Abstract

Within the scope of the Vaulted South Project, an open-source platform was implemented using Omeka-S software to store and interconnect digital data and enable research and dissemination – based on the FAIR principles (Findable, Accessible, Interoperable and Reusable) – of knowledge of vernacular vaulted buildings in Southern Portugal. The corpus was generated by crossing several methodologies and interrelated heterogeneous data on vaults, covering digital transcription, digital photography, laser measurement, terrestrial laser scanning, parametric BIM modelling, and non-destructive inspection techniques such as infrared thermography. This article presents the structure of the database and reflects on the operability of the exploratory methodological approach developed in the project, which encompasses data from several fieldwork campaigns, covering a specific geographical area. It reveals the importance of using innovative methods to achieve accurate data in a more efficient and less intrusive way when dealing with unstudied current buildings. Combining traditional and digital methods of surveyance, data acquisition, data management, communication and scientific dissemination, which are often employed separately in the fields of Architecture, History of Art and Engineering, the Vaulted South Project provided opportunities to bring these scientific fields together as a common field to the History of Architecture and the Digital Humanities.

keywords

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Digital vaulted territories:

development of a cross-tool platform for vaults knowledge

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Introduction

This article aims to present and discuss the methodological approach developed in the Vaulted South Project.[1] The project combined traditional and digital methods of surveyance, data acquisition, data management and science communication and dissemination, often employed separately in research fields of Architecture, History of Art and Civil Engineering, and applied in this project to vernacular vaulted buildings knowledge, demonstrating an exploratory character in the scope of the Digital Humanities.

The Vaulted South Project had an exploratory component in the field of the History of Architecture and Construction that emerged from the need to fill in the gap in studies on vernacular vaulted houses and construction processes. In conventional historiography, methodologies have mostly been based on archival research, fieldwork case studies and comparative methods. However, this project developed research based on interdisciplinary perspectives and methods in order to intersect the study of architectural treatises and construction manuals, complemented and compared with analysis of vaulted buildings in the Portuguese regions of the Alentejo and the Algarve, as surveyed through photography, laser measurement, terrestrial laser scanning (TLS), and then inspected using non-destructive techniques such as infrared thermography.

In our interdisciplinary approach, vaults were taken as connectors between the theoretical geometry referenced in books, the built geometry of buildings, and

the parameterised object files of 3D models. The transition from analogue to digital and parameterised geometries through the modelling of vault types and the creation of a BIM library (a catalogue of BIM object files) enables scientific comparison between vault case studies along with their re-use in future contexts.
The main activities of the Vaulted South Project were: 1) the compilation and study of treatises and construction manuals about vaulted systems used in Portugal between the 16th and the 19th centuries; 2) the survey and study of vernacular vaulted houses in southern Portugal, namely in the regions of Baixo Alentejo and Algarve; 3) the identification and study of influential buildings in the surroundings of vernacular vaulted houses that may have served as sources of knowledge; 4) the characterisation of vault geometry, assemblage systems and materials; 5) the generation of a corpus based on written knowledge, vernacular buildings, vault typologies and geographical distribution; 6) the creation of digital, three-dimensional and parameterised data; 7) the creation of thematic routes; and 8) the storage and curation of the corpus on an open-source online platform, as a structured and georeferenced database, made available to the scholarly community and the general public.
Discussion of the Vaulted South Project methodology will be based on case studies involving different sources, scales and methods of approach, taken from 21 handwritten and printed documents, 190 buildings surveyed and georeferenced in Baixo Alentejo and Algarve, 41 representative technical drawings of them, 5 thematic optimised routes covering 35 buildings in Moura, and an in-depth study of two buildings in Serpa: the Quinta de São Brás house and Ficalho Palace.

Vaults under study: a digital methodological approach

Vernacular buildings and architectural treatises are rarely connected or even documented in the archival sources. However, to fully understand vernacular construction systems, it is necessary to study the textbooks and treatises used to instruct not only architects but also builders. The challenge of researching vaults is marked by the disparate nature of sources (oral testimonies, written documents and buildings) within specific social and geographical contexts that rarely have the opportunity to be read simultaneously with a unified scope. Many differences stand out when dealing with written documents – both handwritten and printed – and vaulted buildings, from erudite buildings to common houses. This dichotomy was stressed in the project's tasks and specific objectives.

The main goal of the task 'Learned Sources' was to research how architectural treatises and textbooks written for the master builders' instruction could provide important information about vaulted systems, with their geometry, building materials and construction techniques (Conceição and Pacheco 2023; Cardamone and Martens 2017). Previous research demonstrated that architectural writings often include prescriptions about construction techniques, namely vaulted systems, with stone vaulting being the only method usually studied (Pacheco 2021; Conceição 2020). Thus, this kind of data from architectural writings, both manuscript and in print, widespread in Portugal between the 16th and the 19th centuries, was surveyed and extracted to develop comprehensive research on vernacular vaulting and its connections with the so-called erudite or learned architecture.

The 'Cultured Buildings' task sought to understand how religious, military, infrastructural and noble buildings could work as a source of technological knowledge, formal composition and inspiration for detail. In other words, how construction sites work as places for knowledge exchange and transmission (Costa et al. 2023; Pacheco 2021). In this case, formal and constructive comparison between cultured and vernacular buildings was the method to clarify the hypothesis and to research the boundaries and contact points within architectural knowledge, which are usually perceived as opposites. It was noted that vault constructive systems are the link between cultured architecture as perceived as a reference constructional model for vernacular architecture.

In turn, 'Vernacular Buildings' explored the apparent relationship between place and form, or place and time (Joyeux-Prunel 2020), by assessing specific constructional features. This was carried out by looking at buildings as primary sources, through surveying and mapping vaulted houses still extant in the regions of the Alentejo and Algarve (south of Portugal), built between the late 18th and the early 20th century. On-site research is one of the most profitable methods of enquiry in popular architectural studies, since these vaulted houses were built thanks to the oral transmission of knowledge and technical rules, without support from educated experts and designers, nor documents.

The survey focused on vault materials and constructive systems in the Baixo Alentejo region, with the hypothesis of the predominance of brick vaults with the 'bed' face showing (*à face)* constructive system, in the West Guadiana river line (at Reguengos, Portel, Alvito and Vidigueira) and the East Guadiana river line (at Moura, Amareleja, Safara, Serpa and Vila Verde de Ficalho). In the Algarve region, with the hypothesis of the brick vaults with the 'stretcher' face showing (*ao cutelo*) constructive system predominating, surveys were conducted in the windward region west of Faro (Monchique, Silves, Paderne and Boliqueime) and the leeward region at east of Faro (Loulé, São Brás de Alportel, Estói, Olhão, Fuzeta, Moncarapacho and Tavira),

among other relevant towns. This task articulated the theoretical references concerning learned written sources and references to cultured buildings with vernacular houses, which formed the basis for the study of the vault systems task.

Next, the task on 'Vault Systems and Materials' focused on the prospection and evaluation of vaulted constructive systems, which occurred during the survey of vernacular buildings. This covered the variety of systems (with and without formwork) and brick vaults with 'stretcher' or 'bed' face showing, also called timbrel vaults (locally called *abobadilha*), and materials and finishes (bricks, stones and mortars), and vault geometries from the simplest to the most complex (barrel, recessed barrel, groin, ribs, sail, domical or cloister, lunette and dome) and their variations of different generator arches, helped when possible by infrared thermography, a non-destructive prospection technique.

In the context of the fifth task, 'Learning from Vaulted South', in the field of the Digital Humanities, the corpus of knowledge on vernacular vaulted houses was fed with transcriptions, surveys, observations, analyses and reflections about the history, architectural and constructional features of such buildings. Once digitised, data was compiled, processed and stored on a database on an online platform, accompanied by photographs, technical drawings and three-dimensional digital models of buildings and parameterised models of vaults and arches, the application of which can be extended outside the project as a BIM library. The parameterisation process involved deciding what could be measured and how, according to the purpose of analysis and comparison (Drucker 2021).

Finally, besides the process of choosing the most suitable platform, the main challenges of the 'Vaulted South Platform' were structural organisation, operability workflow, and the curation of the data to provide access to stored items that were collected and processed or digitally created, in a way that facilitated the digital synthesis of collected and created knowledge about the vernacular constructive system of vaults while making it available online.

Structuring and correlating vaults

The 'Vaulted South Platform' was developed to enable the organisation, storage, categorisation, curation, visualisation and filtering of linked data of different kinds in a geo-referenced and open-access digital database. The criteria for choosing the software to create the digital platform was based on the three 'Es' – Economy, Efficiency and Effectiveness – and the FAIR principles – Findable, Accessible, Interoperable, and Reusable (EC 2016). It was essential for the platform to be open-source and freely accessible for long-term use.

The platform was implemented using Omeka-S, an open-source web-publishing and content management system (CMS) specifically designed for the Humanities (Omeka 2024), increasingly used by the scientific community to digitise galleries, libraries, archives, and museums (GLAMs). Omeka (Classic) was launched in 2008 by the Roy Rosenzweig Center for History and New Media at George Mason University (Hardesty 2014). Since 2016, the Omeka project has been developed by the non-profit Corporation for Digital Scholarship, with the release in 2017 of Omeka-S, a new version designed for institutional use, providing the capability to host multiple sites drawing from a common pool of resources. Omeka has been applied for functions such as digitisation, metadating, geolocation and online publishing per international standards (Brown 2020). One of the key strengths of Omeka as an open-source web tool is its thriving community, which contributes to the development of numerous plugins and presentation themes, enhancing the core software functionality and enabling a wide range of features. At NOVA FCSH University, the use of Omeka-S to develop research projects is increasing thanks to the support and hosting services of the Digital Humanities Lab (DHLab).

Previous experiments with the use of Omeka software applied to the Humanities with computational methods in GLAMs have demonstrated both its potential and some shortcomings and technical challenges. In 2008, the Metropolitan New York Library Council (METRO) used Omeka to create a directory of digital collections 'as a test to determine the viability of this platform for member libraries interested in using Omeka to build and deliver their own collections' (Kucsma 2010). The *Routledge Companion to Digital Humanities and Art History* reports testing of Omeka-S on the history of the Association of European Historians (AsE), a network of historians from several European and non-European countries founded in 1983, devoted to European historiography. The use of Omeka-S, in combination with traditional methodologies and network analysis, allows a more in-depth examination of the AsE network and its historiographical paradigm (Brown 2020). In another example of the implementation of Omeka, the Indiana University Libraries provided access to fragile items by making them available through online exhibition, revealing the benefits of Omeka for different types of digital library collection exhibits and different levels of technical expertise, although recognising it is 'limited in the ability to manage multiple exhibits of separate digital collections' and the need to improve tools for the GLAM community (Hardesty 2014). The adoption and implementation of metadata standards at Omeka also raises some different perspectives on what it means to 'adopt a standard' among Omeka creators and its users, insofar as 'these values are not equally shared amongst all stakeholders in a digital library ecosystem' (Maron and Feinberg 2018). Omeka-S was chosen as the platform for the project to guarantee the operation

of the project's online activities and for the long-term lifecycle of the digital work and platform. In this way, different data (images, texts, maps, three-dimensional models, and media files) have been combined and subjected to computational processing (data mining and statistical analysis).[2]

Some of the data used at the first stage of the project were collected in analogue form from manuscripts and printed architectural treatises and manual constructions, and thus needed to be digitised through a process of mediation: digitised, transcribed, sectioned, uniformised and linked (Drucker 2021). The same process was followed for the metrical measurements captured during fieldwork of the buildings that needed to be drawn, scaled, typified, uniformised and linked in digital format. Other data collected directly in digital format and similarly made uniform and linked together included photographs of buildings and houses and volumetric and thermographic prospections of selected case studies. New data was directly created in digital format through the use of software, committing to maintain uniformisation and linkage.

The design of the Vaulted South database with Omeka-S (Version 3.2.3) involved the hierarchisation and characterisation of the research items, their organisation according to topic, and their linkage according to the logic underlying the software and the implementation of the metadata standards. Five types of items were used in the research: 1) words comprising the technical vocabulary; 2) written documents comprising quotes from architectural treatises and construction manuals (handwritten and in print); 3) buildings comprising case studies of residential houses and religious buildings, through the use of photographs, drawings and coordinates; 4) drawings consisting of uniformised plan representations of buildings; and 5) parameterised 3D models of the types of vaults and buildings **[Fig. 1]**.

For the creation of these types of items, specific 'Resource Models' were developed: 'Vaulted South-Glossary', 'Vaulted South-Written Elements', 'Vaulted South-Built Elements', 'Vaulted South-Drawn Elements', 'Vaulted South-3D Elements', and finally 'Vaulted South-Vaults', which connects vaults listed in the other Resource Models. Each Resource Model is composed of a set of values with different terms that are preferably part of a metadata standard vocabulary. The most common terms used (title, author, date, quotes, type, etc.) are part of the Dublin Core vocabulary.[3] Each term is assigned an unequivocal ID and a customised label for more intuitive use when visualising. Other metadata standard vocabularies are available to combine and use in combination with DCMT to create the resource models 'Glossary', 'Written Elements' and 'Drawn Elements'. The resource model 'Built Elements' needed its own ontology to better adapt to the buildings' terminology. For that, a 'Custom Ontology' file was created and imported to the Omeka-S, being composed of terms adapted to buildings' specific needs, such as 'typology',

[2] According to Drucker (2021, 1), the components of Digital Humanities work are expressed in the sequence materials, processing and presentation, and are based on digital files and computational processes.

[3] Dublin Core vocabulary is Omeka's default vocabulary, also known as the Dublin Core Metadata Terms (DCMT).

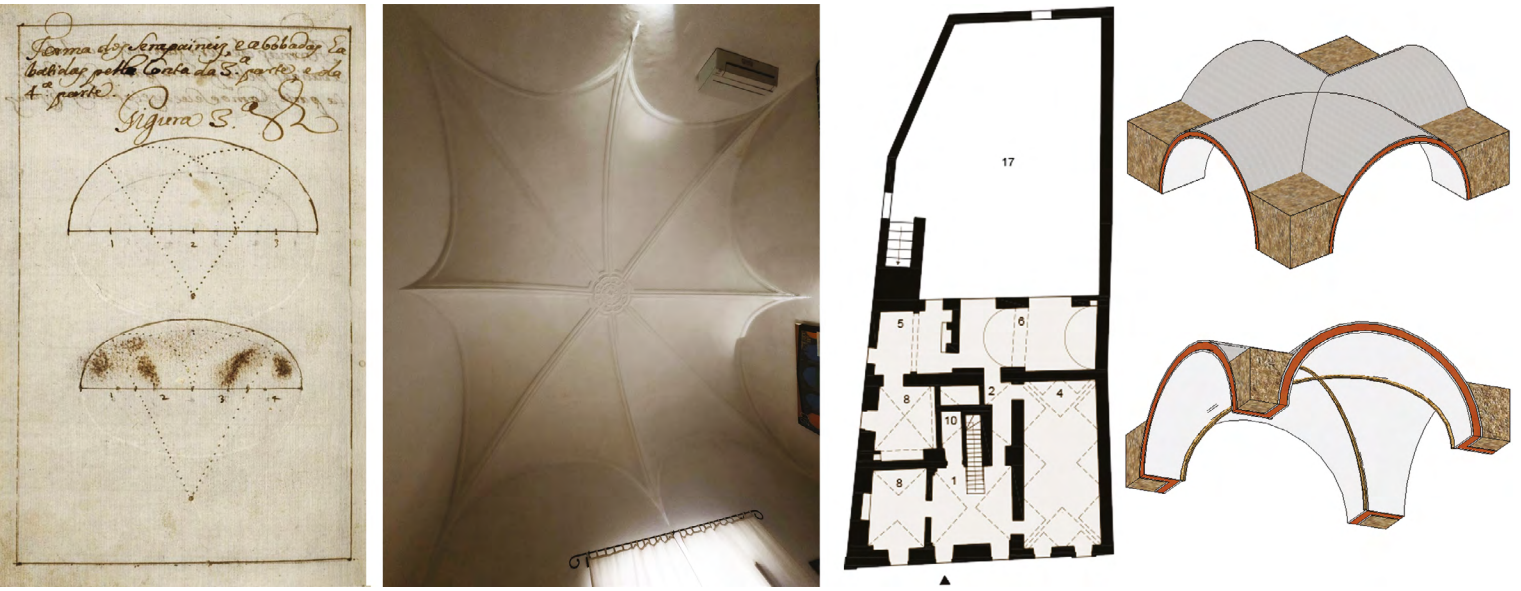

Fig. 1 Different types of items linked at the platform, from manuscripts, to photographs, architectural plans and 3D parameterised models of vaults. Source: Tinoco 1660, [fol. 43v]. BNP Cod. 5166 (left); authors, 2024 (rest).

'category', 'context', 'number of floors', 'materials', 'vault types', 'constructive systems', among others (VSEC – *Vaulted South Elementos construídos*).

Open fields include titles, authors, and quotes, while others offer predefined multiple choices to avoid errors when processing the data. In the latter cases, a list of permitted answers was created through the customised vocabularies Omeka module. Among other values, the value 'vault types' was applied, referring to items of the 'Vaulted South-Vaults' Resource Model. In addition to the values, items also have multimedia files attached (images, files, links for URL, HTML, YouTube and other digital sources), as well as location coordinates on an open source, geo-referenced and synchronised map (powered by OpenStreetMap). Therefore, the items are attached to one or more sets of items and one or more webpages.

Items were aggregated in 'Item Sets' according to type: 1) word items in 'Glossary'; 2) document items in 'Written Elements'; 3) building items in 'Built Elements'; 4) scaled drawing items in 'Drawn Elements'; and 5) 3D BIM model items in '3D Elements'. Items were linked to each other through each of the ten types of vault geometries found in the Glossary (Barrel, Recessed barrel, Groin, Ribs, Domical, Lunette, Octopartite, Reticulated, Sail, and Dome). Item Sets are part of the navigation bar on the webpage (under the same name) and allow lists with the same type of items to be visualised. The 'DigitalMuret' theme was chosen from a set of Omeka themes to give the database a visual appearance as a webpage.

A digital 'Map' was added to the navigation bar to provide a synchronised visualisation of the coordinates of the 'buildings' items in the south of Portugal,

allowing users to navigate, zoom and search, and opening up 'possible encounters or proximities (…) and unsuspected connections' (Joyeux-Prunel 2020). Indeed, digital maps are a way to share findings, bridge the past and present, unlock spatial and social relations, and bring together academic and popular users (Terpstra 2016). The map visualisation is enabled by Omeka's 'Mapping Module'. Other modules were also incorporated into the Omeka-S database, such as the 'Custom Ontology', which makes it possible to create specific classes and properties to describe resources when no standard ontologies are available, the 'CSSEditor' to customise the visualisation aspects of the webpage, and the 'Bulk Export' tool to export the database in *.csv format to be processed by external software, such as ArcGIS for calculating the most efficient routes (i.e. optimised routes) and for statistical analysis.

Creating the database with Omeka allowed multiple, simultaneous users with different levels of permissions to create, modify and/or visualise contents. Mainly, three groups interacted in the database: art and architectural historians in the Glossary and Written Elements, architects and architectural historians in the Built Elements and Drawn Elements, and architects and engineers in Maps and 3D Elements. We envision the Vaulted South database and maps, which contain the corpus of the knowledge of vernacular vaulted houses, as a kind of 'Digital Vaulted Territories'.

Collecting vaults from books and buildings

The challenge of crossing information between 'written' and built vaults, coming from starkly different contexts of erudition in the vernacular setting of southern Portugal between the 16th and 19th centuries, requires an understanding of learned sources that were no strangers to the vault construction sites, and were thus likely to influence smaller-scale constructions and builders. Simultaneously, the search, identification, study and characterisation of the vernacular vaults in unexpected contexts were pivotal to assessing how far a construction system reached. Taking the most representative and better-known local buildings (religious, aristocratic, military, and infrastructural) with vaults as the starting point, the search for 'anonymous vaults' in the surrounding areas began, and so these findings were entered into the discourse of construction history. Consequently, the project compiled 21 handwritten and printed documents, surveyed 190 buildings in a georeferenced map of the Alentejo and Algarve regions, analysed routes for 35 buildings in Moura, and studied the Quinta de São Brás house and the Ficalho Palace in Serpa in depth.

From architectural writings to digital 'Written Elements'

Architectural literature frequently outlines construction methods, particularly focusing on vaulted systems, with stone vaulting being the primary technique examined. To conduct comprehensive research on vernacular vaulting and its relationship with scholarly architecture, it is essential to review the treatises and construction manuals on vaulted systems used in Portugal from the 16th to the 20th centuries. A selection was compiled of 21 architectural books and construction manuals, representative of those found in Portugal referencing vaults as a general roofing system.[4] These dataset items were selected from an initial survey within the broader scope of the so-called architectural treatises. The review was designated as 'Written Elements' to reflect the variety of texts in terms of internal consistency and cultural context.

The primary goal of the sources compilation was to investigate the origins and definitions of the vault, as a concept, focusing on both construction and cultural aspects from the scholarly sources. Starting with modern editions of Vitruvius' book and Alberti's treatise, and including the systematisation of the Encyclopedia and technical knowledge cultivated in the 19th century, the selection was based on the richness and representativeness of the content. Manuscripts and printed works were chosen for their chronological, typological, and geographical diversity, utilising resources from the National Library of Portugal and the Library of the National Palace of Mafra.

The ultimate aim of this section was to provide the material needed to explore the connection between theoretical and codified knowledge about construction techniques and vernacular vaulted constructions, and to examine the transmission of such knowledge.

Items in 'Written Elements' are composed of four sections: 1) Selected images of the document; 2) General information section identifying the book (title, author, date, editor, place, type, etc.); 3) Content section, featuring transcriptions relating to vaults followed by the list of vaults and materials mentioned in the transcriptions, linked to the Glossary; and 4) References section with the bibliography, access to the digital repository and digital images of the written sources. The Resource Model used in this Items Set mainly consists of a combination of metadata standard vocabularies from the Dublin Core (*.dcterms) and Bibliographic Ontology (.*bibo) ontologies.

Since the books are written in different languages – Portuguese, Spanish, French, Italian and Latin – the digitised pages containing quotes relating to vaults were fed into Transkribus, an AI-powered tool for text recognition, image analysis and structure recognition of historical documents, for the automated transcription of

[4] For the complete list of documents consult the section Written Elements – Vaulted South

writing and searching (Baudry 2023). Transkribus has publicly available AI models, in particular the 'Transkribus Print Multi-Language', developed by the Transkribus Team, which was applied to the printed books mentioned before. The use of Transkribus increased the accuracy of transcriptions made available on the Vaulted South platform **[Fig. 2 left]**.

From vaulted buildings to digital 'Built Elements'

Research on cultured buildings as sources for technological knowledge, formal compositions, and inspiration for details – with construction sites serving also to exchange and transmit knowledge – was essential for the formal and constructional comparison between erudite and vernacular buildings. A significant number of vaults in buildings was registered, creating a representative corpus (190 buildings: 154 residential and 36 religious). A digital collection was generated, encompassing constructional features such as the type and number of vaults in a building, constructional systems, materials, and the function of the building, among others.

Since one of the research themes was to identify the erudite sources for vaults, or at least schooled/educational/cultured sources in popular contexts, the survey of buildings began with those with an erudite character, such as palaces, noble houses, convents, monasteries, churches and chapels, more likely to have been influenced by technical knowledge from written sources, in the same way that the systematisation of current houses and the know-how of master builders of vaults, transmitted over the last centuries, were integrated.

Case studies were selected taking into account the richness of the constructions and their chronological and typological (occasionally, geographical) representativeness, bringing together erudite and popular buildings. Data acquisition methods included photographic surveying, metric laser measurement, terrestrial laser scanning, and thermographic surveying of the exterior and/or interior of the buildings, to be discussed in full in the next section.

The 'Built Elements' set is made up of 190 items, corresponding to a sample of buildings with brick vaults used for roofing or floor systems, located in south Portugal. This compilation was aimed firstly at querying the variety of vault geometries and construction systems, their geographical and chronological spans, and at further analysing their convergence with written sources. This dataset was gathered from fieldwork campaigns conducted in the Moura, Vidigueira and Serpa regions in Baixo Alentejo and in the Algarve region, consisting of an initial exploration within a broader territorial context. The designation 'Built Elements' is intended

to encompass the various types of buildings, considering their uses, settings, and construction consistency, as well as their cultural context.

The 'Built Elements' set is organised around the Alentejo region (with 113 items), comprising the towns of Alvito, Amareleja, Brinches, Moura, Portel, Safara, Serpa, Vidigueira, and Vila Verde de Ficalho; and the Algarve region (with 77 items), comprising the towns of Boliqueime, Faro, Fuzeta, Loulé, Moncarapacho, Monchique, Olhão, Paderne, Portimão, São Brás de Alportel, Silves, and Tavira.

Each item in the 'Built Elements' comprises six sections: 1) Selected images of the buildings: 2) General information (e.g. title, address, place, region, coordinates, etc.); 3) Form and use of the building (e.g. type of use, category, classification, number of floors, context, allotment, building genesis, etc.); 4) Vaults (e.g. type(s), quantity, construction and decorative elements, materials, constructive techniques, interior and exterior coatings, etc.); 5) Access to buildings (type of property and access); and 6) Digital architectural drawings linked to the 'Drawn Elements' set.

The Resource Model used in this Items Set is composed of 35 terms (around half of which are mandatory), mainly from a Customised Ontology, VSEC (*Vaulted South Elementos construídos*) (*.vsec), purposely created for the project, as there was no metadata standard vocabularies suitable for the characteristics of the item.

As the Vaulted South Omeka-S database has the dual function of storing and visualising data, some of the terms attached to items were left public and others private, according to their role in research. This can mean, for instance, that some data are only stored for management and processing, such as that data used for statistical analysis or for preparing routes **[Fig. 2 centre]**.

Creating digital vaulted territories

At the core of the Vaulted South Project is the aim of transforming analogue data of knowledge about vaults into digital formats so as to enable scientific comparison between case studies and their future re-use in other research contexts. These contents were named 'Digital Vaulted Territories' to reflect the diverse and interconnected knowledge of vaults anchored in the digital domain. The digitalisation of textual elements concerning vaults – via transcribing passages from digitised documents – to a metadata standard vocabulary Resource Model, integrated into the 'Written Elements' section, was already approached in section 3. Thus, the vaults and the vaulted buildings surveyed and registered in 'Built Elements' were subjected to various digitalisation processes.

Regarding the territorial scale, coordinates data in the 'Built Elements' section were used to generate a map with the buildings geo-referenced. This composite map

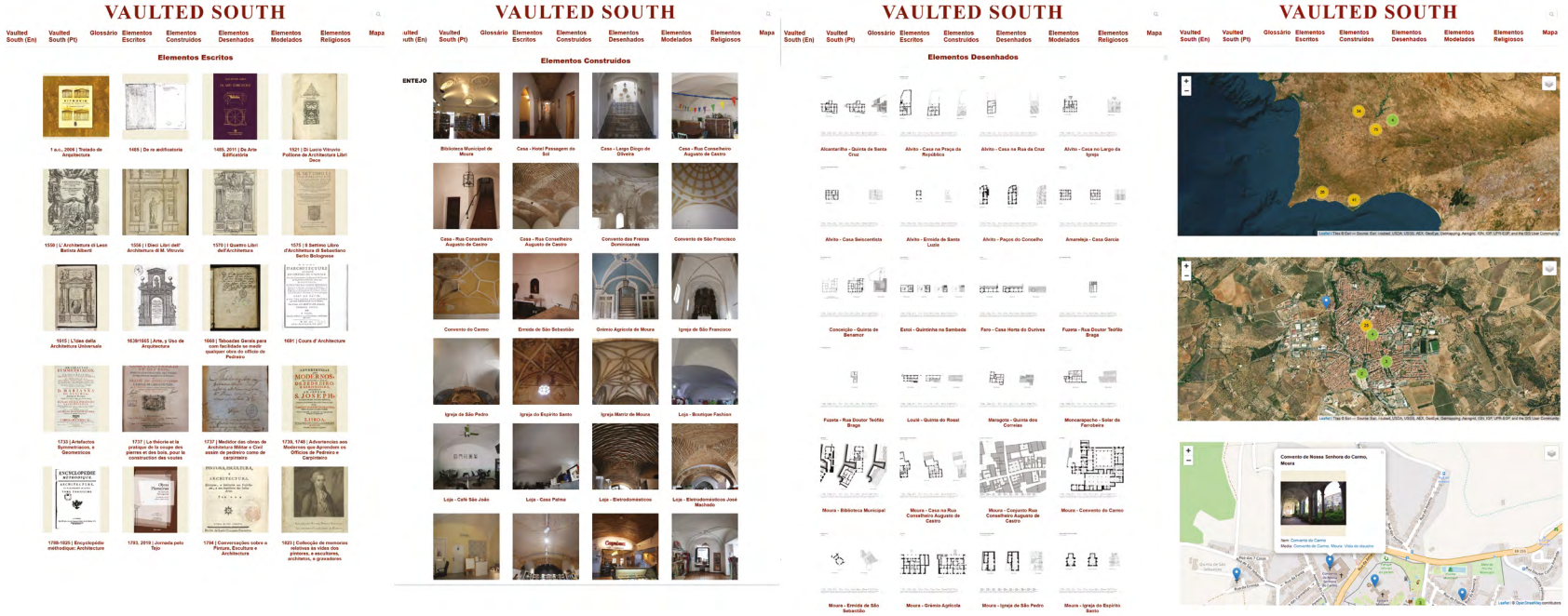

Fig. 2 Item Sets at the Vaulted South platform powered by Omeka-S: Written Elements; Built Elements; Drawn Elements; and Maps (from left to right). Source: Vaulted South Project 2024.

was added to the navigation bar of the webpage to provide a simple visualisation of the locations of the 'buildings' items in south Portugal. Although the Omeka-S does enable map visualisation through the 'Mapping Module', the map generated does not allow data manipulation for run analysis. To address this constraint, the database was exported to *.csv format and imported into Geographic Information System (GIS) software to generate virtual routes.

Creating digitally generated routes

The use of GIS tools to define virtual routes with the goal of promoting architectural knowledge has been explored by Finno et al. (2022), namely by suggesting a methodological workflow based on themed virtual tours of 360° scenes, integrating a variety of informative contents and digital products as external hotspots/switches. GIS maps should be designed for easy access online through websites and smartphone apps, allowing for their customisation and adaptation to various audiences. These maps can offer an immersive experience that engages both virtual and physical visitors, fostering universal access to knowledge and cultural heritage (Volzone et al. 2022). On the other hand, Fauzi et al. (2022) highlight the importance of Web-GIS routes in combatting over-crowding at tourist attractions. Indeed, in the

Fig. 3 Generation of optimised route in GIS environment for vaulted buildings in Moura, Alentejo. Source: authors, 2024.

scope of a public presentation of the Vaulted South Project in the European Heritage Days 2023[5] in Moura, it was understood that thematic routes could be particularly efficient in promoting and disseminating built heritage knowledge.

The automatic route generation for determining the most efficient path was made using the ESRI ArcGIS PRO Network Analyst module, considering the Dijkstra algorithm and the Euclidean distance as a cost function. For the city of Moura, four pilot optimised routes were generated, starting at the Moura City Council building [Fig. 3]:

1. The Moura Vaults Route, including the surveyed buildings in the town of Moura, covering a total distance of 3,260 km with 35 stops and informative bullet points about the buildings' uses;
2. The Religious Vaults Route, comprehending a tour across the religious buildings in Moura, such as churches, chapels and convents, at a total distance of 2,503 km with 8 stops;

[5] This public presentation at Moura European Heritage Days 2023, entitled 'The vaulted Alentejo', is available in Talking with Vault Builders, in documentary format.

3. The Vault Typologies Route, to discover the variety of vaulting types and geometries by visiting buildings with more than three different types of vaults, along 2,254 km with 8 stops;
4. The Most-Vaulted Buildings Route, featuring a short visit to three buildings with more than 10 vaults, with a distance of 1,450 km.

Creating 2D digital vaulted elements

Different scales and complexity levels of digitalisation were addressed according to the objectives, from the scale of urban blocks to the geometry of vaults. From the buildings surveyed and made available in 'Built Elements', digitally scaled architectural plans were elaborated for an urban block in the historical centre of Moura, comprising 18 buildings located on the same street, and 40 individual buildings located in 15 other towns. The process of representing the drawings was an effort to record, standardise, analyse and communicate the built vault heritage. A template layout for the drawings webpage was developed with symbols for the types of vaults, room uses, the representation of scales and building orientations to enable the categorisation of building and vaults. The drawings were digitally elaborated using Autocad 2D, a Computer-Aided Design program from Autodesk, and curated as items in the Omeka-S database in a set designated 'Drawn Elements', in line with 'Written Elements' and 'Built Elements', which were linked to the drawing plans. The Drawn Elements set reflects the need to compare different types of built vaults, construction systems and uses in a standardised way to enable research into regional trends, exceptions and similarities between erudite and popular examples.

Creating 3D digital vaulted elements

While it is well known that the digitalisation of objects, particularly buildings, is a complex task that requires considerable amounts of time and human and monetary resources, the practice does enable scientific comparison between objects and their re-use in other contexts (Drucker 2011). In this sense, two buildings particularly relevant for the study of vaults were chosen for complete three-dimensional study using Terrestrial Laser Scanning (TLS) for the acquisition of point clouds, a discrete set of data points in space positioned according to their coordinates (X, Y, Z) and later imported to be converted into a 3D model in a Building Information Model (BIM) environment using the Autodesk Revit 2024 software.

Bagnolo and Argiolas (2021) describe in detail the Scan-to-BIM workflow used to generate the vaulted system of the main body of the church of Nostra Signora della Speranza in Cagliari, Italy, emphasising the critical role of employing a TLS (Terrestrial Laser Scanning) system to guarantee precision in the structure's geometric representation. In Portugal, Trovatelli et al. (2023) proposed a parametric approach to model a lunette vault and evaluate its structural behaviour in a chamber in the National Palace of Sintra.

The Quinta de São Brás house and the Ficalho Palace, located in Serpa, were the chosen case studies for 3D modelling due to their complexity and richness of vaults and building techniques. Quinta de São Brás[6] is a rural recreational home located five kilometres south-southwest of Serpa and built after the Great Earthquake of 1755 in around 1761, the date inscribed on the iron gate of the entrance (Costa 2024). The single-floor house sits atop the sloped property and features vaulted rooms with plaster finish of different geometries, building techniques and construction periods. Access to the extrados of the vaults through the attic was relevant to the 3D modelling, as it allowed for a complete scan of the vaults, including their thickness, a fundamental feature for assessing the building process and transformations over time. Access to the vault extrados was also possible in the case of the Ficalho Palace, justifying its 3D modelling.

The Ficalho Palace[7] is an aristocratic residence dating from the second half of the 17th century and was built into the medieval wall that surrounds the historic centre of Serpa. During the 20th century, the Marquesses of Ficalho carried out restoration and rehabilitation works between 1946 and 1973. The palace is composed of two floors. Except for the entrance hall, with the stairs covered by a wooden roof, all rooms are vaulted with plaster finishing, with the ground floor having a lower ceiling and older vaults, insofar as it was constructed before the rest. In this building, different construction phases are connected to different vault geometries and building techniques. Complete 3D data acquisition of the intrados and extrados of the vaults provided insight on the variation in thickness of the materials, allowing the accuracy of the geometry and the building processes to be assessed and compared with the São Brás house.

The 3D models of the Quinta de São Brás house and the Ficalho Palace were based on a point cloud acquired through Terrestrial Laser Scanning (TLS) Faro Focus S70, with a total of 15 scans of the house and 25 of the palace, corresponding to two scans per room, merged into a single point cloud for each case study, with the support of flat paper targets placed on vertical walls **[Figs. 4 and 5]**. The Quinta de São Brás house and Ficalho Palace were 3D-modelled using Autodesk Revit 2024 software, based on the point clouds obtained from TLS. A total of 28 compartments were modelled for the house and 60 for the palace. To model the

[6] See the entry for Quinta de São Brás house on the Vaulted South Platform.

[7] See the entry for Ficalho Palace on the Vaulted South Platform.

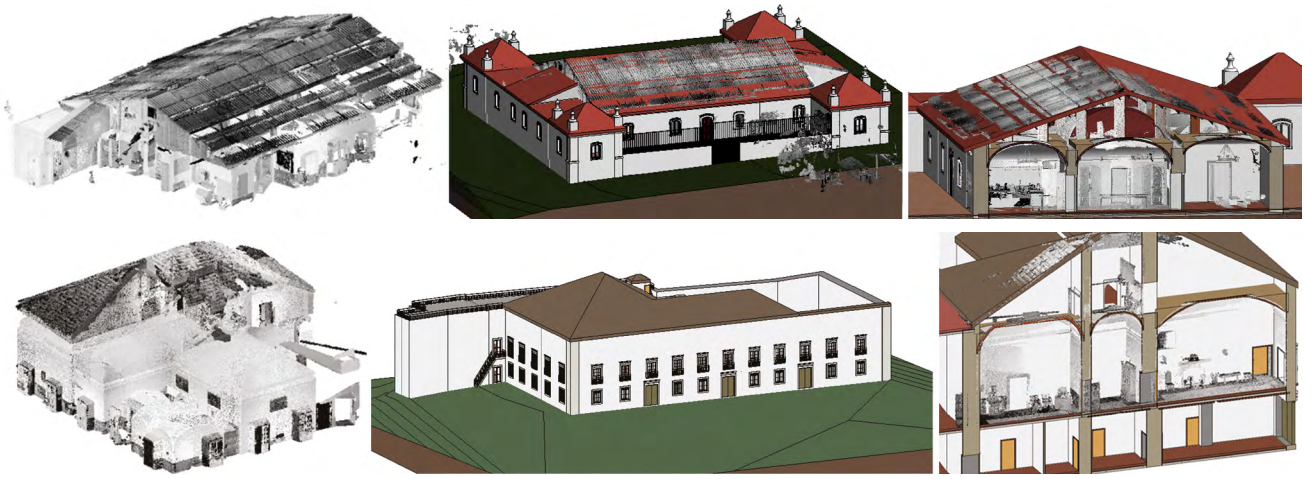

Fig. 4 3D models of the Quinta de São Brás house in Serpa: Point clouds with TLS (left) and compatibilisation of point clouds with BIM model (centre and right). Source: Folgado 2024,34, 44.

Fig. 5 3D models of the Ficalho Palace in Serpa: Point clouds with TLS (left) and compatibilization of point clouds with BIM model (centre and right). Source: Folgado 2024, 34, 48.

buildings, the various elements were divided into main and secondary elements, respectively: vaults, interior and exterior walls, floors, slabs, roof and pillars; and windows, doors, beams, railings, gates, and stairs.

In the absence of an existing BIM library for different geometries of vaults in a parameterised 3D format, one was purposely created and applied to 23 vaults in the 3D model of Quinta de São Brás house and 30 vaults in Ficalho Palace, in a process described further ahead. This BIM library is now available for public use in the '3D Elements' section of the Vaulted South webpage.

A BIM library of 3D parameterised format for different types of vaults was created to respond to a more suitable scale concerning the vaults: the analogue elements of vault geometry were digitalised through a procedure involving the parameterisation of the vaults' geometrical construction, from the trace of the arches to the generation of the volumetry of the vaults, digitally replicating the manual procedures learned from the books inscribed in 'Written Elements'. The parameterised modelling of vaults, done in Autodesk Revit 2024, created an unreleased BIM library of six vaults (barrel, sail, groin, ribs, domical and dome) and their variation according to the 3 types of arches (perfect round, elliptic, and three-centres). Each vault has four layers, the first of which is plaster, followed by the structural material, in this case brick, then mortar, and finally the filling. Vaults have different parameters according to geometry, namely the thickness of the interior plaster, the thickness of the structural material and the mortar, the height of the filling, the span, rise, length, and thickness of the ribs section [Fig. 6].

This BIM library allows users to change the parameter values according to their needs, as was done for conducting the comparison between the parametric model and the point cloud acquired. The items corresponding to the 3D digital vaults

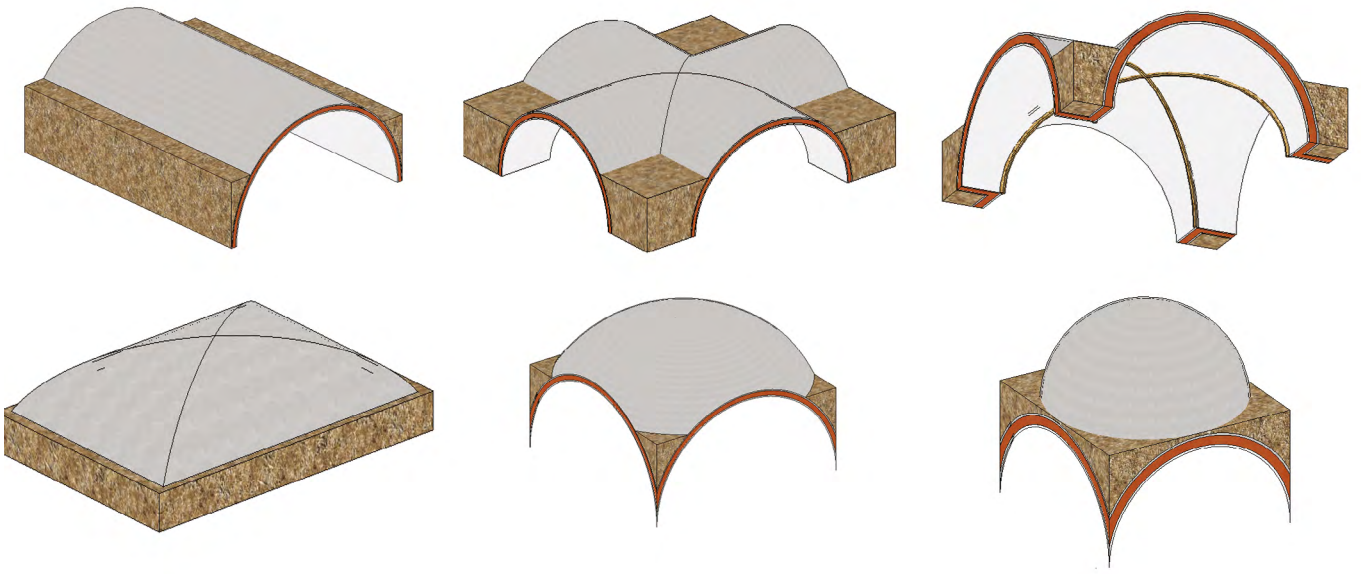

Fig. 6 3D library of parametric vaults modelled in Autodesk Revit 2024. Source: authors, 2024.

were curated at the '3D Elements' set at Omeka-S database, being linked to the 'Written' and 'Built Elements' through the 'Glossary' set.

The following procedure was adopted for modelling the remaining main elements: the slabs and floors were modelled on the boundaries created by the walls, while the pillars were modelled using the outer line and the beams were modelled using a structural beam system, delimiting their perimeter and the distance between beams. The roofs were modelled using their perimeter, with Quinta de São Brás house having a central gabled roof and pyramid hip roofs on the four corners and Ficalho Palace with two contiguous hipped roofs. As there was no BIM library corresponding doors and windows, one was created [Fig. 4 and 5]. Challenges have arisen when adapting BIM modelling approaches to masonry structures in ancient architectural constructions, such as arches, vaults, and domes (Ben Lashihar 2024). An automated iterative process within a scan-to-BIM methodology to support the final phase of the 3D parametric/adaptive reconstruction when applied to masonry vaulted systems was tested by Buldo et al. (2023).

Creating digital coefficients of vaults' building physics

Hitherto, the study of vaults has been approached based on vault volumetry and considering geometry and tectonics, in disregard of construction materials and sys-

tems. Nevertheless, building materials have a decisive influence on constructive systems, as the sources in 'Written Elements' make clear. Two constructive procedures for brick vaults in the vernacular context of southern Portugal can be adopted, depending on the way bricks are placed side by side: either with the 'stretcher' or 'bed' face showing. In most cases, assessing the system employed is hard, even impossible, due to the plaster in the intrados surface (commonly limewashed) and to the capping and filling in the extrados with clay and lime mortar.

A non-destructive prospection technique (NDT) consisting of the capture of thermograms with the use of a thermographic camera to record heat transmission in the materials, helps assess the constructive features, simultaneously recording the different temperatures on the surface, which is crucial for determining the thermal behaviour of buildings. Infrared Thermography (IRT) makes it possible to identify constructive elements, irregularities and heterogeneity by measuring the infrared radiation emitted by different materials (brick, stone and mortar) (Gomes and Tomé 2023, Barreira and Freitas 2007), by following several standards (ASTM 2003, BSI 1999). To maximize the difference between materials, this should preferably be done during the afternoon in indirect sunlight, after the materials have absorbed solar radiation.

Indeed, all bodies emit thermal radiation at a temperature higher than 0 K, and the emitted thermal radiation will be greater for higher surface temperatures, which depends on each material's thermophysical properties. Therefore, considering that there is variation in the thermophysical properties of different zones – such as defects or construction solution heterogeneities (e.g., zones where different materials or thicknesses exist in parallel, leading to thermal bridges) – variations in surface temperature will be easily detected by thermograms. This non-destructive technique has been successfully employed in vaults made of stone masonry (Chácara et al. 2023) and timber arches, reeds, and plaster (Quagliarini et al. 2013).

The thermographic approach was used to identify constructive solutions for vaults in the intrados of different types of buildings. Prospection was carried out in the interior of the rooms without contact or mechanical iteration with the surface **[Fig. 7]**. Through this procedure, thermograms clearly show the existence of internal reinforcements in the vaulted surface **[Fig. 7 left]** and the existence of different materials in the ribs (stone and brick) **[Fig. 7 centre and right]**, hidden by the plaster which could not be detected by only examining the vault surfaces. These findings led us to understand the process of vault construction concerning assemblage, materials used, and the role materials perform in the structural and filling dimensions. Moreover, the data obtained sheds light on the distribution of temperature on vault surfaces, emphasising differences between the start and closure segments of vaults.

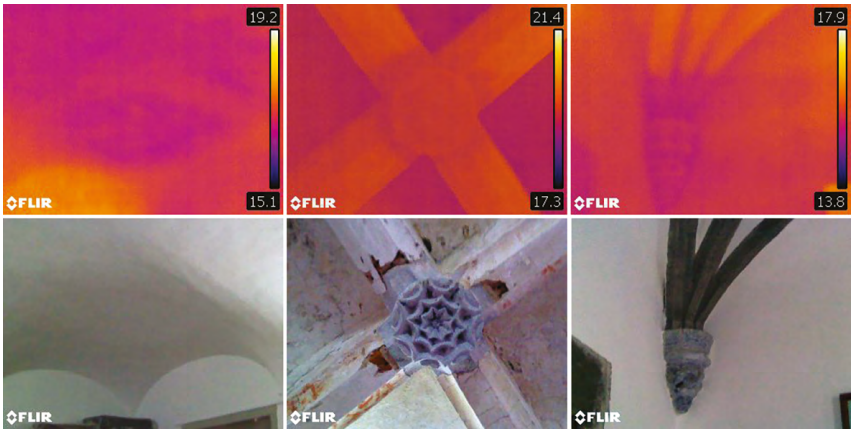

Fig. 7 Thermograms (above) and matching photographs (below) of the thermographic non-destructive prospection campaign to detect different materials (brick and stone) in vaults in the Convent of São Francisco, Serpa. Source: authors, 2024.

Conclusions

In the historiography of Architectural History, research methods have been mostly supported by archival research and fieldwork surveys. The Vaulted South Project has approached architectural research using innovative methodologies from related disciplines. Transposing analogue data from written sources and building records to a digital format (texts, technical drawings, and 3D models) and completing these with digitally captured data (photographs, point clouds, and thermograms) and digitally created data (3D and parameterised models) stored in an online structured database has contributed to generating new knowledge on the constructive systems of vaults. Through interdisciplinary analysis of vaults as connectors of different element collections (Written, Built, Drawn and 3D collection), we have clarified how and where vaults were built, which processes and materials were used, whether in an erudite or popular context, and whether construction processes were in alignment with written records.

This article reveals the importance of using innovative methods to achieve and manage accurate data in a more economical, efficient and effective way that is also less intrusive. Thanks to the interoperability of the platform, it was possible to identify which constructive details were traced back to scholarly sources, and those which emerged from popular contexts. In articulating vernacular vaults and codified or theorised knowledge about construction techniques, means of knowledge transmission have been questioned.

By generating these 'digital vaulted territories', the platform contributes to assessing the features and geographical extension of vaulted buildings, and to disseminating this cultural knowledge in different scientific fields, as well as standing as a collection and tool for use in future studies.

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