Archaeological and Anthropological Sciences (2024) 16:71
https://doi.org/10.1007/s12520-024-01979-6

RESEARCH

Potential scale of industrial outputs of the bronze bell casting industry in 500 BCE China

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Received: 13 December 2023 / Accepted: 18 March 2024

Abstract

The potential scale of industrial outputs in the ancient world is often underestimated in current archaeological studies due to the lack of surviving artifacts for validation of the production scale. However, production traces left on extant artifacts can help us reconstruct production methods, and thus reveal the potential scale of production outputs of certain industries, even although there may not be a sufficient number of existing artifacts to demonstrate such volumes. The bronze bell casting industry operating in around 500 BCE in Xinzheng in Henan province, China, can be used as an example to demonstrate the then use by bell casters of the "pattern-block method" to efficiently create multiple bells sharing identical components. With their strong focus on efficiency, production speed, and low production costs, these casters intelligently designed assembly lines and assembled identical components replicated from models to prepare molds for casting. Knowledge of their production methods and currently preserved bells can provide evidence that the bell casting industry produced industrial outputs on a massive scale that was rare in the ancient world. This article also shows how innovative methods such as 3D model superimposition can be used to validate these hypotheses.

Keywords Bell · Casting · Industrial output · Xinzheng · China · Model · Mold

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Published online: 10 April 2024

Introduction and background

It is seldom possible to quantify the scale of the industrial outputs of the bronze bell casting industry in any part of the world over any particular period, due to the fact that bell casting has not been historically regarded as a pre-eminent business. The magnificent European history of casting church bells before the period of Industrial Revolution, for example, is rarely described as an industrial practice (Percival et al. 2001, p. 177; Lehr 2005, pp. 10–19; Brzeski et al. 2015, pp. 177–178; Cekus et al. 2020, p. 1; Cekus et al. 2021, p. 1042; O'Brien 2021). The reasons behind this may be multi-fold, which are although rarely discussed, such as historians refusing to describe it in such a way, or the then scale of church bell casting in Europe was not as vast as those sectors during the period of the Industrial Revolution.

The case of the bell casting industry in 500 BCE China does, however, present a drastically different situation. It demonstrates that huge industrial scale production and consumption sectors that boosted the scale of bell casting did, at least in Central China specifically, indeed then exist. Although, as is the case for many other sectors around the world, the absolute industrial scale is inestimable, we can, from the existing material records and, most importantly, from the production methods of extant bells, estimate the probable scale of the industrial outputs of the bell industry in that period. It must be noted that existing material records represent only the tip of the iceberg of the actual scale of their outputs. What is more revealing is the industrial potential that their production methods released.

Industrial production in ancient China was defined by the practices of replication and a focus on efficiency (Keyser 1979; Bagley 1995; Li KS 2017; Su RY 2017; Li KS et al. 2021). The items under examination here are bronzes of complicated designs and structures such as vessels and sculptures, but not including items with simple, nearly two-dimensional structures such as discs or blades requiring bivalve molds (Karlbeck 1935; Hirokawa 2004). In 1200 – 600 BCE China, bronze vessels were not replicated, although the vessel casters had, theoretically, mastered this technique (Karlbeck 1935; Bagley 1990, 2009). According to current consensus, there are no two identical bronzes from this period that share the same decorated model (Chen ZD 1986; Yue and Yue 2014). These model and mold-making practices did not involve any practices of efficiency. From 500 BCE onwards, however, replication and the focus on efficiency became all the more important (Keyser 1979; Bagley 1995; Su RY 2017; Li KS et al. 2021). Assembly line production, sophisticated divisions of labor, and multiple transfers between the production of single components that were used to assemble larger products defined the major features of efficiency. Identical bronzes sharing the same decorated models of even very complicated structures were produced.

Among the products that demonstrate such identified evidence of replication visible until the present day are sculptures and mirrors (Hirokawa 2004; Li KS 2017; Li KS et al. 2021). These replication methods are generally referred to as the "multiple-transfer method," which includes the pattern-block method mainly used to produce vessels and many other methods used to create sculptures and mirrors (Keyser 1979; Bagley 1995; Li KS 2017). A bronze-casting workshop could adopt numerous methods simultaneously, and these methods were not regional- or workshop-specific; rather, technological communication and interaction seemed to be very active and frequent between all workshops in China at the time (Li KS 2017).

In approximately 500 BCE, two main replication methods were prominent (Fig. 1) (Karlbeck 1935; Keyser 1979; Bagley 1990, 1995, 1999, 2009; Hirokawa 2004; Li KS 2017; Li KS et al. 2021). One of them was the model-decorating method (Fig. 1a, b, and c); although with a history of use traceable to at least 1500 BCE, this was not put into practice in replication techniques until 500 BCE. Casters using this method would start their work by carving a clay model, which they decorated to the extent that it looked exactly like the desired finished bronze product. The model was created as a positive – all elements that were to be raised on the finished product were raised on the decorated model, and all that were to be sunken were sunken on the model. The casters would then invest the model with clay, so making a mold around the model. A mold was a negative – all elements that were raised on the finished product were sunken on the mold, and vice versa. They then sliced the mold into sections and removed those mold sections from the model. The model was then set aside. The sliced mold sections were subsequently re-assembled and formed into an outer mold ready for casting. A clay core might or might not be inserted into this mold, depending on the casters' technical judgment. Metal spacers might occasionally be inserted in the space between the core and the outer mold to avoid the two surfaces coming into contact. Finally, the casters would pour molten bronze into the mold and obtain the finished product when the bronze solidified. The mold for casting was smashed open and no longer usable. Theoretically, however, as long as the decorated model was not deformed or damaged, it could be re-used to make multiple identical molds for casting. This method was at least used for the replication of sculptures and mirrors.

The other method, illustrated in Fig. 1d and e, was the pattern-block method. The casters first created a rough model that bore the general shape of the intended finished product without any decorative pattern. They then invested this model with clay and formed multiple outer molds from

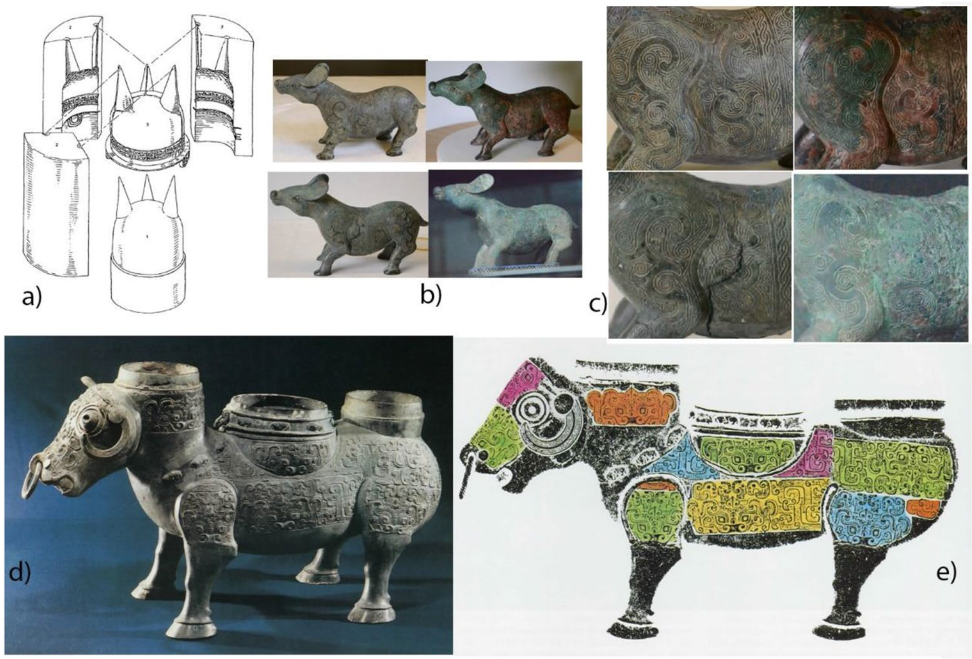


Fig. 1 Diagrams explaining the two main replication methods: model-decorating method (top sub-images, a-c) and pattern-block method (bottom sub-images, d and e).
Top: (a) three mold sections taken off the decorated model at the center, with a core at the bottom; (b) four identical bronze quadrupeds produced from the same decorated model, now housed in four separate museums: Freer Gallery, British Museum, Asian Art Museum of San Francisco, and Yurinkan Museum; (c) the almost identical decorative patterns of the four quadrupeds.
Bottom: d) bronze buffalo made by the pattern-block method, now housed in the Shanghai Museum; e) diagram explaining how multiple identical pattern units were made from the same pattern block. Such pattern units were made by unit molds replicated from the pattern block; then pasted onto the body of the outer mold of the buffalo, eventually becoming units on the finished bronze buffalo.
Image credit: sub-images a), d), and e): courtesy of Robert Bagley. After Bagley 1999, p. 143, Fig. 3.1; Bagley 1995, p. 215, Fig. 3; Bagley 1995, p. 216, Fig. 5. Others by the correspondence author.

it. Each outer mold was also, as in the previous method described, sliced into sections for later re-assembling. Since this model bore no decorative pattern, supposedly it was easier to produce empty outer molds from this undecorated model than from a decorated one. The casters separately created several clay blocks decorated with patterns in positive, which we refer to as “pattern blocks.” These pattern blocks were created as units of the complete planned pattern and were used to replicate pattern unit molds, which were pasted onto the inner walls of the rough, sliced-open outer molds. These mold sections were at this moment decorated by unit molds, and then re-assembled. Clay cores might or might not be inserted. Eventually molten bronze was poured in, and the finished bronze product was obtained. Since the molds were destroyed during the process of extracting the finished products, and each time’s pasting of the unit molds onto the inner walls of the rough molds was different, no identical bronzes were produced by using this method, although replication and transfers had taken place multiple times. This method was at least used for the casting of multiple groups of bronze vessels.

The outer molds of most bells produced during this period were made by assembling two sections, which had been dissected along the central line of the bell handle. This can be easily confirmed by the presence of a mold line running across the handle and extending to the mouth of the bell. A clay core was inserted into the mold to preserve the bell cavity. The molten bronze was usually poured into the mold when it was held upright on the ground, housing the core inside. A mold would rarely have been held upside down with a core inside, since the core might accidentally drop, meeting the outer mold and creating defects on the finished bell. If casters had to hold the core up in the air when the mold was laid upside down, spacers might be inserted into the space between the top of the core and the outer mold.

Main questions and materials

We will now begin examining the industry of bronze bells, and investigate whether bells were suitable products for replication. Were there any replication practices in bell casting, and, if so, how were the bells replicated? It is a well-known fact that bells produced in 500 BCE were mostly two-tone bells. Namely, one bell could generate two different absolute pitches depending on which strike position this bell was struck (Fig. 2) (Huang XP 1978–1980, 1992; Chen and Zheng 1980; Ma CY 1981; Shen SY 1987; Qin X 1990; Feng GS 2002).[1] Despite our knowledge that the almond shape cross section of a bell is the factor essential to creating two tones, in contrast to the round shape of most one-tone bells in later period China and around the world, designing a two-tone bell from scratch remains to the present day a very challenging acoustic and engineering project (Zeng Hou Yi bianzhong fuzhi yanjiuzu 1983; Li MA 2012). In order to save research and development time and efforts, most two-tone bells currently produced are in fact replicated from bells with known tones. With this in mind, if the technological level of the 500 BCE Chinese was not far superior to that of the present, replication of bells then seems to have been a very plausible practice. As designing a bell from scratch requires such tremendous effort in experimentation and tempering (Lindley 2001), replicating existing bells could have saved a great deal of effort. The practice of replication in ancient times would also imply a preferential focus on efficiency, production speed, and lower costs.

From 1993 to 1997, 254 bells were excavated in a large complex in Xinzheng county, Zhengzhou, Henan province, China (Map 1, 34°23’44.3"N 113°44’55.5"E). These bells have yielded many clues to the bell replication issue and to the related production scale of the bell industry. These 254 bells can be divided into eleven sets according to their burial context (Henan sheng wenwu kaogu yanjiusuo 2006, vol. 1, pp. 50–69, 215–337, vol. 2, p. 994; Wang ZC 2006; Falkenhausen 2009). Nine of the eleven sets were found from 1996 to 1997 in the Bank of China construction site, in nine pits numbered 1, 4, 5, 7, 8, 9, 14, 16, and 17. Most of the pits yielded twenty *niu*-bells and four *bo*-bells each. Both *niu*-bells and *bo*-bells feature a handle on top; however, *bo*-bells have a flat base or mouth, whereas *niu*-bells have a curved base. These twenty *niu*-bells in each pit can be further divided into ten groups; within each group two bells share a very similar size, shape, decorative pattern, and their two-tones. These groups constitute useful evidence through which the bell replication phenomenon can be explored. Here we will select the twenty *niu*-bells from Pit 16 (Fig. 3; Table 1) for further exploration (Henan sheng wenwu kaogu yanjiusuo 2006, vol. 1, pp. 311–327; Wang ZC 2006). The correspondence author of this article has measured and tested these bells, and re-numbered them so that matching bells that share very similar size, shape, pattern, and their two-tones are grouped together. For example, bells G1x and G1y are placed together as they correspond to each other, and so on, the new numbers not being the same as their numbering in the original archaeological reports.[2]

The bell being tested was lifted by the correspondence author with its handle on top. The A-tone strike position for one side of the bell was struck three times, then three times on the other side. The correspondence author subsequently turned to the four B-tone strike positions, and struck every B-tone position three times, or more than three if the tone

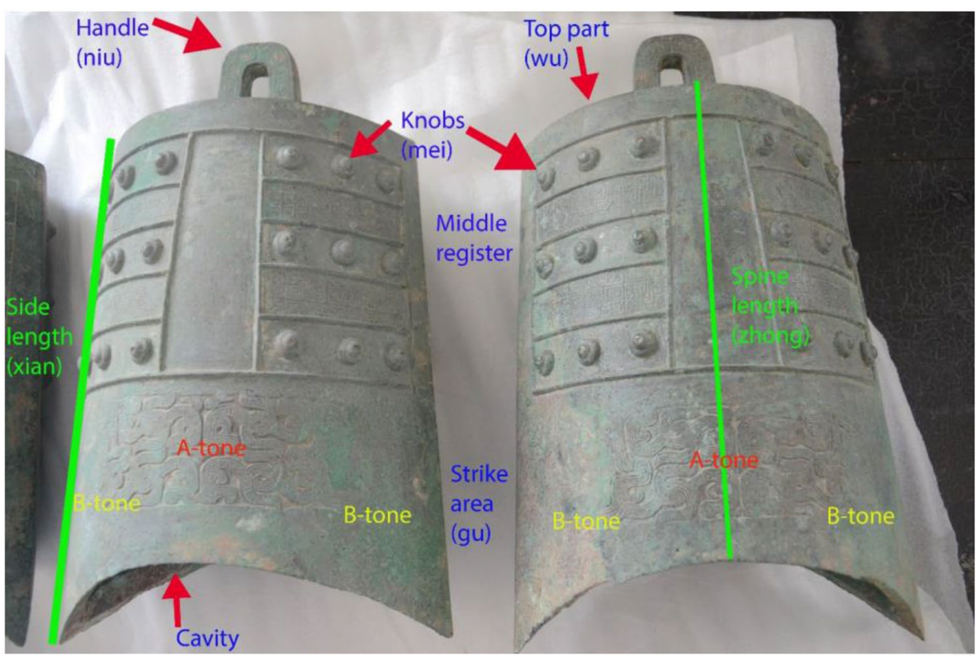
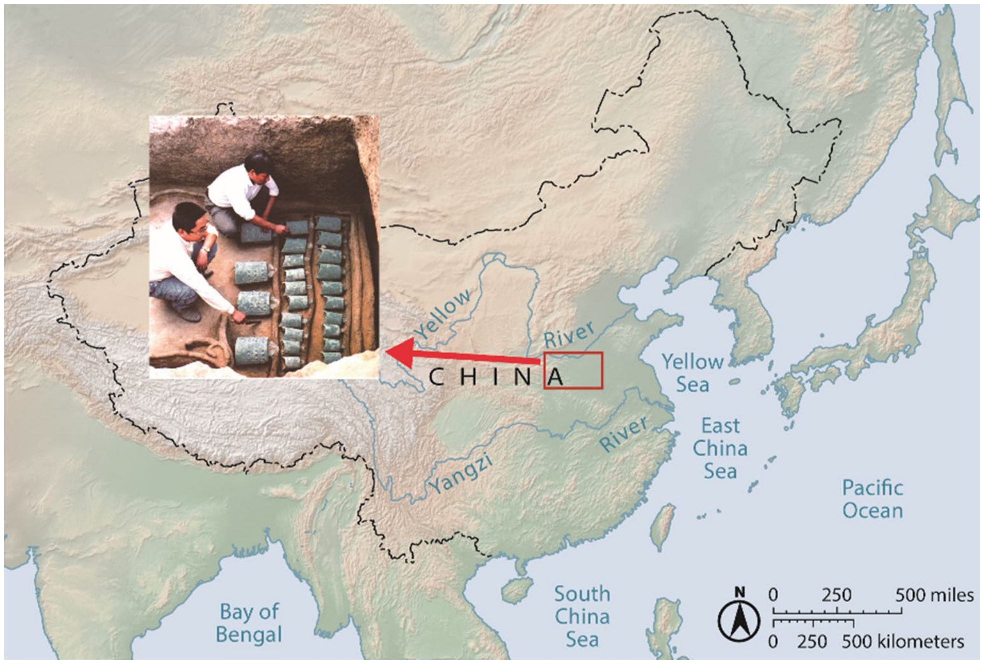


Fig. 2 Names of elements of ancient Chinese bells. These two bells are bells Pit16-G1x and G1y from Xinzheng, Henan. Image credit: correspondence author.

[1] This article will not delve into the explanation of acoustic mechanisms of how a two-tone bell functions.

[2] The numbers of the bells in this article are different from the numbers in musical historian Wang Zichu’s report (Wang ZC 2006, 986).



Map 1 Location of Xinzheng, Zhengzhou, Henan, China; and Pit 16 where the bells were freshly excavated.
Image credit: inset, after Henan sheng wenwu kaogu yanjiusuo 2006, vol. 3, color pl. 4.2. Map made by Ben Pease.

Fig. 3 The 20 *niu*-bells from Pit 16 of the Bank of China construction site in Xinzheng, Henan.
Image credit: correspondence author.

is not clear. The internal recording device of a laptop computer (Samsung Galaxy Book Pro) and the audial software Audacity were used to record and analyze the sounds generated by the bells.[3] Since the two-tones of these bells are very clear, not much a range of tonal frequencies was recorded. Indeed, only a single frequency was found from the two A-tone positions and another single frequency from the four B-tone positions on each bell.

Before going into details of the investigation of the preparation of models and molds, it can be helpful to first envision the casting workshop setting. Piles of metal ingots, copper, tin, and lead, would have been stocked in one corner, with the furnace heated and a large crucible of molten bronze ready for pouring. A line of molds ready for casting would be set out on the ground, stabilized and waiting to be filled. The casters would mix the particular ratios of copper, tin, and lead required to cast the bells in order to produce the desired two-tones. The analyses on some of the Xinzheng bells from various pits in the original excavation report reveal a tin content of 6.6-12.5%, which is higher than that of ordinary vessels (Huang and Li 2006, pp. 1008–1010; Li YX 2006). This relatively higher proportion of tin was added to make the tones more distinctive and decorative patterns appear clearer (Huang and Li 2006, p. 1022; Scott 2011, pp. 200–204; Falkenhausen and Rossing 1995, p. 437). Lead, used to make the molten bronze flow better, ranges from 6.6 to 17.9% (Huang and Li 2006, p. 1010). At the highest 17.9%, this lead might reduce the vibration rate of the bell and thus hamper its tones (Huang and Li 2006, pp. 1010, 1022). At least three problems may have arisen in the generation of an absolute ratio of metallurgical composition of the bells.[4] First, the data sets gathered by the metallurgists may not have been comprehensive. Second, variations in the cooling times of the molten metal and the presence of

[3] Audacity Team. 2021. Audacity(R): Free Audio Editor and Recorder [Computer application]. Version 3.1.3. Accessed on August 9, 2021. Audacity® software is copyright © 1999–2021 Audacity Team. Website: https://audacityteam.org/. It is free software distributed under the terms of the GNU General Public License. The name Audacity® is a registered trademark.

[4] The report describes that fragments or damaged areas of the bells were tested (Huang and Li 2006, pp. 1001–1003). The mouths of eight *niu*-bells from Pits 7 and 16, and two *bo*-bells from Pits 4 and 16 were tested by using a scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS).

Table 1 Author's list of the 20 *niu*-bells from Pit 16 of the Bank of China construction site in Xinzheng, Henan

Name	Pit16-G1 x and y		-G2 x and y		-G3		-G4		-G5		-G6		-G7		-G8		-G9		-G10	
A-tone musical note (Hz)	B4-31 (485)	B4-35 (484)	D5-43 (573)	D5-23 (578)	D5+49 (640)	E5-32 (647)	G5+2 (785)	G5+7 (787)	A5-22 (869)	A5-24 (868)	B5-30 (971)	B5-35 (968)	E6-13 (1309)	E6-7 (1313)	A6+28 (1789)	A6-4 (1756)	B6+36 (2017)	B6+37 (2018)	E7-12 (2619)	E7-22 (2603)
B-tone	D5+20 (594)	D5+34 (599)	E5+31 (671)	F5+1 (699)	G5-40 (766)	G5+31 (798)	A#5–8 (928)	A#5+22 (944)	C#6+28 (1127)	C#6+37 (1133)	D6+6 (1179)	D6+15 (1185)	G6+10 (1577)	G6+13 (1580)	D7-46 (2288)	C#7+3 (2221)	D#7+3 (2494)	D#7−6 (2480)	G7-28 (3085)	G7-21 (3098)
Original no.	16A1	16B1	16A2	16B2	16A3	16A4	16B3	16B4	16A5	16B5	16B6	16B7	16A6	16B8	16A7	16A8	16A9	16B9	16A10	16B10
Height of the handle	5	5	4.8	4.8	4.5	4.5	4.2	4.2	3.6	3.6	3.5	3.5	3.3	3.3	3.1	3.1	2.9	2.9	2.7	2.7
Side length (*xianchang*)	21.8	22	20	Same as bell x	18.5	Same as bell x	17		15.5		14.5		13.5		12.3		11		10	
Spine length (*zhongchang*)	18.3	18.4	17		15.5		14.5		13.5		12.5		11.1		10.3		9.5		9.7	
Length and width of the top section (*wuxiu*, *wuguang*)	14.5, 10	14, 10	13, 9		12, 8.6		11, 7.6		9.5, 7		9.3, 6.2		8.8, 6		8.5, 5		8, 5.2		8.5, 5	
Length and width of the mouth (*xianjian*, *gujian*)	16.4, 11.5	16.3, 11.6	16, 11.5		14.5, 11		12.7, 9.2		11.5, 8		11, 7.7		10.3, 7.4		10.7, 7		9, 6.5		8.3, 5.7	
Girth of lip-mid-hip	37.7-40.5-42	37.2-40.6-42.5	35.5-38.7-41	35.2-39-41	32-36-38	33-36-38	29.2-31.5-33	29.3-31.8-33	26.3-28.5-29.5	26.3-28.4-29	24.8-27.2-28	24.8-27.2-28	23.8-25.2-26.8	23.8-25.2-26.7	22-23.2-25	22-23-25	21.2-22-23.2	21-22-23.2	19.5-21-21.5	19-21-21.5
Side length (cavity)	21	21	18.5	18.5	17		16		15		14		13		11.5		10.3		9.3	
Spine length (cavity)	17.6	17.5	16	16	14.5		13.5		12.5		12		10.5		9		8.7		8	
Length and width of the cavity of the mouth	14.4, 9.6	14.3, 10.3	13.3, 9.2	13.5, 9.5	12, 9		10.7, 7.5		10, 7		9.5, 6.5		8.5, 5.8		7.5, 5		7, 4.5		5.7, 3.5	
Length of the pattern on the strike area	12	12	12	12	10.5	10.5	10.5	10.5	9.5	9.5	9.5	9.5	7.3	7.3	7.3	7.3	6.5	6.5	6.2	6.2

Data measured and tested by the correspondence author in July 2022 in the store house of the Henan Provincial Institute of Cultural Heritage and Archaeology.

Measurements are all in cm, unless indicated otherwise.

The "lip" in the lip-mid-hip (L-M-H) section refers to the girth of the mouth of the bell, "mid" refers to the girth of the section below the top two rows of the knobs, and "hip" the girth of the lowest section of the sounding body of the bell. The correspondence author did not measure the length and width of the top section of the bell cavity since there was no appropriate tool to do so. Since the two bells in every group are identical in size and shape, the correspondence author did not measure all bells y. For the missing data, readers can refer to the original archaeological report (Henan sheng wenwu kaogu yanjiusuo 2006, vol. 2, pp. 1274–1277).

Temperature of the tone testing location: 36 °C.

A4 = 440 Hz.

Only the fundamental frequency of a vibration is recorded; overtones are not deemed the intended tones of the bells.

corrosion may have created problems in our analysis of the composition. Third, the test samples themselves may have been problematic too. For example, for the set of the five *niu*-bells and one *bo*-bell sampled from Pit 16 the metallurgists limited their sampling positions only to the mouths of the bells. They recorded tin composition ranging from 8.5 to 12.5% and lead composition from 6.9 to 11.1% and argued that both elements were in more appropriate proportions for bell casting (Huang and Li 2006, p. 1026). However, since we have not performed our own metallurgical tests on the bells, for now we can consider the statistical data provided in the original report as mere references.

The molds ready for casting were probably set upright on the ground, with cores stabilized inside. In their excavation report, the metallurgists describe finding spacers on the top of the bells, and a trace of sprue on the mouth of a bell (Huang and Li 2006, pp. 1019, 1021).[5] However, the correspondence author of this article could neither identify any spacer on the bells from Pit 16, nor find any traces of sprue and gate on the bells, which were probably erased during post-processing. What the metallurgists envisioned in the excavation report was that the molds for casting were held upside down, meaning that the bell mouth faced up towards the sky for the molten bronze to be poured in (Huang and Li 2006, p. 1018). This pouring method was risky as it gave the possibility that the core might drop, meld with the outer mold and so generate defects and holes on the finished bell. This could also have been why the metallurgists claimed that they found spacers, which were used to sustain the cores in space away from the outer mold, on the top of the bells. They did not, however, provide any clear images of the spacers. If the correspondence author of this article is correct in surmising that the molds for casting were in fact set upright, with the bell mouths facing the ground and the cores and outer molds stabilized on the ground, casting defects were less likely to occur, since these bottom sections were formed first, when the molten bronze first touched the base of the molds. In this scenario, defects such as holes and indistinct patterns would only occur on the upper sections of the bells. The patterns on the strike areas would form clearly and the tones of the bells would be distinctive. Any gaseous impurities in the molten bronze would float to the top of the molds, that is on the upper sections of the bells. This can be observed on the decorative patterns of the bells in each of their sections; on the top areas of the bells they appear coarser and rougher, while on the bottom sections, the strike areas, they appear clearer and more precisely formed.[6]

Observations, discussion, and results

Pattern-block method

Table 1 shows strong similarities in data for the size of the details and components of corresponding bells. A careful visual inspection of the corresponding bells shows, however, that while their decorative patterns may be identical, the positioning of these patterns may not be (see bells G1x and G1y in Fig. 4). This has constituted one of the most convincing proofs that they were not produced by replication from decorated models, that is not by the first method outlined above, the model-decorating method. Bronzes made by the model-decorating method would share identical sizes, shapes, decorative patterns, and the positioning of the patterns, because the finished products were exactly the same as the decorated model they replicated. The question is then whether they were produced by using the pattern-block method, or by other methods?

The production method employed can be understood through an explanation of the technical procedures of the pattern-block method. The casters of bells G1x and G1y replicated two identical, rough, outer molds made from an undecorated model. As these two outer molds shared the same size and shape, the size data of the finished bells are highly similar. As the outer molds did not bear any decorative patterns, the casters then replicated at least four clay unit molds from a block that bore the intertwined-dragon pattern shown on the strike areas of bell G1x and G1y. These four unit molds were subsequently pasted onto the inner walls of the two rough molds, each mold bearing a unit mold on each of its two strike areas. It is important to note that the unit molds were pasted since the strike areas are curved rather than flat surfaces. Impressing or stamping on the strike areas of the rough mold, which was an intuitive thought appealing to ordinary readers, would not have been able to produce the curved pattern and may have damaged the inner walls of the rough mold. Leaving sunken areas for the unit molds to be pasted onto the inner walls and removing the squeezed-out clay would have been integral for the success of the pasting, which was part of the casters' sophisticated technical corpus. Since this pasting was done at least four separate times, the positioning of the unit molds would not have been identical, resulting in the different positions of the patterns on the finished bells. However, since the unit molds, which were replicated from the same pattern block, are identical, the individual intertwined-dragon patterns on the strike areas appear identical.

Figure 5 shows the rectangular decorative patterns, called "*zhuan*," and knobs (*mei*) on the middle register of bell G1x.

[5] The spacers are merely described in texts, but no image is provided. The image of the sprue is not clear.

[6] Thanks to the comments from the anonymous reviewer(s), we can perform further composition analyses of the entire bells to map the distribution of lead segregates, which tend to sink to the bottoms of the molds. We may have more hints about how the molds were set for pouring.

Fig. 4 Comparison of the intertwined-dragon patterns of the strike areas of bells G1x (left, sub-images c and e) and G1y (right, sub-images d and f) from Pit 16 (original no. 16A1 and 16B1). The cropped pattern on one side of bell G1x in the middle left sub-image (sub-image c) is shown at the top left for readers' identification of the rectangular pattern on a curved surface (sub-image a).
Image credit: correspondence author.

Fig. 5 Patterns within the rectangular frames and knobs on the middle register of bell G1x.
Image credit: correspondence author.

These rectangular patterns, separated into grids defined by rows of knobs, show the casters' complicated yet comprehensible techniques. Since they were executed on curved areas as well, impressing or stamping did not work on these areas either. In this case, pasting was again used to transfer the patterns from the blocks to the rough outer molds, and so eventually to the bronzes. Careful inspection demonstrates that within each grid, the patterns seem not to end, and so to visually "extend" out of the grid. Patterns within different grids appear to be highly similar, but, again, are not identical. This can be explained by the cutting and pasting of the unit molds. The patterns seemingly all came from one single block bearing patterns much larger than the area of each grid. Multiple unit molds were replicated from this block, this time cut to the size of a rectangular grid. This implies that only some parts of a unit mold were pasted onto a grid. The remaining parts of the same unit mold might have been pasted onto other grids to fill any remaining empty areas of other grids. The cutting and pasting was seemingly random, with the empty grid areas not filled in a standardized fashion. This was, however, an intended visual effect, so that the patterns of each grid seem to have extended past the rectangular frame and not to be repetitive. The casters did not need to attend too carefully to the size of each rectangular grid as they could produce this special visual effect by randomly cutting and pasting the unit molds. The knobs seemed to have been impressed into the inner walls of the outer mold so that they appear raised on the finished bell. The positioning of the knobs is different on bells G1x and G1y, thus the knobs did not exist on the undecorated model.

The individual impression of the knobs made their positioning slightly different on the outer molds of the two bells.

The decorative patterns on the top areas of the bells were executed in a similar way to that of the *zhuan* patterns on the middle register. The interlaced-dragon motifs on the top areas (Fig. 6), also seem to have been cut at the edge despite appearing coarser. This suggests that a complete unit mold was first cut and pasted onto the top areas of the inner sides of the outer mold. Different phases of cutting and pasting meant that their final appearance and positioning on the two bells were different on each of them.

Reasons for using the pattern-block method

The above observations of the two bells suggest that they were made by the pattern-block, rather than by the model-decorating method. Lay observers may have intuitively assumed that if they were made by the model-decorating method, it would have been a straightforward and easy task for the casters to replicate them from a decorated model. The casters, however, evidently had their own concerns, considering that replication from a decorated model would have created many additional problems. Transferring all the patterns from the decorated model to the finished bells, and positioning them at exactly the same corresponding places, would have been unnecessarily difficult. This can be confirmed by the challenges encountered by the casters of three identical quadrupeds produced at Houma, Shanxi province, in around 500 BCE (Li KS et al. 2021).

Replicating the size and shape was sufficient to produce bells with the very similar two-tones desired. The patterns on the bells were merely decorative display additions that did not serve the essential musical function. The rough outer mold and core determined the size, shape, and thickness of the bell walls, which were the important factors generating the vibration of the bell. As long as the size, shape, and thickness of the walls of a group of bells were highly similar or identical, their vibration frequencies, the key to the replication of bells that produced the same two-tones, would be very similar. With these factors in mind, the casters would have deemed the pattern-block method their most practical and effective working technique.

Fig. 6 Interlaced-dragon motifs on the top areas of bell G1x. Image credit: correspondence author.

The casters, therefore, mainly attended to the replication of size, shape, thickness of the walls, using an undecorated model, a rough outer mold, and the accompanying core, to achieve the desired vibration frequencies. Decorating the bells was done on the inner walls of the outer molds at the stage when the size, shape, and thickness of the bells were mostly finalized. Replicating and pasting unit molds from the pattern blocks could help casters adapt to the curvature of the inner walls of the molds, which could avoid problems in transferring the patterns from a decorated model to a mold. The casters could touch up the unit molds before pouring molten bronze into the larger outer mold for casting, and they did not need to pursue identical positioning of the patterns on each mold, thus significantly reducing the potential for pattern transfer problems.

The casters of the Xinzheng bells had to fine-tune the inner walls of the finished bronze bells in order to attain their desired two-tones. Most of the bells that the correspondence author of this article handled had inner walls that had been scraped, chiseled, and polished, with multiple grooves visible on the inner walls of any one bell. If the newly cast bells did not produce the desired two-tones, the grooves and polishing could significantly modify the two-tones. As the casters knew that altering the A-tone would simultaneously change its B-tone, they had to expertly polish and tune a bell in order to simultaneously attain both of the desired tones. These mechanical, post-processing methods were therefore essential to the musical function of the bells. This does show, however, that the use or not of the model-decorating method was not of primary significance, as the casters would have had to fine-tune the bells eventually. Simply replicating the size, shape, and thickness of the walls of the bells was not acoustically adequate, with fine-tuning playing an essential role at the final stage.

It must also be noted that the casters were replicating ten groups of *niu*-bells for the set found in Pit 16. After designing the molds for bells G1x and G1y, they still had to design the molds for bells G2x and G2y, and all the other bells in the set. At this stage in their work, the blocks for some of the patterns for the G1 bells would have been of even further use. Because the two-tones of the G2 bells were different from those of the G1 bells, a completely different undecorated model and a new core were required to produce their two rough outer molds. The pattern blocks for the G1 bells

Fig. 7 Intertwined-dragon patterns on the strike areas of bells Pit16-G2x (a) and G2y (b). Image credit: correspondence author.

Fig. 8 Interlaced-dragon motifs on the top areas of bells G2x (a) and G3y (b). Image credit: correspondence author.

could, however, be re-used. For example, the unit molds for the intertwined-dragon patterns on the strike areas of the G1 bells were applied onto the molds of the G2 bells (Fig. 7). The lengths of the intertwined-dragon patterns of the four G1 and G2 bells are the same at twelve centimeters (Table 1). The unit molds of the interlaced-dragon motifs on the top areas of the G1 bells were also applied onto the G2 and G3 bells (Fig. 8), simply requiring to be cut differently in order to fit the top areas of the G2 and G3 bells. Other decorative patterns were executed in similar ways.

Since the strike areas of the bells in the different groups diminished in size, they required different sizes of the intertwined-dragon pattern blocks. As shown in Table 1, these different sizes include those of 12, 10.5, 9.5, 7.3, 6.5, and 6.2 cm. Therefore, at least six groups of the intertwined-dragon pattern blocks were created for the strike areas of these six groups of bells: G1 + G2, G3 + G4, G5 + G6, G7 + G8, G9 (single group), and G10 (another single group).

The intertwined-dragon patterns also served as a visual reminder of the most appropriate strike positions of the two-tones of a bell. While an experienced player would not need any visual reminder of the strike positions, if these bells also functioned as valuable display items to amuse a bell owner's guests, then visual reminders of the strike positions would have been very welcome. Generally, as a consensus, the central position of the intertwined-dragon pattern was the most appropriate position for generating the A-tone, and so the bell had two effective positions for sounding an A-tone, one on each side of the bell. According to the testing experiences of the correspondence author of this article, the bottom left and right corners of the nearly rectangular intertwined-dragon pattern were the most effective positions for generating a B-tone, and so the bell had, then, four effective positions for sounding a B-tone. As the correspondence author is right-handed, the bottom right corner was the preferred position for generating a B-tone. As a result, the different lengths of the six groups of the intertwined-dragon patterns not only fitted the size of the strike areas of the bells, but also served as visual reminders to any ordinary person who wished to enjoy playing the two-tones of the bells.

The casters would generally have needed to prepare a set of components before casting these twenty bells deposited into Pit 16 that would have comprised:

- 10 undecorated models, accompanied by 10 sizes of core models, resulting in at least 20 rough outer molds and 20 cores for casting;
- 6 sizes of intertwined-dragon pattern blocks for the strike areas of the bells;
- 1 interlaced-dragon pattern block for the top areas of the bells;
- 1 rectangular pattern block for the *zhuan* on the middle register;
- 1 stamp for knobs;
- Knives of different sharpness for carving different patterns;
- Clay, sand, and water for mixing clay to different material ratios for various working sections….

At least twenty rough outer molds would have been replicated from the ten undecorated models in a gradating range of sizes, with each mold for casting requiring a correspondingly sized internal casting core. Multiple unit molds could have been replicated from the pattern blocks to be cut and pasted for decoration. The remaining parts of the unit molds, or the residues after the main patterns had been cut to size, could have been applied on the corners of remaining empty areas to fill every square inch of the areas intended to be decorated. The residual patterned sections could possibly have been applied onto bells from other sets. This working practice was designed to serve the entire operational needs of an assembly line in a workshop or even in a factory, rather than solely any one-off casting.

The casters needed to prepare a large crucible of molten bronze to pour into the molds that were ready for casting. Not only did they have to fill the twenty molds for the *niu*-bells from Pit 16, but other bells from the other pits were also likely to have been cast in the workshop. At least 254 bells were found in the already identified pits in Xinzheng. Whilst all of those 254 bells may not have been cast in one session, industrial scale production may well have required the casters to cast in batches, probably creating around twenty bells in each batch.

3D model superimposition of the bells

Our hypotheses and reconstruction of the pattern-block method used to create the models and molds of the bells can be further tested by 3D scanning and modelling (Debut et al. 2016, 2018; Cekus et al. 2020; Carvalho et al. 2021; Parfenov et al. 2022). The correspondence author 3D-scanned bells G2x and G2y for comparison. Table 1 and our hypotheses propose that they shared the same undecorated model and pattern blocks, and the same size and shape of their outer molds, but that minute differences exist between their final molds.

Figure 9 shows the superimposition results of the 3D models of the two bells, shown in true colors and in point cloud. Bell G2x is shown in true color, that is the textured bell as the basis for comparison, in Fig. 9a and b, while bell

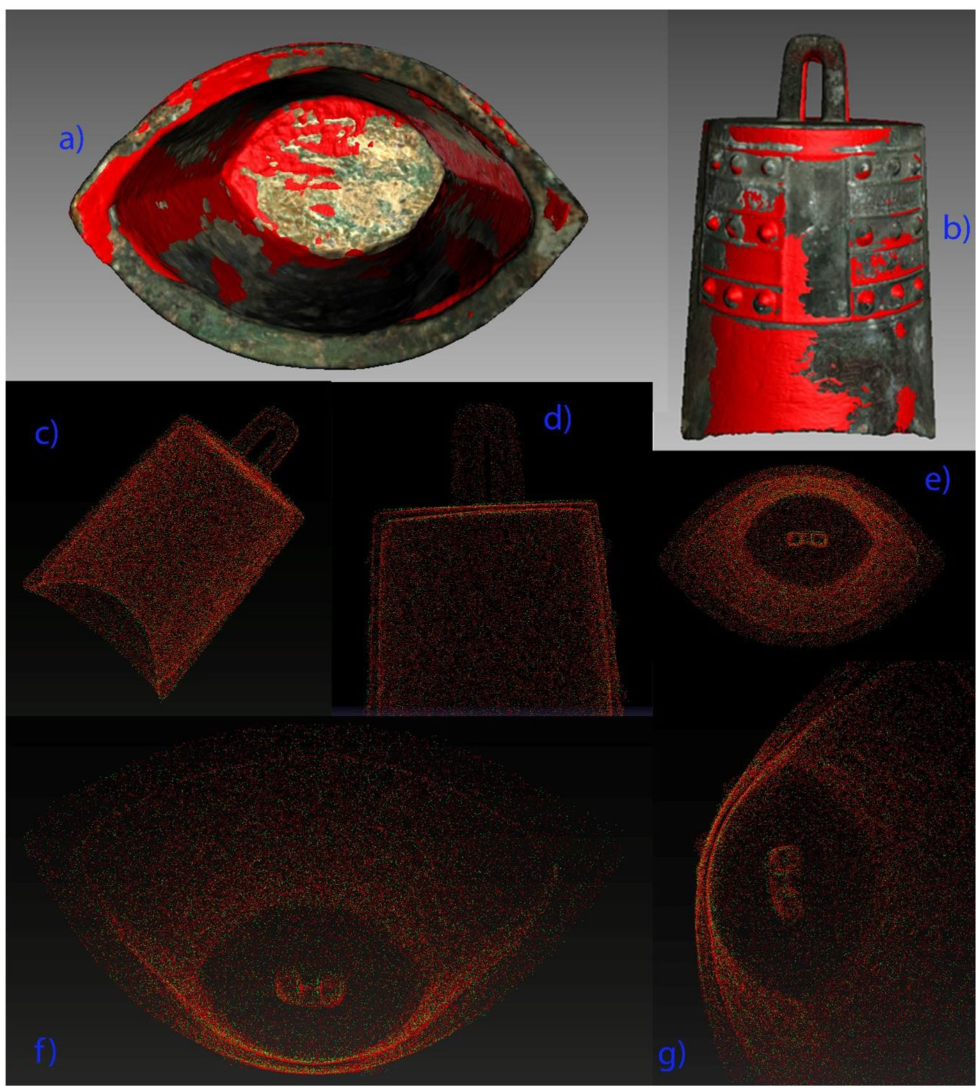


Fig. 9 Superimposed 3D models of bells Pit16-G2x and G2y in two formats: textured 3D models (upper two sub-images, a and b) and point clouds (other sub-images, c to g). Bell G2x appears as the textured basis in true color or green, and G2y in red. Top: (a) view of the mouths; (b) knobs not perfectly overlapped. Center: c) comparisons of the point clouds of the entire bodies of the two bells; d) detail of the top sections of the two bells; e) view from the mouth to the handles. Bottom: f) view of the walls of the bells; g) another view of the bell walls. Image credit: correspondence author.

G2y is shown in red in all sub-images, to be superimposed over bell G2x. Their almost perfect overlapping proves that their size and shape are almost identical, with the slight protrusion of only some minor red parts showing their minute differences in shape. The size and shape of their cores are also highly similar. Figure 9f and g show that the walls of the two bells overlap to a great extent, demonstrating almost identical thicknesses caused by their sharing cores of the same size and shape. The similar wall thicknesses also determine the similarity of the two-tones of each bell to those of the other.

Scrutiny of the superimposed 3D models shows that the positions of the corresponding knobs on the two bells are not the same. Figure 9b shows that the positions of the knobs of the red 3D model, bell G2y, slightly diverge from those on the base model. This proves that the knobs were individually impressed into their respective outer molds. Individual chiseling and scraping carried out on the mouths of the bells also made the two superimposed 3D models slightly differ from each other (Fig. 9a). However, this was not due to the replication of the outer molds.

The making of the handles of bell G1x and G1y was a delicate action. Figure 9b shows that the positioning of the handles of the two bells do not exactly overlap. Figure 9e and g also demonstrate that the positions of the two handles shift slightly between the two bells. It is possible that the two handles were created separately on the outer molds, rather than having been replicated from the undecorated model. A re-investigation of the photographs of the two handles suggests that no one side of the handle pattern is identical to any other, validating the hypotheses that their patterns were individually executed (Fig. 10). They were not, then, replicated from any pattern block or from any model. Rather, the mold worker had created the cavity of the handle on each outer mold for casting and carved the patterns on the outer mold line by line. We can suppose that before the two sections of the outer mold were assembled, the mold worker could have decorated any side of the handle by creating a mirror-reversed pattern on the mold. The patterns would then eventually become the positive version on the finished bell. For each outer mold, the hole in the handle was created by inserting a solid tube between the two mold sections. The execution of the mirror-reversed patterns would have

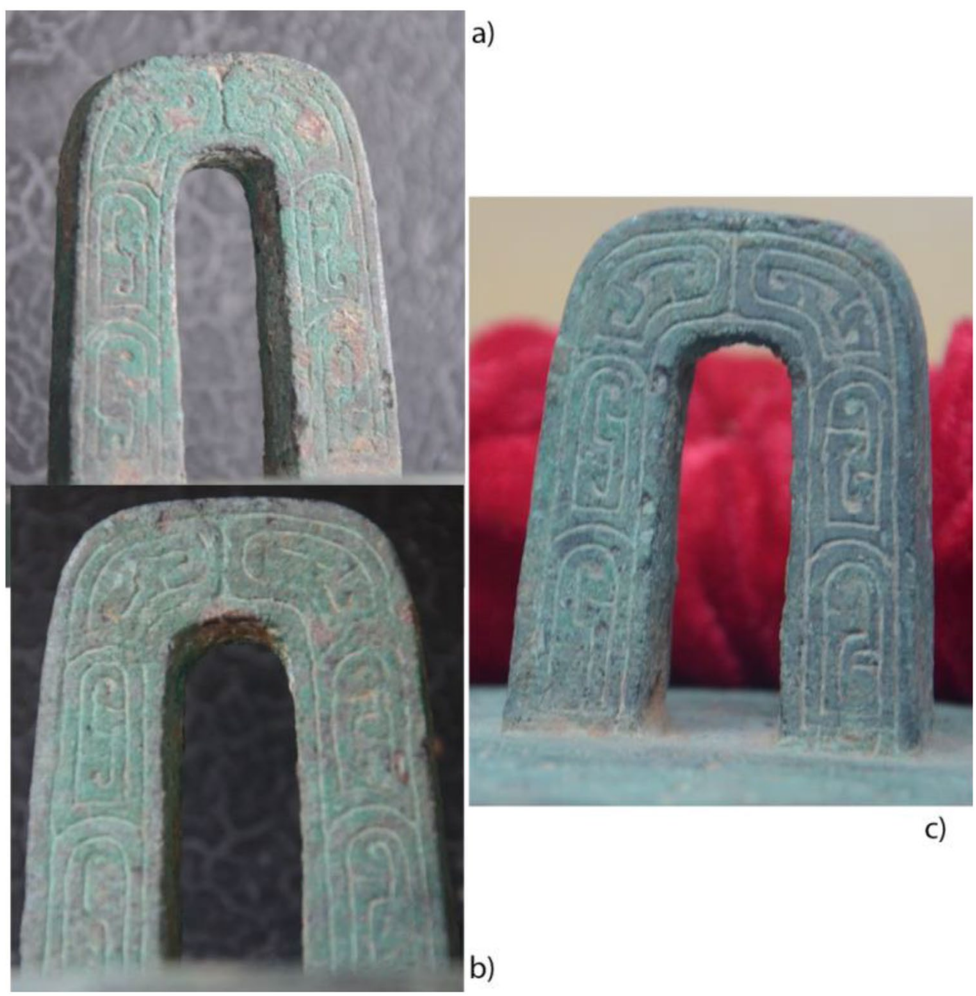


Fig. 10 Patterns on the handles of bells G1x (left, a and b) and G1y (right, c). Image credit: correspondence author.

required some experience to undertake, but since the handle patterns were made on mostly flat surfaces and relatively simple, it was not impossible for the worker to create them in this fashion. This demonstrates that even in an assembly line production where replication and component assembly were the main working processes, individual creations would not have slowed down the production progress; they may in fact have made the entire replication and transfer processes smoother since it was then not necessary to replicate the more complicated shapes of the handles.

Overall, it can be shown that the most important parts of bells G2x and G2y were replicated from the same undecorated model, and that their respective outer molds were thus mostly identical in size and shape. The superimposed 3D models demonstrate that bells G2x and G2y were made by the pattern-block method. Other groups of bells were highly likely to have been made by similar methods, despite this not having been validated by superimpositions of 3D models for all of the bells.

Conclusions

From 500 BCE onwards, bronzes of complicated structures such as bells and sculptures were mass produced, and the quantities of their industrial outputs were enormous. The absolute number of currently remaining bronzes from this period is tremendous. The burial of these 254 bells of sophisticated casting within one single complex reveals a lavish consumption pattern and, simultaneously, the astonishing reality of the period's huge bronze industrial production power, reflected in the techniques developed to produce such bronze products. The pattern-block and model-decorating methods are evidence for the potential scale of the production outputs. Replication and transfers between models and molds at various stages of the production process are clear indicators of the techniques developed. The molds and models could store the efforts and skills of the casters, and the components such as pattern blocks and unit molds can be seen as devices used to aid on the production lines. Assemblage of the components made the whole production process highly complicated in terms of division of labor. The workers responsible for producing the pattern blocks, unit molds, rough models, outer molds and cores, and final molds for casting, along with those who attended to the furnace and the crucible of molten bronze, constituted a large labor force who were highly professional in their own tasks. Multiple assembly lines for producing the Xinzheng bells may have been formed.

These bells and the people who made them demonstrate the huge potential scale of industrial outputs of bronzes in this period. The scope for exploration should not be limited by the currently existing archaeological remains. Instead, research into industrial outputs with the potential to uncover their scale in the ancient past, aided by detailed investigation of production methods and traces on existing artifacts, should be revealed with our expanded vision and re-imagination of the histories of any industries.

Acknowledgements Josh Yiu of the Art Museum, The Chinese University of Hong Kong allowed the team to examine the bell collection of the museum.

Author contributions KSSL is the correspondence author who designed the framework of the project, acquired most of the data, interpreted the data, drafted the first version of the manuscript, and is responsible for all other tasks not mentioned here, and the errors that are found herein are his alone. HWL, KW, QF, and YL provided the team with access to the research materials and technical assistance in their institutes. XQC, KSL, and THC, were the 3D scanning experts who performed the 3D scanning and 3D model superimposition experiments. XQ provided advice from a musical historian's perspective to the team. HRJ assisted in collecting research materials. They all reviewed the manuscript.

Funding Open access funding provided by Hong Kong Baptist University Library. The work described in this paper was partially supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region (HKSAR), People's Republic of China (Project No. HKBU 12618422 and 22601019), and Quality Education Fund E-Learning Ancillary Facilities Programme (2021/0257) awarded to the corresponding author.
Open access funding provided by Hong Kong Baptist University Library

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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