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Modelling the possible archaeological past(s): Agent-based modelling of Harappan seal use and survival

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Abstract

The Harappan i.e. Indus Valley civilization, flourished in South Asia in the middle of the third millennium BCE. Among the millions of artefacts excavated from hundreds of sites, the most remarkable and extensively analysed are the ones with peculiar signs. Within this set, the most characteristic item is the Harappan seal which is at the centre of discourse in Harappan archaeology. This scholarship mostly revolves around three conjectures: (i) the signs or sign sequences indicate linguistic components and are part of a script with fixed set of signs, (ii) the 'seals' were used as amulets or as objects of economic or administrative activities, and (iii) the primary use of seals is for creating the impressions which form `sealings'. However, the small number of actual sealings found in Harappan sites seems to challenge this last conjecture. This paper approaches the question of seal function by using agent-based modelling (ABM) to model the quantities of seals and their impressions in Harappan culture. The model seeks to suggest a hypothetical baseline for the number of sealings one might expect to find, and to see if and under which conditions the model results in the quantities of artefacts that are currently available as archaeological evidence.

Keywords: Harappan archaeology, Indus civilisation, Agent-based Modelling, Netlogo, Seals and sealings

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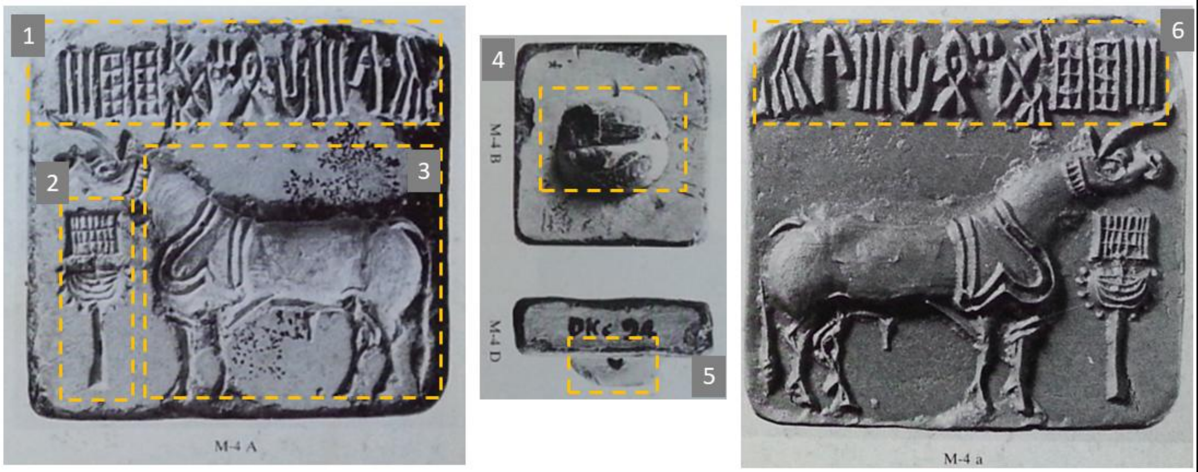
1. Introduction

Seals and other inscribed Harappan artefacts have captured the imagination of both the general public and scholars because they are one of the primary sources for this culture's still undeciphered script. Unfortunately, the wide variety of inscribed and incised artefacts found in Harappan contexts has over time led to some confusion in nomenclature, with objects that would not have been used to make impressions often indiscriminately referred to as seals. A typical seal and its hypothetical impression can be seen in Figure 1, an example of seal M-4 from the first volume of the CISI series.[1]



1. Signs/Script; 2. Cult Object/ Stand/ Standard; 3. Primary icon/ Symbol; 4. Perforation in boss; 5. Boss/ knob; 6. Impression of seal i.e. sealing with reversed sign sequence

Figure 1: Typical morphology of square steatite seal of Harappan culture and its impression.

The variety of these artefacts can be seen in Figure 2 with more examples of seal and impression highlighted in separate colours. While these artefacts are clearly important elements of Harappan material culture, as well as the study of the Harappan script, most don't play a central role in seal based administration discourse and will not be discussed in depth here.

[1] Corpus of Indus Seals and Inscriptions - Multivolume photographic corpus of inscribed objects of Indus culture, briefly described in the later section.

Figure 2: Typical examples of seal (highlighted in red outline), sealing (highlighted in blue outline), and other artefacts in the class of Harappan seals and inscribed objects – (1) copper tablets with only signs, (2) square steatite unicorn seal, (3) multi-sided bas-relief tablets, (4) multi-sided copper tablets, (5) incisions on ceramics, (6) multi-sided seal, (7, 9, 13) seals of different material with geometric motifs and no signs. (8, 10) seal impressions on clay sealings, (11) multi-sided incised tablets, (12) square steatite seal with only signs, (14) rectangular or plano-convex seal with only signs, (15) Bas-relief tablets in different shapes, (16) square steatite seal with different animal motifs.

In the context of this study, the term "seal" is used to refer to an object made from steatite or similar hard material, usually decorated in intaglio or incised, and which can be used to make an impression on the malleable surface of a clay sealing (see below). The standard seal type of the Harappan Civilization is a square stamp that has a pierced, rounded boss with an incision on the back. The front typically features an animal motif and an inscription carved into its surface. The term "seal impression" is used to refer to the positive impression made by the carved face of the seal. In prehistoric South Asia, the surface on which a seal impression was made was often a lump of clay used to secure a door or container; it is referred to as a "sealing." Seals and sealings form the basic building blocks of what has been referred to by scholars as the Transcultural Administrative Sealing System (TASS) (Frenez and Tosi, 2005), or more simply, seal-based administration.

As mentioned above, the most basic tenet of seal-based administration is that seals were used to create impressions which acted as guarantees of integrity within a larger economic system. This understanding of seal based administration, which was practised to differing degrees throughout the ancient world (Ameri et al. 2018), is very much based on evidence from Mesopotamia and the

Aegean, where this system was first extensively studied and defined (Frenez, 2005).[2] In the Harappan context, the existence of seal-based administration is assumed based on evidence of impressions on shaped clay and ceramic pots (or other utilitarian forms), but it is also heavily influenced by our understanding of Mesopotamian material culture. The artefacts identified as Harappan or Indus seals share physical characteristics such as knob or handle on the back, intaglio carving, and strengthened material with those known from Mesopotamia and elsewhere. However, it is worth pointing out here that in the very first excavation report of Mohenjo-daro, excavators raised concern about classifying these objects as seals because no true sealing - that is impression on clay attached to a jar or object of merchandise - had been found (Marshall, 1931, p.380).

Marshall was not the only one to question whether the seals found at Harappan sites would have been used for sealing. Based on careful observation of the extant material, Greg Possehl also cautioned that these objects may have had different functions than their Mesopotamian counterparts. He highlights the fact that many of these still retain the original edges of the carving and are mostly unworn. He thus proposes that the seal itself acted as an object of visual identification. A shallow incised terracotta seal from Allah Dino demonstrates his point that the political economy of Harappans could be different than the seal-based one of that of Mesopotamians (Possehl, 1996, p.26).

In their analysis of the Lothal sealings, Frenez and Tosi raised a possibility that the animal icon or complex scenes probably acted as identifier but the inscriptions provided other information (Frenez and Tosi, 2005, p. 67). In his recent work that extends the morphological study of these sealings into their interpretation, Frenez has also pointed out quantitative differences in seal and sealing proportions from the studies done on Middle Eastern such as Uruk materials as well as Minoan sites. It is now understood that the seal-based administration systematised the management and record of access to goods stored within storehouses rather than securing the shipments of trade (Frenez, 2020, p. 22). Based on morphological analysis of sealings, and two or three pairs of seals and sealings discovered at Lothal, Frenez has also argued that the usage of Harappan sealings was local rather than that for the shipping (Frenez, 2020, p. 22).

In addition to proposing this comparable use of the seal-based administration in Harappan contexts, Frenez has also illustrated causes for the quantitative differences. In the absence of firing (accidental or intentional)[3] sealings were too small and delicate to survive during the site formation process. Delicate unbaked sealings may have been too inconspicuous to be recovered using the excavation methods of the 1930s (Frenez, 2020, p. 25). Mackay noted how some of the sealings that were excavated at Chanhu-Daro disintegrated while workers were attempting to wash them (Frenez, 2020, p. 25). In addition to highlighting the difficulty of sealing survival, Frenez concludes that the use of the seal-based administrative procedures was limited to the control of important material and it was not implemented for the daily management of food (Frenez 2020, p. 34). It thus points towards the possible difference in frequency of need and consequent lesser production of sealings in Harappan contexts compared to other ancient cultures such as Mesopotamia or the Aegean.

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[2] There are multiple studies by Fiandra & Ferioli in this regard which have been referred to by Frenez.

[3] Regarding the burnt status of sealings, Frenez mentions ambiguities regarding whether the firing was intentional (Frenez, 2005, p.71) or accidental (Frenez, 2020, p.25). While Frenez has suggested that the sealings at Lothal may have been fired intentionally, there is little evidence that this was done elsewhere in the Indus. In fact, the other sealings that were found seem to have been unintentionally burnt.

On the artefact typology front, the lack of refinement has meant that terms such as `seals and sealings' continue to be used collectively for the diverse collection of Harappan inscribed objects seen in Figure 2. This has created a preconception for generalised interpretation and it has contributed to critical hypotheses about (i) the direction of reading the script, and (ii) the usage of seals for creation of sealings. The wider academic scholarship, including the authors of CISI volumes, which catalogues all the excavated inscribed materials, have assumed that the `inscribed steatite stamp seals' fundamentally functioned as means to make the impressions to create sealings. It notes that the impressions prove that the seals were instruments of control in trade and administration as in west Asia (CISI, vol. I, p. XV). All the academic publications thus print the seal and its impression where such an impressed object, i.e. the sealing, is presumed to be the object of consumption. Meadow and Kenoyer (2000) bring this up and question this practice of publishing. They argue that such normative academic exercise creates a subtext for interpretation.[4] A more precise understanding of the ways in which seals were used by the Harappans can help us to better approach these artefact and the role they may have played in Harappan society.

2. Problem

The evidence of close contact between Mesopotamian and Harappan cultures, based in part on the identification of Meluhha (a region repeatedly mentioned in Mesopotamian texts) with the Harappan region, as well as on the existence of similar artefacts has supported these assumptions about the seal and sealing relationship. However, the seal-sealing hypothesis needs to be evaluated in the light of the evolving picture presented by continued excavations and recent material studies. As seen from the earlier discussion, the use of seals as a mechanism to impress multiple clay lumps to create sealings (at times attached to other objects or for sealing the containers) has been the most plausible theory to date. Needless to say, all the seals and sealings or impressions of every seal will never be recovered.[5] A number of other factors may also determine the number of sealings that will be found. For example, if the administrative system itself demanded the sealings to remain unbaked or their breakage in order to open the container or any other item, then the possibility of recovering any intact artefacts of this kind is significantly reduced. If these were being purposely discarded or taken out from the everyday working space, then the contemporary usage mechanism will further continue to obstruct their recovery in excavations. Finally artefact discoveries are impacted by inevitable archaeological probabilities such as survival of intact or broken artefacts through the site formation phases and climate changes, proportion of excavated areas, the artefacts being spotted, and then retrieved through the excavations. Though many of these scenarios are similar to Mesopotamian materials, and as mentioned earlier, ideas of typologies and interpretation have been borrowed, the stark difference in the overall artefact quantities recovered from these cultures cannot be ignored. Following paragraphs discuss this in detail.

A tentative summary of the quantities of artefacts from Harappan culture can be seen in the CISI volumes as well as the ICIT database (Wells and Fuls, 2010-2023) . A slight revision of typology and

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4 It should also be noted that the image carved onto a seal is often much easier to see and understand from an impression than it is in the seal itself. This is another reason that people have typically assumed that seals were in fact designed to create impressions.

5 The recovery of artefacts is a result of multiple phenomena that take place at different times and at different scales.

some improvements in categorisation can be seen in the doctoral thesis by Gokhale (2023). The presently published and available quantities of seals viz. ~2200 and impressions[6] viz. ~250 make it difficult to accept the present hypothesis that every seal was used to produce multiple artefacts through its impression. Though the hypothesis is a reflection of Mesopotamian scholarship, it's applied as a deductive reasoning in this case. Figure 3 shows rare pairs of seals and possible sealings from the presently available Harappan artefacts' dataset. Reversal of iconographic motif and sign sequence can be observed in each sealing.

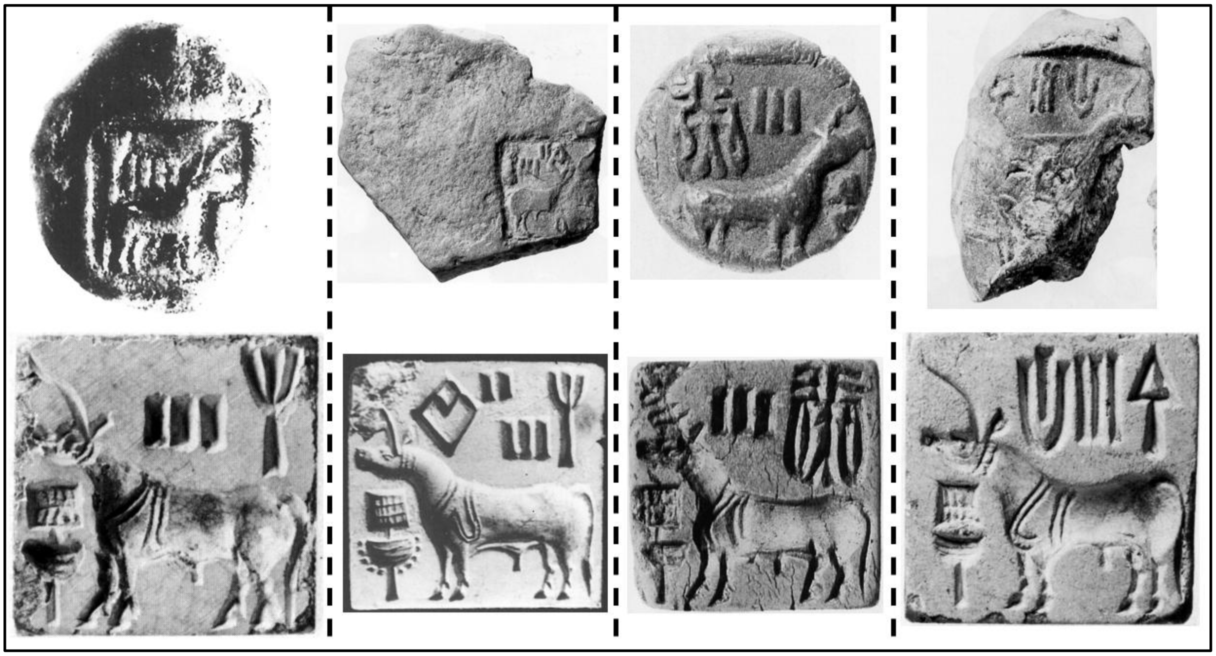

Figure 3: Example pairs of Harappan seals (bottom row - L to R: M-179, M-1697, H-499, M-122) and possible sealings (top row - L to R: M-2010, K-82, M-429, L-146)

Catalogues such the CDLI[7] and ETCSL[8] demonstrate both the artefactual wealth and the exemplary documentation program of the cuneiform inscriptions belonging to Mesopotamian and other proveniences. Though CDLI is similar to the CISI publication project, the progress report by Tsouparopoulou (2014) and a detailed note on the nitty-gritty of digitisation and standardisation of records (Englund, 2014) exemplify complexities in collating this dataset for any meaningful further research. The sheer number of sealings and/ or impressessions, their contexts, examples of relevant seals (cylindrical or stamp), and our ability to situate them in the historic context (due to the successful reading of cuneiform content) transition the concept of 'seal-sealing practice' into a tangible construct for this corpus. A volume dedicated to excavations at Arslantepe has several mentions about the quantity of sealings and their usage. Though this material pre-dates Harappan artefacts, it is important to understand how usage patterns continued over the period of time. Here,

[6] The quantity accounts for impressions on ceramics, intact clay lumps, or broken unidentified terracotta objects which carry impressions. This does not include the artefacts identified as bas-relief tablets.

[7] Cuneiform Digital Library Initiative - https://cdli.mpiwg-berlin.mpg.de/about.

[8] The Electronic Text Corpus of Sumerian Literature - https://etcsl.orinst.ox.ac.uk/

thousands of discarded sealing fragments with a variety of impressions have been recovered. These indicate the preservation of a possible archive of administrative records, possibly ".... an elaborate system of food distribution in exchange for labour or commodities." (Pittman, 2019, p.137). The scholarly analysis of this abundant material for its context and usage pattern illustrates a vivid picture of these artefacts and the manifold roles they played in the social as well as individual lives of the people in the past (Pittman, 2018; Matthews and Richardson, 2019). In a context that is contemporary with the Harappan period, the administrative role of seals in Akkadian period Mesopotamia is proven by the sheer number of contemporary sealings impressed by those seals (Rakic, 2018, p.85). When Frenez compares the quantity of sealings from Lothal to those in Iran and Mesopotamia, he notes that the number of sealings found in the entire site of Lothal are equivalent to a collection in a single house in Shahr-i Sokhta (Frenez, 2005, p.82). Despite the fact that the sealings are made of clay in both locations and assumed to be participating in similar administrative systems, these differences in the number of extant sealings have been obscured in favour of a focus on the similarities with the Mesopotamian system.

Ten sealings with impressions of an identical elephant motif and sign sequence were found at Lothal. Working from the hypothetical assumption that these could be around 20% of the total impressions created by the yet unrecovered seal, and that each seal was used to create at least 50 impressions if not more, we might expect that there would have been at least 110,000 sealings in the past for number of Harappan seals excavated in the past century. The total ~250 impressions on hand are 0.227% of the hypothetical total impressions. Twenty percent could be an optimistic number because it is generally believed that only a fraction of what might have existed in the past is excavated. Thus, if each seal was used more than 50 times to make an impression, this proportion would be even lesser.

The main possible causes which have been hypothesised for the small number of sealings in the Harappan context are: (i) material difference - seals were mostly made of steatite stone and were baked during the manufacturing process; hence those became sturdy and more reliable than the impressions made on clay which might not have been routinely baked, and (ii) usage pattern - seals were expected to last longer for repeated use for impressions but clay objects were to be broken to open traded goods or locked doors, were discarded at the end of the transaction, or even recycled in some cases.

Detailed analyses of seals that seek to understand how these artefacts were made by using metric measurements made under Scanning Electron Microscopes or similar instruments (Jamison, 2017; Green, 2015; Konasukawa, 2015) have not typically taken the wear and tear of seal use into account. These studies measure the carved incisions, their depths, and stroke details, and use these measurements for further analysis and grouping of seals. Such measurements would inherently comprise the wear that the artefacts have undergone. If the usage involved making frequent impressions on a material, then the wear would have gradually increased. In absence of knowledge about usage patterns and the subsequent range of deterioration, the grouping logic should either assume uniform wear of all seals or not at all. In real life, both these are unrealistic hence a mix of these should be assumed. If we assume a diverse usage of seals, the wear would be of varying natures and degrees, systemic in the cultural past, and is also a result of post-depositional deterioration until its recovery. The fact that these studies do not necessarily account for these pre and post depositional systemic deteriorations leaves a substantial gap in our understanding of Harappan seal use.[9]

Many Harappan seals observed in ASI's Central Antiquity Centre appeared rarely used and carefully preserved. The intricate carving of signs and decorative patterns of animals or other motifs looked almost intact. The wear and tear was minimal in most of the objects. Had these been used multiple times around 4500 years ago, and then abandoned or discarded till ~1930 CE, they would have appeared in a more weathered state. Based on their proposed use-case, the surface abrasion should have been more prominent in most of the seals. However, in some cases, it appeared like peeling off of the coating layer and it suggested ageing. Figure 4 shows seals in different stages or deterioration as well as their almost intact nature.

Figure 4: Example of seals showing different levels and types of deterioration - 1. Intact surface and carving - H-5, 2. Intact surface and carving, corner broken - M-3 3. Intact surface and carving - H-135, 4. Broken boss - M-130, 5. Some deterioration - M-21, 6. Comparatively more deterioration - SKTD-1, 7. Peeling of surface coating - H-89, 8. Broken but intact carving - H-97, 9. Peeling of surface coating over years - H-44 (Photographed at CAC in Dec 2021 and photo from CISI vol. I, tentatively photographed around 1980s).

While it is difficult to ascertain what effect extensive use would have on the physical appearance of a seal without more detailed artifactual and experimental studies of the effects of use, and depositional circumstances (for example, are seals that were found in drains more worn than seals that were found in houses?) on the condition of an excavated seal, the near-perfect condition of some excavated seals does seem to suggest that they were not extensively used for sealing.

[9] The measuring exercise only measures the incisions. It does not differentiate between the original carving and impact of use. Thus, the differential deterioration or wear pattern goes unaccounted. To use the measured parameters for any further analysis or grouping, one must assume that either the wear is uniform or not at all. If we assume the wear is different for each (which is actually a reality), is there a way to measure it?

In addition to these findings, there is a notable absence of impressions created by rectangular seals in the presently published sealings.[10] Though there are rectangular clay tablets where signs and icons appear in bas-relief, there is no study yet that possibly links those with rectangular seals. None of the seals depict the form, scenes, or other details observed on these tablets and thus these were probably created using moulds from perishable materials like wood (Ameri, 2018).

Against the background of incomparable artefact evidence, it is worth mentioning that Fairservis (1986) had demonstrated presence of territory based or regional need based characteristics of Mesopotamian and Egyptian counterparts, and their absence in Harappans culture. It means that even if we identify these as civilisations or urban spaces of contemporary times, they might have possessed some very specific or unique characteristics of their own which were a result of their own geographies, and socio-cultural and economic systems.

This discussion demonstrates that the disproportionate artefact inventories hinder the interpretation of Harappan material due to the incomparable material evidence from other cultures such as Mesopotamia. Observations on the seals pose serious questions about their persistent use and the subsequent expected wear and tear. Finally, the lack of matching pairs question the generalisation of the seal-sealing hypothesis. These observations together may tentatively reject the hypothesis that all seals were meant for creating multiple impressions. However, prior to it, it is critical to simulate this present hypothesis by using the conditions and quantities described till now.

3. Agent-based Modelling

Agent-based modelling (ABM) is a computational modelling technique that simulates phenomena involving individual or grouped entities. It helps understand the system behaviour and its outcomes. It combines concepts from multiple domains such as game theory, multi-agent systems, and many more. Though this has been widely used in biology, especially epidemiology, its recent applications in social sciences has revolutionised the way researchers could simulate diverse scenarios and study their outcomes. The tool like Netlogo has democratised the application of this otherwise complex concept (Wilensky, 1999). Our ABM experiment of the current topic has been implemented in NetLogo Desktop version 6.4.0.[11]

The modelling experiment assumes the hypothesis that all the seals were used to create impressions. Seals and sealings are treated as agents which have their own life-cycles. Though the sealings are produced by seals, once created, both follow their own usage pattern which could be completely independent from each other and also diverse within themselves. As of now, the owner/ user/ producer persona of either of these artefacts has not been precisely defined. However, their collective interaction with probabilities of creation, survival, and decay leads to a systemic pattern. For this experiment, the DK-G(S)[12] mound of Mohenjo-daro is selected as a frame of reference. It

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[10] A small number of these have also been observed impressed on the pottery so perhaps their function was different.

[11] Introductory understanding and training was received at the CAA2023 conference that happened in Amsterdam. The authors have later studied the tool using its online resources and have developed a functional model for the present experiment. Also, Ketika Garg (Post-doc at Caltech) and Sugat Dabholkar (Tufts University) have helped to understand basic concepts about ABM and the use of Netlogo tool respectively. This work was presented at the CAA2024 Auckland conference.

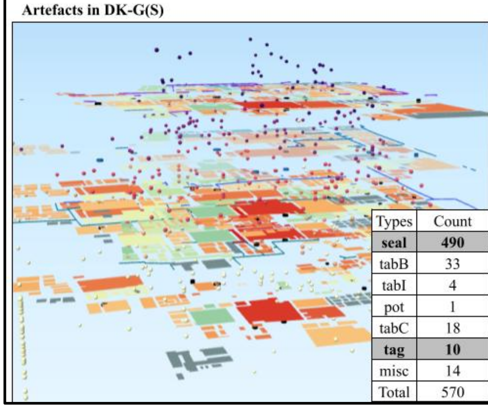
[12] Known after its first Excavator Rao Bahadur Kashinath Narayana Dikshit

offers one of the largest inventories from a single site with detailed documentation of the artefacts' attributes and findspots. A total of 490 seals and 10 sealings have been recovered in over 20 feet of depth from this mound. Cultural periods were identified at certain depths as seen in the graphic in Figure 5. This single mound comprises more than 15% of the seals discovered across all Harappan sites. It thus creates an interesting case study for this experiment.

Map	Period	Depth *	Total rooms	Room polygons	# of Houses	~ # of people	# of Seals
1	Late I-II	3-7	707	511	54	540	**56**
2	Late III - Int I	10	711	223	53	530	**94**
3	Int I	13	612	302	52	520	**116**
4	Int II	15.9	604	365	54	540	**90**
5	Int III	20.4	587	137	31	310	**134**

* below datum - ft

Artefacts in DK-G(S)



Types	Count
seal	**490**
tabB	33
tabI	4
pot	1
tabC	18
tag	**10**
misc	14
Total	570

	Subtypes								-
Sites	seal	tabB	tabI	pot	tabC	tag	misc	u	Total
Harappa	635	643	579	369	0	16	52	1	2295
Mohenjo-daro	1504	118	5	66	254	25	84	4	2060
Dholavira	150	2	18	1	0	67	3	0	241
Lothal	120	1	0	16	0	94	2	20	253
Kalibangan	73	4	1	85	1	19	7	1	191
Chanhu-daro	67	3	0	5	0	2	5	1	83
Nausharo	18	0	0	21	0	2	0	0	41
Banavali	22	1	0	7	0	1	1	0	32
Lakhanjo-daro	8	2	0	3	0	5	0	0	18
Allahdino	7	0	0	2	0	1	2	0	12
Kunal	11	0	0	0	0	1	0	0	12
Kanmer	3	0	0	2	0	4	0	0	9
Kot diji	1	0	0	9	0	0	0	0	10
Others	114	5	1	46	0	14	4	1	185
Total	2733	779	604	632	255	251	160	28	5442

Figure 5: Left top - Quantities of seals, number of rooms, houses, and possible occupants at DK-G(S) across five cultural periods; Left bottom - 3D visualisation of structural remains and spread of artefacts at DK-G(S); Right - Quantities of different types of artefacts across major Harappan culture sites (Gokhale, 2023)

The core parameters of the model can be described as follows.

3.1. Duration

Based on the existing archaeological studies, the peak of Harappan material culture and the associated society is proposed to have existed from around 2600 BCE to 1900 BCE. With respect to Mohenjo-daro and the mound of DK-G(S) in the present study, Mackay proposed that the deposit was a result of three hundred years of occupation (Mackay, 1938, p. 7).[13] The span of years can thus be tentatively assumed between 300 to 700 years.[14] This model incorporates one year as an interval for modelling the phenomenon. This essentially means that creation and decay of seals, sealings, and houses is being hypothetically monitored for every year. The model can run for the set number of

[13] May be with some gaps due to flood or other reasons

[14] Later critical analysis of Mackay's excavation strategies, stratigraphic understanding, and identification of cultural periods, Can be found in the Interim Reports published by IsMEO Aachen University Mission during the 1980s.

years or it can continue to run based on the conditions of the agents. It must be noted that in the present Harappan scholarship, inscribed artefacts, especially seals, have a tight association with this period. While this has led to their consideration as a homogeneous and monolithic group, recent studies are investigating the aspects of regional and temporal variation which can help identify boundaries in this otherwise complex dataset (Ameri, 2013; Jamison, 2017; Konasukawa, 2015; Kenoyer, 2006; Kenoyer, 2020).

3.2. Agents

Seals, sealings, and houses are agents in the present framework. Each has a specific age property. Age essentially defines the amount of time for which it is present in the model and thus participates in the scenario. The 'birth' or 'production' of either of these three entail the beginning of their presence and participation in the model. The 'death' of an agent means that it ceases to exist thereafter. There could be many different causes to this such as it was broken beyond recovery, permanently lost, moved to different sites, or reused and then disposed of. These details are not explicitly part of the current experiment. To simulate those causes, In addition to random-float, colour property has been added to each agent and has been used to invoke additional probability at the time of birth or death. Besides these basic properties, each seal also has energy which describes its capacity to produce impressions and thus create a sealing.

3.3. Houses

The excavated layout of DK-G(S) has been used for the simulation. Houses that were identified in different cultural periods, have been digitised from the published plans. Within the model, the probability of house creation arises every 25th year[15] and decay probability triggers if it has reached its age limit. This models the rebuilding of houses on this mound. There are events of floods documented by the excavator which probably forced the then population to vacate the area and then resettle. Also, there could have been intermittent abandonment and rebuilding of the houses as seen from the stacks of bricks located within the structures (Mackay, 1938, p. 53).

House areas are patch agents. These can be used to restrict where seals or sealings can be produced or can survive since these have been recovered only from certain areas within DK-G(S). Also, these patches can be created for multiple cultural periods as documented in the excavation report. However, these will be implemented in the later phases of the experiment.

It must be noted that the stratigraphic interpretation and cultural period definitions were in a nascent stage at the time of this excavation. Thus, the possibilities of undulations of the mounds, presence of contemporary neighbourhoods at different levels, and differential occupation and abandonment of parts of mound have not played a significant role in the interpretation.

3.4. Seals

Seals are produced at a higher rate than they die. This reflects meticulous production of these artefacts, made of a specific material, and for long-term survival. Seal expiry probability arises if it has reached its age limit and has also produced the stipulated number of sealings based on the set energy level. The 'death' or expiration in this context entails that the seal was absent from its systemic

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[15] The number is a broad mapping to the generation of the population.

context and was no longer used after that moment. This could be because of official decommissioning, breakage, loss, or any other contemporary cultural reasons.

3.5. *Sealings*

All the seals continue to produce sealings until they exhaust the set energy level. This mimics the idea that each seal was expected to produce multiple sealings. It is unlikely that each seal was used with the same frequency to produce sealings. However, in absence of insights about a more specific usage pattern, it is considered equal for this experiment. Their decay probability arises as and when they reach the age limit. In order to replicate possible real life scenarios of the past, the age of seals should be significantly higher than that of sealing.

For seals, sealings, and houses, initial and maximum quantities can be set. As mentioned earlier, all the three agents are created with multiple colours. At the time of expiry, in addition to conditions of age, count, energy, and random probability, only certain colours are chosen. This mechanism essentially mimics unknown systemic characteristics which have played a role in selective survival and loss of artefacts. It is evident that there will be many of such systemic or even external contributors but in the current model it is limited to one. Essentially these mimic the causes behind the present day artefact recoveries and the duration of cultural period during which these events happened.

4. Experiment Details

The basic parameters can be seen listed in Table 1 below. Range shows the possible values each parameter can take. Initial setup shows the possible starting values for each parameter. The last column provides a brief description of the parameters.

Table 1: Basic parameters used in ABM experiments and their details

Parameters	Range	Initial Setup	Description
Map	1 to 5	NA	Cultural period maps of DK-G(S)
Years	0 to 2000	500	Number of years (tics) the model simulates
Houses-initial	0 to 20	10	Initial number of houses
Houses-Max	500	50	Maximum number of houses
House-Repro-Prob	0-1	0.25	Probability of new houses being added
Seals-initial	0 to 50	3	Initial number of seals
Seals-Max	3000	500	Maximum number of seals
Seal-Death-Prob	0-1	0.2	Probability of seals being destroyed/ discarded
Seal-energy	0 to 50	3 and 10	Ability of seal to create impressions for sealings
Seal-age	0-50	25	Active period of seal
Impressions-initial	0 to 50	5	Initial number of sealings
Impressions-Max	50000	10000	Maximum number of sealings
Impression-age	0-5	1	Active period of sealing

Figure 6: The interface of the model within the NetLogo tool

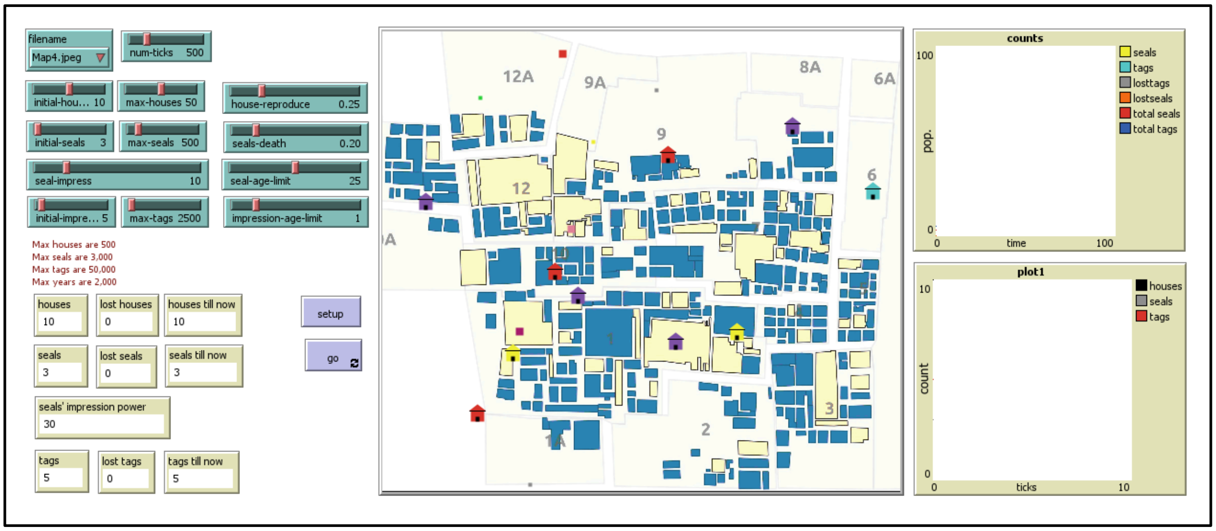

Figure 6: NetLogo model interface for Agent-based modelling experiment on Harappan seals and sealings

It is evident that there can be numerous combinations to create the initial setup. Out of many possible scenarios, the following four scenarios have been simulated through the above model. For each scenario, as the simulation runs, the quantities of seals, sealings, and houses being produced, destroyed, and finally retained are monitored. Also, each of these four scenarios are run for higher and lower seal-energies, i.e. ability of seals to produce sealings. These cases are 10 and 3 respectively. These two cases have been introduced to add possibilities of seals being used very frequently or rarely. The 10 identical sealings found in Lothal show that seals were definitely used to impress those many times. On the other hand, due to the general scarcity of sealings for the majority of the seals and based on other contextual observations described above, seals could only rarely have been used to make an impression on the clay. This is unlike the present understanding about the Mesopotamian seals. The energy level of 3 thus depicts the very limited or conservative use of seals for the production of sealings. As mentioned earlier, we do not have insight into the actual numbers. Also, those could have varied from seal to seal even within the scenario of the same energy level. However, that variation is not considered within the scope of the present experiment.

The four scenarios can be listed out as follows:

- **How the artefacts and houses evolve in a span of 500 years -** Time is considered as a limiting factor. The tentative duration of material peak and the span in which the mound was formed needs to be correlated to some extent. Since a varied number of artefacts have been found at different depths, even in pre and post flood contexts, it is important to visualise this as an event over time.
- **What is the status of artefacts and houses by the time 500 total seals are produced** - The total number of seals recovered from DK-G(S) mound is around 490 but the number of sealings from the same excavation is about 10. These quantities demand more investigation into the absence of sealings. Since these have been excavated from the depths of 20 ft up to the surface, it is a collection across time. However, it is very likely

that artefacts from different depths were simultaneously in use because the contemporaneous occupation levels were different. Or, during the discard or site-formation processes, the artefacts landed in locations and depths which then became the pseudo contexts. This uncertainty about the findspot of an artefact is intrinsic to archaeological theory. This case thus simulates the accumulation of total count with some of these possibilities being modelled through creation and decay probabilities of seals. It also creates an insight for the expected number of sealings which could have been present here.

- **What is the status of artefacts and houses by the time 2500 total sealings are produced -** A very small number of sealings has been recovered from this mound. However, based on the presently accepted hypothesis that runs parallel to Mesopotamian material, this simulation assumes that ideally we should have recovered a lot more sealings than what we have. It thus continues to run until there are at least 5 sealings per seal found on this mound.
- **What is the status of artefacts by the time 50 total houses are present -** A detailed GIS case study that is built based on the excavation report of DK-G(S) demonstrates that the mound could accommodate a maximum of 50 to 55 houses (Gokhale, 2023).[16] At present we are constrained by the definition and identification of houses as described in the excavation report. That said, the depths of structural remains, expansion of drainage networks, and spread of building activity in different areas indicates that the number of houses also grew over a period of time. With multiple phases of abandonment and reoccupation, the numbers will continue to fluctuate. Thus the houses also cease to exist after a certain period. This scenario simulates this phenomenon.

Finally, for each case of seal-energy, each model has been run for 50 iterations to get the average result. These iterations and their combined results account for random probabilities in each scenario and thus help create a more robust experiment.[17] The scenarios can be seen tabulated in Table 2.

[16] This tentative number of Intermediate and Late periods was calculated based on plans published by Mackay in the Mohenjo-daro excavation reports. His identification of rooms, their connectivity, and association with a specific house have driven these numbers. These numbers could vary for different cultural periods because however, there is inadequate understanding about the undulations of this mound and the differential abandonment or reoccupation that would have happened on it in different periods.

[17] Except for one case of the fourth scenario which could not complete those many iterations.

Table 2: Parameters for four scenarios which are modelled in the present experiment

Parameters	Range	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Map	1 to 5	NA	NA	NA	NA
Years	0 to 2000	500	500	500	500
Houses-initial	0 to 20	10	10	10	10
Houses-Max	500	50	50	50	50
House-Repro-Prob	0-1	0.25	0.25	0.25	0.25
Seals-initial	0 to 50	3	3	3	3
Seals-Max	3000	500	500	500	500
Seal-Death-Prob	0-1	0.2	0.2	0.2	0.2
Seal-energy	0 to 50	3	3	3	3
Seal-age	0-50	25	25	25	25
Impressions-initial	0 to 50	5	5	5	5
Impressions-Max	50000	10000	10000	2500	10000
Impression-age	0-5	1	1	1	1
Seal-energy = 3		50	50	50	50
Seal-energy = 10		50	50	50	31

5. Results and Interpretations

Theoretically, out of many more possibilities, the four scenarios mentioned above create alternate pasts which could have existed. Each assumes a constraint imposed by one of the four agents and thus evolves over a period of time. Time itself has also been used as a constraint in the first case.

For a single sample run, Table 3 shows counts of total, lost, and survived numbers of seals, sealings, and houses for each of the four scenarios and for both cases of seal-energy. The counts of total artefacts (totalseals, totalsealings, totalhouses) entail the actual total number of artefacts which became part of the cultural system for each specific scenario. However, as discussed earlier, the structure or artefacts are lost due to several reasons, both systemic and external. As part of academic excavations and related historical or archaeological work, it is rare to have factual insights into these numbers. These experiments, the parameters, and the probabilities demonstrate a possibility of estimating these quantities of lost material (lostseals, lostsealings, losthouses). The end result of each scenario is a hypothetical case of material, both structures and artefacts, which would be recovered as part of excavations (seals, sealings, houses). These numbers thus create a tentative baseline for what we could expect should any of those scenarios had occurred in the past. Thus, the quantities of total artefacts include both what could have been lost and excavated in those alternate hypothetical pasts. This model and formulation is at an incipient stage but demonstrates a potential for improvement through addition of parameters and their attributes.

Table 3: Model result for a single run of four scenarios for two different seal energies

Counts	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	500 years	500 seals	2500 imp	50 houses
Seal-energy = 3				
lostseals	386	474	944	278
totalseals	407	501	965	302
seals	21	27	21	24
lostsealings	652	737	1495	506
totalsealings	1103	1291	2504	855
sealings	451	554	1009	349
losthouses	70	90	1195	29
totalhouses	169	203	2708	56
houses	99	113	1513	27
Seal-energy = 10				
lostseals	388	483	718	189
totalseals	412	501	745	212
seals	24	18	27	23
lostsealings	983	1081	1512	737
totalsealings	1625	1779	2506	1197
sealings	642	698	994	460
losthouses	87	96	381	22
totalhouses	205	220	877	53
houses	118	124	496	31

The combined result of 50 iterations on these four scenarios, each with two cases of seal-energy, can be seen in Table 4. It shows the number of years taken to run each case and the number of seals, impressions, and houses that have survived at the end. This essentially forms the alternate sets of material that could have been excavated in each scenario. The survival of this material, both loose and in-situ, is a result of archaeological and post-depositional processes. It must be noted that the number of years in Table 4 do not account for the post-depositional period. For each scenario, the model ceases to run as soon as it meets the criteria. A few examples below can illustrate the data in the table.

- For both cases of seal-energies, for the first scenario, the model concluded as soon as it entered the 501st year. The number of seals, sealings and houses can be seen for both cases on seal-energy 3 and 10.
- For seal-energy 10, for scenario 2, as soon as the count of total seals goes above 500, the model concludes. It can be seen that this version of the virtual past took 653 years. At the end, 24 seals, 725 sealings, and 158 houses could have survived and been excavated through the archaeological excavation.
- For seal-energy 3, for scenario 3, as soon as the total count of sealings went above 2500, the model stopped. In this virtual past at this point, 1271 years have passed, 24 seals and 1071 sealings could have survived and recovered from the site, and houses have increased

to an unrealistic quantity of 1702. For a limited space on this mound, the house numbers given out by the model need further revision. This is because houses will occupy certain spaces and hence the contemporary houses may not overlap each other. This will need changes in the model where, as mentioned in earlier, the house areas need to be treated as patch agents.

Table 4: Model result for 50 iterations of four scenarios for two different seal energies

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	500 years	500 seals	2500 sealings	50 houses
Seal-energy = 3				
years	501	645	1271	551
seals	24.2	23	24	22
sealings	451.3	549	1071	491
houses	73.94	171	1702	23
Seal-energy = 10				
years	501	653	1083	501
seals	24.12	24	22	23
sealings	636.66	725	1044	637
houses	74.56	158	766	17.33

These results can be collectively interpreted as follows:

Despite the distinct conditions such as seal-impression energies of 3 and 10, i.e. forcing each seal to produce those many sealings, and sealings decaying at a higher rate than the seals, all scenarios seen in Table 4 suggest there should have been more sealings than what has been found on the mound. It is important to note that this is a mean result of 50 iterations. As seen in Table 3, for a random iteration of first and second scenario for seal-energy 3, the number of total seals are comparable to present evidence, i.e. the 407 & 501 seals respectively as compared to 490 actual seals documented from DK-G(S). In these cases, the total number of sealings are 1103 and 1291 and those expected to be recovered from the excavation are 451 and 554 respectively.

However,

1. We actually find far fewer sealings than we should expect. The actual sealings recovered from this mound are only 10. The numbers 490 and 10 can be evaluated on the background of total numbers of seals and sealings recovered from all Harappan sites, i.e. ~2200 and ~250 respectively. However, as discussed in the initial section, these proportions are not equivalent to Mesopotamian material. It has been noted by Frenez that sealings could have been consistently missed in excavations due to those being mostly unbaked and too delicate. The difficulty in recognising and preserving those in the century old excavation techniques could have been another challenge (Frenez, 2020, p. 25). That could also be the case when

the frequent presence of sealings itself was not anticipated. However, for all the later excavations when the possibility of finding sealings has been well-established, except for Lothal and Dholavira (combined quantity ~150), there is no large amount of sealings recovered.

2. Our evidence for the administrative system is not nearly as clear as it is in Mesopotamia. Besides the information revealed by the readable script, many sealings in Mesopotamian sites could be interpreted as manifestations of administrative or economic systems due to their strong contextual associations. At Arslantepe they are stored, but in other places they are discarded, and in some cases the sealing clay is found to be recycled (Zettler, 1987). At Gilund, sealings were found in a pit, suggesting that they were thrown out and not stored (Ameri, 2021). For better understanding the context of these, the questions which emerge are if the seals were used and stored in the same places, if not, where were seals used? For the sealings, what would have happened to sealings after they were opened? At Lothal they are found in the "warehouse", but only because there was an episode of burning. At Mohenjo-daro and Dholavira, the sealings have been found scattered at multiple locations. For example, Dholavira report mentions sealing find-spots such as castle, middle town, reservoir, lower town, bailey, annexe, and promenade (Bisht, 2015).
3. Many of the seals don't seem to have evidence of the extensive wear we might expect if they were used intensively. Here we should also note that even though the seals are fire-hardened, steatite remains one of the softest stones out there and so would probably show signs of wear. The primary hypothesis prompts for recurrent use of seals to impress multiple clay lumps to create sealings. Wearing of carved surfaces of seals is an inevitable outcome of this process. However, the successive scholarly work has proposed inconsistent methodologies which do not align with this theory. The studies have employed high-end techniques for the detailed measurements of these carved surfaces of the seals and subsequent theorisation of possible carving groups. These measurements inadvertently account for the wear and tear due to the primary use of seals in the cultural past. In absence of knowledge about the original intact state of the carving, potentially varied usage patterns of different seals, and the nature and scale of wear, these measurements produce an aggregate of original carving and its deterioration. Using these convoluted quantitative observations for theorising the carving groups is a challenging proposal. This, in the light of the almost intact state of many of the physically observed seals compel to reappraise the present hypothesis.
4. Finally, there are very few examples of matching seal and sealing pairs. Though this is also a common scenario in excavations of other material cultures where thousands of sealings have been found, the scenario cannot be ignored. In the later case, many seals also appear worn out, possibly resulting from their persistent use.

Thus, the experiment seems to provide further support to suggestions made by authors that have suggested that Harappan seals may not have been intended primarily as administrative objects meant to make impressions in the form of administrative sealing.

This modelling experiment is critical in the space of Harappan artefact studies for the following reasons.

1. Focusing on the seal/sealing or administrative sealing model limits how we understand and interpret the information provided by Harappan seals.

2. Focusing on similarities to Near Eastern or Aegean models may cause us to overlook distinctly Harappan aspects of seal production and use.
3. There are direct implications for the study of the Indus script. The consensus that the seals are made to be impressed has led to the unconditional acceptance of the idea that the inscriptions on the seals themselves are executed in reverse. For example, if the inscription on a seal was incised as ATЯAM, it should be read MARTA.[18] This belief has become a fundamental tenet of the study of Harappan script and has affected everything from the interpretation of sign sequences to assumptions about specific signs that may function as signifiers based on their position.[19] However, if the seals were not meant to be impressed, this would challenge many of the existing hypotheses for understanding the Harappan script.

These observations from the simulation experiment, from the dataset and existing scholarship, and, their interdependency infer that this Agent-Based Modelling experiment does not support the present hypothesis that all seals were being used for creating multiple impressions. In order to explain the fewer number of sealings, it is important to investigate the causes for the rate of degradation of sealings in South Asia versus those in Mesopotamian region. It may help for better estimates and to the revision of the present hypothesis. Present experiment suggests a less generalised version - Only some seals of Harappan culture might have been used for creating an impression and thus produce the sealings. As a consequence, we may not be able to interpret these artefacts and the associated society in the same framework as that of Mesopotamian culture. As discussed earlier, this experiment, the basic parameters, and the results raise further questions which can help refine this model.

Supplementary Materials

The primary data used for this experiment is sourced from published online and printed repositories of Harappan artefacts such as volumes of Corpus of Indus Seals and Inscriptions and ICIT database.

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None

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[18] While this is true in principle, studies from Mesopotamia (Tessier, 1994, p. 72), where we are able to read the inscriptions on seals, show that it is not altogether uncommon for inscriptions to be incised on the seal directly rather than in reverse, possibly because the scribe and the seal carver were not the same person. In the present dataset, it is seen that when sign sequences of seals are reversed (prospective sequence on sealings), there is hardly any overlap with the sign sequences of other non-seal artefacts such as terracotta tablets, copper tablets, or ceramic sequences. This absence indicates that either it is not necessary to assume the reversal of sign sequence or the content of seals (and their impressions) and other types is totally different. The observation is statistically against the seal-sealing hypothesis. On the contrary, if the sign sequences on seals are not reversed and then compared with other non-seal artefacts, we continue to observe an absence of overlap. This needs further investigation.

[19] Assumptions about the directionality of the script on seals are also based on the execution of the carving itself. In particular, Parpola and others have suggested that when signs on one side of the inscription appear to be crammed into a limited space, as if the carver had run out of space, this represents the end of a word or inscription. It must be noted here that both sequences of carving and reading are being simultaneously discussed.

Data Availability Statement.

The preliminary model developed in Netlogo has been uploaded to Zenodo.

Conflicts of Interest

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

Author Contributions

Pallavee Gokhale has analysed the existing artefact data and literature, and has designed the experiment in NetLogo. Marta Ameri has provided comparative analysis as well as inputs regarding the parameters being used in the model.

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