The Journal of
HISTORICAL
NETWORK
RESEARCH

12 | 2025
special issue

Time and Temporality as Categories of Connectedness

CINDARELLA PETZ | ALINE DEICKE | JULIAN JAROSCH

C2DH
LUXEMBOURG CENTRE FOR
CONTEMPORARY AND DIGITAL HISTORY

uni.lu
UNIVERSITY OF
LUXEMBOURG

The Journal of HISTORICAL NETWORK RESEARCH

FLORIAN THIERY/ALLARD W. MEES

Dating Dated Sites: Using Correspondence Analysis to handle Chronologies as Graphs

Journal of Historical Network Research 12 (2025)

Keywords Semantic modeling, time modeling, Roman archaeology, terra sigillata, Academic Meta Tool

Abstract This article discusses digital methods to model and handle the ordering of so-called dated sites in archaeology. This findspot attribute is usually elaborated by indirect evidence based on the chronology of find materials, which are often based on material derived from other assumed dated sites, thus potentially resulting in a *circulus vitiosus*. To avoid self-fulfilling dating methods, comparative tools such as correspondence analysis or algorithms like Allen's interval algebra can be applied to stamped Roman terra sigillata (Samian) pottery vessels and their occurrences in Roman sites. The TiGeR method and the Alligator method demonstrate ways to establish and visualize the chronological order of dated sites. With the TiGeR method, a sequential order of chronologically sensitive material can be plotted on a map, where the coloring of the dots is realized by calculating hue color values from the normalized values of the first component of the correspondence analysis. The resulting maps and graphs chronologically display the historical conquering of the Roman provinces of Britannia and Germania. Based on Allen's interval algebra, the Alligator method is able to chronologically sort groups of dated sites, such as limes sections, when only a few chronological indications are known beforehand and other limes sections can only be judged by the overlap of material which they have in common. The Academic Meta Tool offers a decision procedure (reasoning) to calculate the chronological relative order of limes sections. This tool is also capable of visualizing the results as graph structures.

C²DH LUXEMBOURG CENTRE FOR CONTEMPORARY AND DIGITAL HISTORY

UNIVERSITY OF LUXEMBOURG

1. Introduction

Dated sites in archaeology are usually not *dated sites* in a strict sense. In the first century AD, for example, there were very few verifiable *absolute dated sites,* the best known of which are Pompei[1] and Inchtuthil[2], whose dates and locations are reliably indicated by ancient authors. The rest of the *dated sites* have less strictly defined time attributes. At times, the temporality of these *dated sites* can be set in relation to each other, e.g., if they belong to a group of sites within a newly occupied area, or if they are part of a string of military sites related to a military campaign, etc. This allows for comparisons between *dated sites,* especially when they have the same types of finds in common, in which a chronological development can be speculated. To this end, we can use Allen's interval algebra[3], such as *after*

Corresponding author: Florian Thiery, Leibniz-Zentrum für Archäologie (LEIZA). Department of Scientific IT, Digital Platforms and Tools. Mainz, Germany. florian.thiery@leiza.de
Acknowledgements: We would like to thank Sophie C. Schmidt for the reciprocal inspiration when integrating the Correspondence Analysis and the Alligator format into a reproducible R workflow (https://github.com/leiza-rse/alligator-ca). Timo Homburg codeveloped the SPARQL Unicorn Research Toolkit and Dirk Seidensticker was an inspiring sparring partner related to the relative time topic at CAA Tübingen 2018. He presented our first lecture on "RDF based modeling of relative and absolute chronological data: Examples from the central African rainforest and Roman periodisation" at the 24th Annual Meeting of the European Association of Archaeologists (EAA2018), Barcelona, Spain, 8th September 2018 (DOI: 10.5281/zenodo.1410516). This work is also integrated into the RDM-based NFDI4Objects initiative to demonstrate the potential of computational approaches in FAIR data modeling.
Data accessibility: Thiery, Florian and Mees, Allard W. (2025). Supplementary Materials to "Dating Dated Sites: Using Correspondence Analysis to handle Chronologies as Graphs" (leiza-scit/GrapHNR-2023-supplementary-material: v1.0). In Squirrel Papers (v1.0, Bd. 7, Nummer 2, S. λ2). Squirrel Papers, via Zenodo. https://doi.org/10.5281/zenodo.14906709.
Funding Information: This work, especially Alligator and TiGeR, was funded by the Leibniz-Zentrum für Archäologie (LEIZA) within the Dauerforschungsgebiet 1, related to the projects Dating Mechanisms, Semantic Modelling & Knowledge Graphs as well as NFDI4Objects (DFG project number 501836407). LEIZA is a foundation under public law of the State of Rhineland-Palatinate and the City of Mainz. LEIZA is a research museum of the Leibniz Association, funded publicly to equal parts by the federal government and the federal states (Bundesländer). The AMT was developed by the Mainz Centre for Digitality in the Humanities and Cultural Studies (mainzed), funded by the Hochschule Mainz University of Applied Sciences and the LEIZA (formerly RGZM).
Competing interests: The author(s) has/have no competing interests to declare.
Authors' contributions: According to the CreDIT (Contributor Roles Taxonomy) guidelines all authors have contributed equally to Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft and Writing – review & editing.

1 Pliny, *Letters,* book VI, pp. 16, 20, 425 ff.
2 Tacitus, *Agricola,* p. 13.
3 Allen 1983; Freksa 1991.

or *during,* to describe relative chronologies. However, most of the temporality of *dated sites* is usually derived from historical assumptions and interpolations. Furthermore, the chronology of these materials is often based on material derived from other assumed *dated sites,* thus potentially resulting in a *circulus vitiosus.* On top of this, *dated sites* frequently give dates like *from – to,* suggesting a date that is merely a probability. A methodological way out of this dilemma is possible when we enhance the assumed external dating evidence and go back to the factual occurrences and overlaps in the data from the suspected *dated sites,* since these are the only data that are free from temporal interpretations. This results in four different research questions that will be tackled in this paper:

1) How can any resulting time order of *dated sites* be comprehensively encoded and semantically modeled, e.g., using Allen's interval algebra and graph technologies[4,5]?
2) How can a reproducible algorithm deal with incomplete or vague dates to fix the missing start or endpoints by creating *virtual fuzzy and wobbly dates*? Are graph-based digital tools like Alligator or the Academic Meta Tool (AMT) usable for this purpose?
3) How can the results be visualized for researchers using graphs, timelines, or maps?
4) Do we need a different concept of temporalities for such *dated sites*?

1.1 Dated Sites in Archaeology – Do they exist?

In the first century AD, there were very few verifiable *absolute dated sites,* namely Pompei (Roman Italy) and Inchtuthil (Roman Scotland), whose dates were indicated by ancient authors. Most other sites have some implied temporal start or endpoint, and are usually only called *dated sites.* Overarching groups of *dated sites* can be placed relative to each other, e.g., if they belong to a group of sites that are part of a string of military sites related to a military campaign, e.g., AD 83–87 in Scotland, or when they have comparable find material in common, such as Roman terra sigillata (Samian) stamped by the same potter. At Inchtuthil, the coin series stopped in AD 87, and the ancient author Tacitus reported the military campaign in AD 83–87. The AD 79 catastrophe of Pompei was reported to the senate by the son of Plinius the Elder (who died there). Hadrian's Wall was built at some point (during the 3rd consulate?) after the start of his reign in AD 117. Hence, although there is only a vague possible starting date known during Hadrian's reign (after AD 122), we know neither the precise start date, nor the end date.

4 cf. https://www.w3.org/TR/owl-time/#topology and https://www.w3.org/2006/time
5 Shaw 2022.

Suggesting a reality which does not exist, potter dates are frequently given dates that are *from – to,* advocating a dating certainty that is in fact only a probability. However, most Roman first century AD *dated sites* are usually dated by Samian potters' stamps, which occur on other assumed *dated sites,* which are in turn dated by Samian potters' stamps, thus potentially resulting in a *circulus vitiosus.* A methodological way out of this dilemma is possible when we enhance the assumed external dating evidence and return to the factual occurrences and overlaps *in the data from the suspected dated sites, since only these data are free from any temporal interpretations.* In practice, South Gaulish potters' stamps occur in different military camps within different sections of the Roman Empire Limes, enabling a comparison between its different sections.

1.2 FAIRification using LOD to implement Open Science

Open Science is the key to creating comprehensible and reproducible research processes, including data and tools[6]. Making data FAIR[7] (Findable, Accessible, Interoperable, and Reproducible) and including this data FAIRification process[8] in the research process as part of the research data management (RDM) strategy helps to answer the following questions: (f) Where is the data? (a) How can I access the data? (i) How can I read and work with the data? (r) How can I reuse the data?

In Germany, the National Research Data Infrastructure (NFDI) is helping to establish sustainable structures. Four NFDI Humanities consortia (NFDI4Objects[9], NFDI4Culture, NFDI4Memory, and Text+) are working together to establish standards and RDM knowledge to lead the humanities and archaeology in something called Archaeology 4.0[10]. One standard that is being applied within the NFDI to model metadata is semantic modeling using the Resource Description Framework[11] (RDF). RDF's main concept is the modeling of triples, where a statement consists of two nodes and one semantic edge (a directed, colored graph) – so-called "subject-predicate-object" structures. These triples create a corrected and semantically aligned network, resulting in a huge graph. These nodes can be classes or derived individuals (instances), edge properties as object properties (nodes interlinked to nodes), or data properties (nodes interlinked to literals). The Linked Open Data (LOD) principles[12] interlink these RDF structures: (1) use URIs as names for things; (2) use HTTP URIs so that people can look

6 cf. FAIR and LOD: https://leiza-scit.github.io/GrapHNR-2023-supplementary-material/#fair-and-lod
7 Wilkinson 2016.
8 Thiery 2019.
9 Bibby et al. 2023; Thiery, Mees, et al. 2023; Bibby et al. 2021.
10 Thiery, Veller, et al. 2023; Thiery 2019.
11 cf. https://www.w3.org/TR/rdf11-primer/
12 Berners-Lee 2006.

up those names; (3) when someone looks up a URI, provide useful information, using the standards (RDF*, SPARQL); and (4) include links to other URIs. so that they can discover more things. LOD creates a growing Linked Open Data Cloud. To make LOD usable, the concept of LO(U)D was introduced by Robert Sanderson[13]. One implementation within the LOD community is the SPARQL Unicorn,[14] composed of the SPARQLing Unicorn QGIS Plugin[15] and the SPARQL Unicorn Ontology Documentation[16] tool.

Metadata is data about data, and is used to make data accessible and interoperable to enable subsequent use. Standards for interoperable metadata aim to make metadata from different sources usable. These comprise of semantics, the data model, syntax, and identification. Semantics describes the meaning, which is usually defined by standardization bodies. The data model defines the structure of the metadata. In the metadata context, data can be defined as statements about an object to be described. The model component of the term 'data model' can be understood as a description of how the statements are structured. The data model is represented by a syntax. To meaningfully process metadata from different sources, the semantics, data model, and syntax involved must be clearly identified. This requires an identification mechanism, such as that provided by URIs (Uniform Resource Identifiers). All four aspects – semantics, data model, syntax, and identification – must create standards for interoperable metadata. The commonly used framework for metadata within the NFDI is based on RDF. The individual layers can be assigned as follows: semantics (the use of ontologies as domain-specific semantics); data model (using RDF as a triple [subject, predicate, object]); syntax (the use of RDF [e.g., RDF/XML, JSON-LD, Turtle] to represent statements); and identification (using URIs as identifiers).

2. Materials and Methods

In terms of method, the chronological assumptions used to define *dated sites* based on archaeological find materials in the first century AD must be deconstructed and restricted to the occurrences and overlaps within and between find materials from suspected *dated sites,* in order to arrive at a relative chronology. This can be achieved by using correspondence analysis and visualizing the resulting dimension values on maps which are recalculated as Hue values. By applying the *Alligator Method,* including the Alligator and AMT tools, we are able to fix (or enhance) the missing existing start- or endpoints by adding information about the vagueness/uncertainties of the previous *from-to* information. The resulting

13 cf. https://linked.art/loud/
14 Thiery et al. 2020.
15 Thiery & Homburg 2024.
16 Homburg & Thiery 2024; Thiery & Homburg 2024; Thiery et al. 18. 03. 2024.

relative chronology can be transferred and refined using Allen's interval algebra and visualized in graph structures such as the Resource Description Framework (RDF). To cover as many assumed *dated sites* as possible, the Samian (Terra Sigillata) system is used, which is curated in the Open Data accessible research infrastructure Samian Research[17], comprising 250,000 potter's stamps from all over Europe. The paper is focused on data related to the historical southern German Limes developments and the enrollment of the Roman occupation of Britain in order to cross-check for statistically achieved relative chronologies.

The materials and methods section will introduce the fundamental research data (Section 2.1), the mathematical methods to achieve relative chronologies based on statistics using correspondence analysis (Section 2.2), Allen's interval algebra (Section 2.3), two methods to create relative chronologies, TiGeR (Section 2.4) and Alligator (Section 2.5), and the AMT framework to implement and apply temporal reasoning (Section 2.6).

2.1 Samian Research Database

The online relational database Samian Research comprises records and images of a quarter of a million finds of potters' stamps, which have been found throughout the Western Roman Empire. The resource is continuously curated by the European scientific community, supported by curating workshops throughout Europe, while the server is maintained at the LEIZA research institute in Mainz[18].

Although the resource is – apart from identifying potters' stamps – often used for research related to aspects of Roman economic history[19], the research scope is also extended to epigraphy and sociolinguistic features such as ethnicity[20]. The chronological aspects within the material (the appearance and disappearance of potters, new vessel forms) are used to study chronological changes within the distribution markets of (dated) sites, such as changes in buying/consumption patterns. Broken down into individual sites, the dating of individual potters' stamps can be used to display the overall dating of each site. The granularity of the material even allows researchers to glimpse the careers of specific individual potters[21].

Whereas the online editing masks enable direct, web-based curation of the data in a PostgreSQL database, the data themselves are accessible not only via a RESTfull API but also published as Linked Open Data. On top of this, the geo-

17 cf. https://www.rgzm.de/samian
18 cf. http://www.leiza.de
19 Flückiger 2022.
20 cf. https://latinnow.eu
21 Mees 2013.

referenced data is also being made accessible in Wikidata, enhanced with backlink functionality to also ensure the feedback of the Wikiversum community.

Whereas the classical *from – to* dating of individual potters is presented as legacy information, which lacks transparency on how this information was generated, a set of tools has been added to the web resource to allow for more transparency on how this legacy information might be judged.

2.2 Correspondence Analysis and the Horseshoe Paradigm

An example of how to interpret a matrix that can potentially be sorted chronologically may rely on data where the chronological order is already established. A good example is a matrix containing information about children's secondary dentition, in which the chronological sequence is secure. The ordering of units (classes) and variables (amount of milk teeth) within the first two dimensions of the correspondence analysis reflects the chronological order of children's secondary dentition (Fig. 1).

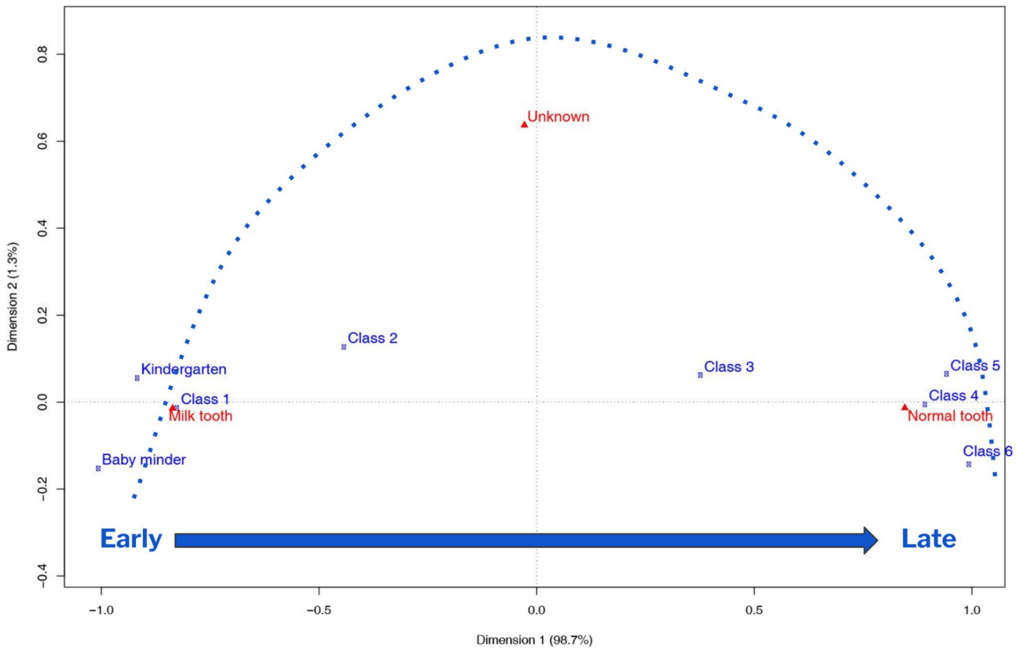
Following the horseshoe paradigm, a CA result may provide a measure of (possibly chronological) overlap[22]. However, it is important to note that a CA does not represent any pre-known dating information, and that conclusions concerning an assumed time order must stem from independent information. The horseshoe parabola can be flipped vertically or horizontally (Fig. 2).

2.3 Allen Interval Algebra

James Allen introduced a simple, transparent, and easy-to-implement temporal logic based on intervals and their qualitative relationships over time[23]. Allen's theory[24] consists of intervals corresponding to events, qualitative relations between these intervals, and an algebra for reasoning about the relations between intervals[25]. Allen created thirteen relations[26] between two events: before (<), after (>), during (d), contains (di), overlaps (o), overlapped-by (oi), meets (m), met-by (mi), starts (s), started-by (si), finishes (f), finished-by (fi), and equals (=)[27] (Fig. 3).

Allen proposes his thirteen relations between two events as the basis for a theoretical framework of temporal reasoning. However, by observing the real world,

22 Madsen 1988, p. 24.
23 Allen 1983.
24 also implemented in https://www.w3.org/TR/owl-time/
25 Freksa 1991, p. 1.
26 Freksa 1991, p. 5.
27 Thiery 2013, pp. 152–181.



Baby minder		**Milk tooth**	**100**
Baby minder		**Normal tooth**	**0**
Baby minder		Unknown	0
Kindergarten		**Milk tooth**	**94**
Kindergarten	T	**Normal tooth**	**3**
Kindergarten	I	Unknown	3
Class 1	M E	**Milk tooth**	**90**
Class 1		**Normal tooth**	**8**
Class 1		Unknown	2
Class 2		**Milk tooth**	**70**
Class 2		**Normal tooth**	**26**
Class 2		Unknown	4

Class 3		**Milk tooth**	**30**
Class 3		**Normal tooth**	**67**
Class 3		Unknown	3
Class 4		**Milk tooth**	**5**
Class 4		**Normal tooth**	**93**
Class 4	T I	Unknown	2
Class 5	M	**Milk tooth**	**2**
Class 5	E	**Normal tooth**	**95**
Class 5		Unknown	3
Class 6		**Milk tooth**	**1**
Class 6		**Normal tooth**	**96**
Class 6		Unknown	3

Fig. 1 Left: Temporal development of milk/normal teeth. The output of a CA of children's secondary dentition showing a horseshoe parabola. Right: Temporal development of milk/normal teeth. Graphics: Allard W. Mees, CC BY 4.0

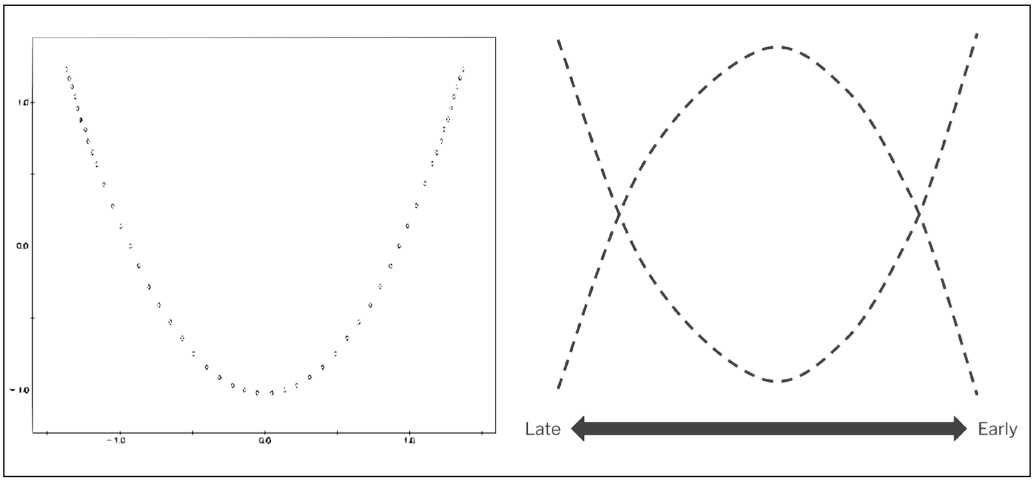


Fig. 2 Horseshoe paradigm, after Madsen (1988, fig. 11). Graphic: Allard W. Mees/Florian Thiery, CC BY 4.0

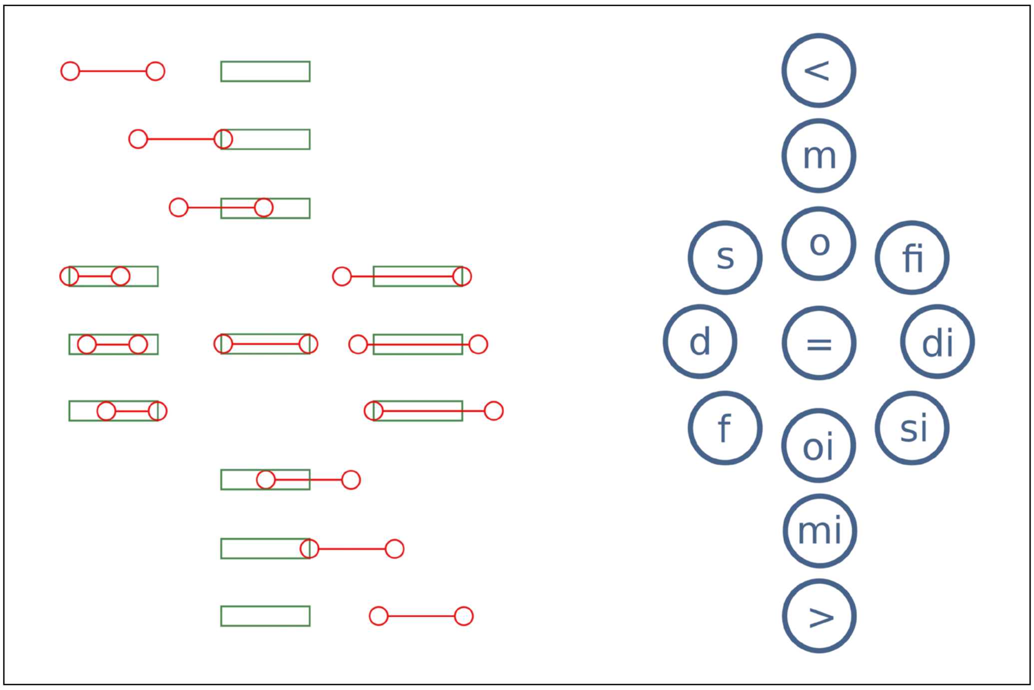


Fig. 3 Left: Temporal relations according to Allen's interval algebra between two events (red: event A, green: event B; e.g., event A < (= before) event B) arranged according to their conceptual neighborhood. Right: The corresponding labels are arranged accordingly. After Freksa (1992, S. 14), Fig. 3 (Thiery 2013, fig. 3). Graphic: Florian Thiery CC BY 4.0, via Wikimedia Commons

sometimes only partial knowledge about the events is available, and uncertainty is present[28]. This can only be modeled by using relative relationships instead of absolute dating. The transformation of Allen's algebra to triple-structures offers the possibility of relative dating and temporal reasoning using Linked (Open Data) in the Semantic Web data cloud.

For example, Freksa describes how to determine that Newton lived before Einstein. Knowing that Newton's death occurred before Einstein's birth is sufficient; it does not help if we also know when Newton was born or when Einstein died. In this case, we only know that X was born before Y's death and X died after Y, but we do not know who was born first[29]. Using Allen's algebra, we can model this as follows:

> "X was born before Y's death" can be expressed as "X lived before Y or X' life meets Y's life or X' life overlaps Y's life or X' life is finished by Y's life or X' life contains Y's life or X' life is started by Y's life or X' life equals Y's life or X' life starts Y's life or X lived during Y's life or X finishes Y's life or X' life is overlapped by Y's life", and "X died after Y" can be expressed as "X' life contains Y's life or X' life is started by Y's life or X' life is overlapped by Y's life or X' life is started by Y's life or X lived after Y". The inference step then consists of forming the conjunction of the two sets of disjunctions: "X' life contains Y's life or X' life is started by Y's life or X' life is overlapped by Y's life" which is equivalent to the conclusion derived above.[30]"

Freksa calls the beginnings and endings of events 'semi-intervals' (equivalent to what Allen and Hayes call nests[31]). One example could be if

> "X is older (ol) than Y when the beginning of X is less than the beginning of Y. X is head to head (hh) with Y when their beginnings are equal and X is younger (yo) than Y when the beginning of X is greater than the beginning of Y[32]".

All of these considerations are the basis for neighborhood-based reasoning, as Freksa calls it. An easy example using the thirteen Allen relation could be reasoning of Limes sections. If Hadrian's Wall *during* Wetteraulimes, which is *after* Elisabethenstraße, this results in Hadrian's Wall being *after* Elisabethenstraße. If Elisabethenstrasse is *before* Wetteraulimes, which *contains* Hadrian's Wall, this results in Elisabethenstrasse being before Hadrian's Wall. This reading can also be extended to Freksa's semi-intervals:

28 Freksa 1992, p. 7.
29 Freksa 1992, p. 7.
30 Freksa 1992, p. 7–8.
31 Allen & Hayes 1985.
32 Freksa 1992, p. 11.

> "For example, if we know that X is an older contemporary of (oc) Y and Y is a younger contemporary of (yc) Z, we can infer that X is a contemporary of (ct) Z or if instead Y is head to head with (hh) Z then X is also an older contemporary of (oc) Z.[33]".

A combined example is shown in Fig. 4[34]. Here, four Limes sections are in a relative chronological relationship: Although the Elisabethenstraße can be considered as the predecessor of the Wetteraulimes, it is unlikely that this area was left completely empty after the military left the Elisabethenstraße and started constructing the Wetteraulimes, since both structures were built in a hostile environment. Therefore, one can assume a short temporal overlapping by (oi) parts of the Wetteraulimes, which were also temporally overlapped by (oi) modifications of the Taunus Limes. These in turn temporarily overlap (o) with parts of the Raethian Limes. Thus, temporal reasoning and the concepts of Allen and Freksa may help to identify the temporal relation between the Limes parts of the Elisabethenstraße and the Raethian Limes. Looking into the reasoning rules[35], the combined result is that Elisabethenstraße *ended before the creation of* (db) the Raethian Limes, which is historically valid. Here, the db semi-interval includes the Allen relations o, fi, di, si, =, s, d, f, oi, mi and >[36]. However, this statement also includes a number of questionable reasoning results.

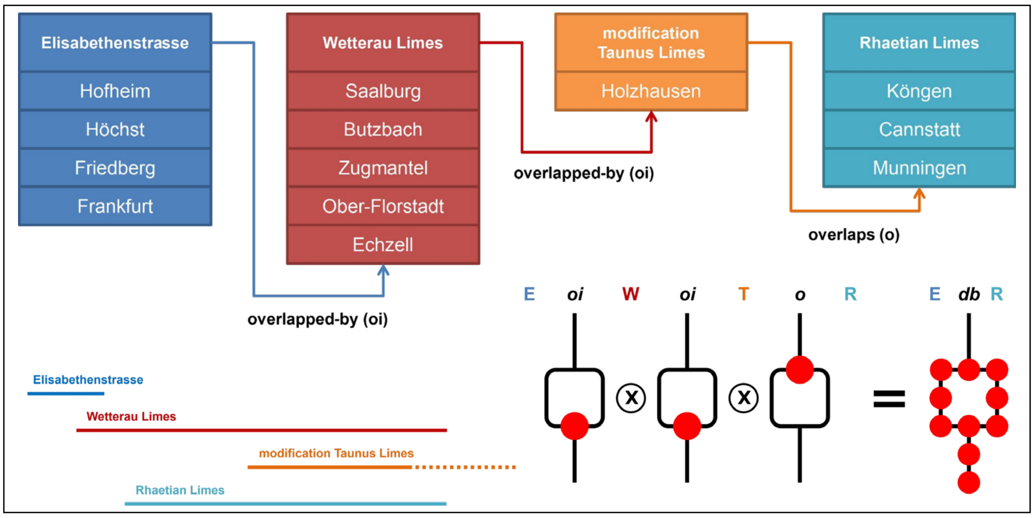


Fig. 4 Example of temporal reasoning using four Limes sections. Graphic: Florian Thiery, CC BY 4.0

33 Freksa 1992, p. 25.
34 cf. https://doi.org/10.5281/zenodo.292957
35 Freksa 1992, p. 29.
36 Freksa 1992, fig. 7.

2.4 TiGeR Method

The TiGeR (Time Geospatial RDF) method is based on the results of the correspondence analysis (Section 2.2). It uses the normalized first CA dimension, which it then converts into gradient colors using a JavaScript library called rainbow.js[37]. For this paper, the colors #00fffb and #310769 were used for the gradient. The TiGeR method provides Python scripts[38] as well as an ontology to represent and FAIRify the results as RDF and LOD[39]. The TiGeR vocabulary[40] (current Stegosaurus Edition from July 2023) consists of one class (TiGeR_Event) and five properties (eventname, cax, cay, cax_norm, cax_hex), which are combined into an ontology[41] as part of the Linked Archaeological Ontology[42] (LADO), provided by the archaeology.link[43] data hub. Examples of the TiGeR method and the resulting LOD are shown in Section 3.1.

2.5 Alligator Method

The *Alligator Method* was introduced at EAA Barcelona[44] and applied to examples from the central African rainforest and Roman periodization. The aim of using the Alligator Method is to create a reproducible RDF representation of the state of knowledge concerning the temporal sequences of time intervals based on correspondence analysis. It converts the results of a CA (Section 2.2) into a relative chronology following Allen's interval algebra (Section 2.3), and enables temporal reasoning (Section 2.6) and visualization in graphs or timelines, as well as the ability to export in standards such as RDF.

The Alligator Method[45] can be divided into several steps (A to J). An AGT-file[46] (Step A) is the initial information document comprising the name, XYZ-coordinates, start/end dates (if available), and any uncertainty concerning 'fixed' absolute dates and 'floating' endings. This file is generated from the correspondence analysis output in which the quantitative relations of the Euclidean distances between finds and proposed time intervals are calculated. Following the *horseshoe paradigm,* the CA result may provide a measure of (possibly chronological) overlap between the Limes intervals. It is important to note that a CA does not comprise any pre-known dating information. Therefore, the AGT file is

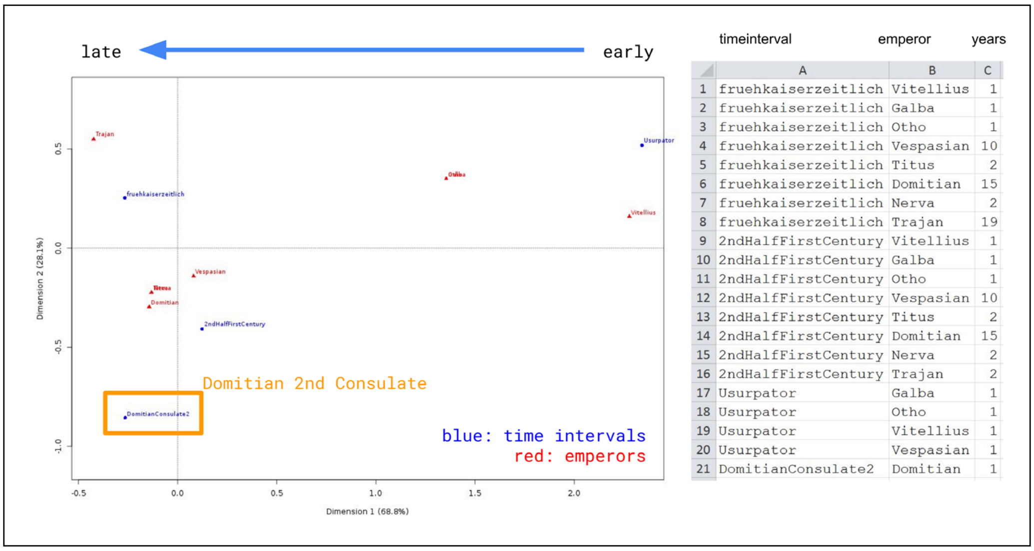
37 cf. https://craig.is/making/rainbows
38 Thiery & Mees 2024 (TiGeR).
39 cf. https://github.com/leiza-rse/tiger
40 cf. https://leiza-rse.github.io/tiger/vocab/
41 cf. https://github.com/leiza-rse/tiger/blob/main/ontology/TiGeR.ttl
42 Thiery 2022.
43 cf. https://archaeology.link/
44 Seidensticker et al. 2018.
45 Thiery and Mees 2023.
46 cf. https://leiza-rse.github.io/alligator-format/

enhanced with dating metadata (start and end dates, uncertainty information). The *Alligator Algorithm* starts with 3D distance calculations (Step B) using the coordinates of the first 3 CA dimensions. It then calculates the un-dated wobbly floating periods by finding the next 3D CA neighbor (Step C). Following this, the new virtual time intervals are calculated, and the resulting *virtual fuzzy years* (Step D) – which are virtually generated absolute dates – are transformed by simple mathematical calculations[47] into a relative chronology of *virtual fuzzy temporal intervals* (containing virtual from-to dates), based on Allen's interval algebra. For example, six *virtual fuzzy temporal intervals* of Roman emperors – four of them during the Year of the Four Emperors[48] (*YOFE*) AD 69 – can be transformed from virtual absolute dates to a relative chronology: *Nero* (AD 54–68) *Galba* (AD 68–69), *Otho* (AD 69), *Vitellius* (AD 69), *Vespasian* (AD 69–79), and *Titus* (AD 79–81), *YOFE* (AD 69). Allen's interval algebra places Nero *before* Galba, Titus *after* Vespasian, Galba *during* YOFE, and Vespasian *during* YOFE, with the result that Nero *meets* YOFE and Titus is *met by* YOFE. Any resulting relative *virtual fuzzy temporal interval* is then transformed and stored in the RDF format[49], along with all the initial and calculated results, as well as the Allen intervals (Step E). The transformation between Step D and E is also performed by an algorithm[50]. This is the basis for visualization, e.g., as a graph or a timeline (Step F). Each relation contains a degree of connection (also called weight in the range of 0 to 1) that is based on the rules of vagueness. In the case of the AMT approach, we have to transform the intervals into the AMT format and include the degree of connection, e.g., a (normalized) Pearson correlation coefficient (Step G). This RDF file (Step H) then serves as input for the AMT. With AMT, temporal reasoning (Step I) according to the specific ontology can be calculated, before being exported and visualized (Step J).

A fictive example of Roman emperors serves as a methodological test[51]. The input data for the correspondence analysis includes information on time intervals, emperors, and reign years (Fig. 5).

On top of this, each emperor has a start and end year (e.g., Traian: AD 98–117); most – but not all – time intervals have a start and end year (e.g., second half first century: AD 50–100); some intervals have unknown floating start and/or end years (e.g., the unknown time period of the fictive second Domitian consulate); the horizontal CA dimension axis defines the amount of overlap between

47 c.f. https://github.com/leiza-rse/alligator/blob/master/src/main/java/de/rgzm/alligator/allen/AllenInttervalAlgebra.java; function getAllenRelationSigns()
48 Tacitus, *Histories,* book I–III, 3 ff.
49 c.f. https://leiza-rse.github.io/alligator/vocab/
50 c.f. https://github.com/leiza-rse/alligator/blob/master/src/main/java/de/rgzm/alligator/functions/RDFEvents.java
51 cf. https://github.com/RGZM/alligator-mt-data/tree/master/v1



	A	B	C
1	fruehkaiserzeitlich	Vitellius	1
2	fruehkaiserzeitlich	Galba	1
3	fruehkaiserzeitlich	Otho	1
4	fruehkaiserzeitlich	Vespasian	10
5	fruehkaiserzeitlich	Titus	2
6	fruehkaiserzeitlich	Domitian	15
7	fruehkaiserzeitlich	Nerva	2
8	fruehkaiserzeitlich	Trajan	19
9	2ndHalfFirstCentury	Vitellius	1
10	2ndHalfFirstCentury	Galba	1
11	2ndHalfFirstCentury	Otho	1
12	2ndHalfFirstCentury	Vespasian	10
13	2ndHalfFirstCentury	Titus	2
14	2ndHalfFirstCentury	Domitian	15
15	2ndHalfFirstCentury	Nerva	2
16	2ndHalfFirstCentury	Trajan	2
17	Usurpator	Galba	1
18	Usurpator	Otho	1
19	Usurpator	Vitellius	1
20	Usurpator	Vespasian	1
21	DomitianConsulate2	Domitian	1

Fig. 5 Alligator method test of *Roman emperors*, correspondence analysis. Graphic: Florian Thiery/Allard W. Mees, CC BY 4.0

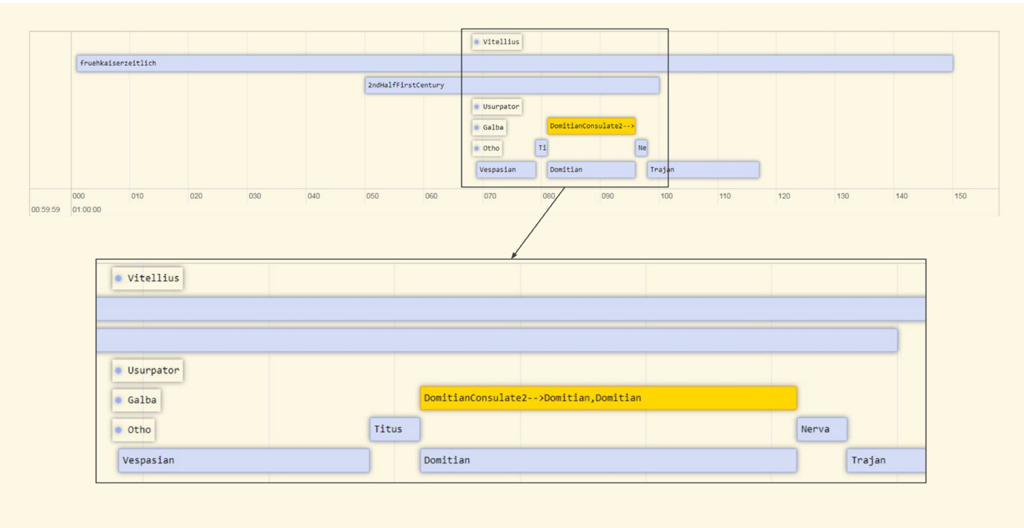


Fig. 6 Alligator method test of *Roman emperors*, result as a virtual timeline. Graphic: Florian Thiery/Allard W. Mees, CC BY 4.0

		1	2	3	4	5	6	7	8	9	10	11	12
1	fruehkaiserzeitlich	e	di				di	di	di	di	di		di
2	2ndHalfFirstCentury	d	e				di	di	di	di	o		di
3	Usurpator			e	e	e						e	
4	Galba			e	e	e						e	
5	Otho			e	e	e						e	
6	Vespasian	d	d				e	m	b	b	b		b
7	Titus	d	d				mi	e	m	b	b		m
8	Domitian	d	d				a	mi	e	m	b		e
9	Nerva	d	d				a	a	mi	e	m		mi
10	Trajan	d	oi				a	a	a	mi	e		a
11	Vitellius			e	e	e						e	
12	DomitianConsulate2	d	d				a	mi	e	m	b		e

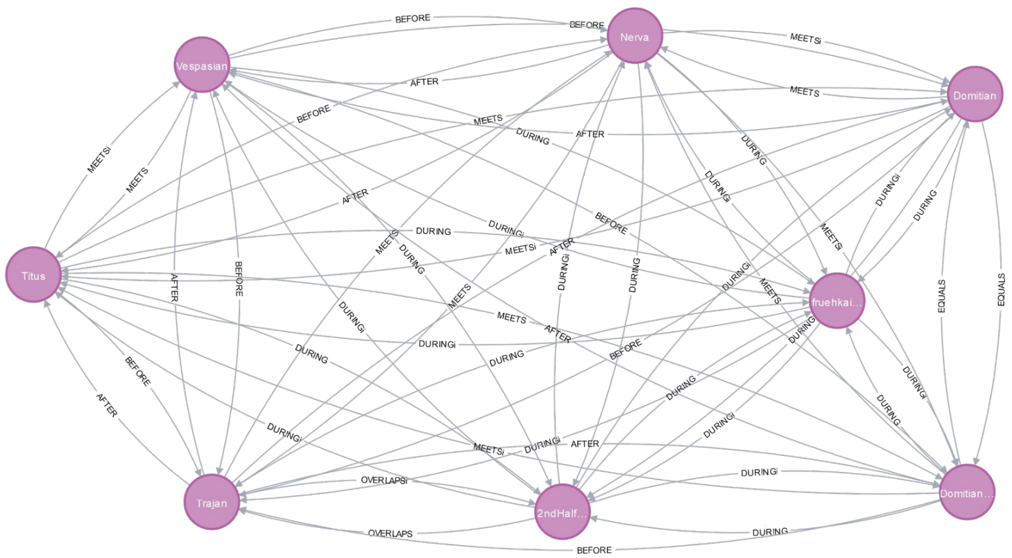


Fig. 7 Alligator method test of *Roman emperors,* result as a relative chronology. Graphic: Florian Thiery/Allard W. Mees, CC BY 4.0

the time intervals. The aim is to date *Domitian Consulate2*[52] and get the *virtual fuzzy start and end years.* After performing the *Alligator Algorithm,* the fictitious *Domitian Consulate2* period is dated to AD 81–96, with *Domitian* as the nearest neighbor for the start and end dates (Fig. 6).

The *Domitian Consulate2* period is also related as equal to *Domitian* when using Allen's interval algebra (Fig. 7).

The *Alligator – Allen Transformer*[53] is available as both a web tool[54] and an API[55] based on a JAVA application[56]. An ontology was created to represent and FAIRify the results as RDF and LOD. The current Alligator vocabulary[57] (current Triceratops Edition from March 2024) consists of one class (Alligator_Event), twelve properties (eventname, estimatedstart, estimatedend, cax, cay, caz, startfixed, endfixed, nfsn, nfen, nfsnE, nfenE) and the Allen interval algebra properties from OWL-Time[58] (such as time:intervalBefore), which are combined into an ontology[59] as part of the Linked Archaeological Ontology (LADO), Examples of the Alligator method and the resulting LOD are shown in Section 3.2.

2.6 Academic Meta Tool

The Academic Meta Tool[60] (AMT) provides a framework consisting of a meta-ontology and a web tool (including JavaScript reasoning) to model vagueness in RDF data and perform reasoning. The meta-ontology compromises an ontology[61] (data model) and a vocabulary[62] (specific classes and properties). The main entities are amt:Concept and amt:Role, as well as axioms (amt:Axiom) such as amt:RoleChainAxoim, amt:InverseAxiom, amt:DisjointAxiom and amt:SelfDisjointAxoim. The vagueness is represented by a *degree of connection* (amt:weight) within a range of [0;1]. The RDF triple is extended to a quadruple, starting with a blank node, and has four edges: two for concepts (rdf:subject, rdf:object), one for a role (rdf:predicate), and one for the weight. The role-chain-axiom in partic-

52 cf. https://github.com/leiza-rse/alligator-format/blob/main/example/example_romanempire.agt
53 Thiery & Mees 2024 (Alligator).
54 cf. https://tools.leiza.de/alligator/
55 cf. https://api.leiza.de/alligator/
56 cf. https://github.com/leiza-rse/alligator
57 cf. https://leiza-rse.github.io/alligator/vocab/
58 cf. https://www.w3.org/2006/time
59 cf. https://github.com/leiza-rse/alligator/blob/master/ontology/alligator.ttl
60 Unold et al. 2019.
61 cf. http://academic-meta-tool.xyz/ontology/ and https://zenodo.org/doi/10.5281/zenodo.1157985
62 cf. http://academic-meta-tool.xyz/vocab/

ular needs several logics to perform the reasoning; here, three logics[63] are implemented: amt:ProductLogic ($r = p*q$), amt:LukasiewiczLogic ($r = min(p,q)$) and amt:GoedelLogic ($r = max(p + q – 1.0)$). Each application of the AMT needs its own domain-specific ontology. For temporal reasoning with Allen's interval algebra (Section 2.3), the Allen relations can be modeled as role-chain-axiom (RCA) using the product logic[64]:

- ex:RCA rdf:type amt:RoleChainAxiom .
- ex:RCA amt:antecedent1 ex:during .
- ex:RCA amt:antecedent2 ex:after .
- ex:RCA amt:consequent ex:after .
- ex:RCA amt:logic amt:ProductLogic .

Following the example in Section 2.3, the three Limes parts are amt:Concepts (Hadrian's Wall, Wetteraulimes, Elisabethenstraße), which are connected by relative chronological properties and a degree of connection (w) of p/q=0.9. Following the RCA and the product logic, which results in: (HW)-[ex:during;p=0.9]-(WL)-[ex:after;q=0.9]-(ES) ⇒ (HW)-[w=0.81]-(ES).

3. Results

Using the materials and methods described previously (Section 2), we will showcase that it is possible to visualize historical development on maps, timelines, and graph structures without using historical assumptions about individual *dated sites*. Simultaneously, this section demonstrates that dating individual sites with the help of Samian cannot give the precise datings that are usually expected in archaeology, instead requiring the application of a different concept of temporality. The development of Samian consumption patterns in the progressing Southern German Limes and the enrollment of the occupation of Britain appear to be gradual. Hence, the precise dating ability of the find category Samian has been overcharged ever since the beginning of Samian studies in the 19th century. Applying the aforementioned methods, based on semantic modeling and W3C standards such as RDF and inspired by LOD techniques, enables the FAIRification of these data related to temporality, especially by creating interoperability and reproducibility.

We will demonstrate our results in two use cases by using the Samian Research database as data fundament (Section 2.1), the correspondence analysis as mathematical and methodological bases (Section 2.2), and Allen's interval algebra as

63 cf. https://www.adwmainz.de/fileadmin/user_upload/digitale-akademie/graphentechnologien/Bruhn-Unold-Unsicherheit_Graphdatenbanken.pdf
64 cf. https://github.com/RGZM/amt-caauk2018/blob/master/ontology/ontology.ttl

overall paradigm (Section 2.3): (1) correspondence analysis to colorful maps & RDF graphs by applying TiGeR (Section 3.1), and (2) correspondence analysis to a virtual timeline & RDF graphs by applying the Alligator Method and the Academic Meta Tool (Section 3.2).

3.1 Use Case 1: CA to colorful maps & RDF graphs

Multivariate analyses, in this case correspondence analysis (CA), have become a standard exploratory tool for analyzing and interpreting variance in different archaeological assemblages, such as assumed *dated sites*[65]. With a spatial visualization of the CA results, the results of the analyses can be interpreted considerably more intuitively[66]. The method works by transforming the resultant bi-plots of the CA into colored dots on maps using the Hue color model, in which the similarities and differences between assemblages directly corresponds to the difference in colors used to display them on a map.

3.1.1 *Province Britannia*

The Roman conquest of Britannia began in AD 43 and was largely completed by AD 122, when the defensive Hadrian's Wall was established. This was also the period when the large Samian production center of La Graufesenque flooded the markets of the Northwestern Roman Empire with name-marked *terra sigillata.* This chronologically sensitive material (as new potters and potforms appeared and disappeared over time), combined with the geographical limitations of the British island that caused the Roman conquest to create *dated sites* from the South to the North, forms an ideal testbed to test this material in terms of its ability to demonstrate chronological developments in a spatial context.

A CA of all the British sites which were founded during the ongoing conquest, as well as the terra sigillata found at these *dated sites,* displays a horseshoe shaped sequence within the first CA dimension, which can be interpreted as a chronological order[67] (Fig. 8).

The visualization of the normalized values of the first CA dimension (represented by the color blue) makes it easier to interpret the results, whereby the earliest foundations of the Roman conquest are displayed as light blue dots, while the latest Roman sites are visualized as dark blue dots.

The first dimension of the CA analysis enables us to define temporal neighbors (earlier than; later than etc.), which can also be visualized (Fig. 9).

---

65 Mees 2013.
66 Sterry 2018.
67 Mees 2013.

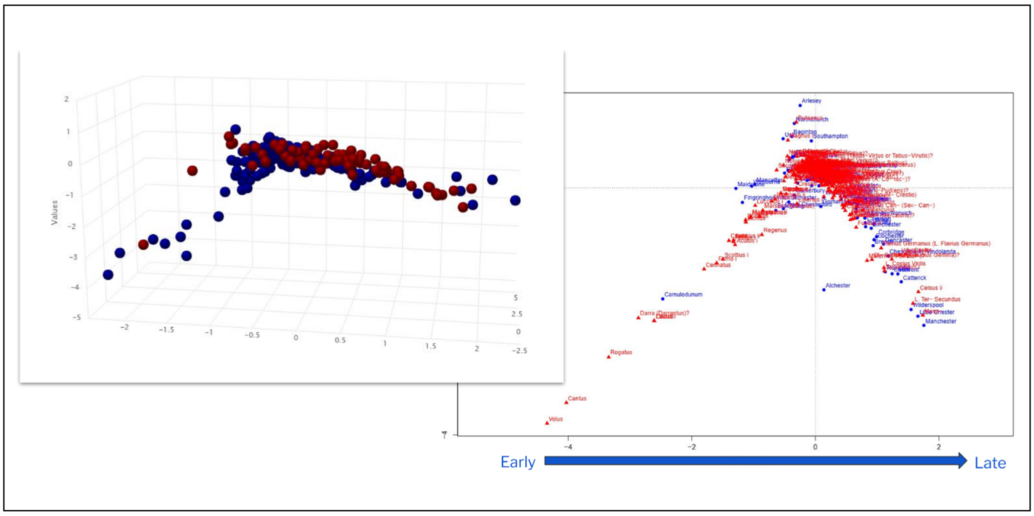


Fig. 8 *Dated sites* in Britannia in a CA. Graphic: Allard W. Mees, CC BY 4.0

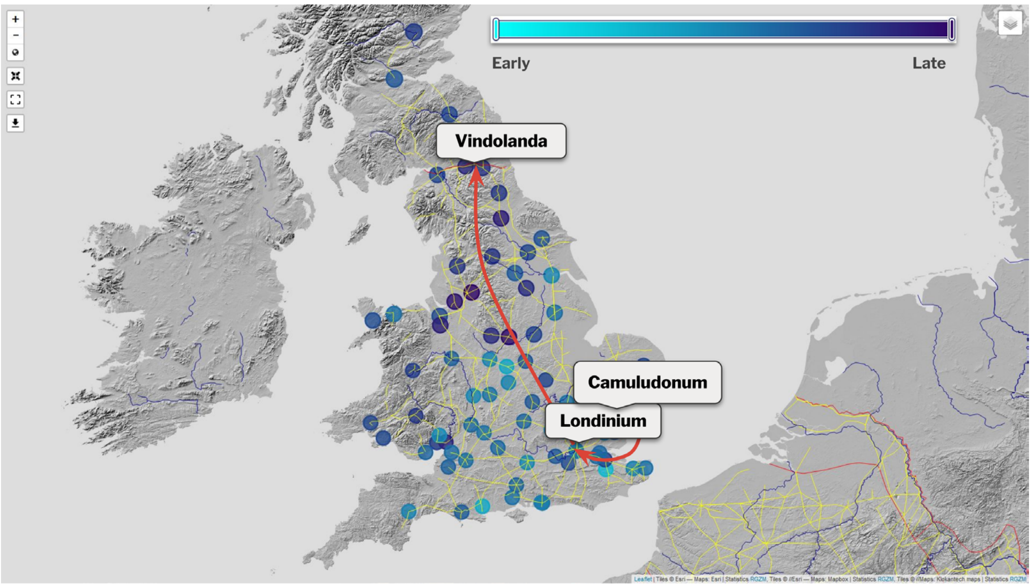


Fig. 9 Londinium and its temporal neighbors on a map. Graphic: Florian Thiery/Allard Mees, CC BY 4.0

3.1.2 *Germania Inferior, Germania Superior and Raetia*

The geographical constraints that the Romans encountered in Britannia featured less when conquering the Rhine provinces of Germania Inferior, Germania Superior and the adjacent province of Raetia. However, a CA of the *dated sites* which were involved in the occupational process and the terra sigillata found at these locations also display an identical pattern, which can be interpreted as going from 'early' to 'late'. When visualized on a map, it is easy to conclude that the earliest occupation (light blue dots) began e.g., with the military camp of Velsen, while the last military strongholds (dark blue dots) were established at the Wetterau Limes north of Frankfurt. As in Britannia, temporal neighbors can be visualized on a map.

3.1.3 *Creating RDF and LOUD with TiGeR*

Using the TiGeR ontology[68,69], the CSV results demonstrated in Sections 3.1.1 and 3.1.2 are FAIRified using RDF and Linked Open Data. Instances of the lado:TiGeR_Event class are described with specific properties: (a) for the correspondence analysis result lado:tiger_cax, lado:tiger_cay, lado:tiger_cax_norm (normalized x-axis) and lado:tiger_cax_hex (hex color value for the x-axis); (b) for the spatial appearance geosparql:hasGeometry and geosparql:asWKT using the GeoSPARQL[70] vocabulary; and (c) for the temporal modeling time:intervalBefore from the OWL Time[71] ontology. For the LODification, Python scripts[72] were used to transform the pipe-separated CSVs into RDF.

Fig. 9 shows the situation related to the site *Londinium* (discovery site id = 1000136) from Linked Open Samian Ware. Its temporal neighbors can be modeled as LOD, resulting in RDF. The LOD is FAIRified by utilizing the process metadata (using the PROV-O[73] ontology), and standardized vocabularies such as GeoSPARQL (for spatial entities) and OWL Time (for temporal entities). *Londinium* – POINT(−0.0918 51.5128) – can be described by the CA x-axis value −0.0207, y-value 0.1535, normalized x-value 0.5794, and the resulting color #1597be. *Londinium* is part of an interval-before chain: *Camulodunum*[74] is before *Londinium,* which is before *Vindolanda*[75].

68 Thiery & Mees 2024 (TiGeR).
69 cf. https://github.com/leiza-rse/tiger/blob/main/ontology/TiGeR.ttl
70 Car & Homburg 2022; Jovanovik et al. 2021.
71 cf. https://www.w3.org/TR/owl-time/
72 cf. https://github.com/leiza-rse/tiger/tree/main/py
73 cf. https://www.w3.org/TR/prov-o/
74 samian:loc_ds_1001570, POINT(0.9000 51.8833)
75 samian:loc_ds_1003470, POINT(−2.3595 54.9916)

Another example is the Saalburg site (discovery site id = 1000737[76]). In this case, Saalburg – POINT(8.5667 50.2715) – is described by the CA x-axis value –1.5541, y-value 0.0468, normalized x-value 0.0821, and the resulting color #2d1b75. Saalburg is also part of an interval-before chain, as is Londinium: Günzburg[77] is before Saalburg, which is before Bad Cannstatt[78].

Research software like the SPARQL Unicorn can make Linked Open Data usable (LOUD). The SPARQL Unicorn Ontology Documentation[79] tool creates HTML pages, e.g., by using GitHub actions, like the resulting TiGeR event feature collection[80]. LO(U)D individual TiGeR events like *Londinium* or Saalburg are machine and human-readable on an HTML page.

The TiGeR events are also part of the Linked Open Data Cloud and the Archaeological Knowledge Graph. *Londinium* is included in Wikidata.[81]

3.2 Use Case 2: CA to a virtual timeline & RDF graphs

Although individual analyses of the occurrences of terra sigillata within *dated sites* already provide a temporal order based on a mutual alternation of potters and findspots, this process can be honed if one aggregates these *dated sites* into, where available, ancient organizational units such as Limes sections.

3.2.1 *Limes Sections*

Many of the assumed *dated sites* belonged to Limes sections, which are thought to have been conceived and constructed as huge defensive structures, each comprising a series of military camps.

Within the first 3 dimensions of a CA result, each Limes section is located with its Euclidean CA distance (x,y,z). Similar to emperor reign years (Fig. 5), these coordinates are stored together with an indication of whether the time interval of a Limes section has a floating and/or fixed start or end time in a starting table.

76 cf. http://data.archaeology.link/data/samian/loc_ds_1000737
77 samian:loc_ds_1001327, POINT(10.2667 48.4500)
78 samian:loc_ds_1000346, POINT(9.2145 48.8048)
79 Homburg & Thiery 2024.
80 cf. https://leiza-rse.github.io/tiger/TiGeR_Event_collection/index.html
81 Q103177460: London (Samian Ware Discovery Site); Q927198: *Londinium;* also *Camulodunum* (Q630604: *Camulodunum,* Q103159803: Colchester (Samian Ware Discovery Site), Q103135744: Colchester (Samian Ware Production Centre)) and Saalburg (Q103192439: Saalburg (Samian Ware Discovery Site), Q542329: Saalburg Roman Fort/castrum).

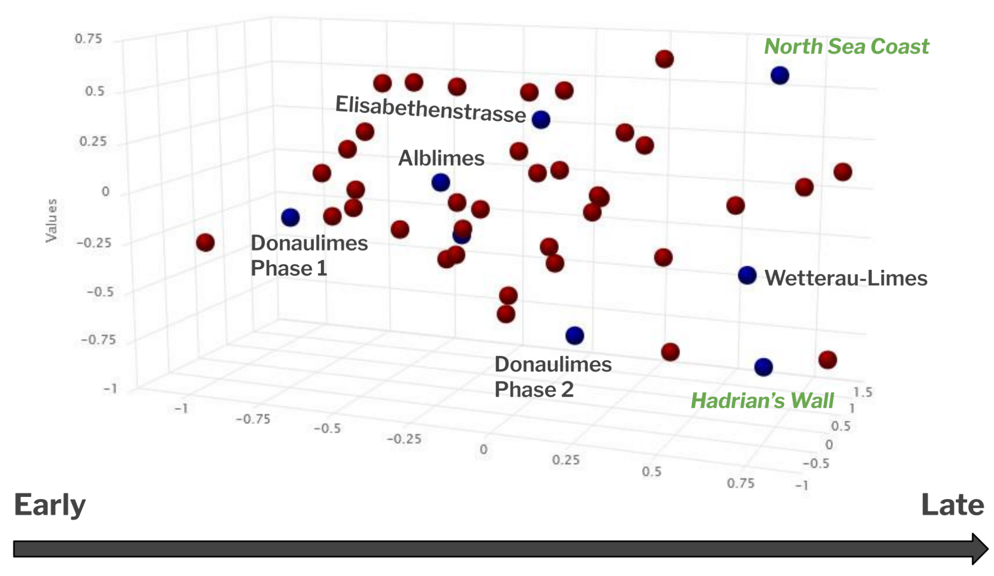


Fig. 10 CA Result. Graphic: Florian Thiery/Allard W. Mees, CC BY 4.0

Based on the terra sigillata found on these sites, the Alligator method calculates vague floating intervals for the Limes sections of Hadrian's Wall and the North Sea Coast, hence fixing the missing start and end dates. The process of finding nearest neighbors suggests a starting date for Hadrian's Wall similar to Wetterau Limes. The calculated virtual fuzzy years seem to confirm the hypothesis that Hadrian's Wall, the North Sea Coast foundations, and the Wetterau Limes were founded in the same decades. Based on very similar Samian consumption profiles, Hadrian's Wall, the North Sea Coast and the Wetterau-Limes are all located on the right (interpretable as 'late') side of the first CA dimension (Fig. 10).

The Estimated Allen's Interval Algebra and Potter's overlap of the Limes parts can also be described with the (normalized) Pearson correlation coefficient, allowing for further reasoning (cf. Section 3.2.3).

3.2.2 *Creating RDF and LOUD with Alligator*

The Alligator Ontology[82] can transform the Alligator Method results (Section 3.2.1) into RDF by using the Alligator web tool[83] and API[84]. Instances of the *lado:Alligator_Event* class are described with specific properties: (a) for the correspondence analysis result *lado:cax, lado:cay, lado:caz;* (b) for the virtual fuzzy years *lado:estimatedstart, lado:estimatedend;* and (c) for the Alligator method result *lado:startfixed* (boolean), *lado:endfixed* (boolean), *lado:nfsn* / *lado:nfsnE* (next fixed start neighbor event), *lado:nfen* / *lado:nfenE* (next fixed end neighbor event).

The RDF example of Hadrian's Wall is based on a correspondence analysis of the overlap of Terra Sigillata finds from Hadrian's Wall and the continental Limes sections. The Alligator Limes event (id = Ye7K01) correspondence analysis results in the following 3D-coordinates: *lado:cax* '0.786', *lado:cay* '–0.558', and *lado:caz* '–0.915'. The start and end dating was floating: *lado:startfixed* 'false' and *lado:endfixed* 'false'. The Alligator Algorithm calculated an estimated virtual start and end dating *lado:estimatedstart* of '110 AD' and *lado:estimatedend* '260 AD' by using the next fixed neighbors *lado:nfsn* 'Wetteraulimes' and *lado:nfen* 'Wetteraulimes' (id = Me2Pl1). The *NoordzeeKust* (North Sea coast; id = zGVB42) gets an estimated end date *lado:estimatedend* of '260 AD' by using the CA values of *lado:cax* '0.625', *lado:cay* '0.561', *lado:caz* '1.304' and the next fixed end neighbor *lado:nfen* 'Wetteraulimes'.

After fixing the missing datings, the Hadrian's Wall and *NoordzeeKust* Limes sections can be integrated into a relative chronological network, modeled with Allen's interval algebra. The Hadrian's Wall Limes section is *time:intervalEquals* 'Wetteraulimes' and *time:intervalFinishedBy* 'NoordzeeKust' and 'Neckarlimes'. It is also temporally related to other Limes sections: 'AlbLimes' and 'DonauLimesPhase2' are *time:intervalFinishedBy* 'Hadrian's Wall', while 'DonauLimesPhase1' and 'Elisabethenstrasse' are *time:intervalBefore* 'Hadrian's Wall'. The *NoordzeeKust* Limes section is *time:intervalFinishes* 'Wetteraulimes' and, e.g., 'DonauLimesPhase1' and 'Elisabethenstrasse' are *time:intervalBefore NoordzeeKust*.

The SPARQL Unicorn can make this result LOUD. The two fixed Limes Sections (Hadrian's Wall[85], *NoordzeeKust*) can be represented as an HTML page, showing the *Alligator Method* results.

---

82 Thiery & Mees 2024 (Alligator); cf. https://github.com/leiza-rse/alligator/blob/master/ontology/alligator.ttl
83 cf. https://tools.leiza.de/alligator/
84 cf. https://api.leiza.de/alligator/ and https://github.com/leiza-rse/alligator
85 cf. https://leiza-scit.github.io/grapHNR23/Ye7K01/index.html

3.2.3 *Applying Temporal Reasoning with AMT*

The *Alligator Method* is able to perform temporal reasoning according to Allen's interval algebra in steps G–J. To do this, the Academic Meta Tool (Section 2.6) and a domain-specific time ontology can be used. AMT needs a degree of connection on the edges, although we can just use 1.0 if we assume that the statement made is valid with a probability of 100 %. If we are not 100 % sure, we could use statements, as Nation did[86]. This could include statements like 'Almost Certainly' with a median reliability of ~95 % and mean of ~93 %, or 'Highly Likely' with a median reliability of ~90 % and mean of ~86 %. Fortunately, the Samian Research Database and archaeological research are able to model a degree of connection (*amt:weight*) in a more statistical and comprehensible way: the estimated potter's overlap of the Limes parts can be described with the (normalized) Pearson correlation coefficient[87].

The AMT application ontology[88] can be modeled very easily (Fig. 11 A): Limes Parts (*ex:LimesPart*) as *amt:Concept* and the Allen/Freksa temporal relations as *amt:Role*. For the sake of clarity, only a fraction of the relations are described here. The roles are ex:b (before), ex:a (after), ex:f (finishes), ex:eq (equals), ex:sb (survived by). These roles cause Role-Chain-Axioms using the product logic (Fig. 11 B): RCA0001: (A)-[eq/p%]-(B)-[a/q%]-(C) ⇒ (A)-[a/p*q]-(C); RCA0002: (A)-[b/p%]-(B)-[f/q%]-(C) ⇒ (A)-[sb/p*q]-(C).

To demonstrate the AMT temporal reasoning using the (normalized) Pearson correlation coefficient, we use the Limes Parts Hadrian's Wall (HW), Wetterau-limes (WL), Elisabethentraße (ES), and North Sea Cost (NSC):

- _:01/02: (HW)-[eq/0.645]-(WL)-[a/0.970]-(ES) ⇒ (HW)-[a/p*q=0.626]-(ES)
- _:03/04: (ES)-[b/0.774]-(NSC)-[f/0.808]-(WL) ⇒ (ES)-[a/p*q=0.625]-(WL)

The AMT web tool on GitHub can be used to make this model and the temporal reasoning LOUD, but also human-readable and understandable. Fig. 11 (C) showcases the aforementioned example without reasoning. The blank nodes 01–04, which represent the AMT quadruples, can also be explored via the SPARQL Unicorn GitHub Action tool, i.e., Node 01[89] (HW)-[eq/0.645]-(WL) or Node 02[90] (WL)-[a/0.970]-(ES). The applied temporal reasoning is shown in Fig. 11 (D).

86 Nation 2017.
87 Pearson & Filon 1898.
88 cf. https://github.com/leiza-scit/grapHNR23-amt/blob/main/data/LimesExample.ttl
89 cf. https://leiza-scit.github.io/grapHNR23-amt/n03c399d455f4463aaa1a84d1857da672b2/index.html
90 cf. https://leiza-scit.github.io/grapHNR23-amt/n03c399d455f4463aaa1a84d1857da672b3/index.html

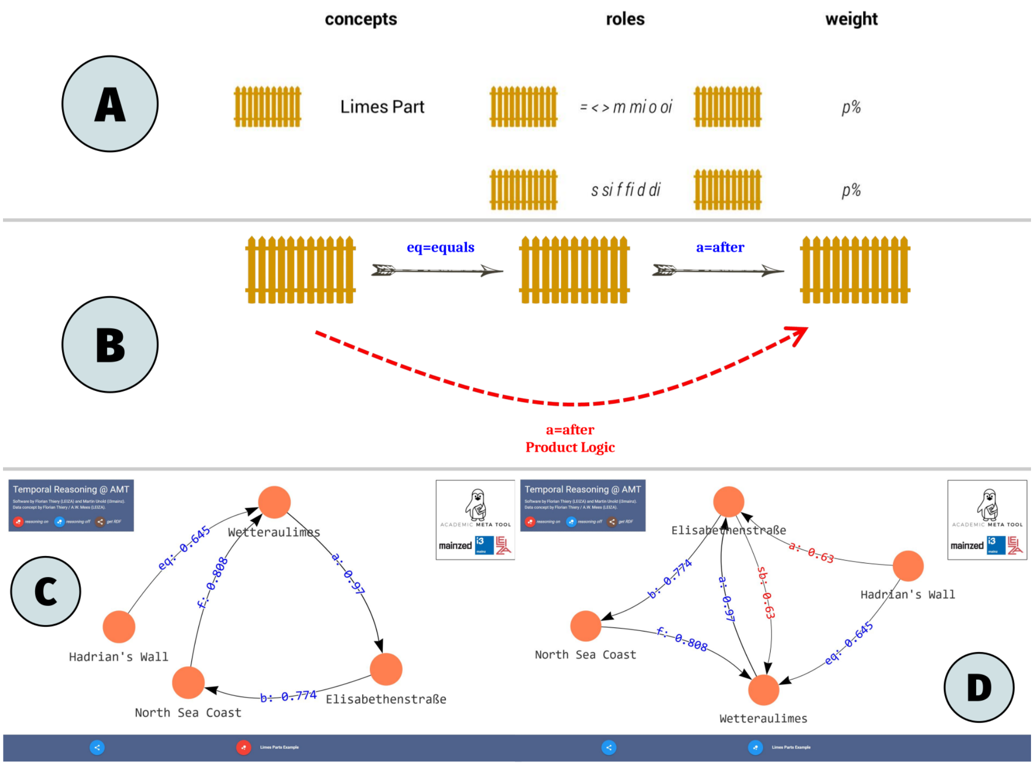


Fig. 11 A: The AMT time ontology using Allen's interval algebra. B: AMT Axiom to perform reasoning using the during and after intervals and the product logic. C: Exemplary AMT modeling with the AMT web tool (cf. https://leiza-scit.github.io/amt-limes/). D: Exemplary AMT reasoning with the AMT web tool. Graphic: Florian Thiery CC BY 4.0

This small model creates new knowledge by taking the Pearson correlation coefficient into account: Hadrian's Wall is temporally after Elisabethenstraße (p = 0.626), and Elisabethenstraße is survived by Wetteraulimes (p = 0.625), which also includes the Allen relations < (before), m (meets), o (overlaps) s (starts), and d (during).

4. Discussion & Conclusion

Although we can conclude that the method itself works, and it is highly feasible to establish relative chronologies with Samian as a find category, it appears to be less reliable for yielding absolute dates. However, this is not due to the methods we introduced here, but rather to the hitherto expected dating capabilities or 'dating quality' of the material involved. This leads us to an enhanced concept of temporalities for such *dated sites*. This broader concept consists of several different aspects.

For practical reasons we have chosen examples from the Roman period, since it is here that we can immediately crosscheck the methods proposed with dates of historically handed down events, e.g., in written sources. Applying these methods, however, to e.g., Iron Age samples from the African continent demonstrates that these methods are also applicable for historically different time periods that are notoriously lacking in sharply *dated sites.* In this context, it appears to even be particularly helpful for handling 14C dating issues, since methodologically these are themselves time intervals with a certain amount of uncertainty, rather than exact datings as known from the Roman period[91]. Any radiocarbon dating implies a statement in which we might say that we could be 95 % sure that the sample comes, e.g., from between 1375 cal BC and 1129 cal BC[92]. For the material finds, the method has also been successfully applied to ceramic finds from the Iron Age, where stylistic decoration motifs on pottery were taken as a starting point for correspondence analysis[93]. Wobbling dating information in our examples from the Roman period are essentially due to the varying underlying production cycles and the varying (dis)continuities of the *dated sites* involved. Whereas the underlying production cycles can be modeled, the problems start with defining the time intervals related to *dated sites*[94]. Testing this new concept with real archaeological use cases suggests that we are in fact looking at gradual processes, which must be put in relation to the stated *dated sites.* Thus, the trusty *from-to* shortcut for *dated sites* – which is full of hidden assumptions – must be replaced. Instead of sticking to vague expressions such as *highly likely,* this method makes the individual steps behind the hidden assumptions visible by modeling the elements within the hidden assumptions. As a side effect, the new reproducible relative ordering of Limes sections fits with the dating evidence elaborated by other, independent modern authoritative studies on the Limes chronology based on Roman coin series[95]. This enhanced concept of temporalities also implies the modeling of the individual elements within the hidden assumptions in the traditional dating process, essentially allowing for weighted values which can be used in reasoning, resulting in calculated outcomes (which ultimately define the degree of *dating quality*) as well as defining any Allen or Freksa temporal relations as a role. Viewing the relations between Limes sections as interval-chains is pivotal to this concept. However, although these values are often perfectly quantifiable and make dating statements reproducible, archaeological tradition holds that a dating statement with a built in likelihood, e.g., in decimals, indicating the *dating quality,* does not appear to be very popular outside the archaeologies that use natural sciences.

---

91 Seidensticker et al. 2018.
92 cf. https://c14.arch.ox.ac.uk/calibration.html
93 cf. https://github.com/dirkseidensticker/ChronoCongo
94 Mees 2024.
95 Kortüm 1998.

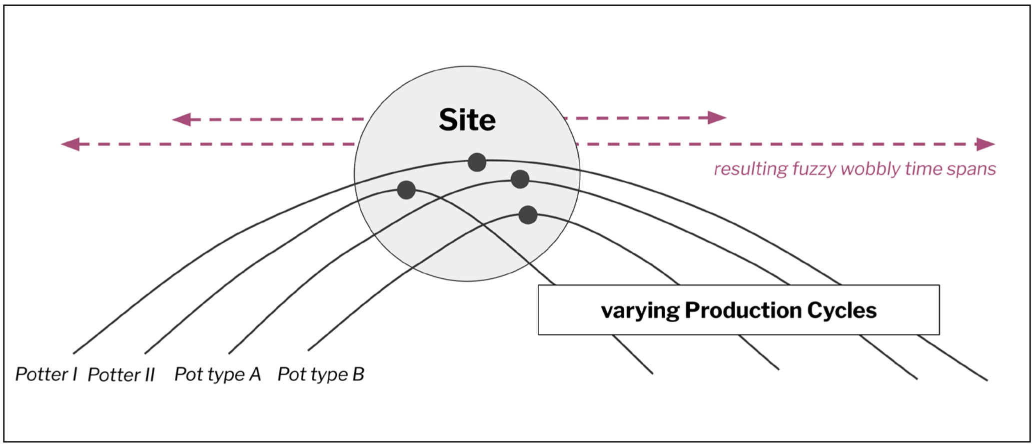


Fig. 12 Wobbling datings due to varying underlying production cycles. Graphic: Allard W. Mees CC BY 4.0

In technical terms, based on a correspondence analysis, using the Alligator tool, we can embed floating time intervals, create a relative chronology according to Allen's interval algebra, and apply temporal reasoning with the AMT tool. This enhances our interpretation of the original correspondence analysis. As an archaeological result, find categories like Samian can contribute to independent relative chronologies if one applies vagueness modeling. This permits a new concept of a measurable *dating quality* that is attributable to specific archaeological materials. Based on hitherto applied research, the *dating quality* of coins, terra sigillata or stamped legionary tiles are considered high, while other materials may lead to a measurably lower degree of *dating quality* when placed in relation to *dated sites*.

In the future, two improvements are conceivable to achieve:

1) taking into account not only relative temporality, but also absolute site datings which might influence the relative order within the CA dimensions, could eventually sharpen the dating statement.
2) the underlying volatile production cycles of, e.g., potters and the potforms which they produced are currently not yet taken into account (e.g., certain potforms not appearing before or after a group of *dated sites*). In future, this may reduce the fuzzy wobbly time spans (Fig. 12) and sharpen possible statements about the dating quality of the different archaeological materials involved.

In terms of data sharing, specific time intervals could be published and shared alongside all their uncertainty information, as well as the provenance of how they were solved by applying the FAIR principles, using LOD formalisms or Wikibase instances such as Wikidata. This approach has already been implemented for fuzzy spatial locations within the *fuzzy-sl Wikibase*[96]; within, it could also be transferred to fuzzy time intervals.

Bibliography

Allen, James F. "Maintaining Knowledge about Temporal Intervals." *Communications of the ACM* 26, no. 11 (1983): 832–43. https://doi.org/10.1145/182.358434.

Allen, James F., and Patrick J. Hayes. "A Common-Sense Theory of Time." In *Proceedings of the 9th International Joint Conference on Artificial Intelligence,* 528–31. San Francisco: Morgan Kaufmann, 1985.

Berners-Lee, Tim. "Linked Data – Design Issues." 2006. https://www.w3.org/DesignIssues/LinkedData.html.

Bibby, D., Kai-Christian Bruhn, Frank Dührkohp, Christian Eckmann, U. Himmelmann, B. Höke, Christian Keller, et al. "Digitales Forschungsdatenmanagement in der Archäologie und die Initiative NFDI4Objects." *Blickpunkt Archäologie* 2 (2021): 150–63. https://doi.org/10.5281/zenodo.5823867.

Bibby, David, Kai-Christian Bruhn, Alexandra Busch, Frank Dührkohp, et al. "NFDI4Objects – Proposal." *NFDI4Objects Zenodo Community,* 2023. https://doi.org/10.5281/zenodo.10409227.

Car, Nicholas J., and Timo Homburg. "GeoSPARQL 1.1: Motivations, Details and Applications of the Decadal Update to the Most Important Geospatial LOD Standard." *ISPRS International Journal of Geo-Information* 11, no. 2 (2022): 117. https://doi.org/10.3390/ijgi11020117.

Flückiger, Matthias, Erik Hornung, Mario Larch, Markus Ludwig, and Allard Mees. "Roman Transport Network Connectivity and Economic Integration." *The Review of Economic Studies* 89, no. 2 (2022): 774–810. https://doi.org/10.1093/restud/rdab036.

Freksa, Christian. "Conceptual Neighborhood and Its Role in Temporal and Spatial Reasoning." In *Proceedings of the IMACS Workshop on Decision Support Systems and Qualitative Reasoning,* edited by M. G. Singh and L. Travé-Massuyés, 181–87. Amsterdam: North-Holland, 1991.

—. "Temporal Reasoning Based on Semi-Intervals." *Artificial Intelligence* 54, no. 1 (1992): 199–227. https://doi.org/10.1016/0004-3702(92)90090-K.

Homburg, Timo, and Florian Thiery. "SPARQL Unicorn Ontology Documentation." *Squirrel Papers* 6, no. 2 (2024): no. 2. https://doi.org/10.5281/zenodo.10780476.

Jovanovik, Milos, Timo Homburg, and Mirko Spasić. "Software for the GeoSPARQL Compliance Benchmark." *Software Impacts* 8 (2021): 100071. https://doi.org/10.1016/j.simpa.2021.100071.

96 c.f. https://fuzzy-sl.wikibase.cloud/; Thiery et al. 2024; Thiery et al. 2023; Thiery 2024.

Kortüm, Klaus. “Zur Datierung der römischen Militäranlagen im obergermanisch-rätischen Limesgebiet.” *Saalburg-Jahrbuch* 49 (1998): 5–65.

Madsen, Torsten. Multivariate *Archaeology: Numerical Approaches in Scandinavian Archaeology* Jutland Archaeological Society Publications 21. Højbjerg: Jutland Archaeological Society; Århus: Århus University Press, 1988.

Mees, Allard W. “The Internal Organisation of Terra Sigillata (Samian) Workshops.” In *Seeing Red: New Economic and Social Perspectives on Terra Sigillata,* edited by Michael Fulford and Emma Durham, 66–96. *Bulletin of the Institute of Classical Studies Supplement* 102. London: Institute of Classical Studies, School of Advanced Study, University of London, 2013.

Mees, Allard W. “Economic Principles in the Roman Economy: Modelling Mass Ceramic Production and Trade.” In *Technology, Crafting and Artisanal Networks in the Greek and Roman World,* edited by Diego Elia, Eleni Hasaki, and Marco Serino, 285–302. Berlin: De Gruyter, 2024. https://doi.org/10.1515/9783111189635-024.

Mees, Allard W., and Rien Polak. “Scattered Pots. Exploring Spatial and Chronological Aspects of Samian Ware.” In *Seeing Red: New Economic and Social Perspectives on Terra Sigillata,* edited by Michael Fulford and Emma Durham, 36–48. *Bulletin of the Institute of Classical Studies Supplement* 102. London: Institute of Classical Studies, School of Advanced Study, University of London, 2013.

Nation, Zoni. “Perceptions of Probability and Numbers.” 25 August 2017. https://github.com/zonination/perceptions.

Pearson, Karl, and Louis Napoleon George Filon. “VII. Mathematical Contributions to the Theory of Evolution – IV. On the Probable Errors of Frequency Constants and on the Influence of Random Selection on Variation and Correlation.” *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* 191 (1898): 229–311. https://doi.org/10.1098/rsta.1898.0007.

Pliny the Younger. *Letters, Volume I: Books 1–7.* Translated by Betty Radice. Loeb Classical Library 55. Cambridge, MA: Harvard University Press, 1969.

Seidensticker, Dirk, Timo Thiery, Florian, Allard W. Mees, and Clemens Schmid. “RDF Based Modeling of Relative and Absolute Chronological Data: Examples from the Central African Rainforest and Roman Periodisation.” *Squirrel Papers* 1, no. 7 (2018): no. 1. https://doi.org/10.5281/zenodo.1410516.

Shaw, Ryan. “Modeling and Reasoning about Incomplete, Uncertain, and Approximate Historical Dates.” In *Graphs and Networks in the Humanities 2022,* 2022. https://t1p.de/5m3ow.

Sterry, Martin. “Multivariate and Spatial Visualisation of Archaeological Assemblages.” *Internet Archaeology* 50 (2018). https://doi.org/10.11141/ia.50.15.

Tacitus. *Agricola. Germania. Dialogue on Oratory.* Translated by M. Hutton and W. Peterson. Revised by R. M. Ogilvie, E. H. Warmington, and Michael Winterbottom. Loeb Classical Library 35. Cambridge, MA: Harvard University Press, 1914.

Tacitus. *Histories: Books 1–3.* Translated by Clifford H. Moore. Loeb Classical Library 111. Cambridge, MA: Harvard University Press, 1925.

Thiery, Florian. "Semantic Web und Linked Data: Generierung von Interoperabilität in archäologischen Fachdaten am Beispiel römischer Töpferstempel." *Squirrel Papers* 4, no. 1 (2013): no. 3. https://doi.org/10.5281/zenodo.774861.

—. "Archaeology 4.0: Archaeology in the Third Era of Computing." *Squirrel Papers* 1, no. 1 (2019): no. 2. https://doi.org/10.5281/zenodo.2629595.

—. "Sphere 7 Data: LOUD and FAIR Data for the Research Community." *Squirrel Papers* 1, no. 1 (2019): no. 3. https://doi.org/10.5281/zenodo.2643469.

—. "Linked Archaeological Data Ontology." *Squirrel Papers* 4, no. 2 (2022): no. 6. https://doi.org/10.5281/zenodo.7377740.

—. "Modelling in the fuzzy-sl Wikibase." *Squirrel Papers* 6, no. 1 (2024): no. 3. https://doi.org/10.5281/zenodo.14260359.

Thiery, Florian, and Timo Homburg. "SPARQLing Unicorn QGIS Plugin." *Squirrel Papers* 6, no. 2 (2024): no. 1. https://doi.org/10.5281/zenodo.10779466.

—. "The SPARQL Unicorn Ontology Documentation: Exposing RDF Geodata Using Static GeoAPIs." In *Tagungsband FOSSGIS-Konferenz 2024* (2024): 82–90. https://doi.org/10.5281/zenodo.10570985.

Thiery, Florian, and Allard Mees. —. "Alligator Method." *Squirrel Papers* 5, no. 1 (2023): no. 2. https://doi.org/10.5281/zenodo.7624870.

—. "Taming Ambiguity – Dealing with Doubts in Archaeological Datasets Using LOD." In *CAA 2018: Human History and Digital Future,* 31 October 2023. https://doi.org/10.15496/PUBLIKATION-87762.

—. "Alligator – Allen Transformer." *Squirrel Papers* 6, no. 2 (2024): no. 4. https://doi.org/10.5281/zenodo.2540709.

—. "TiGeR – Time Geospatial RDF." *Squirrel Papers* 6, no. 2 (2024): no. 3. https://doi.org/10.5281/zenodo.11064282.

—. "GrapHNR2023 – Supplementary Material." *Squirrel Papers* 7, no. 2 (2025): λ2. https://doi.org/10.5281/zenodo.14906708.

Thiery, Florian, Allard W. Mees, Bernhard Weisser, Felix F. Schäfer, Stefanie Baars, Sonja Nolte, Henriette Senst, and Philipp Von Rummel. "Object-Related Research Data Workflows Within NFDI4Objects and Beyond." *Proceedings of the Conference on Research Data Infrastructure* 1 (2023). https://doi.org/10.52825/cordi.v1i.326.

Thiery, Florian, Fiona Schenk, Stefanie Baars, Karsten Tolle, and Peter Thiery. "Modellierung von Fuzzyness/Wobbliness in Geodaten." In *Tagungsband FOSSGIS-Konferenz 2024* (2024): 64–73. https://doi.org/10.5281/zenodo.10571859.

Thiery, Florian, Fiona Schenk, and Stefanie Baars. "Dealing with Doubts: Site Georeferencing in Archaeology and in the Geosciences." *Squirrel Papers* 5, no. 1 (2023): no. 6. https://doi.org/10.5281/zenodo.10291889.

Thiery, Florian, Sophie Charlotte Schmidt, Timo Homburg, and Martina Trognitz. "The SPARQL Unicorn: An Introduction." *Squirrel Papers* 2, no. 1 (2020): no. 1. https://doi.org/10.5281/zenodo.3742185.

Thiery, Florian, Jonas Veller, Laura Raddatz, Louise Rokohl, Frank Boochs, and Allard W. Mees. "A Semi-Automatic Semantic-Model-Based Comparison Workflow for Archaeological Features on Roman Ceramics." *ISPRS International Journal of Geo-Information* 12, no. 4 (2023): 167. https://doi.org/10.3390/ijgi12040167.

Thiery, Florian, Kristina Fella, Lasse Mempel-Länger, and Andreas Puhl. "Digitale Services in Der Archäologie: Aktuelle Entwicklungen und Angebote aus den NFDI4Objects Task Areas Collecting und Protecting." *Archäologische Informationen* 47, NWDVA 2024 Bochum: Digitale Archäologie (2025): 99–114. https://doi.org/10.5281/zenodo.14801145.

Thiery, Florian, Fiona Schenk, and Peter Thiery. "Das Research Squirrel Engineers Network: FAIRification Tools und LOD-Projekte aus der Archäoinformatik und den Geowissenschaften." *Archäologische Informationen* 47, NWDVA 2024 Bochum: Digitale Archäologie (2025): 115–140. https://doi.org/10.5281/zenodo.14801070.

Unold, Martin, Florian Thiery, and Allard Mees. "Academic Meta Tool. Ein Web-Tool Zur Modellierung von Vagheit." *Zeitschrift Für Digitale Geisteswissenschaften,* Sonderband 4 (2019). https://doi.org/10.17175/SB004_004.

Wilkinson, Mark D., Michel Dumontier, IJsbrand Jan Aalbersberg, Gabrielle Appleton, Myles Axton, Arie Baak, Niklas Blomberg, et al. "The FAIR Guiding Principles for Scientific Data Management and Stewardship." *Scientific Data* 3 (2016): 160018. https://doi.org/10.1038/sdata.2016.18.