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After the Revolution: A Review of 3D Modelling as a Tool for Stone Artefact Analysis

REVIEW

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ABSTRACT

With over 200 peer-reviewed papers published over the last 20 years, 3D modelling is no longer a gimmick but an established and increasingly common analytical tool for stone artefact analysis. Laser and structured light scanning, photogrammetry, and CT scanning have all been used to model stone artefacts. These have been combined with a variety of different analytical approaches, from geometric morphometrics to custom reduction indices to digital elevation maps. 3D lithic analyses are increasingly global in scope and studies aim to address an ever-broadening breadth of research topics ranging from testing the functional efficiency of artefacts to assessing the cognitive capabilities of hominid populations. While the impact of the computational revolution on lithic analysis has been reviewed, the impact of 3D modelling on lithic analysis has yet to be comprehensively assessed. This paper presents a review of how 3D modelling in particular has impacted the field of stone artefact analysis. It combines a quantitative bibliometric analysis with a qualitative review to assess just how "revolutionary" 3D modelling has been for lithic analysis. It explores trends in the use of 3D modelling in stone artefact analysis, its impact on the wider lithic analysis field, and methodological, regional and theoretical gaps which future research projects could explore.

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1. INTRODUCTION

Digital 3D modelling has been repeatedly described as having had a "revolutionary" impact on archaeology (Grosman 2016; Magnani et al. 2020; Porter, Roussel and Soressi 2016; Shott 2014). Digital 3D models have been made of archaeological landscapes (e.g. Benjamin et al. 2019; Magnani et al. 2020; Richards-Rissetto 2017), sites and features (e.g. Douglass, Lin and Chodoronek 2015; Jalandoni and May 2020; Robinson et al. 2019), excavations (e.g. Discamps et al. 2016; Emmitt et al. 2021), biological remains (e.g. Evin et al. 2016; Koungoulos 2020; Spyrou et al. 2022) and artefacts (e.g. Emmitt, Mackrell and Armstrong 2021; Whitford et al. 2020; Yahalom-Mack et al. 2020). Over the last 20 years, more than 200 peer-reviewed papers have been published that use 3D models to either analyse or illustrate stone artefacts. The field has matured and is no longer dominated by, as Shott (2014: 2) – not unkindly – put it, '"See what I did because I could do it" contributions.' While modelling methodology papers are still occasionally published (e.g. Bisson-Larrivée and LeMoine 2022), the majority of papers published in the last five years have used 3D modelling to address archaeological questions.

However, after 20 years of publications there have been no major reviews on the application of 3D modelling to lithic analysis. While three broader digital archaeology review papers included 3D lithic analyses as case studies (Grosman 2016; Magnani et al. 2020; Shott 2014), none are – nor aim to be – an exhaustive review of the field. As the field has rapidly grown and diversified there is a pressing need to take stock of how it is developing. This article will combine a quantitative bibliometric analysis with a qualitative review to assess just how "revolutionary" 3D modelling has been for lithic analysis. It will focus on exploring how the field has developed socially, intellectually, and conceptually over the last 20 years, and identify trends and gaps in the 3D lithic analysis literature.

2. BACKGROUND

The first peer-reviewed paper that featured 3D models of a stone artefact was published in 2002 in the journal *Antiquity* (Riel-Salvatore et al. 2002). This 2-page paper reported on a successful trial attempt at using a 3D scanner for digitising stone artefacts, semi-automated the identification of the faces of an artefact, and suggested possible future applications (Riel-Salvatore et al. 2002). While initial growth was slow, the 2010s saw spikes in the number of papers published (see Figure 1).

Published 3D modelling techniques include laser and structured light scanning (e.g. Riel-Salvatore et al. 2002), computer tomography (CT) scanning (e.g. Abel et al. 2011) and photogrammetry (e.g. Sumner and Riddle 2008). Objects modelled include flaked stone artefacts (e.g. Boulanger, Miller and Fisher 2021; Lin et al. 2010), non-flaked stone artefacts (e.g. Furey et al. 2020; Hayes et al. 2021; Pedergnana et al. 2021), and non-artefactual stone tools (e.g. Benito-Calvo et al. 2015; Haslam et al. 2013).

The resulting models have been used for a wide range of analyses. Early 3D lithic analyses placed an emphasis

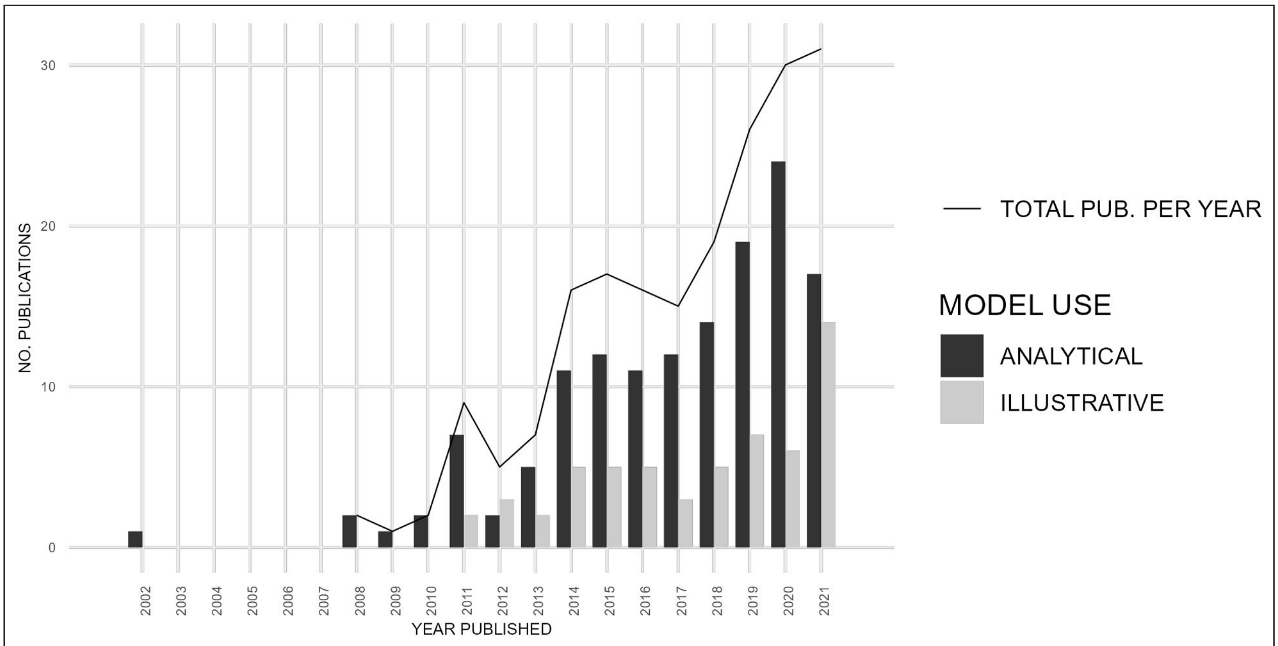

Figure 1 Annual number of published peer-reviewed papers where 3D modelling is used as either an analytical, archival, or pedagogical tool or illustrative technique for lithic analysis. Papers published in 2022 – from January to May – (n = 16) have been excluded. The drop in papers in 2021 likely reflects the impact of COVID-19, and the number of papers in 2022 is on track to continue the field's growth. Figure produced using the ggplot package.

on recording discrete, often complex, measurements with a high degree of accuracy, making 3D modelling a particularly attractive analytical tool for quantitative studies (Bretzke and Conard 2012). The development and growth of 3D lithic analysis can therefore be linked to the same intellectual move towards more quantitative and materialist forms of lithic analysis (*sensu* Hiscock 2007; see also Lycett and Chauhan 2010). These developments are particularly prevalent in the Anglophone tradition of lithic analysis (Bleed 2001; Hussain 2019, 2021). This intellectual movement has led to the adoption of geometric morphometrics as a method of stone artefact analysis (e.g. Buchanan and Collard 2010; Ioviţă 2010; Lycett, von Cramon-Taubadel and Foley 2006) and the development of different indices – such as the Scar Density Index (Clarkson 2013; Shipton 2011), Scar Pattern Index (Clarkson, Vinicius and Lahr 2006), Initial/Terminal-Mass Comparison (Clarkson and Hiscock 2011), Cortex Ratio (Dibble et al. 2005), and Volume Ratio (Phillipps and Holdaway 2016) – for lithic analysis. While most of these analytical approaches were not developed with 3D models in mind, all have since been used in 3D lithic analysis papers (e.g. Lin et al. 2010; Maloney 2020; Middleton and Phillipps In Press; Shipton and Clarkson 2015a; Shott and Trail 2010).

The other stated reasons for modelling stone artefacts are for archival, pedagogical, and illustrative purposes. The creation of digital archives of stone artefacts is generally linked to open science (Abel et al. 2011; Ahmed, Carter and Ferris 2014; Douglass et al. 2017), or for teaching purposes. Though the pedagogical potential of 3D models of stone artefacts has been recognised, little has been published on examples of stone artefacts being used for digital object-based learning (though see Wyatt-Spratt and Thoeming 2019). More commonly, models have also been used for illustrative purposes, replacing or supplementing scientific illustrations or photographs of stone artefacts (e.g. Hayes et al. 2021; Perston et al. 2022; Sano et al. 2020; Schmid et al. 2019, see also Barone et al. 2018; Felicísimo, Polo and Peris 2013; Magnani 2014 for discussion on 3D models as an alternative to illustration and photography).

3. METHOD AND MATERIALS

3.1. DATA COLLECTION

The final dataset contains 213 papers where 3D modelling is used as either an analytical, archival, or pedagogical tool (n = 152, 71.3%) or solely as an illustrative technique (n = 61, 28.6%). The papers in the dataset were initially identified by searching Google Scholar and Web of Science databases with the search terms: "stone art*fact", "lithic", "3D model*ing", "scanning", and "photogrammetry". Additional papers were found by reviewing the publishing history of identified authors and by searching for documents that cited or that were cited within identified papers. Full bibliographic data for identified papers was then exported from Web of Science to import into R. Partial data for identified papers not listed on Web of Science was manually added (see Supplementary Information for details).

Papers on both flaked stone artefacts and non-flaked stone artefacts or tools were included in the dataset. Studies that incorporated flaked glass were also added (e.g. Dogandžić et al. 2020; Perston et al. 2022). The dataset includes both archaeological and experimental studies. Artefacts identified exclusively as "art" objects were excluded (e.g. Grosman et al. 2017). Papers where the models were created by 3D scanners, photogrammetry, and various forms of computer tomography scanning were all included. Papers where models were created by 3D microscopy (e.g. Hiscock et al. 2016; Morales and Vergès 2014) were excluded as these studies typically only partially model artefacts, and in terms of their content and intellectual history owe more to microscopy papers than they do 3D modelling papers (see Stemp, Watson and Evans 2015 for further discussion).

Books, book chapters, theses, and conference proceedings, as well as publications in languages other than English were also excluded as they are not consistently listed in the academic databases necessary for bibliometric analysis. However it is important to recognise that 3D lithic analysis research has been published in Chinese (e.g. Zhou and Guan 2017), Czech (e.g. Kaňáková, Šmerda and Nosek 2016), French (e.g. Martin-Moya et al. 2020), German (e.g. Dietrich 2021), Italian (e.g. Caricola et al. 2018b; Cristiani et al. 2018), Japanese (e.g. Noguchi 2019), Russian (e.g. Chistyakov and Kovalev 2019; Kolobova et al. 2020b; Shalagina et al. 2020) and Spanish (e.g. Cebrià et al. 2014; Duque Martínez and de Francisco Rodríguez 2015; Morales et al. 2013; Soto et al. 2018) and undoubtedly other languages that were not identified.

Data cleaning was carried out, primarily to identify and consolidate multiple names that represented a single author. Each paper was manually given a set of keywords based on the following categories (see Supplementary Information for further details):

- *Thematic* – Keywords in this category were designed to capture the general conceptual focus of papers.
- *Analysis* – This category included keywords relating to the methodological approach that a paper utilised.
- *Industry* – Keywords in this category relate to the industry, or techno-complex of the artefacts being analysed. These terms were sourced directly from the paper.
- *Artefact* – This category always included the generic keywords: "core"; "flake"; "retouched flake"; "point"; "biface"; "other artefact/tool type" where relevant. Author designated terms were also included.

Papers could have multiple keywords in each category. Additional information about whether the study included an experimental component, study region, modelling methodology, and analytical software used was also recorded for each paper.

3.2. DATA ANALYSIS AND VISUALISATION

Bibliometric analysis is a quantitative, systematic, and transparent method of synthesising a body of research (Aria and Cuccurullo 2017; Cobo et al. 2011). There are two main outputs of bibliometric studies, performance analysis and scientific mapping (Cobo et al. 2011). Performance analysis aims to measure the impact on an academic field of scientific actors, i.e. researchers, institutions, countries, journals, or papers (Cobo et al. 2011). Science mapping is a way of spatially representing the networks between different scientific actors or keywords to map the social, intellectual, and conceptual structure of a research field (Aria and Cuccurullo 2017; Cobo et al. 2011).

For this study, only papers where 3D models of stone artefacts were used for analytical, archival, or pedagogical purposes were analysed. The overall aim was to identify the historic development of 3D lithic analysis and summarise the current state of the field. To that end, key authors, journals, and papers were identified. A collaboration network of all authors who have published ≥3 articles was created to explore the social structure of the field (Glänzel and Schubert 2005) and a historiograph of the 25 highest locally cited papers was created to explore the intellectual development of the field (Aria and Cuccurullo 2017). Co-word analysis of the manually added keywords was used to map patterns between the types of artefacts being analysed, the methodologies being used to analyse them, and the research questions they were being used to answer (Cobo et al. 2011). Trends in modelling method, software use, and study region were also analysed.

Bibliometric and other quantitative analyses were all carried out in R v.4.2.1 (R Core Team 2022), using the packages bibliometrix v.4.0.0 (Aria and Cuccurullo 2017), igraph v.1.3.1 (Csárdi and Nepusz 2006), qgraph v.1.9.2 (Epskamp et al. 2012) and tidyverse v.1.3.2 (Wickham et al. 2019).

4. RESULTS

4.1. SOURCES, AUTHORS, AND INSTITUTIONS

Bibliometric analysis of the analytical dataset showed clear patterns of publishing and collaboration. 3D lithic analysis studies have primarily been published in archaeological science journals and journals focused on Pleistocene-age archaeology (see Figure 2). Per Bradford's Law, there are three "core" journals, seven "zone 2" journals and thirty-two "zone 3" journals that have each published approximately a third of all papers (Bradford 1934). Regional and more humanities-orientated archaeological journals are less well-represented and are only found in "zone 3" journals.

A collaboration network of all researchers who have published ≥ 3 articles (n = 57) identified 12 clusters of authors (see Figure 3). Clusters either map to institutions (Clusters 1, 2, 7, 8, 10, and 12) or multi-institutional research projects (Clusters 3, 5, 6, and 11). The first five clusters are centred on the 10 most productive authors (see Figure 4). The prominence of researchers affiliated with Israeli and Australian institutions reflects the early adoption of 3D modelling by researchers at the Hebrew

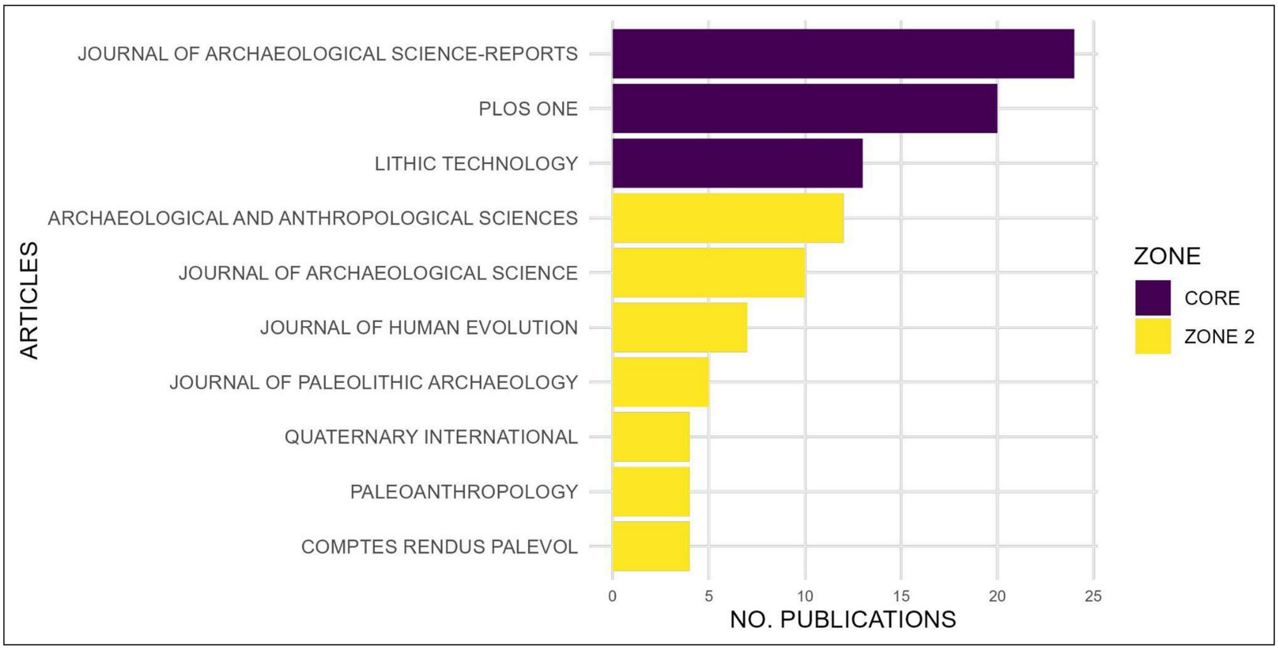

Figure 2 Top 10 journals by number of publications. Only core and zone 2 journals are present in the top 10 journals. Figure produced using the ggplot package.

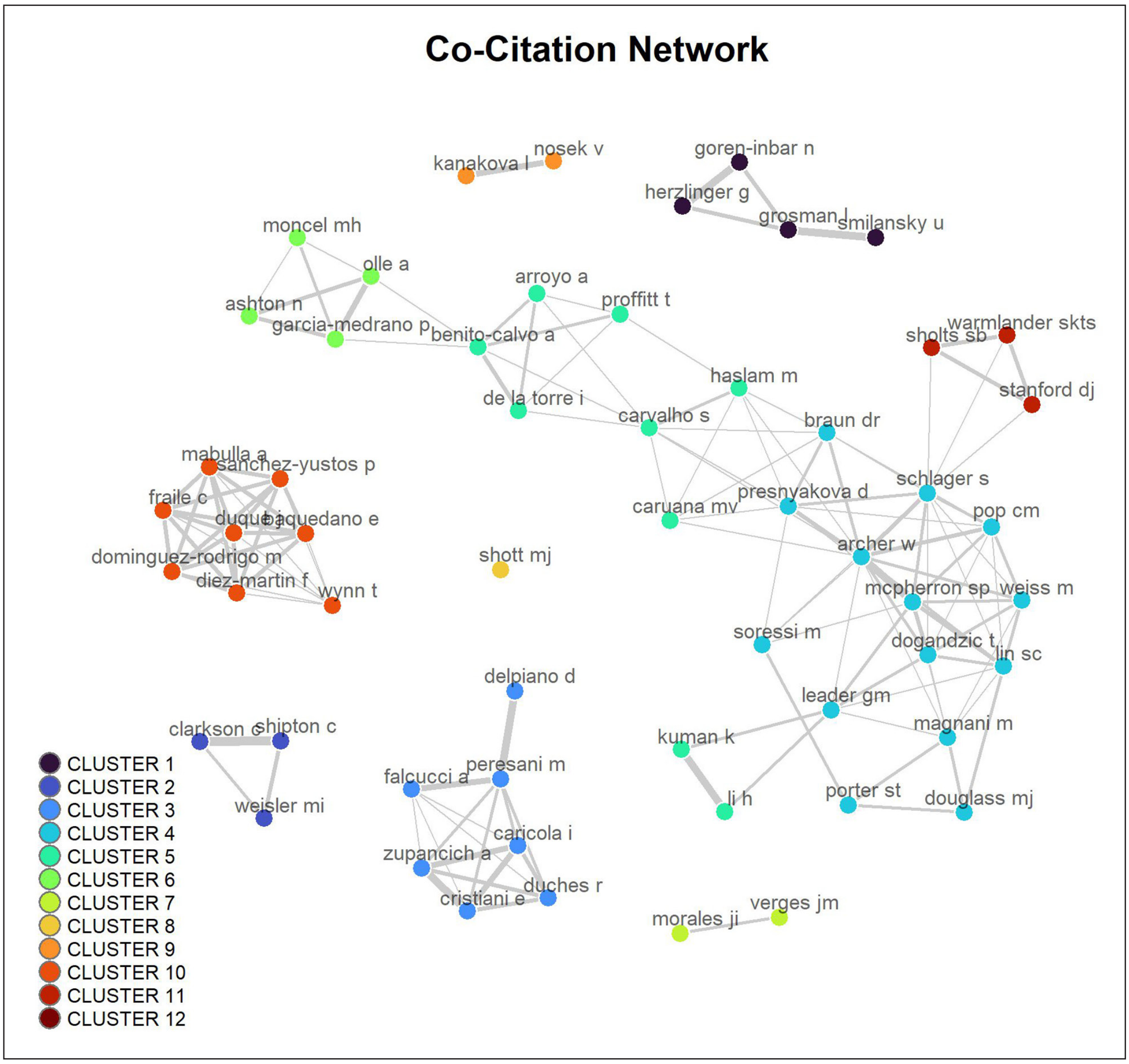

Figure 3 Collaboration network of all authors who have published ≥ 3 articles (n = 57). A Fruchterman-Reingold layout and the Louvain clustering algorithm were used to produce the network. The community repulsion force was 0.5 and the minimum number of edges was 1. Isolated nodes were kept. Figure produced using the bibliometrix, igraph, and qgraph packages.

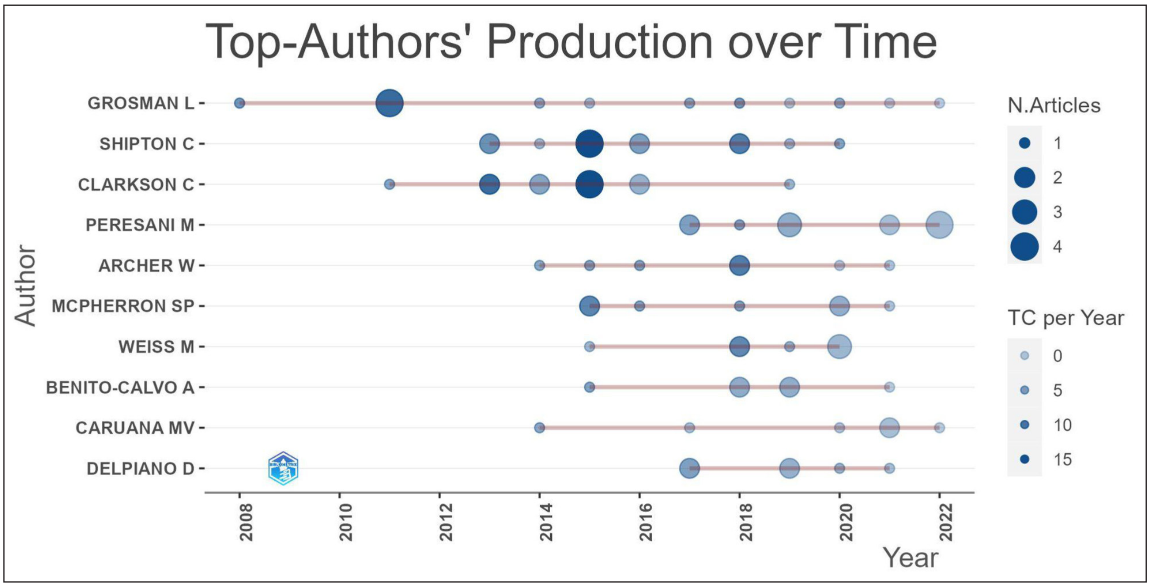

Figure 4 Top 10 Authors' Production over time. The number of articles published in a year is indicated by the size of the bubble. The colour intensity is proportional to the number of times articles published in that year have been cited. The line represents an author's publication timeline. Figure produced using the bibliometrix package.

University in Jerusalem (Cluster 1) and the University of Queensland (Cluster 2).

Researchers affiliated with the Hebrew University in Jerusalem have been pioneers in the development of software packages for analysis of 3D models (Grosman et al. 2014, 2022; Herzlinger and Grosman 2018; Valletta, Dag and Grosman 2021). University of Queensland affiliated researchers have published experimental quantitative studies, generally focusing on testing new reduction indices (Clarkson 2013; Clarkson and Hiscock 2011; Muller and Clarkson 2014, 2016; Shipton and Clarkson 2015a). Both groups have published studies on experimental artefacts (e.g. Clarkson 2013; Clarkson and Hiscock 2011; Grosman et al. 2011; Grosman, Smikt and Smilansky 2008) and on Acheulean bifaces (e.g. Grosman, Goldsmith and Smilansky 2011; Herzlinger, Goren-Inbar and Grosman 2017; Muller, Shipton and Clarkson 2022; Shipton and Clarkson 2015a, 2015b). The influence of these key authors and institutions can be seen in a direct historic citation network of the field (Figure 5). Key early papers in the development of the field from these institutions include Grosman, Smikt and Smilansky (2008), Clarkson and Hiscock (2011), and Grosman et al. (2011). Early, influential work done outside of these institutions, namely Bretzke and Conard (2012), Lin et al. (2010) and Shott and Trail (2010), is also visible in the historiograph. More broadly, the historiograph maps the impact on the development of the field of papers that have tested modelling workflows and accuracy (Grosman, Smikt and Smilansky 2008; Lin et al. 2010; Porter, Roussel and Soressi 2016; Shott and Trail 2010), trialled new methodological approaches (Clarkson 2013; Clarkson and Hiscock 2011; Herzlinger, Goren-Inbar and Grosman 2017; Morales, Lorenzo and Vergès 2015; Muller and Clarkson 2014), developed analytical software (Archer et al. 2015; Herzlinger and Grosman 2018) or have an experimental component (Caruana et al. 2014; García-Medrano et al. 2019; Grosman et al. 2011; Herzlinger, Goren-Inbar and Grosman 2017; Shipton and Clarkson 2015a, 2015b).

4.2. MODELLING, SOFTWARE, AND ACCESSIBILITY

Laser and structured light scanning have been the most common modelling methods throughout the field's history. Photogrammetry has become more common since 2016 (see Figure 6), reflecting the impact of Porter, Roussel and Soressi's (2016) methodology paper.

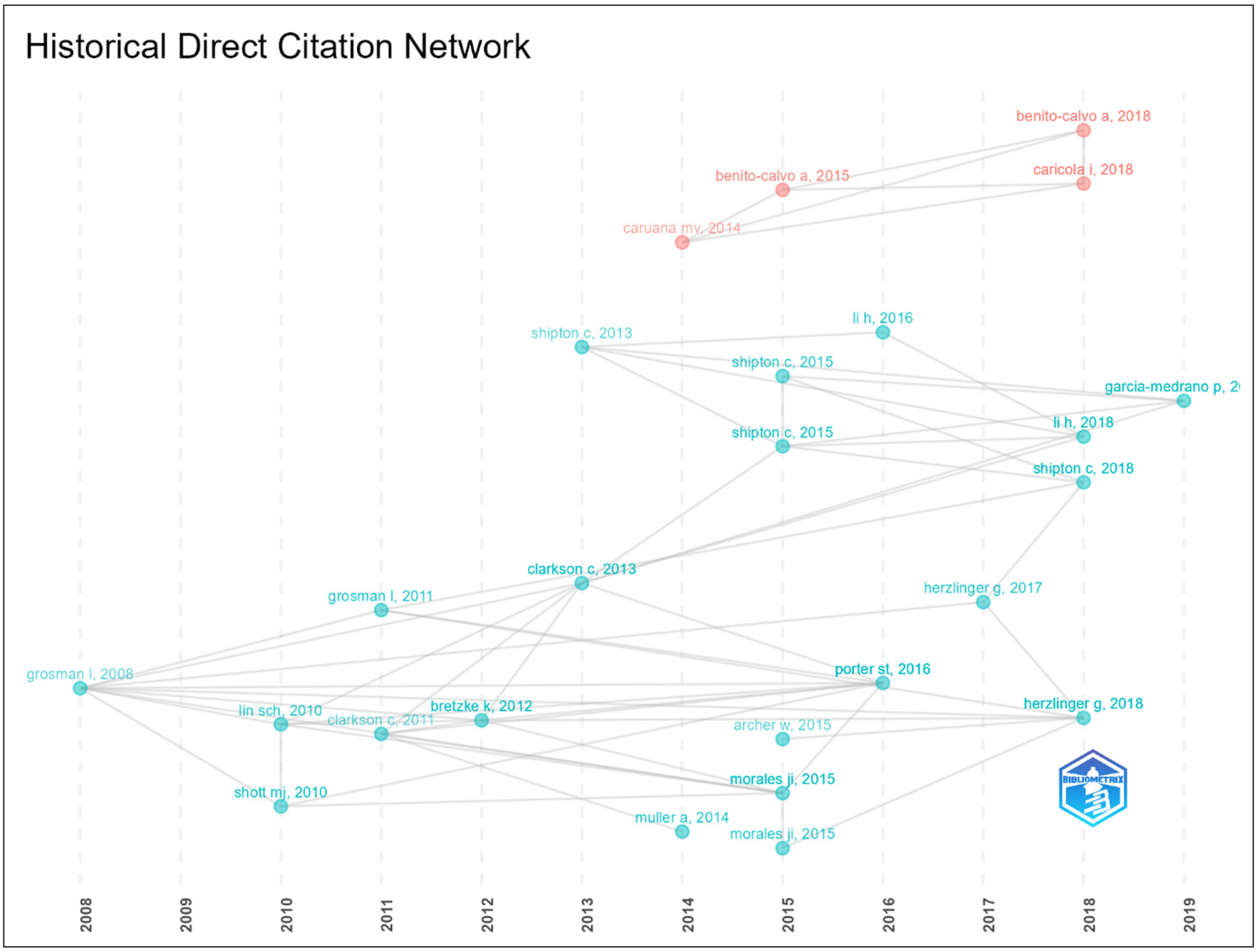

Figure 5 Historical Direct Citation Network of the top 25 papers by number of local citations, i.e. papers that are cited by papers within the dataset. Figure produced using the bibliometrix package.

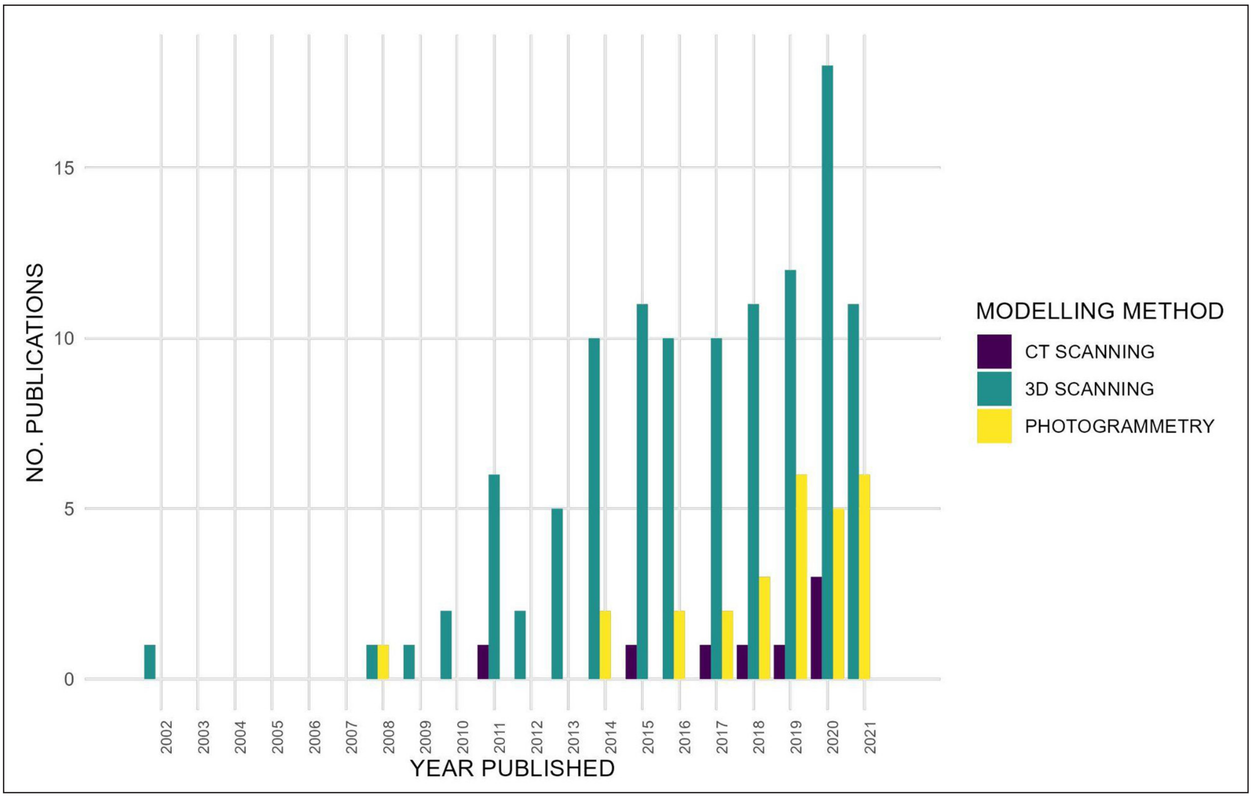

Figure 6 Number of papers published per year by modelling method. Papers published in 2022 have been excluded. Figure produced using the ggplot package.

Studies have found the quality of the resulting models to be comparable, with the primary difference between methods coming down to the cost, time, and skill required to produce a high quality model (Magnani 2014; Porter, Roussel and Soressi 2016; Slizewski and Semal 2009). While not represented in Figure 6, there has been a record number of papers published in 2022 where CT scanning was used, with an emphasis on efficiently modelling large numbers of artefacts (Falcucci et al. 2022; Falcucci and Peresani 2022; Göldner, Karakostis and Falcucci 2022).

A broad range of software has been utilised for 3D lithic analysis (see Figure 7). Early papers tended to not report on what software was used, reflected in the high number of "unreported". Published papers continue to use a mix of proprietary software, such as Avizo (e.g. Li, Kuman and Li 2015; Viallet 2019; Weiss 2015; Wiśniewski et al. 2019) and GeoMagic Design (e.g. Caruana and Herries 2021; Feizi, Vahdati Nasab and Wynn 2020; Lin et al. 2019), custom-designed packages for existing proprietary software, such as GLiMR (e.g. Davis et al. 2015; Davis, Bean and Nyers 2017) and Artifact3-D (e.g. Grosman et al. 2014, 2022), custom freeware such as AGMT3-D (e.g. Herzlinger and Grosman 2018) and open source software such as QGIS (e.g. Paixão et al. 2021; Zangrossi et al. 2019; Zupancich et al. 2019) and CloudCompare (e.g. Benito-Calvo et al. 2018a, 2018b; Cristiani et al. 2021; Dietrich and Haibt 2020; Proffitt et al. 2021). More recently there has been a shift towards using the coding language R, most commonly for geometric morphometric studies (e.g. Archer et al. 2015; Selden, Dockall and Shafer 2018; Weiss et al. 2018; Wiśiewski et al. 2020). The recent and ongoing development of the R package Lithics3D (Pop 2019) will hopefully expand the range of analyses able to be conducted directly in R.

4.3. REGIONAL TRENDS

The geographic distribution of 3D lithic analysis of archaeological material has been heavily concentrated on European assemblages (see Figure 8). West Asian, North American, and Southern and Eastern Africa assemblages all have ≥ 10 studies. Much of the early published research was on bifaces (e.g. Clarkson 2013; Grosman et al. 2011; Grosman, Goldsmith and Smilansky 2011; Grosman, Smikt and Smilansky 2008; Shipton et al. 2013; Sumner and Riddle 2008). The early development of indices for 3D analysis of bifaces provided a methodological template for later researchers to build upon and, consequently, studies have been concentrated on regions which have Acheulean assemblages. Bifaces are not the only artefact that have had a strong influence on where studies have been carried out. The prominence of North America as a study region reflects extensive research on ancestral First Nations American points (e.g. Davis et al. 2015; Gingerich et al. 2014; Sholts et al. 2012).

4.4. CO-WORD ANALYSIS: ARTEFACTS, METHODS, AND RESEARCH THEMES

A network analysis was performed to understand the relationship between keywords. Based on results of the

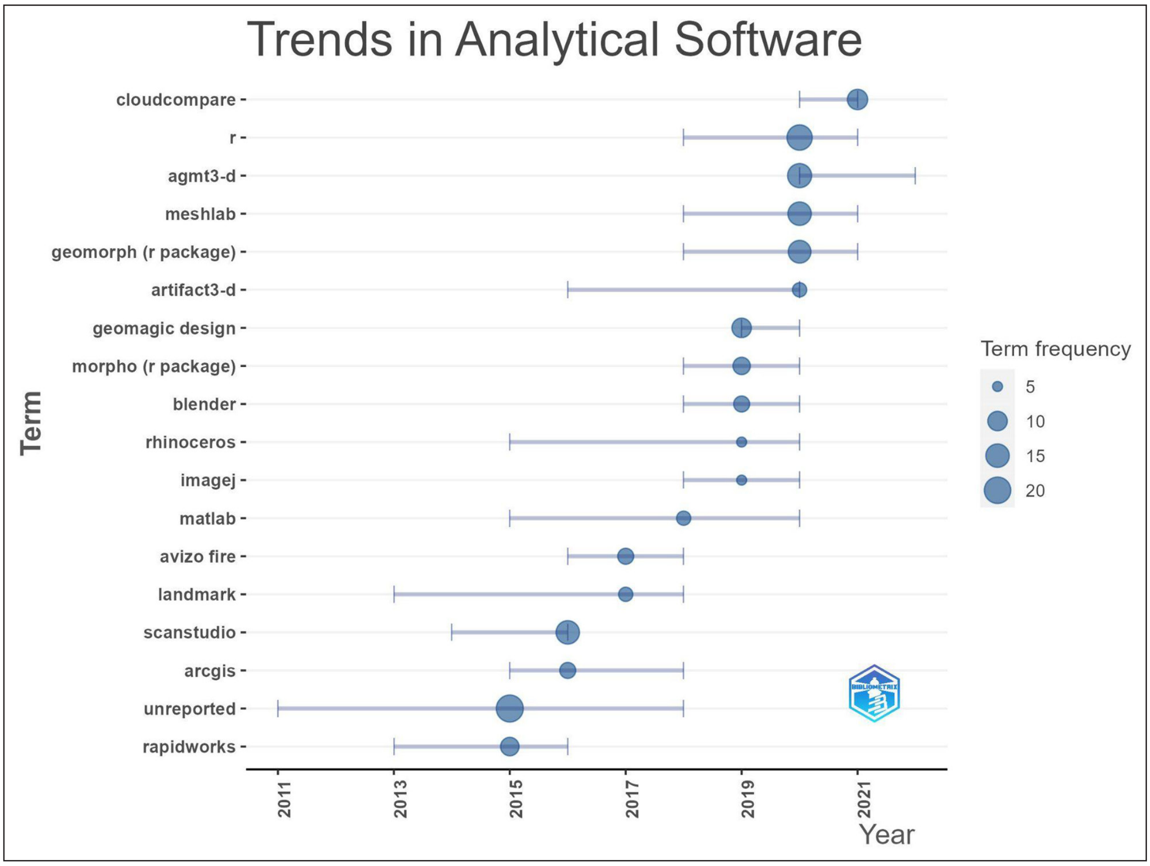

Figure 7 Software trends over time. The dot indicates the median year for each keyword. Word minimum frequency 5, number of words per year 5. The category "n/a" generally refers to studies where the 3D models were used for 3D printing, archival, diagnostic, or pedagogical purposes. Figure produced using the bibliometrix package.

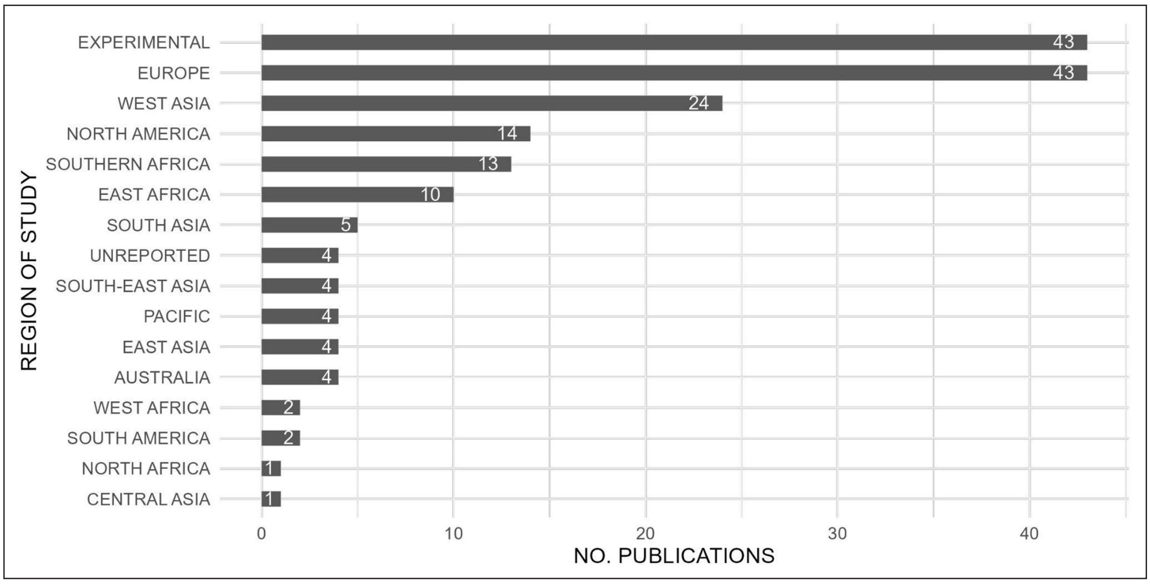

Figure 8 Regions of study by number of publications. Note that studies could be multi-regional and could include both an experimental and archaeological component. Figure produced using the ggplot package.

analysis of the 150 most common keywords across the four categories (see Table 1), five main clusters were identified (see Table 2 and Figure 9).

The centrality of techno-morphological studies of Acheulean bifaces to the field is reflected in the prominence of keywords relating to these studies in Cluster 1 (e.g. "biface", "Acheulean", "handaxe", "large cutting tool", "Lower Palaeolithic" etc.). Analytically these studies explore handaxe symmetry (e.g. Li et al. 2018; Li, Kuman and Li 2016; Presnyakova et al. 2018; Sánchez-Yustos et al. 2017; Shipton, Clarkson and Cobden 2019), and volume loss (e.g. García-Medrano et al. 2019,

KEYWORD (THEMATIC)	NO.	KEYWORD (ANALYSIS)	NO.	KEYWORD (ARTEFACT)	NO.	KEYWORD (INDUSTRY)	NO.
techno-morphological	80	landmark morphometrics	37	biface	54	Acheulean	40
reduction strategy	46	3D gmm	32	core	38	Middle Palaeolithic	18
experimental	43	volume	30	handaxe	38	First Nations American	16
methodological (analytical)	24	scar density index	25	flake	33	Levallois	10
typological	20	cross section	23	point	30	Upper Palaeolithic	9
functional	16	symmetry	22	retouched flake	28	Micoquian	7
methodological (modelling)	14	edge angle	18	other artefact/tool	14	modern	7
archival	9	2D gmm	14	large cutting tool	13	Lower Palaeolithic	6
knapping skill	9	digital elevation model	11	blade	11	Mousterian	6
open science	9	refitting	10	cleaver	11	Protoaurignacian	6

Table 1 The top 10 keywords in the four keyword categories. Note, the numbers in the artefact category do not indicate how prominent or how many artefacts were included in a given study, merely whether they had been modelled and analysed.

CLUSTER 1 KEYWORDS	NO.	CLUSTER 2 KEYWORDS	NO.	CLUSTER 3 KEYWORDS	NO.	CLUSTER 4 KEYWORDS	NO.	CLUSTER 5 KEYWORDS	NO.
techno-morphological	80	*reduction strategy*	46	*point*	30	*retouched flake*	28	*functional*	16
biface	54	*experimental*	43	*First Nations American*	16	*cross section*	23	*other artefact/tool*	14
Acheulean	40	*core*	38	*2D gmm*	14	*edge angle*	18	*digital elevation model*	11
handaxe	38	*flake*	33	*archival*	9	*middle palaeolithic*	18	*hammerstone*	9
landmark morphometrics	37	*volume*	30	*open science*	9	*backed artefact*	9	*usewear*	9

Table 2 List of the 5 most common keywords in each cluster. Cluster 6 has been excluded as it only contained three keywords.

2020a; García-Medrano, Despriée and Moncel 2022; Li et al. 2018; Li, Kuman and Li 2015; Shipton and Clarkson 2015a, 2015b) to address questions on hominid cognition (e.g. Li et al. 2017; Li, Kuman and Li 2016; Shipton 2016; Shipton and White 2020), with a large number of studies using knapping skill as a proxy (e.g. Caruana 2020, 2022; Caruana and Herries 2021; Herzlinger, Wynn and Goren-Inbar 2017).

Keywords linked to geometric morphometrics are also prominent in Cluster 1 due to the widespread use of 3D landmark geometric morphometrics as a tool for analysing bifaces (e.g. García-Medrano et al. 2020a, 2020b; Herzlinger and Goren-Inbar 2019; Presnyakova et al. 2018; Shipton et al. 2013). Keywords relating to geometric morphometrics are also prominent in Cluster 3, e.g. "2D gmm" and "elliptical Fourier analysis", which are strongly linked to North American point studies, though it should be noted that North American point studies use a mixture of landmark morphometrics (e.g. Davis et al. 2015; Davis, Bean and Nyers 2017; Selden, Dockall and Dubied 2020; Selden, Dockall and Shafer 2018) and elliptical Fourier analysis (e.g. Ahmed, Carter and Ferris 2014; Gingerich et al. 2014; Sholts et al. 2012, 2017). Geometric morphometrics has been the most widely used analytical approach in 3D lithic analysis, and has been successfully applied to both flakes and retouched flakes (e.g. Archer et al. 2018; Chacón et al. 2016; Delpiano, Gennai and Peresani 2021; Weiss et al. 2018). Its use is conspicuously absent in studies on cores, where it has proven to have limited analytical application (see Porter, Roussel and Soressi 2019).

Almost a third of all 3D lithic analysis studies include experimental stone artefacts, often to assess a methodology before applying it to an archaeological assemblage. Experimental reduction studies frequently take advantage of the fact that an experimental artefact can be modelled at different stages of reduction (e.g. Clarkson 2013; Grosman et al. 2011; Lombao et al. 2020; Morales, Lorenzo and Vergès 2015). Unsurprisingly, the keywords "experimental" and "reduction strategy" co-

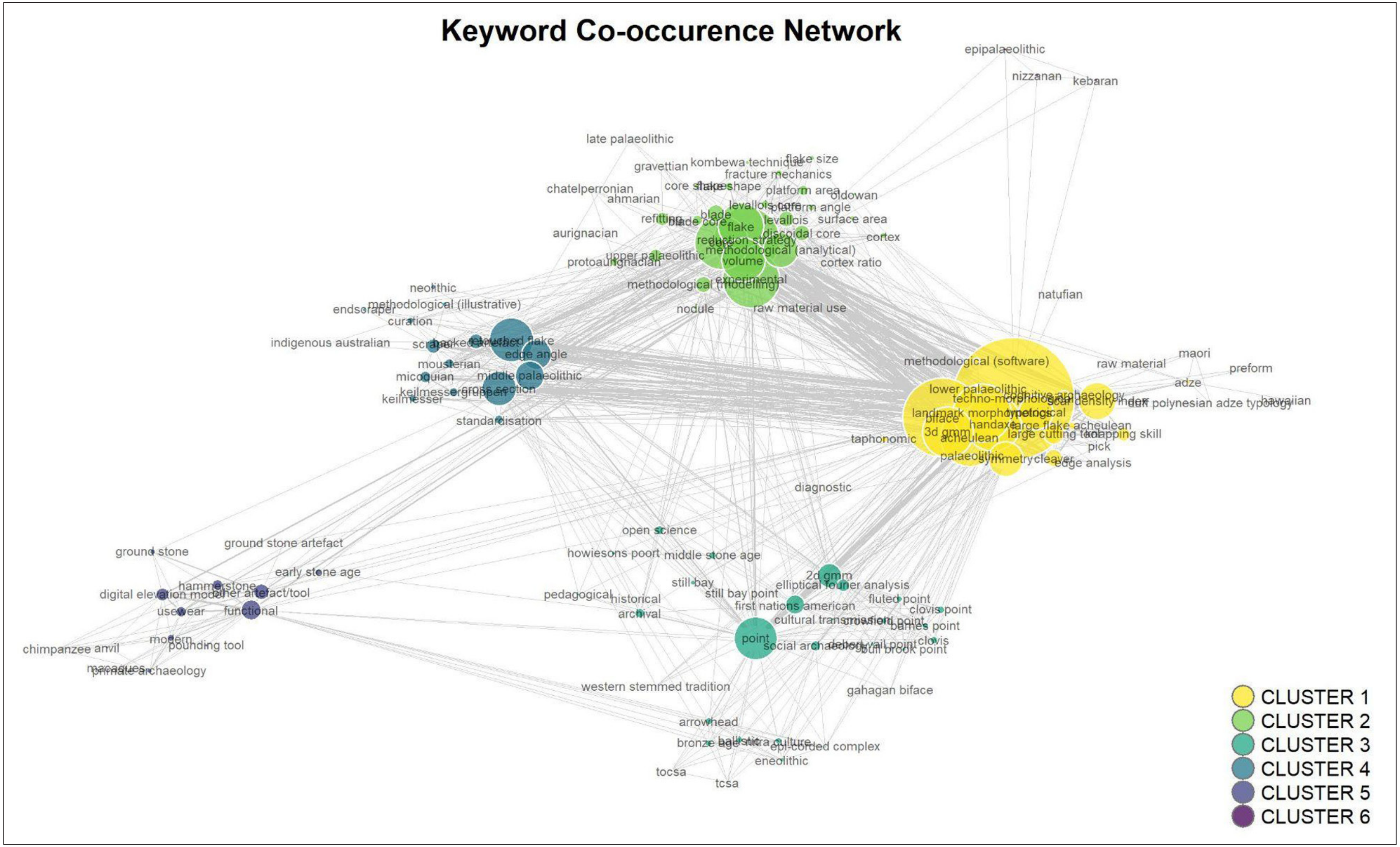

Figure 9 Co-occurrence Network Map of the dataset. The layout algorithm was generated with the "layout_nicely" function in igraph and a Louvain clustering algorithm was used to produce the network. The community repulsion force was 0.5 and the minimum number of edges was 2. Isolated nodes were removed. The size of the node reflects how many times the keyword occurs. Figure produced using the bibliometrix and igraph packages.

occur in Cluster 2. Most noticeably, experimental 3D lithic studies have been used to evaluate older lithic reduction indices and to develop and trial new indices to quantify mass and volume loss (e.g. Clarkson and Hiscock 2011; Lombao et al. 2019, 2020; Maloney 2020; Morales, Lorenzo and Vergès 2015; Ranhorn et al. 2019; Shipton and Clarkson 2015a, 2015b) or fracture mechanics (e.g. Archer et al. 2018; Dogandžić et al. 2020; McPherron et al. 2020; Muller and Clarkson 2014, 2016). A growing body of 3D refitting studies have also been key in the study of reduction strategies (e.g. Delpiano et al. 2019; Delpiano and Peresani 2017; Delpiano, Peresani and Pastoors 2017; Weiss 2015).

Functional studies, defined as papers investigating the physical traces of use, are a relatively new and niche development in 3D lithic analysis. Keywords associated with these studies cluster tightly together (Cluster 5) but are relatively unconnected to the rest of the field. GIS software and CloudCompare are commonly used in these studies to create digital elevation maps to identify macroscopic use-wear on a worked surface (e.g. Arroyo and de la Torre 2020; Benito-Calvo et al. 2015; Caricola et al. 2018a; Luncz et al. 2016). There are three key differences between 3D functional studies and other 3D lithic technology papers. The first is that the use of 3D modelling is primarily used to supplement traditional approaches to functional analysis (e.g. Caruana et al. 2014; Zupancich and Cristiani 2020), rather than supplanting it entirely as is generally the case with techno-morphological studies. Second is that these papers almost exclusively analyse non-flaked stone artefacts or non-artefactual tools (e.g. Cristiani et al. 2021; Dietrich and Haibt 2020; Paixão et al. 2021). The third is the strong link between functional studies and primate archaeology (e.g. Benito-Calvo et al. 2015; Haslam et al. 2013; Luncz et al. 2016; Proffitt et al. 2021). Almost all functional papers include an experimental component (with primate archaeology studies being the notable exception).

Artefact and industry keywords are split across multiple clusters. As discussed above, Cluster 1 is closely associated with Acheulean bifaces. Keywords present in Cluster 3 strongly reflect point studies from both North America (see above) and central Europe (Kaňáková et al. 2022; Kaňáková, Bátora and Nosek 2019, 2020; Nosek and Kaňáková 2021; Weiss et al. 2018). In Cluster 2, keywords are associated with industries with highly standardised reduction strategies, such as blade production (e.g. Bretzke and Conard 2012; Clarkson 2013; Porter, Roussel and Soressi 2019; Valletta, Dag and Grosman 2021; Valletta and Grosman 2021), discoidal cores (e.g. Clarkson 2013; Lombao et al. 2020; Malinsky-Buller, Grosman and Marder 2011; Ranhorn et al. 2019) and other types of prepared cores (e.g. Clarkson 2013; Li et al. 2017; Ranhorn et al. 2019).

5. DISCUSSION AND CONCLUSIONS

3D modelling has been repeatedly described as having a revolutionary impact, or at least revolutionary potential, for lithic analysis and archaeology more generally. But just how revolutionary have 3D lithic analyses been in practice? Both Grosman (2016) and Magnani *et al.* (2020) posed this question, and were sceptical as to whether 3D modelling had achieved its potential.

Contrary to Magnani *et al.*'s (2020) findings for photogrammetry, 3D lithic analysis has moved beyond being proof-of-concept or best practice papers. While new methods and indices are still proposed and tested, most papers are trying to answer archaeological questions, with 3D modelling simply the chosen analytical tool. The repeated and inter-institutional use of AGMT3-D (e.g. Delpiano, Gennai and Peresani 2021; García-Medrano et al. 2020a; Kolobova et al. 2020a; Li et al. 2021; Shipton and White 2020) and R (e.g. Archer et al. 2021; Caruana 2021; Gill et al. 2021; Presnyakova et al. 2018; Sholts et al. 2017) suggests that existing tools can be successfully applied to different regions and artefact types.

In spite of this, it has not been a global revolution. North, West, and Central Africa, Central, South and South-East Asia, Australia, the Pacific and South America combined make up less than a fifth of all studies (see Cardillo et al. 2021; Forestier et al. 2022b, 2022a; Jennings and Weisler 2020; Maloney and O'Connor 2014; Pérez-Balarezo et al. 2022; Prentiss et al. 2015; Weisler et al. 2013 for exceptions). The impact of differential access to resources between archaeologists working in the developed and developing world is well known (Connah 2013; Mapunda and Lane 2004; Marwick, Pham and Ko 2020; Shepherd 2002). While 3D modelling has become more accessible, particularly with the growth of photogrammetry (Magnani et al. 2020), there are still comparatively few studies of assemblages from low-to-middle income countries and even fewer papers have lead authors affiliated with institutions in the Global South. The two main exceptions to this rule are southern and east Africa, however both regions are home to well-published sites that have a long history of attracting international researchers and funding (Connah 2013).

The increasing prevalence of 3D modelling apps on mobile devices may make 3D modelling more accessible, though to date only one published paper has used a mobile device to create (relatively low-quality) 3D models of stone artefacts (Lauer et al. 2020). More concretely, making more analytical tools, code, and datasets open access would allow for a wider range of researchers to contribute to the field, even if modelling technology remains inaccessible. Funding the production and maintenance of large, open access 3D model repositories has been identified as a priority for archaeology more generally in a peri-COVID world where there are moves to reduce the environmental and economic costs of fieldwork (Magnani

2014; Scerri et al. 2020). Perreault (2019) has recently argued that comparative studies of large-scale datasets will solve many of the intractable problems of resolution and scale that are inherent in the archaeological record. By increasing accessibility to datasets, 3D lithic analysis can play an important contribution to archaeology's problem with underdetermination. Grosman (2016) also looked forward to accessible digital lithic datasets to explore global questions. The creative re-analysis and comparison of multiple 2D geometric morphometric datasets has already shown great potential for lithic analysis (Matzig, Hussain and Riede 2021; Way et al. 2022; Wiśniewski et al. 2020).

This paradigm shift towards open and replicable science is behind the increasing prominence of R and other open-source coding languages in lithic analysis (Marwick 2017; Schmidt and Marwick 2020). The benefits of open science for 3D lithic analysis (and vice versa) were recognised early on (Abel et al. 2011; Shott 2013). However, while an increasingly large number of 3D stone artefact collections have been published, (e.g. Di Maida and Hageneuer 2022; Harmand et al. 2015; Herzlinger et al. 2021; Kaňáková, Bátora and Nosek 2020; Nolan, Shott and Olson 2022) the goal of making 3D data open and accessible is still a long way off. Currently only a few of these databases have models that are downloadable in an accessible format (e.g. Boulanger, Miller and Fisher 2021; Porter, Roussel and Soressi 2019). More often, particularly for older studies, models are inaccessible, or are saved in an obsolete or proprietary file format, wasting the time and resources that went into the creation of the model (Davies et al. 2017).

The need for open data will also need to be balanced with the principles of indigenous data sovereignty when working with First Nations collections (Rainie et al. 2019). Making 3D models accessible potentially increases access to collections that would otherwise be physically inaccessible for First Nations communities (Douglass et al. 2017; Magnani, Guttorm and Magnani 2018), though the benefits of digital repatriation for First Nations communities have been contested (Boast and Enote 2013; Cook and Compton 2018). Digitising lithic assemblages also opens up the possibility of physical repatriation, allowing researchers digital access to a version of an artefact while allowing First Nations communities to have physical access and control of their cultural material (Selden, Perttula and O'Brien 2014). First Nations control of 3D datasets would also allow for principles of indigenous data sovereignty to be achieved.

Regional gaps also reflect biases in the kinds of artefacts that are being modelled. The perceived unimportance of unretouched flakes has been identified as a major fallacy in contemporary lithic analysis (Dibble et al. 2017). Within 3D lithic analysis there is a clear preference towards modelling and analysing bifaces, points, and other typologically distinct artefact types, at the expense of expedient or minimally reduced artefacts. While this is not unique to 3D lithic analysis, the often lengthy nature of the modelling process has compounded this bias. While several experimental methodological studies have trialled 3D indices for these artefact types (e.g. Clarkson and Hiscock 2011; Lombao et al. 2020; Muller and Clarkson 2014, 2016), studies on archaeological material remain rare. More 3D lithic analyses of expedient lithic assemblages would allow for a more geographically and chronologically diverse range of assemblages to be studied. More fundamentally, 3D lithic analysis needs to be more mindful of the implications of the finished artefact fallacy (Dibble et al. 2017).

Different intellectual traditions in lithic analysis may also be a factor into where 3D modelling is adopted as an analytical tool. Fundamental epistemological differences have been identified in different national traditions of lithic analysis, which shapes what research questions are asked, what methodological approaches are used and even how stone artefacts are visually represented (Bleed 2001; Hussain 2019, 2021). 3D lithic analysis has many apparent benefits for quantitative studies, often of specific attributes, potentially making it more a valuable research tool for lithic analysts working within a more analytic Anglophone tradition than for those working within the synthetic Francophone tradition (Hussain 2019, 2021). This may be a factor as to why Francophone institutions are not prominent in the dataset, and French-language papers are rare (though this potentially compounded by the bias towards Anglophone papers being listed in academic databases). How this plays out within other traditions of lithic analysis outside the Anglo-Francophone divide is a potential avenue for further research.

Finally, 3D modelling has not revolutionised all facets of lithic analysis. Okumura and Araujo (2019) have argued that geometric morphometric studies of lithics have been limited to questions of cultural evolution and cultural transmission, and there is much greater scope to use these methods to address questions of raw material use, knapping skill and taphonomic processes. Similar criticisms could be made of 3D lithic analysis. While Grosman (2016: 138) is correct in saying that 3D models have been used to examine all stages of the *chaînes opératoire*, studies are not spread evenly across the life-cycle of a stone artefact. There is significant scope to build upon the limited number of studies that look at raw material use (e.g. Goren-Inbar et al. 2022; Lin et al. 2010, 2019; Lin, McPherron and Dibble 2015), discard (e.g. Dubreuil et al. 2019) or taphonomic processes (e.g. Caruana et al. 2014; Grosman et al. 2011). To date, the main source of diversification in the field has come from the growth in the number of functional studies.

The aim of this paper has been to present the historic development of 3D lithic analysis, to explore its social, intellectual, and conceptual structures, and to assess its impact on lithic analysis more broadly. There has been strong growth in the number of papers published, and in the number of researchers who are using the technology. While there have been new intellectual developments in the field, much of the research is still heavily concentrated on techno-morphological studies of typologically distinct artefacts and is geographically concentrated in only a few regions. If 3D lithic analysis is deserving of the tag revolutionary, more work needs to be done to ensure that studies facilitate open and replicable science, that the tools for 3D modelling are globally accessible, that the technology is applied to a wider range of lithic analyses and regional assemblages, and that the field can move beyond some of the fundamental fallacies held within contemporary lithic analysis. Only when it has addressed all these questions, will 3D lithic analysis be truly revolutionary.

DATA ACCESSIBILITY STATEMENT

The data and R code for the bibliometric and quantitative analyses are available at: https://doi.org/10.5281/zenodo.7037023.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Supplementary information.** Additional information on data collection and a full bibliography for all papers in the dataset. DOI: https://doi.org/10.5334/jcaa.103.s1

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COMPETING INTERESTS

The author has no competing interests to declare.

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