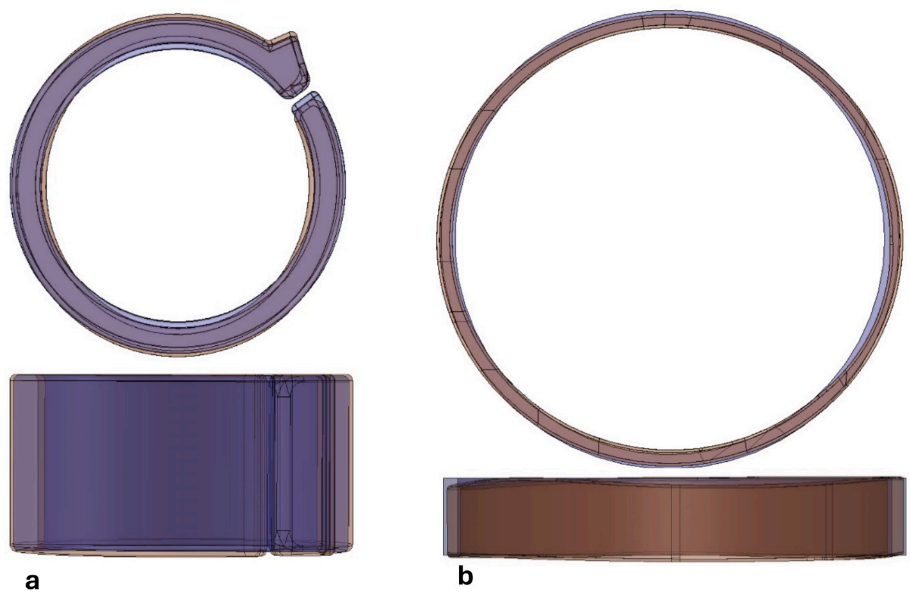

Fig. 9. Superposition of the reconstructed geometry (in brown) with the simplified geometry (in blue), where the latter was obtained by assigning perfectly circular shape and constant thickness and height to the objects: a) internal open ring; b) external closed ring.

Bulgaria (Venedikov, 1975) and Hungary (Kiss, 1989), as well as in Neupotz from the Rhine (Visy, 2008), in addition to an iron tire, the wheel of a Roman wagon featured four rings in the hub area: two larger hub rings and two smaller bushings. Notably, two four-wheeled wagons from Šiškovci and one from Kozármisleny boasted eight hub rings and bushings each, totalling 16 rings; conversely, a two-wheeled wagon from Brezovo had four pairs of rings, amounting to eight rings (Venedikov, 1975).

Iron rings associated with wheel hubs are also evident in several other late Roman hoards from Slovenia. These include hoards in Merišče near Povir (Osmuk, 1976), Tinje above Loka pri Žusmu (Ciglenečki, 1983), Sv. Pavel above Vrtovin (Gaspari et al., 2000), and Limberk above Velika Račna (Božič, 2005). Additionally, a spoke ring was discovered in the southern area of the early Christian complex on Kučar above Podzemelj (Božič, 2005).

Concerning the internal ring, many analogies with the cited finds suggest it was a bushing, aimed at preventing wear of the internal surface of the hub. First, the size of the open ring of Ono San Pietro is comparable with the bushings discovered in the Slovenian hoards mentioned above, which had a diameter ranging between 81 and 128 mm and a width spanning from 34 to 54 mm (Božič, 2005), and with the bushings found in Neupotz, which had a similar diameter and a width predominantly ranging from 54 to 63 mm (Visy, 2008). Roman bushings were typically open rings: such a choice was made to produce a bushing with a slightly larger diameter than the hole drilled in the hub. This bushing would then be compressed to be inserted into the hub, exploiting its elastic properties. Once inserted, it would expand to adhere better, pressing against the hub's surface. Another distinctive feature of finds of Ono San Pietro is a protruding keyway-like structure in corresponding to the border of the circumference opening. This keyway was probably obtained through hot working of an iron strip, which was the starting material to produce bushings or rings. This likely served the purpose of ensuring the coupling between the internal bushing and the hub, preventing relative rotation and excessive wear of the wood. A similar artifact was found in Pillerhohe (Austria) (see Fig. 10), although lower sized: about 70 mm in diameter, 40 mm in height, and 3–5 mm in thickness.

From the literature, it is evident that, during the Roman Age, various techniques were developed to prevent rotation of the bushings inside the hub. All spoke rings from Slovenia had backward-bent wings, often with triangular shape and a wavy cross-section: they were likely produced to fit into the wooden seat of the hub and secure the bushing (Božič, 2005;

Fig. 10. Open ring with keyway-like protrusion found in the Pillerhohe place of worship (courtesy of the Archaeological Museum of Fliess-Austria).

Ciglenečki, 1983; Gaspari et al., 2000). A similar system was found in Sanzeno, where a bushing with a single backward-bent wing was found (Nothdurfter, 1979). On the other hand, in the wheels found at Newstead, this bushing was secured in place by a pair of curved loops protruding from its upper surface, with the inner edges of the loops sharpened for insertion into the wood of the hub (Curle, 1911). In the bushings found at Neupotz, instead, there was a hole, likely serving as a seat for a nail that fulfilled this function (Visy, 2008). A comparison between the various systems for securing the internal bushing against rotation inside the hub is shown in Fig. 11.

Concerning the external hub ring, in the Slovenian hoards mentioned earlier, the diameters of hub rings range from 136 to 192 cm, with widths between 28 and 32 mm (Božič, 2005): these are completely compatible with the dimensions of the external ring of Ono San Pietro.

4. Reconstruction of the wheel

Despite some finds and representations witness the presence of alternatives, the spoked wheel was largely the most diffused in the Roman world. Its parts were meticulously designed to optimize the absorption of stresses arising from the carried weight and roadbed contact by utilizing the inherent strength of the wood fibres. The wheels freely rotated on a fixed axle, a desirable characteristic for making turns: in fact, this design ensures that the wheels can rotate at different speeds during corners, preventing skidding.

A spoked wheel could be crafted from relatively small constituent parts. The nave, the central element of the wheel, could be shaped on a lathe. The cylindrical form was then drilled with a series of augers of increasing sizes to accommodate the axle, then it was mortised with a chisel around the exterior of the cylinder to receive the tenoned spokes. Elm was the preferred wood for the nave (Röring, 1983). The spokes of the wheel were crafted from a robust and flexible wood. The felloes of Roman wheels were formed from multiple curved sections or even single pieces of stock steamed and bent to create a perfect circle. The wheel

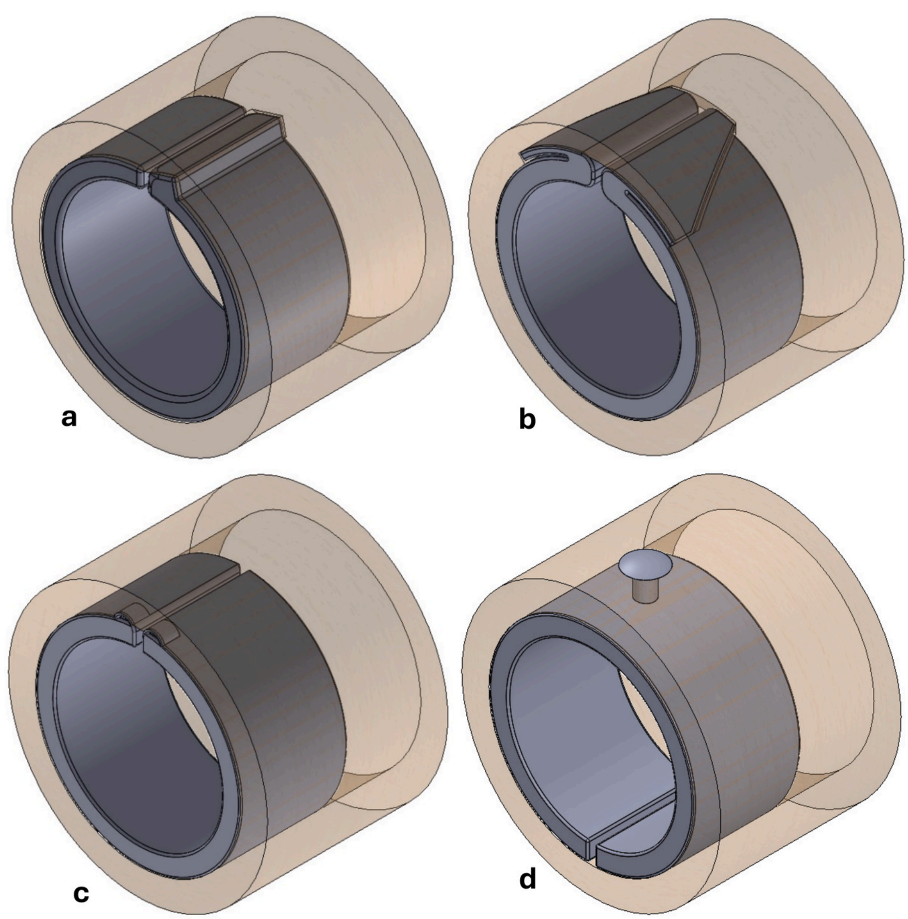

Fig. 11. Schematic of the systems for securing the internal bushings in Roman wheels, where the grey parts represent the metallic bushings and the brown ones the wooden hubs: a) with keyway-like protrusion (Ono San Pietro and Pillerhohe); b) with wings (Slovenia); c) with protruding loops (Newstead); with nail (Neupotz).

itself was reinforced with an iron tire, consisting of an iron hoop protecting the wooden felloe. This band offered advantages such as reducing uneven wear on the wooden wheel and protecting joints between individual felloes. Fitting the iron tire tightly around the rim of a wooden spoked wheel posed a challenge. The blacksmith forged the iron tire to precise dimensions, heated the metal ring to a high temperature, fitted it red-hot to the wooden felloe, and cooled it rapidly with multiple buckets of water to ensure a tight fit before charring the wooden wheel (Ulrich, 2007).

To reconstruct the wheel the iron finds could belong to, a comparison was done between some of the wooden wheels from the Roman Age that have been uncovered by archaeologists, specifically analysing their geometries and construction characteristics. Unfortunately, the number of these findings is not extensive due to the organic nature of wood and its consequent decomposition. The following wheels, identified in relation to their discovery location, were considered:

- Bar Hill (Keppie, 2002): a military chariot wheel, with diameter of 880 mm, 11 spokes, was unearthed from a deep refuse pit at Bar Hill fort (Scotland), allowing for a relative dating estimate of approximately 142–80 CE. The well-preserved condition of the wheel allowed determining that ash and elm wood were employed for the hub and spokes, respectively, with these components bound together by an iron rim.
- Newstead ((Curle, 1911): during the excavations at the Newstead Roman fort (Scotland), three wooden wheels were discovered, which, hereinafter, will be identified as "Newstead-1", "Newstead-2", and "Newstead-3". Newstead-1 and Newstead-2 exhibited a lightweight and elegant design like the one found at Bar Hill. They were dated to the period between 140 and 180 CE and had similar dimensions and design (probably belonging to the same chart). Each wheel had a diameter of 914.4 mm. The felloes were crafted from a single piece of ash bent through artificial softening to present only one joint; the two ends were bolted together with an iron plate. The felloe was then surrounded by an iron rim for reinforcement. These spokes, 11 in number, in willow, were precisely turned, featuring a square tenon for insertion into the hub and a round tenon for insertion into the felloe. The hub, crafted from elm, displayed evidence of lathe turning. At both ends, it was equipped with an iron ring measuring 76.2 mm in depth. At one end, a robust iron ring served as a bushing inside the hub. Newstead-3 likely dates back to the Antonine period (96–192 CE). When intact, the wheel should have had a diameter of approximately 1041 mm. No iron mountings were recovered alongside it. The twelve spokes were nearly square and tapering slightly towards the felloe.
- Holme Pierrepont (McCormick, 1968): in Holme Pierrepont, a wheel with 12 spokes was discovered in an old meander of the river Trent in 1967. It bears similarities to the third type found at Newstead. The wheel with six felloes had a diameter of approximately 838 mm, featured square-section spokes and remnants of an iron rim. The hub showed no signs of a bearing. Notably, this is the sole instance of a wheel with a central hub crafted from birch wood. The wheel is approximately dated to the 2nd century CE.
- Arles (Long, 2016): in 2014 the research endeavours led by the team coordinated by Luc Long in the waters of the Rhône River in southern France resulted in the recovery of a wooden cartwheel, a highly uncommon find given the challenges of preserving wood in a subaqueous environment. The wheel, featuring ten spokes and a diameter of approximately 1 m, is tentatively dated to the late 4th century CE.
- Neupotz (Visy, 2008): in the Neupotz excavations, dated to approximately 278 CE, archaeologists uncovered various components of wooden wheels and iron elements associated with distinct *plaustra* (freight wagons). Among the findings were 48 hub rings designed for hub reinforcement, meticulously preserved alongside wooden fragments, and 48 iron bushings strategically placed within the wheel hub. Additionally, twelve iron rim bandings were identified, characterized by a diameter spanning from 1001 to 1193 mm. Notably, these wheels boasted 10 spokes, with each spoke paired to the hub and the felloe using the same technique observed in other Roman wheels, such as those found in Newstead.

After analysing all these wheels, the dimensions and the design choices (number of spokes, shape of spokes, shape of hubs, etc.) for each of these wheels were compared, using both measurements published in articles and estimations made on images found in the literature. In Table 1 the analysis results are summarized.

From these data, it is evident that the variations in geometric dimensions among the various individuals are not considerable. Additionally, a relationship between the dimensions of the wheel components and the diameter of the wheel can be observed. In particular, it is noticeable that, in general, as the wheel diameter increases, the other dimensions of the wheel also tend to increase.

To reconstruct the wheel of Ono San Pietro, the proportions between the rim diameter and the other dimensions were calculated for each wheel, then the average proportion for each dimension was calculated.

Starting from the internal hub diameter, every other dimension of the Ono San Pietro wheel was reconstructed based on these average proportions. The resulting dimensions are summarized in Table 2. Note that the external diameter of the hub at the ends was determined based on the measurements of the ring of Ono San Pietro, not on the proportions.

As the number and shape of the spokes is concerned, the comparation between the wheels suggests that there was not a fixed rule. The diameter of the Ono San Pietro wheel is relatively small if compared with the others, therefore it is more probable that the number of spokes was 10 rather than 11 or 12; additionally, 10-spoked wheels are the most frequent in the artistic representations. Regarding the shape, two considerations were done. Firstly, elliptical or circular cross-section spokes were easier to manufacture compared to square-section spokes. Additionally, in almost all representations, the spokes exhibited a tapered profile and an elliptical cross-section. Considering all these factors, a final model based on the 10-spoke wheel design was reconstructed for the wheel of Ono San Pietro. This model is shown in Fig. 12. The spokes are tapered, with square tenons in the hub and circular tenons in the felloe; the ellipse axes at the base are 76 mm and 53 mm. A single-piece bent felloe was supposed, held together even by an external nailed bracket.

5. Reconstruction of the axle

Further developments involved a concerted effort to reconstruct the axle to which the artifacts discovered at Ono San Pietro could be attributed. As discussed above, the axle should be fixed with the wheel turning around it, as confirmed also by the presence of the bushing. As the distance between the wheels is concerned, some considerations are needed. In Roman times, the roads were primarily built for military use and domination purpose (Adams, 2012), and it is probable that the initial ruts, to which later wagons had to conform under the risk of axle damage, were carved by vehicles of the Roman army. These vehicles, whose construction was based on a predetermined model, uniformly maintained the same wheel spacing. The standardized track width of Roman vehicles accommodated the necessary space for two horses to pass through, ensuring that vehicles would not get stuck or collide with oncoming ones. This standard track width was not only adhered to in Roman cities but also on all Roman main roads across three continents. Given the enduring use of Roman roads, European carriage builders continued to adhere to these measurements for centuries. Measuring the distance between the ruts left by Roman wagons along paved roads throughout Europe yields a width that roughly corresponds to 1435 mm, providing additional evidence that this measurement was the standard interaxle distance of Roman wagons (Rossi et al., 2016). These

Table 1
Comparison of the features of various Roman wheels.

	Bar Hill	Newstead 1–2	Newstead 3	Holme P.	Arles	Neupotz (min)	Neupotz (max)
Rim diameter [mm]	880	914	1040	838	1000	998	1193
Number of spokes	11	11	12	12	10	10	10
Number of felloes	1	1	6	6			
Felloe height [mm]	80	79	100	77	78		
Felloe thickness [mm]		45	80–29			35	45
Spokes shape	Circular section, shaped	Circular section, shaped	Square section, tapered	Square section, constant	Circular section, tapered	Circular section, tapered	Circular section, tapered
Spokes joint		Square tenon (hub); circular tenon (felloe)	Square tenon (hub);through felloe	Square tenon (hub);through felloe	Square tenon (hub); circular tenon (felloe)	Square tenon (hub); circular tenon (felloe)	Square tenon (hub); circular tenon (felloe)
Spokes section [mm]	Ø40 (max)	Ø40 (max)	63 × 63 (max)	38 × 38	Ø65 (max)		
Spokes length [mm]	265	270	305	245	300		
Hub length [mm]	368	394	406			420	430
Hub internal diameter [mm]	95	100		80	104	97	113
Hub external diameter (central) [mm]	190	216	230	194	244	210	244
Hub external diameter (ends) [mm]	158	150		165		153	180

Table 2
Dimensions of the reconstructed wheel of Ono San Pietro.

Rim diameter [mm]	861,4
Felloe height [mm]	75,7
Felloe thickness [mm]	36,0
Spoke length [mm]	260,3
Hub length [mm]	359,9
Hub internal diameter [mm]	92,4
Hub external diameter (central) [mm]	202,4
Hub external diameter (ends) [mm]	156,5

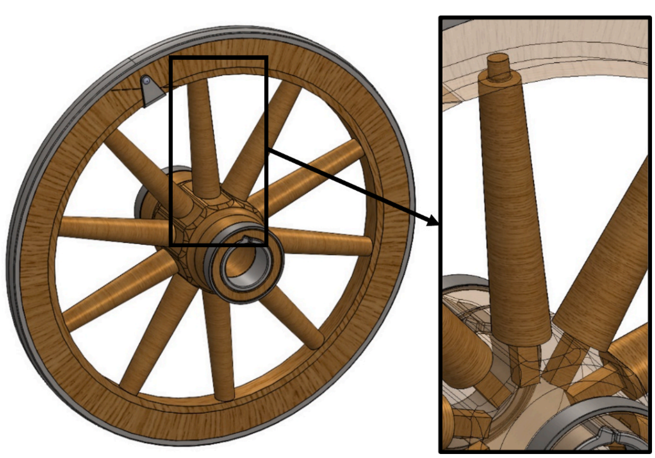

Fig. 12. CAD model of the reconstructed wheel of Ono San Pietro; on the right, a particular with the hub and the felloes in transparency, to highlight the morticing system of the spokes.

considerations were farther supported by the discovery near Castellammare di Stabia (*Stabiae*) of a Roman villa containing two ancient wagons. The track width, still measurable, aligns closely with previously cited data (Miniero, 1987). Maybe this standard distance could have some exceptions in secondary routes or in rural areas where older traditions could survive: for example, Grabherr found an interaxle distance of 107 cm in alpine roads (Grabherr, 2002). However, such uncertainty on the exact interaxle distance does not compromise the overall considerations on the axle load capacity.

Similar to the approach taken with the archaeological findings of wheels illustrated in the previous section, the dimensions of the axle of Ono San Pietro were reconstructed by proportionally comparing them to those of the better conserved one of the two *Stabiae* wagons. The internal diameter of the bushing in the Stabiae wagon (80 mm) was used as a reference point, establishing a ratio with the internal diameter of the bushing in the present case.

Comparisons were then made between the dimensions and design of axles of the *Stabiae* wagon and those of other chariot findings, such as the one discovered in Châteaumeillant, France, (Torrado Alonso, 2015) and those found in Tracia (Venedikov, 1975). In both cases, there were observed correspondences in measurements and a degree of uniformity in construction techniques. The common approach involved a square axle supporting the chariot's body, with two cylindrical extensions at its ends to house the wheels. These cylinders featured a terminal hole for inserting a pin, preventing the wheels from dislodging and ensuring stability within the structure.

The artifacts uncovered in the *Stabiae* excavation also give important information to understand how the coupling between the wheel and the axle was achieved. An iron rod, with a rectangular cross-section, was inserted along the whole length of the cylindrical axle end. This rod was nailed to the lower part of the axle where it enters the hub. The inner end of this rod was bent at a right angle. Additionally, on the upper side of the axle end, a similar iron rod was added, but it was shorter. Similar solutions were found in the cited finds of Neupotz (Visy, 2008), Châteaumeillant (Torrado Alonso, 2015), and in a recently excavated wagon in Pompeii ("the chariot of Civita Giuliana"). This design ensured that during wheel rotation, friction occurred between metal surfaces rather than wood against wood or wood against metal; in addition, grease lubrication should be used. Additional evidence supporting this practice is found in the writings of authors such as Cato ("De re rustica", chapter XCVIII) and Pliny ("Naturalis historia", book XXVIII, paragraph 141), who provided instructions on making and using axle grease.

Based on this information, a CAD model of the axle was designed (see Fig. 13). The features of this model include a total length of 1920 mm, a rectangular cross-sectional profile of the central part measuring 200x200 mm, and a diameter of 80 mm for the two cylindrical sections. In these two parts, seatings for the key elements were then fashioned in the lower and upper portions of the axle. In the model, the two rods were

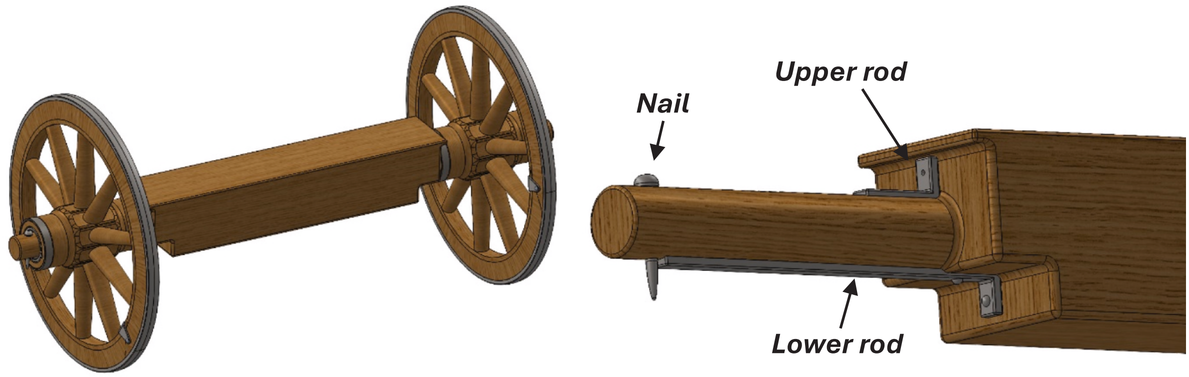

Fig. 13. Reconstruction of the axle of the wheel of Ono San Pietro; on the right, a particular of the axle end, with the metallic parts in grey. The nail was used to secure the wheel to the axle; the rods to avoid direct contact between the metallic bushing of the wheel and the wooden axle end.

then integrated, both having a section of 25 mm in width and 12 mm in height, with lengths of 455 mm and 100 mm, respectively. Finally, an assembly was created including the axle, with its keyways in the appropriate seats and the nails for locking them, the two-wheel models obtained in the previous section and the pins to prevent the wheels from coming out of their housing.

6. Finite Element structural assessment

Finite Element (FE) simulations were done by the SolidWorks Simulation tool to evaluate the load capacity of the axle and the contact condition between the bushing and the iron rods.

For the wooden parts, the typical properties of a hardwood (such as beech, ash or elm) were assumed. As known, wood is an orthotropic material; however, given the thinness of all members, they were supposed to work mainly in bending, with the wood grains being strained along their longitudinal direction. Therefore, the orthotropic effect is considered negligible. The wooden parts were thus modelled as an elastic isotropic material with elasticity modulus $E = 11,600MPa$, Poisson ratio $\gamma = 0.3$, and density $\rho = 615kg/m^3$ (Mazzù et al., 2021, Mazzù et al., 2017).

For the iron components, we know from the Neupotz find that the Romans used iron with a low carbon content to reinforce the wagon. The Romans' ability to produce iron with a very low carbon content is further confirmed by studies conducted on some Roman Age iron finds (Merluzzo et al., 2014; Pagelson et al., 2023; Pagès et al., 2011). Knowing this, the hub reinforcements, axle rods, and tire were modelled as objects made of elastic isotropic material with elasticity modulus $E = 200,000\text{MPa}$, Poisson ratio $\gamma = 0.29$, and density $\rho = 7800\text{kg/m}^3$; a yield stress of about 100 MPa was supposed for such an iron. The overall mass of the system resulted 85.5 kg. All the members were then modelled by solid linear tetrahedra.

First, a simulation with vertical load on the axle was carried out, to determine its load capacity. The boundary conditions were applied to the wheels such to eliminate any rigid motion: in particular, vertical and longitudinal constraints were applied to both wheels in their points of contact with the ground, whereas a lateral constraint was applied in the same point to a single wheel only, to allow lateral expansion of the axle. Longitudinal constraints were applied also to the diametrically opposite points of the wheels, to avoid back and forth rigid rotations. A distributed force was applied on the top surface of the square section part of the axle. A schematic of the FE model is shown in Fig. 14. Increasing force was applied up to have a maximum stress in the rods (which were the most solicitated parts) of about 67 MPa, to keep sufficiently far from the yield limit of the iron.

This condition was approached with an axle load of 1500 kg (see Fig. 15), which was assumed as the load capacity of the axle.

Additionally, a simulation under vertical and lateral load was done.

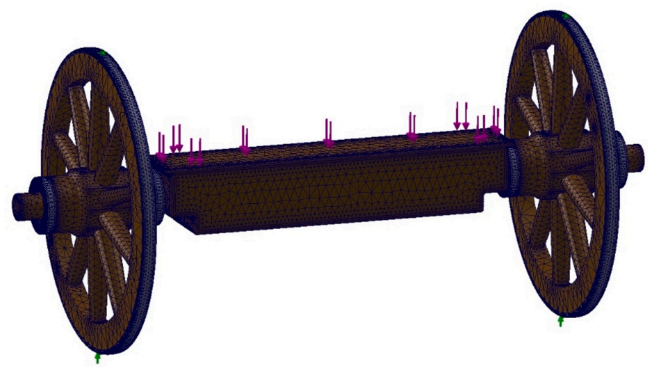

Fig. 14. FE model of the axle under vertical load with constraints (green arrows) and distributed force (violet arrows); the constraints prevent the displacements of the points of contact of the wheel with the floor, while the distributed forces apply the total vertical load along the whole upper surface of the square part of the axle.

The lateral load can be due either to the centrifugal force in curve or to gravity when traveling on roads with lateral inclination, as is possible in a mountainous location. Given the presumably low speed of a wagon carrying a heavy load, the second hypothesis was assumed as the most severe. Assuming a lateral slope of 5 %, a total lateral force equal to 760 N on the axle is obtained, which can be supposed equally distributed between the two wheels. The simulation aimed to verify that this tangential force was not excessively damaging the axle, as well as to understand where contact occurred between the axle and the wheel.

It resulted that the most stressed point shifted to a different position compared to the case of vertical load, specifically at the junction of the upper rod (see Fig. 16). Moreover, there was an increase in the maximum stress, which reached the value of 150 MPa. This result highlights a potentially weak point in the axle, which could be improved by a slight variation of the upper rod design with respect to the present hypothesis, maybe by increasing the fillet radius. However, also a prudential reduction of the load capacity to about 750 kg can be supposed, which implies that a four-wheel wagon could carry from one to two tons. This load capacity is compatible with the transportation of heavy loads, such as roundwood or stones, which were used for the house building. In addition, the remains of cattle bones found in that area is another clue that heavy transportation vehicles should be common in Valle Camonica. In Fig. 17 the map of the contact pressure is shown. The green and blue regions highlight the areas of contact: these are all on the iron components, showing that this system was effective in preventing contact between iron and wood.

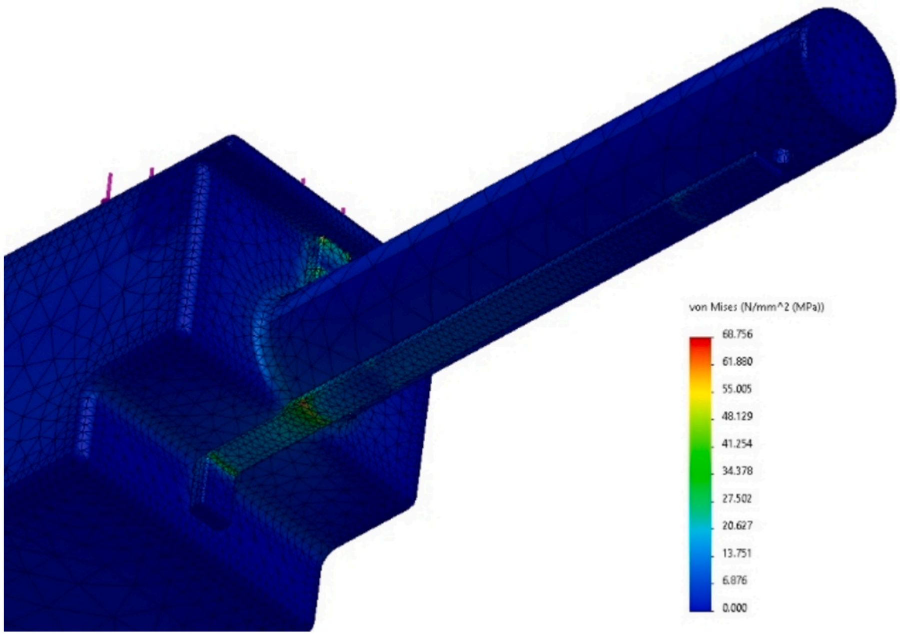

Fig. 15. Highlight of the most stressed region of the rod in the FE analysis under vertical load: the green areas, belonging to the metallic rods, are the most solicitated ones, whereas the blue ones, belonging mainly to the wooden axle, are subjected to low stresses.

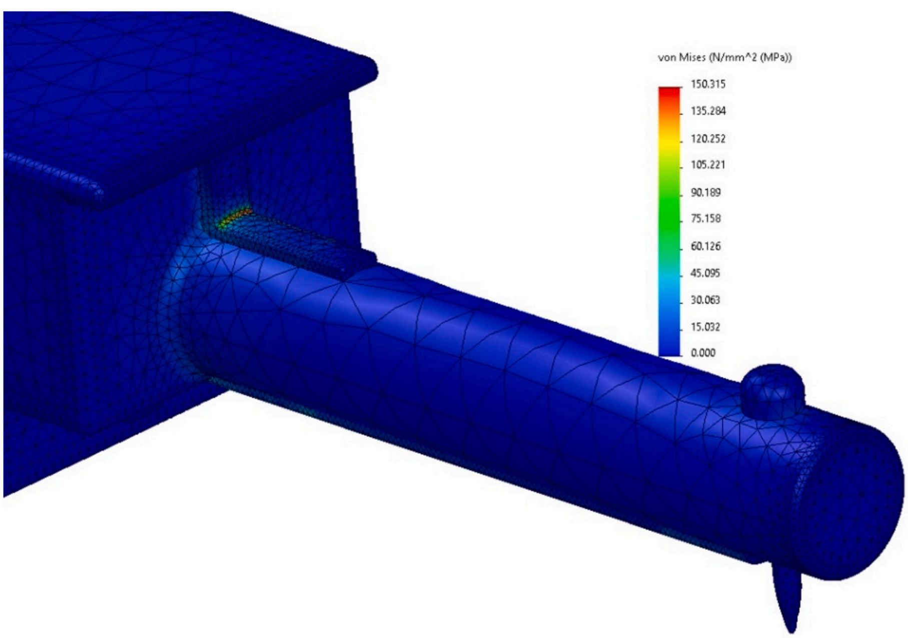

Fig. 16. Details of the Mises stress map of the slope simulation: the zone where the upper metallic rod is bent, coloured in green–red, is the most solicitated one.

7. Discussion

Whereas the reconstruction and interpretation of the iron finds appear rather solid, being based on available data such as their size, shape and analogies with similar objects, the reconstruction of the wheel and the axle is not supported by incontrovertible proofs. We are not completely sure about the material, the shape, the assembly, and the fact it belonged to a 4-wheeled wagon rather than to a 2-wheeled cart. However, the combination of engineering analysis tools with archaeological comparation allows reasonably supporting the hypotheses introduced. A question arising is why the other parts of the presumed wagon were not found. A possible answer is that the resident of Building 1 was not the owner of the wagon, but he had obtained those iron objects as spare or discarded parts, to be recycled in another way, given the high economical value of the metal at that time. Whatever the reason, their presence suggests that a vehicle to which they had belonged should have existed in the area.

A consolidated datum is that the size of the iron finds is compatible with a vehicle for heavy load transportation, which, considering also the context where it was found, puts it in a different field with respect to other reconstructions of Roman vehicles. Considering the vehicles mentioned in the previous sections, the wagon of *Stabiae* was interpreted as a light wagon to supply the *villa* where it was found with farm produce, mainly wine (Miniero, 1987), as well as the vehicles of Neupotz

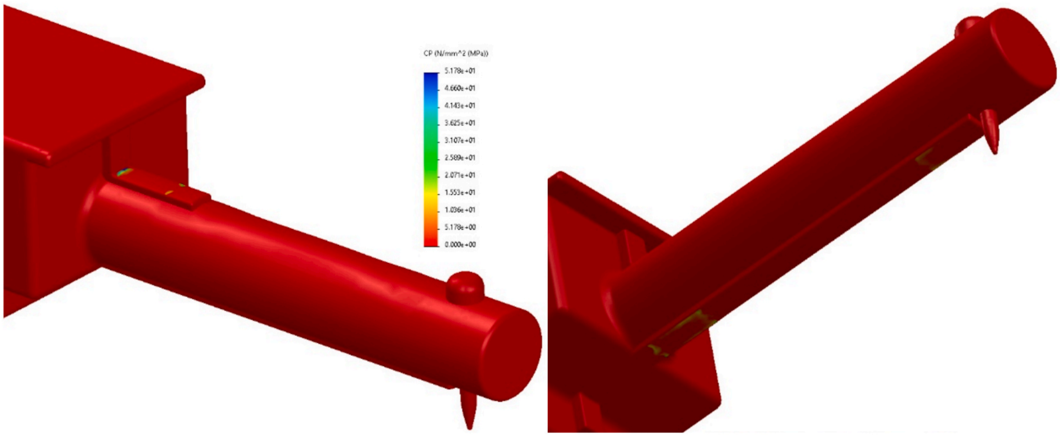

Fig. 17. Details of the contact pressure map of the slope simulation. The red areas correspond to zero contact pressure, meaning that there is no contact between the wheel and the axle; the yellow-blue areas correspond to the zones of effective contact with the wheel hub. No contact was detected between the wooden parts of the axle and the metallic wheel bushing.

(Visy, 2008) and Châteaumeillant (Torrado Alonso, 2015). The chariot of Civita Giuliana appears as a ceremonial vehicle belonging to a high-ranking family. The chariot reconstructed by Röring is a coach for people transportation (Röring, 1983). All these vehicles help understanding the way of life of the urbanised and rich part of the Roman society. In Valle Camonica, such lifestyle could be typical of people living in *Civitas Camunnorum*, as witnessed by the remains of the monumental area and the *thermae*.

Contrary to that, the hypothesized wagon of Ono San Pietro is perfectly compatible with the finds of that area, which depict a rural context characterised by small and poor houses, whose residents should be devoted to agriculture and domestic breeding. In addition, the characteristics of the reconstructed wagon axle suggest they could be devoted to other activities needing the transportation of heavy loads, such as, for instance, timber and stones, also used to build their houses. This scenario puts the village of Ono San Pietro in continuity with the previous indigenous culture witnessed by the rock engravings of Valle Camonica, which show various wagons pulled by oxen or horses. All these clues, together with the bloodless integration into the Roman Empire, suggest the existence of a multicultural and inclusive society (for that time) in the first century of the Roman Age in Valle Camonica (Solano, 2017a).

8. Conclusions

Two iron objects were recently found during the archaeological excavations of a rural settlement of the Roman Age in Ono San Pietro in Valle Camonica (Italy). They were supposed to be parts of a wheel and were analysed by engineering tools to evaluate this hypothesis. First, they were digitalised to facilitate measurements and visual analyses. They were interpreted as the external ring and the internal bushing of a wheel hub. The latter, in particular, exhibits a longitudinal cutting to provide deformability and help its mounting inside the hub. Additionally, it has a protrusion along one border of the cutting, which was interpreted as a keyway-like system to prevent rotation of the bushing inside the hub.

Given the diameter of the two finds, a general assembly of the wheel to which they should belong was reconstructed, based on the comparison with other wheels of the same period found elsewhere. Subsequently, a reconstruction of the whole axle was done, taking as reference, in particular, the wagon of Civita Giuliana found in the area of Pompei.

Finite Element structural analyses on the reconstructed axle allowed estimating in one to two tons the load that could be carried by a four-wheel wagon with such wheels, allowing hypothesizing that heavy-load transportation vehicles were common in the Roman Valle Camonica, despite the mountainous environment. This result adds an element to the reconstruction of the supposed lifestyle of the people living in the discovered village, which appears in continuity with the previous indigenous culture. This suggests that at the beginning of the Roman occupation the culture of the conquered people coexisted with that of the conquerors.

CRediT authorship contribution statement

Angelo Mazzù: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Ileana Bodini:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Simone Pasinetti:** Methodology, Investigation. **Alessandro Bettinsoli:** Methodology, Investigation. **Serena Solano:** Writing – original draft, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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