

REPUBLIC OF TÜRKİYE
AYDIN ADNAN MENDERES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF CIVIL ENGINEERING
MASTER'S PROGRAMME IN SCIENCE EDUCATION
2023-MSc-109

**DIGITAL HERITAGE TWINS:
ONTOLOGY DEVELOPMENT AND
SEMANTIC ENRICHMENT FOR
CULTURAL HERITAGE KNOWLEDGE MANAGEMENT**

Büşra ÖZEN
MASTER'S THESIS

SUPERVISORS:
Assoc. Prof. Gözde Başak ÖZTÜRK
Asst. Prof. Fatih SOYGAZİ

AYDIN-2023

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ACCEPTANCE AND APPROVAL

The thesis with the title of “DIGITAL HERITAGE TWINS: ONTOLOGY DEVELOPMENT AND SEMANTIC ENRICHMENT FOR CULTURAL HERITAGE KNOWLEDGE MANAGEMENT”, prepared by the Büşra ÖZEN a student of Department of Civil Engineering Program at T.C. Aydın Adnan Menderes University, Graduate School Of Natural And Applied Science, was accepted as a Master's Thesis by the jury below.

Date of Thesis Defense: 07/12/2023

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This thesis was approved by the jury above in accordance with the relevant articles of the Aydın Adnan Menderes University Graduate Education and Examination Regulations and was approved on the by from the Board of Directors of the Graduate School of Science in the numbered decision.

Prof. Mustafa SÜRMEN
Institute Director

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SCIENTIFIC ETHICAL STATEMENT

I hereby declare that I composed all the information in my master's thesis entitled “Digital Heritage Twins: Ontology Development and Semantic Enrichment for Cultural Heritage Knowledge Management” within the framework of ethical behavior and academic rules, and that due references were provided and for all kinds of statements and information that do not belong to me in this study in accordance with the guide for writing the thesis. I declare that I accept all kinds of legal consequences when the opposite of what I have stated is revealed.



Büşra ÖZEN

07/12/2023

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LIST OF ABBREVIATIONS

3D	: Three-Dimensional
5G	: Fifth Generation
AI	: Artificial Intelligence
AR	: Augmented Reality
BIM	: Building Information Modelling
CH	: Cultural Heritage
CHKM	: Cultural Heritage Knowledge Management
CHKG	: Cultural Heritage Knowledge Graph
CPS	: Cyber Physical System
DCH	: Digital Cultural Heritage
DCRP	: Digital Closed Range Photogrammetry
DIKW	: Data-Knowledge-Information-Wisdom
DLT	: Distributed Ledger Technology
DT	: Digital Twins
ICT	: Information and Communication Technologies
INSAR	: Interferometric Synthetic-Aperture Radar
IoT	: Internet of Things
GIS	: Geographic Information Systems
GPS	: Global Positioning System
GPRS	: Ground Penetrating Radar Systems
HBIM	: Heritage Building Information Modelling
KM	: Knowledge Management
KG	: Knowledge Graph
LIDAR	: Laser Imaging Detection and Ranging
LLM	: Large Language Model
MR	: Mixed Reality
RAG	: Retrieval-Augmented Generation
SAR	: Synthetic-Aperture Radar

UAV : Unmanned Aerial Vehicles
VR : Virtual Reality
XR : Extended Reality



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ÖZET

DİJİTAL KÜLTÜREL MİRAS İKİZİ: KÜLTÜREL MİRAS BİLGİ YÖNETİMİ İÇİN ONTOLOJİ GELİŞTİRME VE ANLAMSAL ZENGİNLEŞTİRME

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Amaç: Bu çalışmada Kültürel Miras (KM) bilgisinin doğru temsil edilebilmesi ve anlaşılabilmesi için KM Ontolojisi ve anlamsal zenginleştirme ile Dijital Kültürel Miras İkizi altyapısı oluşturmak amaçlanmıştır.

Materyal ve Yöntem: Scopus veri tabanı kullanılarak Dijital Kültürel Miras (DKM) teknolojilerinin ve KM ontolojilerinin bibliyometrik taraması ve sitometrik analizi yapılmıştır. Neo4J uygulaması kullanılarak KM Ontolojisi oluşturulmuştur. Python yazılım dili yardımıyla KM Ontolojisi anlamsal olarak zenginleştirilmiştir.

Bulgular: KM bilgi yönetimi için yapay zeka teknolojilerine ve KM Ontoloji Semantik Web Teknolojilerinin entegrasyonuna eğilim tespit edilmiştir. Bilgi teknolojilerinin entegrasyonu ve dijital ikiz konusunda boşluk görülmüştür. Dijital Kültürel Miras İkizi altyapısı olarak KM Ontolojisi geliştirilmiş ve anlamsal zenginleştirilmesi ile KM Bilgi Çizgesi elde edilmiştir.

Sonuç: KM Bilgi Yönetimi için anlamsal bir platform sağlamıştır. Geliştirilen KM Ontolojisi ve KM Bilgi Çizgesi'nin Tarihi Yapı Bilgi Modellemesi (HBIM), sohbet robotu teknolojilerinin tam entegrasyonu ile Dijital Kültürel Miras İkizi geliştirilebilir.

Anahtar Kelimeler: Kültürel Miras, Dijital Kültürel Miras, Dijital İkiz, Dijital Kültürel Miras İkizi, Ontoloji, Anlamsal Zenginleştirme, Bilgi Yönetimi

ABSTRACT

DIGITAL HERITAGE TWINS: ONTOLOGY DEVELOPMENT AND SEMANTIC ENRICHMENT FOR CULTURAL HERITAGE KNOWLEDGE MANAGEMENT

Ozen B. Aydın Adnan Menderes University, Graduate School of Natural and Applied Sciences, Civil Engineering Program, Master Thesis, Supervisors: Assoc. Prof. Gozde Basak Ozturk and Asst. Prof. Fatih Soygazi, Aydın, 2023

Objective: The Digital Heritage Twins infrastructure through the development of Cultural Heritage (CH) Ontology and semantic enrichment is aimed. The overarching objective is to enhance precision in representing and comprehending CH with a focus on sensitivity.

Material and Methods: Bibliometric search was employed to the Scopus data. Scientometric analysis and mapping was conducted to scrutinize Digital Cultural Heritage (DCH) and CH ontologies. The creation of the CH Ontology was facilitated. Subsequently, CH ontology was semantically enriched by the Python programming language.

Results: A discernible trend in Artificial Intelligence for Knowledge Management (KM) and in the integration of CH Ontology with Semantic Web Technologies were observed. While, a notable gap was identified in the integration of information technologies and in the context of Digital Twins.

Conclusion: CH Ontology has served as a semantic platform for KM. Achieving complete integration of technologies, including Historical Building Information Modeling (HBIM) and chatbots, can pave the way for the development of a Cultural Heritage Digital Twins.

Keywords: Cultural Heritage, Digital Cultural Heritage, Digital Twins, Digital Heritage Twins, Ontology, Semantic Enrichment, Knowledge Management

1. INTRODUCTION

Culture and art have served as significant conduits for recounting human history across ages and civilizations. Within this context, Cultural Heritage (CH) assets play a crucial role in bridging the past and the present, offering a vital means of transmitting information to the future. Ensuring the complete transfer of CH knowledge is paramount for cultural and social sustainability. However, various factors, including natural disasters, environmental influences, and human actions, contribute to the gradual disappearance or incomplete transfer of CH knowledge over time (Figure 1). The recent advancements in technology present an opportunity to digitalize CH knowledge (Oostwegel et al., 2022; Mora et al., 2021; Albourae et al. 2017; Dore and Murphy, 2012). The emergence of Digital Cultural Heritage (DCH) in the literature reflects the growing potential of technology. DCH aligns with CH's objectives of preserving the past and enhancing public awareness. Leveraging digital technologies effectively aims to enrich the representation of CH entities, filling in gaps and maintaining completeness (UNESCO, 2021). Initially, DCH found primary use in facilitating conservation management during restoration efforts. Moreover, DCH applications contribute to preventing time and cost losses by providing easier access to CH elements yet to be unveiled. With the advent of Industry 4.0, Information and Communication Technologies (ICT) have been integrated into DCH processes. This integration reveals that efficient processes can be achieved for CH, not only in conservation management but also in Knowledge Management (KM) (Bruno and Roncella, 2019; Oostwegel et al., 2022; Simeone et al. 2019; Yüksek and Sökmen 2021). Despite these advancements, studies focusing on CH Knowledge Management (CHKM) remain limited in the literature (Oostwegel et al., 2022; Simeone et al., 2019; Messaoudi et al., 2018; Guarnieri et al., 2010; Meyer et al., 2007). Infrastructure challenges, particularly regarding the interoperability of systems, pose significant obstacles to research in this field. Additionally, there is a need to enhance the efficiency of existing technology-supported CHKM systems.

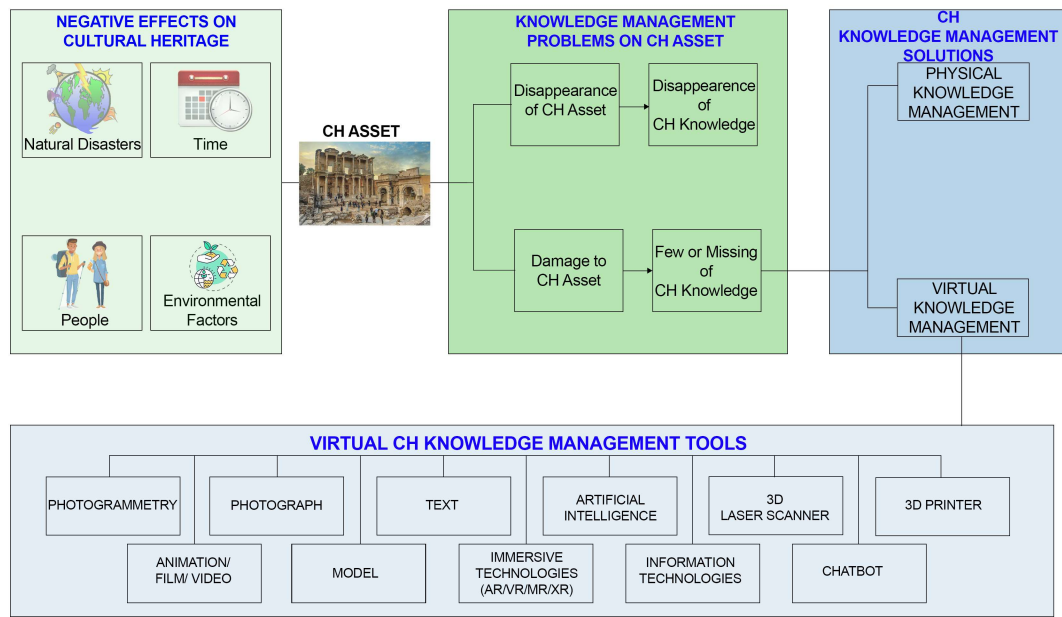


Figure 1. Problems, Solutions, and Tools in Cultural Heritage Knowledge Management

According to the insights provided by Khan et al. (2018), the transition of CH knowledge to the digital realm serves as a facilitator for knowledge sharing. The digitalization of CH introduces a more cost-effective avenue for accessing CH assets. This shift not only holds the promise of sparking heightened interest in CH by transcending temporal and spatial constraints but also presents significant potential across various educational domains and the tourism sector. Moreover, it emerges as an alternative solution, addressing the information and access needs of marginalized groups, including individuals with disabilities and the elderly. Beyond these aspects, it is poised to contribute substantially to on-site, ensuring effective and efficient information sharing that caters to a broad and diverse user base.

The literature on DCH has traditionally approached the subject within specific areas of CH using a project-based methodology (Ozturk and Ozen, 2020; Acierno et al., 2017; Zalamea et al., 2016; Niang et al., 2016). However, the absence of a unified and comprehensive platform that enables the interactive sharing of CH information, encompassing both textual and visual elements, is a notable gap in current research (Khan et al., 2018). While global initiatives primarily emphasize the use of digital technologies for the protection of CH content, it is crucial to recognize that preservation extends

beyond physical aspects. The comprehensive preservation and dissemination of CH information are equally significant. The upcoming focus in DCH research is anticipated to revolve around the development of interactive environments utilizing digital technologies, facilitating CH research, and fostering increased information sharing among various CH stakeholders.

Digitalization gives rise to a digital representation, or "digital shadow," of the actual CH entity. To transition this digital shadow into a fully realized Digital Twins (DT), a seamless flow of information between the physical and digital environments, known as knowledge flow, is imperative. Research on Digital Twins in the CH field is relatively scarce (Themistocleous et al., 2022; Gabellone, 2022; Jouan and Hallot, 2019; Dezen-Kempter et al., 2020; Niccolucci et al., 2022; Luther et al., 2023; Wang et al., 2022; La Russa and Santagatti, 2020; Massafra et al., 2022; Tan et al., 2022). The development of a Digital Heritage Twins (CH Digital Twins) necessitates a digital representation of CH with multidimensional semantic information, fostering interactive information sharing. The components of a DT encompass (1) physical presence in a real space, (2) data and information connections, and (3) a corresponding virtual presence in a virtual space (Grieves and Vickers, 2017). Consequently, the creation of a Digital Heritage Twins (CH Digital Twins) involves combining the physical CH entity with a chatbot for data and information connections; leveraging CH Ontology, CH Knowledge Graph (CHKG), and Heritage Building Information Modeling (HBIM) to generate a virtual representation of the CH (Figure 2).

The objective of this research is to establish the infrastructure for a Digital Heritage Twins (CH Digital Twins) with the purpose of effectively and efficiently representing, sharing, and managing complex and distributed CH knowledge. To achieve this goal, the specific objectives of the thesis involve the development of a CH Ontology and the generation of a CHKG through the semantic enrichment of the CH Ontology. The creation of CH knowledge within an ontology-based semantic structure offers a precise definition of meaning and the relationships among concepts. This clarity enhances the understanding, utilization, and sharing of data. The CH Ontology and CHKG, through semantic modeling, will facilitate the representation of CH knowledge.

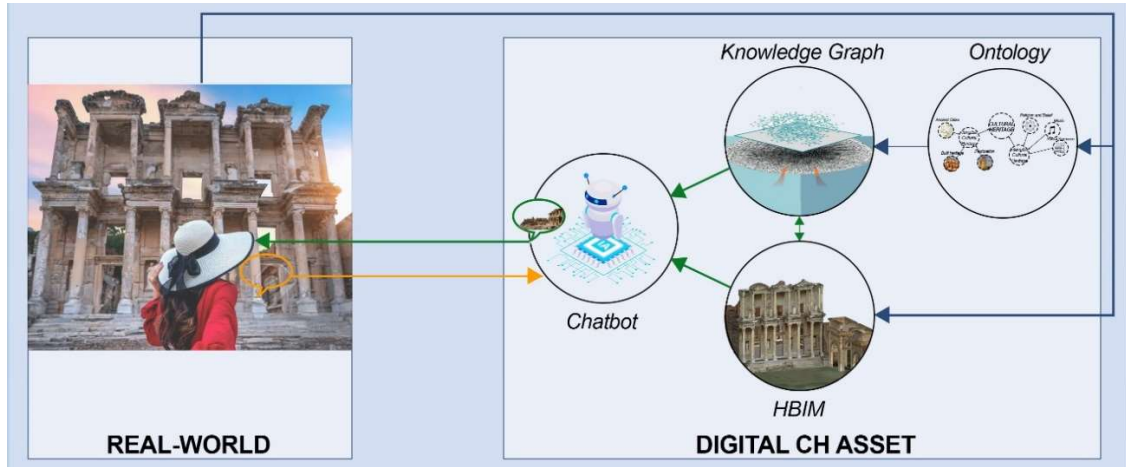


Figure 2. Digital Heritage Twin (CH Digital Twins)

The subsequent sections elaborate on the literature review concerning the CHKM and novel technologies for the digitalization of CH. The methodology delineates the stages of the conducted studies, while the Findings section presents results derived from scientometric analysis and mapping, along with insights into the CH Ontology Development and Semantic Enrichment processes. The Discussion section critically assesses literature trends and gaps in the Digitalization of CH, CH Ontology, and Semantic Enriched CH Ontology. Furthermore, it explores how the developed CH Ontology is poised to guide future research, emphasizing its contributions to CHKM processes. The thesis concludes with a concise summary and a discussion of study limitations, providing a glimpse into potential future research directions.

2. RESEARCH BACKGROUND

CH, as per UNESCO, encompasses elements from the past, existing in the present, and passed on to the future, with a continually evolving concept. The semantics of CH, expressing its richness and complexity, underscore its significance (Pinto et al., 2022). CH elements, laden with semantic information, play a crucial role in narrating humanity's history. Restoration processes, managed by multidisciplinary teams, aim to restore deteriorated parts of historical buildings to their original form, addressing challenges like high costs and risks. While traditional restoration research focuses on physical preservation, Industry 4.0's digital technologies contribute to holistic preservation, fostering long-term conservation of tangible and intangible CH knowledge. Moreover, these technologies enhance public engagement and interest in CH elements through diverse promotional approaches (Ardito et al., 2020).

CH data encompasses architectural, engineering, sociological, historical, and geographical information, forming a complex structure with datasets from diverse interdisciplinary fields in various formats. Managing this intricate CH data necessitates interdisciplinary KM (Tibaut and de Oliveira, 2022). Ontology serves as a common language, facilitating the identification, sharing, and reuse of information across real and virtual realms. Establishing relationships between Ontology and CH concepts on a unified platform ensures the preservation and accessibility of CH information for future generations of researchers and practitioners (Niccolucci et al., 2022). This integration enhances the comprehensiveness of CH research, enabling meaningful connections between ontology and diverse sources, thereby boosting knowledge discoverability. The incorporation of ontologies in CH research integrates heterogeneous data, providing a conceptual framework for CHKM (Previtali et al., 2020).

2.1. Novel Technology Used for Digitalization of Cultural Heritage

CH has a pivotal role in shaping national identity and contributing to the collective memory of society. Urban components serve as a tangible link between the past and present, captivating tourists and bolstering the local economy (Albourae et al., 2017). The preservation of CH is crucial for the benefit of present and future generations (ICOMOS, 1990). Over time, natural disasters, environmental factors, and human activities can lead to distortions in the historical environment. Restoration becomes paramount to renewing deteriorated portions of historical buildings, ensuring their adherence to the original form and transmission to future generations while preventing further damage. Restoration interventions should align with both intangible and tangible heritage elements and living values, integrating CH into contemporary social, cultural, and economic life (ICOMOS, 2011). Leveraging new technologies for the maintenance of CH contributes significantly to minimizing time and economic losses (Rodrigues, 2019).

Preserving tangible CH knowledge, integral to national identity, is crucial for the well-being of present and future generations, emphasizing the importance of accurate CHKM practices (ICOMOS, 1990). Restoration is important in safeguarding CH by renewing deteriorated sections of buildings in line with their original forms, ensuring their transfer to the future, and averting further destruction (ICOMOS, 2011). In the realm of Digital Cultural Heritage (DCH), leveraging contemporary technology for CHKM aims to prevent time and economic losses, fostering sustainability through the transfer of CH to subsequent generations.

2.1.1. Photogrammetry

The evolution of CH over time often results in a scarcity of documentation and technical knowledge, leading to resource-intensive CHKM efforts. Technological advancements, however, offer tools that can alleviate costs and streamline processes. Photogrammetry, relying on high-quality images, captures both semantic and spatial data, facilitating precise three-dimensional (3D) measurements without physical contact with CH structures (López et al., 2018). Digital Closed Range Photogrammetry (DCRP)

enables direct measurement using photos and mathematical equations, particularly beneficial for assessing challenging areas like those affected by fire damage (Yilmaz et al., 2007). Combining photogrammetry with Unmanned Aerial Vehicles (UAVs) allows for direct measurement of distances, angles, and areas. UAVs, equipped with high-resolution cameras and Global Positioning System (GPS) technology, provide cost-effective solutions for image acquisition (Zimmermann et al., 2017; Carvajal-Ramírez et al., 2019), enhancing the acquisition of high-resolution 3D models and detailed insights into object structures.

2.1.2. Laser Technologies

The Laser Scanning method is employed to produce dense 3D point cloud data, facilitating the creation of geometric models. Typically, Digital Photogrammetry data is merged with Laser Scanning data to form comprehensive and intricate 3D objects (Guarnieri et al., 2013). Laser Scanning finds applications in architecture and construction, providing highly accurate and detailed 3D models for the seamless transition of physical objects into digital platforms (Pawlowicz, 2019). Terrestrial Laser Scanning, utilizing lasers, captures 3D spatial information from a distance above the ground, offering speed and portability advantages for rapidly scanning extensive historical areas (Hoon and Hong, 2019). 3D Scanning, a non-contact method utilizing lasers, light, or X-rays, digitally captures objects and generates point clouds representing surface details. This technology is valuable for digitally preserving CH. In the manufacturing sector, 3D printing automates processes, enhances efficiency, and minimizes material wastage, enabling the digital production of objects. Additionally, it can be used to physically restore gaps or imperfections in CH (Ozturk and Ozturk, 2018; Ozturk and Ozturk, 2019a; Xu et al., 2017; Higuera et al., 2021).

2.1.3. Remote Sensing Technologies

The paramount principle in collecting CH data is the preservation of the research target itself, adhering strictly to scientific requirements (ICOMOS, 1990). Rather than excavating all archaeological sites, less intrusive techniques are preferred. Technology introduces innovative methods like remote sensing for non-invasive monitoring of extensive Earth areas at minimal cost (ICOMOS, 1990). Remote sensing involves identifying or analyzing the physical properties of Earth objects. Synthetic-aperture radar (SAR) tracks gradual ground deformations without causing harm, utilizing electronically combined data from multiple radar units. Interferometric Synthetic-Aperture Radar (INSAR) uses multiple SAR images to map surface deformations and digital elevation, measuring changes on a millimeter scale (Sanchez et al., 2014). Laser Imaging Detection and Ranging (LIDAR) is pivotal in detecting covered vegetation and forested areas, contributing significantly to archaeology, especially in Mesoamerica (Chase et al., 2011). Ground Penetrating Radar Systems (GPRS) facilitate non-invasive viewing and surveying of shallow underground layers without excavation (Sato et al., 2012).

2.1.4. Artificial Intelligence

In the Industry 4.0 era, Artificial Intelligence (AI) technologies enable manufacturing by establishing a dynamic connection between the physical and virtual realms. AI, as a field, involves creating machines capable of reasoning, learning, communicating, sensing, planning, and decision-making. Utilizing sophisticated algorithms, AI facilitates swift and precise analysis of extensive datasets, contributing to knowledge sharing and transforming individual knowledge into collective knowledge (Darko et al., 2020). KM encompasses various processes, including knowledge creation, storage, retrieval, sharing, and application. AI methods effectively contribute to each of these stages. In the initial phase of KM, knowledge creation involves developing new insights, a task where AI excels by reconfiguring existing knowledge or generating novel ideas. Once new information is acquired, AI aids in data collection and classification

through self-learning algorithms, supporting long-term storage for reuse (Jarrahi et al., 2022).

AI technologies establish an interactive link between the physical and virtual worlds. In the realm of science and technology, AI aims to equip machines with human-like capabilities, encompassing reasoning, learning, communication, perception, planning, thinking, and behavior (Liao et al., 2022). Utilizing intricate algorithms, AI learns from extensive datasets, facilitating swift and accurate data analysis. Applications of AI extend to Geographic Information System (GIS)-based visualization in the field and the presentation of CH artifacts through mobile devices. Virtual Reality (VR) and Augmented Reality (AR) technologies create unified experiences by blending real and virtual objects, bridging the gap between the physical and digital realms. These technological applications enhance the visualization of CH elements and product digitization, bringing visitors closer to historical heritage sites. Technology acts as a mediator, generating new social, economic, and cultural opportunities at the convergence of visitors and CH (Ozturk, 2021a; Chianese et al., 2015). VR, AR, and Mixed Reality (MR) technologies merge real and virtual environments, providing immersive experiences (Ozturk and Tunca, 2020; Albourae et al., 2017). Expanded Reality (XR) encompasses the properties of VR, AR, and MR, offering a versatile and all-encompassing reality experience (Fast-Berglund et al., 2018).

2.1.5. Internet of Things

The Internet of Things (IoT) constitutes a network encompassing physical objects such as devices, appliances, vehicles, buildings, electronics, circuits, software, and sensors, all equipped with network connectivity. This interconnected network enables the collection and exchange of data among these objects. IoT empowers remote sensing and control of these objects using existing network infrastructure, presenting opportunities for a more direct integration of the physical world into computer-based systems. This integration results in improved efficiency and accuracy (Ozturk, 2021c). Essentially, IoT aims to bridge the gap between the human-inhabited physical world and the virtual world through smart objects. These smart elements facilitate interaction between individuals

and their surroundings by providing, processing, and transmitting information or commands. Buildings, vehicles, and shared environments incorporate embedded sensors and actuators, enabling them to report on their status or the conditions of their surroundings (Madakam et al., 2015).

CH constitutes a worldwide repository of value, including museums, archaeological sites, historical landmarks, and monuments. The increasing interest in these heritage elements requires their modernization and presentation through contemporary technologies. IoT technology assumes a crucial role in the digitization of these efforts (Ravi et al., 2019). Within IoT systems, interconnected physical objects can communicate via the internet. Another vital objective of employing IoT technology is to address the degradation processes impacting CH items. Sensor data can identify signs of deterioration, facilitating timely interventions (Lee and Lee, 2019).

2.1.6. Information and Communication Technologies

The industrial sector has undergone a substantial transformation owing to the rapid advancement of smart connectivity technologies. These progressions have resulted in effective solutions for production management. Notably, advancements in network technologies such as wireless communication and sensors have augmented control over production processes, diminishing the necessity for manual intervention. This achievement is facilitated by the design of a network architecture connecting various devices. The Industrial Internet of Things (IIoT) has gained prominence alongside the growing interest in IoT technology, facilitating communication among connected devices via network architecture. This holds particular significance in various industrial sectors, considering the continuous improvements in network technologies. IIoT offers customized features, reduces lead times, and significantly benefits the industry. This transformative shift enhances industry flexibility and facilitates the generation of extensive data and information (Chekired et al., 2018).

The advent of big data has presented challenges in data transmission and processing. To tackle these issues, contemporary communication solutions are being employed. For instance, fifth-generation (5G) mobile technology integrates mobile

network architecture into end-to-end network design and service delivery. This facilitates real-time communication between IoT devices, machines, and humans. Furthermore, edge computing is utilized to mitigate data transmission challenges and enhance service latency. Through edge computing, data is processed locally, reducing latency and enabling more thorough data analysis (Wang et al., 2020).

The evolution of destination marketing, culture, and tourism communication has gained increasing significance with the advancements in Information and Communication Technologies (ICT). Technologies such as smartphones have simplified the bridging of the physical and digital worlds for tourists, leading to the development of mobile applications for CH. These applications are designed not only for tourism purposes but also to provide users with new information. Integrating ICT and technology-enhanced learning methods represents a significant area of current research, offering effective contributions to disseminating enhanced knowledge about CH. Furthermore, ICT can offer sustainable approaches to CHKM (Ramos-Soler et al., 2019; Ott and Pozzi, 2011). For example, these technologies can calculate energy consumption in CH areas, promoting regional low-carbon economic development and environmental protection (Wu & Xu, 2013). Building Information Modeling (BIM) technology can be employed for the KM of CH items, enhancing functionality (Rodríguez-Moreno et al., 2018).

2.1.7. Cyber-Physical Systems

Cyber-Physical Systems (CPS) represent sophisticated systems crafted to sense, manage, and control the physical world, forging a seamless and continuous connection between intelligent digital components. Positioned as the bedrock of Industry 4.0, these systems assume a crucial role in optimizing industrial processes, markedly improving efficiency in production environments. CPS adeptly gathers data, fostering predictive capabilities that bolster decision-making processes, thereby enabling smart solutions. Operating with a bidirectional link between the physical and cyber environments, CPS utilizes sensors and processors to deliver real-time feedback through physical means (Ozturk, 2019b; Kline and Turk, 2019).

The architecture of Cyber-Physical Systems (CPS) typically unfolds across five levels. Commencing with "Connectivity," it engages in real-time data retrieval from the physical world and the reciprocal exchange of information with the cyber environment. The subsequent stage, termed "Collection," involves the meticulous gathering of precise and reliable information from diverse components through sensors. The "Cyber" stage embodies the Digital Twins (DT), a digital representation of an object in the physical realm, be it presently existing or anticipated in the future. Following this, the "Transformation" phase converts data stored in smart links into valuable information. The "Cognition" phase employs AI technologies for learning and diagnostics. Ultimately, the "Configuration" phase furnishes intelligent, responsive, self-learning, and automatic configuration capabilities (Lee et al., 2015).

2.1.8. Building Information Modelling

Building Information Modeling (BIM) emerges as a technology facilitating the generation, sharing, and utilization of information across the entire lifespan of a project or building. Functioning as a platform, BIM integrates nD project information and various technologies. Pertinent information associated with a project undergoes continuous condensation and transmission from individual professionals, teams, and organizations to the BIM model, serving as a digital intermediary for the built environment. The BIM model essentially serves as a digital representation of a physical object, typically a building, and can encompass nD information, thereby facilitating knowledge creation and sharing (Ozturk, 2020a; Ozturk, 2020b).

BIM holds the potential to optimize efficiency in construction projects by reducing both time and costs. This is achieved through swift and precise analysis, versatile service visualizations, and improved collaboration among all project stakeholders. In contemporary construction practices, BIM finds extensive use in large and intricate projects, enhancing performance, providing reliable predictions, refining designs, and seamlessly integrating vast amounts of data to the benefit of all involved parties (Ozturk et al., 2016; Ozturk, 2019a; Chen & Tang, 2019). BIM also facilitates the seamless transfer of data between different software applications, fostering interoperability and

automating workflow processes. The quality and depth of information within a BIM model are often measured in terms of BIM Maturity, reflecting the levels of advancement in BIM application. Progressing from lower to higher maturity levels enhances control, competence, consistency, and overall applicability, aligning with the objectives of project execution (Ozturk, 2021b).

Many researchers consider BIM a fundamental tool for constructing the DT of a building (Sacks et al., 2020). However, it's crucial to acknowledge that BIM models may become outdated as they lack a feedback loop from the actual building, hindering the continuous and seamless transformation of data into information and knowledge. To address this challenge, the integration of sensors and actuators can facilitate data feedback from the physical building to the BIM model. Subsequently, AI techniques can be deployed to process this data, generating, deriving, storing, sharing, utilizing, and managing it as information for the intended individuals, platforms, and systems (Ozturk 2021).

2.1.9. Heritage Building Information Modelling

BIM functions as a technology facilitating the creation, sharing, and utilization of information across the entire lifespan of construction projects and buildings. It acts as a platform for integrating project information and diverse technologies. In parallel, the Heritage Building Information Modeling (HBIM) platform, tailored for modeling historical buildings, integrates data from sources like photogrammetry and laser scanning into a 3D model. This platform organizes essential documents for conservation management, such as 3D models, programs, details, plans, and sections (Rodrigues et al., 2019). Similar to the BIM platform, stakeholders gain comprehensive insights into the entire project lifecycle through a single model when using HBIM. The primary goal of the HBIM platform is to reduce restoration costs for historical buildings and enhance conservation project efficiency. Even if the original historical structure is lost, the HBIM model serves as a valuable resource for transferring knowledge and culture (Jouan and Hallot, 2019).

2.2. Knowledge Management

KM traces its roots to Horton's 1979 research and gained scholarly recognition through subsequent work by researchers like Sveiby (1988). The pivotal systematic perspective on KM was presented by Nonaka and Takeuchi in 1995, establishing its significance as a crucial element for organizational goals and a valuable asset for sustaining competitiveness (Bruton et al., 2007). KM is a vital process for organizations, integral to effectively managing knowledge assets, improving intellectual capital, and enhancing organizational performance. It encompasses strategies for creating, capturing, evaluating, storing, maintaining, and disseminating knowledge assets, with success hinging on the alignment of KM with business strategy. Nevertheless, organizations grapple with challenges such as defining knowledge, handling tacit knowledge, leveraging information technology, navigating cultural complexities, and addressing heightened competition. This underscores the necessity of a holistic approach to consider and address KM challenges (Dodla et al., 2023).

Over the past two decades, the swift evolution of digital technologies has prompted a dynamic acceleration in knowledge development and an increasing focus on KM. This shift is motivated by the widespread use of information and the imperative to extract value from it, leading to advancements in information management technologies. Information is dispersed across different tiers of organizational hierarchies, repositories, and the collective knowledge of individuals within an organization. Knowledge, emerging through the transformation of data into information and then into practical knowledge, is widely recognized as a critical competitive asset for industries (Zhao et al., 2018; Farooq, 2018). The expansive nature of knowledge, spanning various scientific disciplines, cultural contexts, and experiential backgrounds, inherently contributes to its diversity. The effective management, sharing, and evolution of this diverse knowledge pose a significant challenge.

From a technological standpoint, the ongoing evolution and progression of technologies, spanning from Web 2.0 to cloud computing and the IoT, have been recognized as platforms for both generating and storing information. These technologies, within the computing era, have generated extensive volumes of dynamic data flow. The

substantial and dynamic data flow has subsequently given rise to the phenomenon of big data. As a result, various technical challenges, including concerns related to data confidentiality, security, access, sharing, and storage, have gained prominence (Anum et al., 2018).

In the post-Industry 4.0 era, businesses are not solely examined through an industrial perspective but are also comprehended in terms of KM. Organizations adept at defining, creating, and nurturing information assets are acknowledged as successful trailblazers in the global information society (Birzniece, 2011). KM involves a spectrum of activities, including capturing, sharing, storing, retrieving, using, and reusing information, all directed toward realizing an organization's goals and objectives (Ozturk and Soygazi, 2024; Ozturk and Yitmen, 2019; Wang and Meng, 2019; Farooq, 2018). Bashir and Farooq (2019) posit that effective organizational growth can be achieved through the implementation of KM activities focused on essential knowledge creation and sharing (Weinreich and Groher, 2016).

The conventional KM methodology involves a structured framework that encompasses the following operations (Majumder and Dey, 2022) for generating, processing, extracting, converting, and modifying information:

- (i) Information collection,
- (ii) Evaluating the acquired information,
- (iii) Information share intra an inter-organization
- (iv) Use the data in the solution of a chosen task.

Clearly communicated policies and procedures enhance the likelihood of synergy among knowledge sources (Rundquist, 2014). In this era of digital transformation, digital resources can be enriched, and collaboration can be cultivated by integrating KM with Industry 4.0 technologies. KM is underpinned by ICT. Digitalization, IoT applications, robotization, and data management contribute to the technical advancement of KM. AI technologies augment the conversion of data into knowledge. Researchers assert that studies in semantic web and ontology have significantly elevated the use of Information Technology (IT) in KM. Consequently, Big Data Technologies and IT will be collaboratively employed in future KM applications (Yu and Yang, 2018). Knowledge

systems should be established to facilitate knowledge exchange among a wide array of stakeholders.

2.2.1. Data-Information-Knowledge-Wisdom Model

The DIKW Model, as illustrated in Figure 3, accepts widespread acceptance among researchers (Ruan et al., 2012; Baškarada and Koronios, 2013). Nevertheless, a conflict arises between the traditional DIKW model and the contemporary perspective of knowledge transformation in the information age (Wallace, 2005; Floridi, 2011). This chapter aligns with the rationale of the conventionally acknowledged traditional DIKW Model.

Data signifies the outcome of observing or sensing objects, events, and environments, and it is conveyed through symbols. When data undergoes transformation into valuable, relevant, processed, and meaningful information that addresses questions like 'who, what, where, when, and how many,' it takes on the form of information. Knowledge, conversely, pertains to instructional information used to efficiently control a system, answering the 'how' question. At the zenith of the DIKW pyramid is where wisdom resides, and as researchers posit, this summit is deemed beyond the reach of computers (Dalal, 2012; Hoppe et al., 2011; Liew, 2013). Wisdom is a distinctly human attribute, contributing value through judgment as a mental cognitive process. Nonetheless, the emergence of new ICT, web technologies, and information-based platforms may facilitate applications akin to wisdom, as depicted in Figure 3.

In addressing the challenges within KM, there has been a growing focus on AI methods. AI-based technologies assist in information processing. Automated reasoning techniques empower computer systems to conclude from information (Birzniece, 2011). Moreover, it becomes apparent that mere verification by computer systems is inadequate to ensure information integrity. AI systems play a role in decision-making processes and the preservation of data integrity. The influence of AI systems on the decision-making process in information storage can be elucidated within the DIKW framework.

In facilitating well-informed decisions, it is imperative to deliver the appropriate knowledge to the right location at the right moment. Decision support systems play a crucial role in expediting decisions within information processes. These systems provide assistance in the ultimate decision-making phase without displacing human managers. A decision support system integrates human intelligence, information technology, and software to address complex problems. AI systems have the potential to enhance the efficiency of decision support systems or even be conceptualized as comprehensive human replacement systems. AI contributes to the analysis of extensive and intricate datasets (Mora & Garrido, 2013).

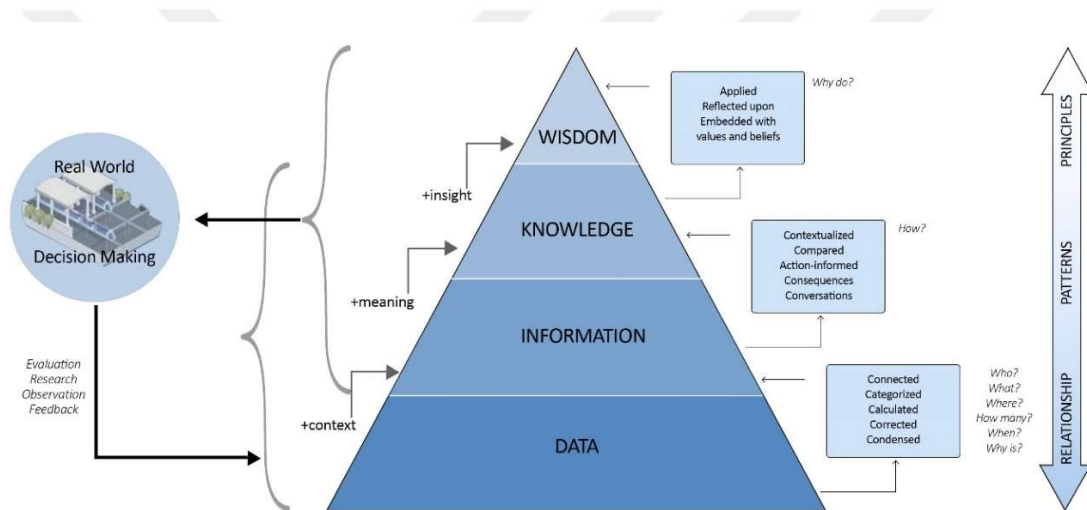


Figure 3. DIKW Model (Ozturk and Ozen; 2024)

In conjunction with input and output units, acknowledged as foundational components of information systems, the environments for information storage assume a pivotal role in KM. Data, positioned at the foundation of the DIKW model, constitutes the focus of information processes, embodying the characteristics of events and their surroundings. Information surfaces through the creation, reception, and processing of data within information systems. Knowledge is delineated as objective, transferable, transformable, and measurable. It can undergo formatting, processing, accessibility, production, transmission, storage, dissemination, searchability, utilization, compression, and duplication. In the sphere of information storage procedures, 'information,' possessing

an object-like quality, can be stored and shared. However, it is 'knowledge' that facilitates the conversion of information derived from data into directives for determining which information should be preserved during the storage process. Once transmuted into knowledge, the information becomes prepared for the decision-making process. In the DIKW model, data is amassed, arranged, and endowed with significance (Team & Organism, 2019). Wisdom surpasses knowledge and transforms knowledge into experiential insights. AI systems have the capacity to leverage knowledge to facilitate decision-making (Baldassarre, 2016).

To arrive at well-informed decisions, the precise delivery of pertinent knowledge to the appropriate location and moment is imperative. Decision support systems assume a pivotal role in expediting prompt decision-making within information processes. These systems provide assistance during the final decision-making stage without displacing the managerial role. Representing a comprehensive framework, a decision support system integrates human intelligence, information technology, and software to address intricate challenges. AI systems have the capacity to enhance the efficiency of decision support systems, and in certain instances, they can be conceived as comprehensive replacements for human decision-makers. AI proves invaluable in the analysis of extensive and intricate datasets (Mora and Garrido, 2013).

2.2.2. Ontology

Ontology serves the crucial function of describing, fostering sharing, and facilitating the reuse of information and data across both software systems and human interactions. This conceptual model is widely employed in various information systems grounded in Semantic Web Technology. Its nomenclature is derived from the philosophical domain and is fundamentally defined as "the study of being as being." Especially within the domains of computer science and knowledge-based engineering, ontology is elucidated as "the explicit and formal specification of a common conceptual framework (Figure 4). This definition intricately interlinks several crucial elements:

"*Conceptualization*" emphasizes the collaborative effort of a group of experts within a specific field who seek to delineate and model an abstract phenomenon existing in the world.

"*Explicit*" underscores the need for concepts and constraints in the field to be meticulously and unambiguously defined.

"*Formal*" highlights the attribute of being structured in a manner that a computer can readily comprehend and use for inferencing through predefined rules.

"*Shared*" emphasizes that ontology is a repository of knowledge collectively recognized and accepted by a community of domain experts.

Therefore, a domain ontology can be characterized as a structured representation of communal knowledge tailored to a specific domain (Messaoudi et al., 2018).

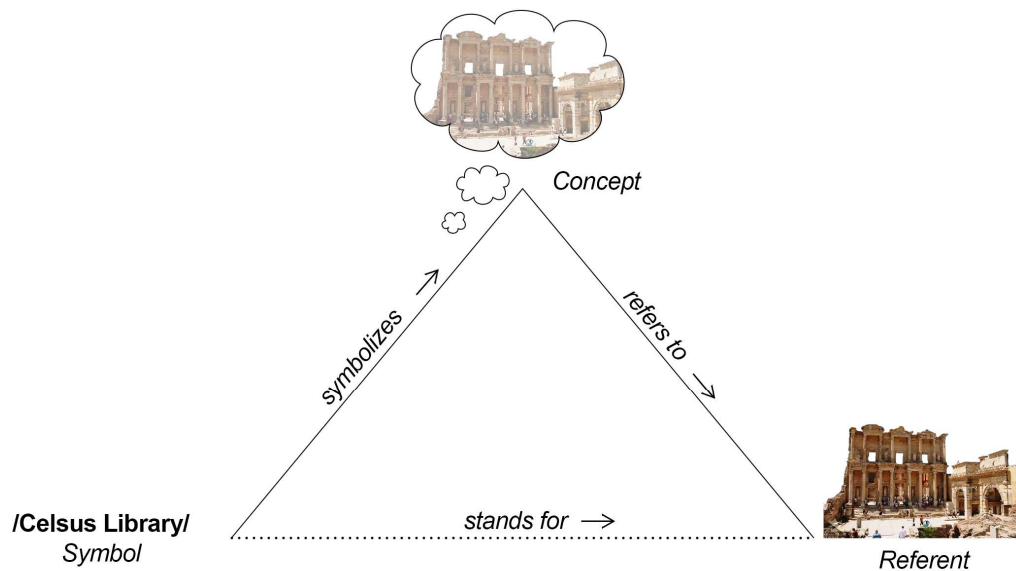


Figure 4. The Meaning of Meaning (Ogden and Richards, 1923)

An ontology serves as the cornerstone for establishing a shared vocabulary among researchers aiming to exchange knowledge within a specific domain. It incorporates machine-interpretable definitions of fundamental concepts within the field, delineating their interconnections (Noy and McGuinness, 2001). Essentially, an ontology operates as a repository of domain-specific knowledge. A semantic network constitutes a distributed web of interlinked information resources associated with each other through uniform

resource identifiers. Ontologies are commonly represented using RDF (Resource Description Framework) or OWL (Web Ontology Language) languages, where concepts and relationships are portrayed within a graphical data structure. The primary objective of ontology development is to articulate the information landscape in a manner understandable to both humans and machines (Cursi et al., 2022). By providing a common framework, ontologies facilitate the organization of data within a field based on its functionality and content. This eliminates the use of informal, idiosyncratic terms and perspectives within the domain, promoting a holistic understanding. Furthermore, ontologies play a pivotal role in semantically preserving extensive data collections, ensuring the meanings and connections between data elements are safeguarded (Ranjgar et al., 2022).

2.2.3. Semantic Enrichment and Knowledge Graph

Semantic enrichment entails augmenting data or information with supplementary meaning and context to enhance comprehension, interpretation, and utilization of the content. This augmentation is realized by incorporating semantic knowledge into existing data or information, frequently leveraging ontologies or knowledge bases to represent and structure the additional meaning. The objective of semantic enrichment is to enhance the indexing, searching, and retrieval processes of knowledge assets, facilitating more efficient utilization of the information (Bloch, 2022; Simeone et al., 2019). The knowledge graph is a graph-based data model structured to represent knowledge, employing entities and their semantic relationships. The process of semantic enrichment actively contributes to the establishment and refinement of knowledge graphs. Techniques for semantic enrichment enhance knowledge graphs by incorporating additional contextual information, thereby elevating the representation and interpretability of the knowledge encapsulated within the graph (Tekbacak and Korkmaz, 2015; Elleuch et al., 2021; Oramas et al., 2016). Crucial among these techniques are semantic classification and refined enrichment, playing a pivotal role in enhancing both the content and structure of knowledge graphs, ultimately bolstering their usability and effectiveness (Wu et al., 2020). The incorporation of semantic enrichment into knowledge

graphs facilitates the portrayal of intricate semantic relationships and augments data with additional contextual meaning, thereby amplifying the knowledge representation capabilities of the graph (Figure 5) (Arruda et al., 2020; Singh et al., 2005). The synergy between semantic enrichment and knowledge graph construction is highlighted by the creation of semantic views, underscoring their interconnected nature (Ikkala et al., 2021).

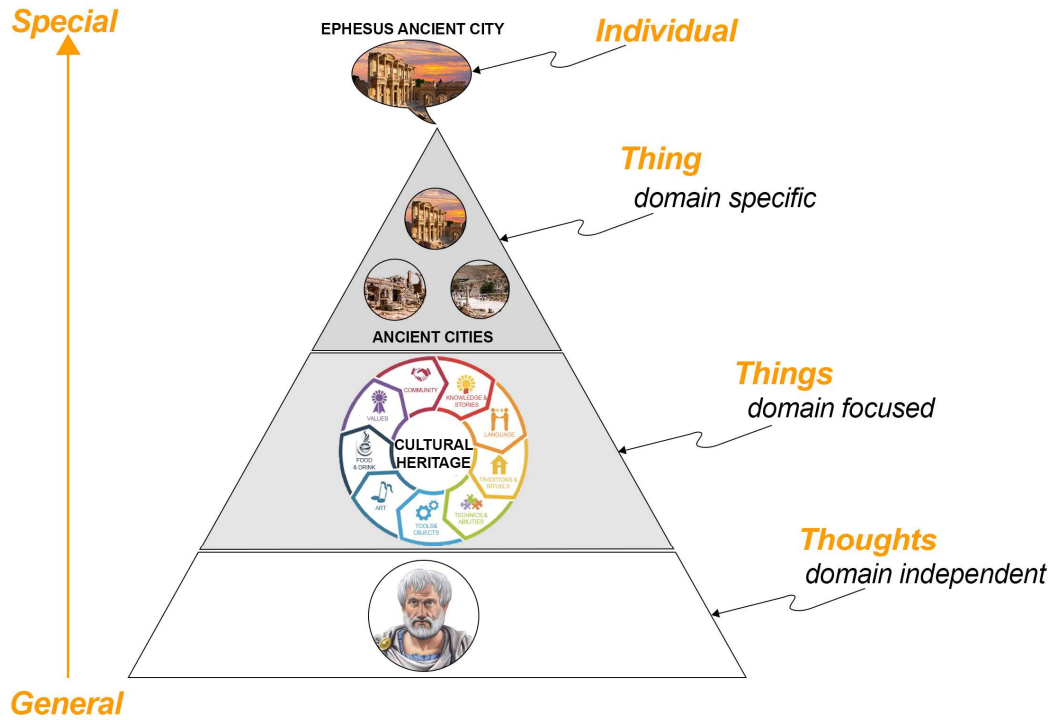


Figure 5. Levels of Semantic Knowledge

2.3. Digital Twins

Changes and developments in technology throughout history have triggered the formation of industrial revolutions. These revolutions facilitated and improved manufacturing processes. Increases in production rates have developed the computational capabilities of companies to solve project complexities. With the dynamic knowledge generation and knowledge mining, open, fast, and accurate cooperation has been achieved with human-computer interactions over time. Through the emergence of Industry 4.0; developments in information and communication technologies (ICT); the use of digital

technologies instead of mechanical and electronic technologies has become an active value proposition. The development of new digital technologies such as virtual reality (VR), AI, the internet of things (IoT), and the Digital Twins (DT) has made new service approaches possible in many sectors.

The cyber-physical production system envisioned with Industry 4.0, which is based on smart manufacturing systems, can be achieved with a DT. Because CPS emerged with the idea of connecting the cyber world and the physical world (Çınar et al., 2021). With the DT, the gaps between physical and digital platforms can be closed by developing simulation tools in the industry. In the early days, data collection and processing methods were limited. However, innovations in ICT in the last decade have provided a rich source of data. As the storage capabilities of sensors and embedded processors improve and become less costly, more realistic representations of the physical world have been created. Sensors enable the integration of data, ensuring the accuracy of virtual vehicle simulations. Real-world data can be integrated into digital models (Ozturk and Celenk; 2023). CPPS occurs with the combination of physical objects and DT (Ding et al., 2019).

The concept of the DT has quickly become important in process management. It consists of three main parts: a physical object in the real environment, a digital object in the digital environment, and data connections between physical and digital objects (Banerjee et al., 2017). The digital representation of the physical product is created in the digital world. Digital models contain the designers' mental expectations and abbreviations of the physical world. DT enables the refinement of design patterns and the iterative optimization of design schemes in product design. Moreover; digital validation, product function, structure, and fast and easy manufacturability can be predicted. Thus, the defect of the design in the digital world can be found correctly, the design can be improved and rapid changes can be made. The entire process, from raw material input to finished product output, can be managed via the DT. Digital models as well as physical models; include rules and dynamic models. Production models and production strategies can be simulated and evaluated. Real-time monitoring is provided with digital-physical interaction and repetition digital models can update themselves based on data in the physical world (Qi & Tao, 2018). However, the Digital Twins literature immensely evolving till its emergence. There is no consensus on the clear definition of Digital Twins

concepts. In addition to the previous common view of Digital Twins as a digital replica of the physical asset, the new perspective suggests a definition for the Digital Twins as the representation of the physical counterpart in a virtual or data model.

2.3. Cultural Heritage Knowledge Management

CH data represents a mosaic of architectural, engineering, sociological, historical, and geographical information. This intricate tapestry of CH data encompasses datasets from diverse fields of expertise, often stored in various formats. Addressing such diversity necessitates an interdisciplinary approach to CHKM (Tibaut and de Oliveira, 2022). The utilization of ontology serves as a universal language, facilitating the comprehension, sharing, and reutilization of information and data across both the physical and digital realms. This application of ontology effectively bridges the gap between Ontology and CH concepts, consolidating them onto a unified platform. Such an approach ensures the preservation of CH knowledge, making it accessible to future generations of researchers and practitioners (Niccolucci et al., 2022). By incorporating ontologies in CH research, it becomes feasible to integrate heterogeneous data sources, thereby establishing a conceptual framework for effective CHKM (Previtali et al., 2020). This approach enhances researchers' capacity to establish meaningful connections between ontology and various data sources, thereby boosting the discoverability of knowledge and fostering integrated and comprehensive CH research.

2.3.1. Cultural Heritage Ontology

CH encapsulates both tangible assets, such as physical objects, and intangible elements like beliefs and philosophical concepts. It embodies the aesthetic, social, and spiritual qualities and values associated with a place or object. Consequently, CH assets serve as invaluable resources for promoting economic, social, and cultural sustainability (UNESCO, 2021). The effectiveness of information sharing hinges on the semiotic depth of the message, influencing its reception. The semiotic triangle, originally expounded by

Ogden and Richards in their 1923 work, 'The Meaning of Meaning,' delineates the relationship between linguistic symbols and the objects they represent (Figure 4). Rooted in Aristotle's 'Peri Hermeneias' from the 4th century BC, the semiotic triangle addresses the philosophical debate on universals, historically dividing ancient and medieval philosophers, particularly realists and nominalists. The semiotic triangle provides a simplified framework for understanding the relationship between (1) the message sender as a subject, (2) a conceptual object or referent, and (3) its sign or signans (Ogden & Richards, 1923). In this context, the most effective and efficient means of transmitting CH knowledge (concept) is by associating this concept with a descriptive symbol. The integration of the concept and its symbol ensures that information can be conveyed in a semantically well-defined manner, enabling users to access the information more comprehensibly.

CH comprises tangible and intangible cultural elements that constitute a nation's identity, reflecting the historical and social activities of its people. CH is characterized by its diversity and multi-conceptual nature, encapsulating various aspects of human life such as eating, dressing, celebrating, and belief (Kalita & Deka, 2020). Given the intricate nature and historical significance of CH issues, it demands an interdisciplinary approach, making CH inherently a knowledge-based discipline. Estimates, interpretations, and conclusions about CH evolve through the comparison of available data with existing information. The collaboration of researchers from different fields, each employing their methods, computational models, or vocabulary, engenders a rich diversity and flow of information (Hellmund et al., 2018). Ontologies play a crucial role in organizing and reusing information. In the context of the semantic web, ontologies empower machines to comprehend information and efficiently query data (Doerr, 2009). Designing an ontological model within the context of CH initiates an interdisciplinary observation and semantic representation of CH elements (Messaoudi et al., 2018).

2.3.2. Cultural Heritage Knowledge Graph via Semantic Enrichment

Semantic enrichment involves the meticulous process of enhancing data or information with additional semantic meaning or context. This method encompasses the

2.4. Conceptual Framework of Digital Heritage Twin (CH Digital Twins)

The conservation of CH knowledge finds a viable solution through the adoption of the Digital Heritage Twin (CH Digital Twins) (Figure 7). In preserving the valuable traces of the past and capturing the shared history of societies, Digital Heritage Twin (CH Digital Twins) facilitates the digitalization of CH, ensuring the protection and effective sharing of CH information. The integration of a chatbot enhances user access to CH, streamlining the interaction with this rich cultural repository. To ensure the enduring sustainability of CH information, Digital Heritage Twin (CH Digital Twins) supports efficient CHKM processes by seamlessly collecting, utilizing, and sharing information. Through Digital Heritage Twin (CH Digital Twins) users gain swift and accurate access to CH information, fostering a deeper appreciation and understanding of CH. Digital Heritage Twin (CH Digital Twins), characterized by a replica of CH information, employs Ontology-based semantic KG to construct a structured knowledge base, enabling rapid and targeted information retrieval. The fusion of HBIM and CH Ontology gives rise to innovative platforms for CH knowledge sharing, while the integration of a chatbot stimulates interactive communication, enhancing the overall accessibility and engagement with CH information. The comprehensive amalgamation of these technologies within Digital Heritage Twin (CH Digital Twins) promises an enriched and interactive comprehension of CH.

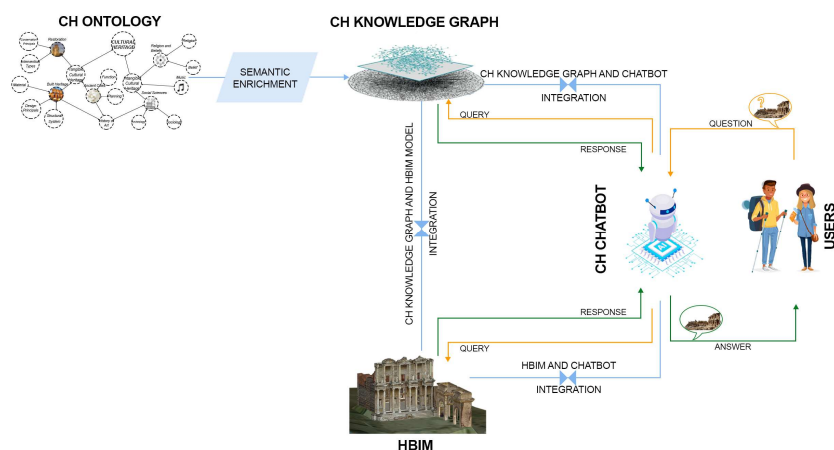


Figure 7. Conceptual Framework of Digital Heritage Twin (CH Digital Twins)

3. METHODOLOGY

The research methodology comprises four steps. Firstly, a comprehensive bibliometric scanning and scientometric analysis were undertaken to scrutinize the application domains of Digital Technologies in Cultural Heritage, thereby elucidating existing gaps and discerning prevailing trends. Subsequently, the research focus was pinpointed through bibliometric research and scientometric analysis within the realm of Cultural Heritage Ontology, guided by the insights derived from the preliminary analysis. In alignment with this established research focus, a dedicated Cultural Heritage Ontology was developed. The final step of the research process involved the acquisition of a Cultural Heritage Knowledge Graph, achieved through the Semantic Enrichment of the Cultural Heritage Ontology (Figure 8).

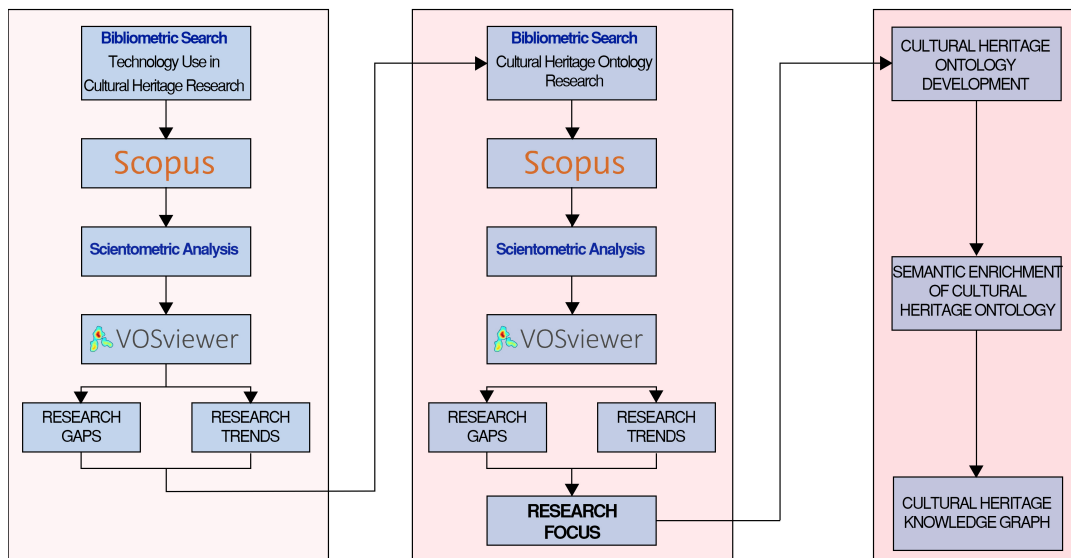


Figure 8. Research Workflow

3.1. Bibliometric Search, Scientometric Analysis and Mapping for Digital Cultural Heritage and Cultural Heritage Ontology

A three-step workflow (Figure 9), encompassing bibliometric search, scientometric mapping, and scientometric analysis, is systematically deployed to explore the existing literature on DCH and CH Ontology research. In the pursuit of a comprehensive study, data is gathered from Scopus, acknowledged for its comprehensive coverage (Aghaei et al., 2013). The initial bibliometric search, conducted exclusively on Scopus, offers a snapshot of the literature within the specified period. It is essential to recognize certain limitations in the research approach. While the utilization of multiple databases holds the potential for broader insights, challenges in data fusion and limitations of existing scientometric analysis tools necessitate a reliance on a single database. Scopus, renowned for its comprehensiveness, aligns with the research objectives. In the subsequent phase of the workflow, the amassed bibliometric data undergoes scientometric mapping, involving an intricate analysis of relationships among disciplines, fields, and individual articles (Cobo et al., 2011). The VOSviewer application, leveraging natural language processing and text mining techniques, is employed for visualization, unraveling intricate networks (van Eck and Waltman, 2014). The application of clustering and ranking techniques to keyword combinations provides valuable insights into DCH and CH Ontology studies. However, it is imperative to be mindful of inherent limitations, such as language restrictions and a focus solely on journal articles. Country-based citation, country-based bibliographic coupling, document-based citation, and keyword co-occurrence analyses are conducted for DCH research, while keyword co-occurrence analysis is applied for CH Ontology. These nuanced analyses facilitate an in-depth examination of both DCH and CH Ontology research.

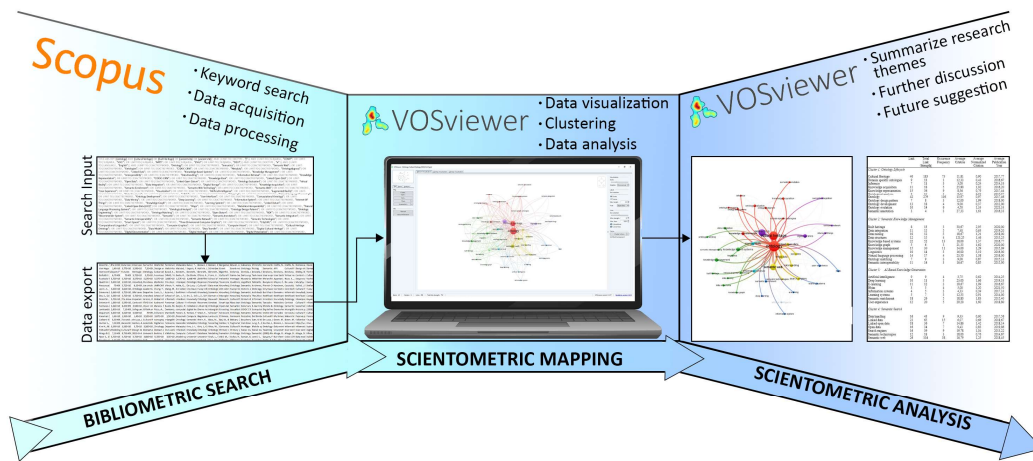


Figure 9. Three-step Workflow of Scientometric Analysis and Mapping

3.2. Cultural Heritage Ontology Development

The ontology development process involved distinct stages, including defining the goal and scope, data acquisition, initial structuring, formalization, and evaluation. These sequential steps were executed to ensure the systematic construction of the CH Ontology (Figure 10).

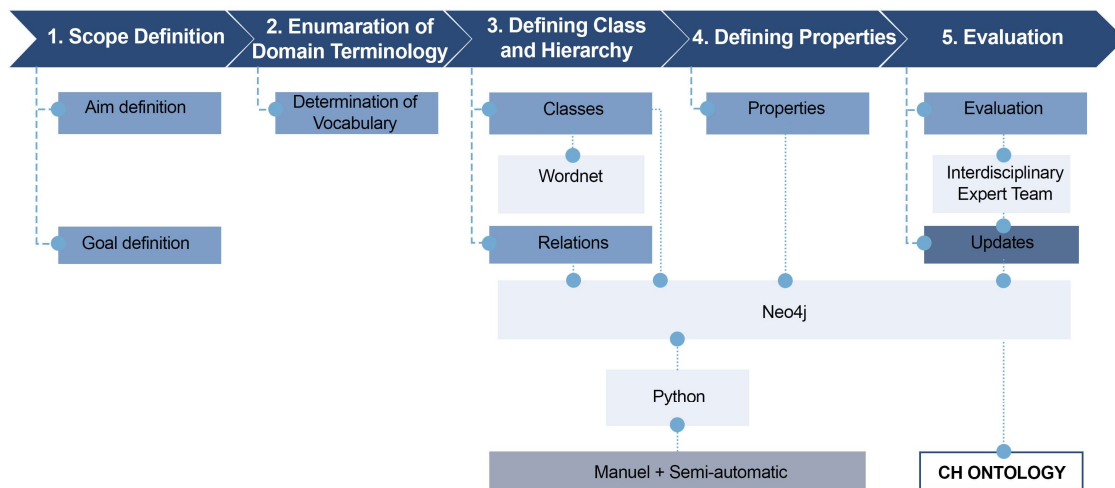


Figure 10. Cultural Heritage Ontology Development

Step 1- Scope Definition: The formulation of scope and goals is crucial in delineating the boundaries and focus of the CH Ontology. Given the interdisciplinary nature of CH, expert opinions from various CH fields were sought through a collaborative approach. The intention is to foster universal access to information, aligning with ensuring accessibility for a diverse user base.

Step 2- Enumeration of Domain Ontology: The examination of CH Ontologies in the literature revealed limitations in the adaptability of the semantic relationships embedded in existing ontologies. To address this, diverse ontologies and data were consolidated in a unified space utilizing the Neo4J application. The data collection process was semi-automatic, where information adhering to semantic web standards (OWL, RDF) and/or accessible through open-source APIs was automatically gathered. Furthermore, textual data related to CH was collected, and its integration into the Neo4J application was facilitated using the Python programming language.

Step 3- Defining Class and Hierarchy: The identification of CH terms involved an analysis of pre-existing ontologies in the CH Ontology field and consultation with domain experts. Lexical databases, including WordNet (2010), were employed to establish hyponyms and hypernyms for the CH Ontology. Once the terms were identified, classes and their semantic relationships were delineated. The Neo4J application facilitated the modeling of these classes and relationships, and a code was developed to represent them.

Step 4- Defining Properties: The classes and relationships established during the initial configuration underwent scrutiny by an expert team. Unnecessary terms were eliminated, and any missing terms were incorporated. Recognizing the inherent limitations of classes in conveying comprehensive information, distinctive features characterizing each class were included in the CH Ontology, leading to its finalization.

Step 5- Evolution: Comprehensive testing has been undertaken to validate the efficacy of the CH Ontology. Syntax testing was executed to ensure syntactic accuracy. Structure tests were conducted to assess the definition and representation of classes, properties, and relationships. Consistency testing was carried out to identify and rectify logical contradictions and inconsistencies. The ontology was subjected to expert evaluation to ascertain its coverage of all essential concepts related to CH. This

iterative process, rooted in systematic testing and expert review, played a crucial role in refining and optimizing the proposed CH Ontology.

3.3. Cultural Heritage Knowledge Graph via Semantic Enrichment

In pursuit of rendering information in a machine-readable format, the CH Ontology undergoes a process of semantic enrichment. This intricate procedure entails the integration of the CH Ontology with external data sources, incorporating data from diverse (Wang et al., 2021). Semantic enrichment involves the utilization of both unstructured and structured data, with deep learning techniques applied to address the complexities of unstructured data. During this phase, unstructured data underwent scrutiny by domain experts, leading to the identification and creation of valuable and accurate text clusters. The initial step involved co-reference resolution on the text set, a process focused on identifying all expressions referencing a specific entity. Subsequently, the text was segmented into sentences with the removal of punctuation marks. The named entity binding segment aimed to extract all named entities and link them to a designated knowledge base. Named entity linking, addressing the challenge of determining entity meaning, was executed in this context. Following this, relationships between these entities were delineated through relationship extraction, establishing connections within the KG by incorporating the identified relationships. This semantically enriched CH Ontology, thus refined, contributes to the representation of information in a manner conducive to machine interpretation (Figure 11).

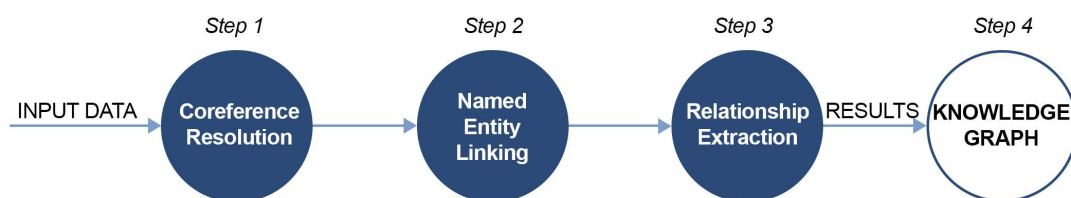


Figure 11. The Steps Followed for Semantic Enrichment of Cultural Heritage Ontology

4. RESULTS

4.1. Scientometric Analysis and Mapping of Digital Cultural Heritage Studies

Scientometric mapping, facilitated through VOSviewer, is employed to unveil the gaps and trends prevalent in Digital Cultural Heritage (DCH) and Cultural Heritage (CH) Ontology research within the scholarly literature. The data derived from scientometric mapping is tabulated, with a dedicated table for each analysis. In the scientometric maps, words are symbolically represented by circles, and the spatial separation between two keywords signifies the degree of semantic interconnection between them.

The column headings in the tables hold specific meanings, elucidated as follows:

Number of Links: This metric gauges the extent to which a keyword is interconnected with other keywords.

Total Link Strength: This metric provides a comprehensive measure of a keyword's overall relational strength with other keywords.

Occurrence Frequency: This metric indicates how frequently a keyword appears in the research field.

Average Published Year: Offering insights into the temporal aspect, this metric informs whether the research linked to the keyword is new or old.

Average Citation: This metric reflects the average number of citations associated with scientific content containing the keyword.

Average Normalized Citation: This metric offers an indication of the impact of documents containing the keyword.

These findings, derived from the meticulous application of scientometric analysis, contribute valuable insights to the understanding of DCH and CH Ontology research.

4.1.1. Bibliometric Search of Digital Cultural Heritage

A bibliometric search was initiated by querying the Scopus database with specific keywords in the TITLE-ABS-KEY ("technology" AND "monumental heritage" OR "archeology" OR "heritage sites" OR "heritage building" OR "built heritage"). This search produced 5,838 results. To enhance the dataset's precision, a language restriction was enforced, resulting in 5,483 articles available in the English language. The search was further refined to 4,843 documents by selecting specific disciplines, including Engineering, Computer Sciences, Social Science, Energy, Arts and Humanities, Environmental Science, Energy, Economy, Decision Science, Business, and Management. To concentrate on scholarly articles, the document type "article" was specified, narrowing down the results to 2,745 articles. Subsequently, the search was limited the source type to journals, yielding 2,046 articles. Further refinement was achieved by incorporating keywords pertinent to the research, ultimately resulting in a curated dataset of 722 articles.

4.1.2. The Literature Sample Size

The Scopus-indexed article addressing the DCH surfaced in 1991. Figure 12 visually illustrates the annual publication trends, illuminating a discernible upward trajectory in the volume of articles over the years, indicative of a burgeoning interest in this research domain. Particularly noteworthy is the substantial surge in research output witnessed in 2008, marking an impressive growth rate of 275%. The past five years have witnessed a notable upswing, with a twofold increase in studies compared to the cumulative count of articles in preceding years (It's important to note that the total number of articles for the year 2022 couldn't be comprehensively examined at the time of this article's preparation). The steep ascent observed between 2018 and 2022 accentuates a pronounced surge in research trend across scientific platforms.

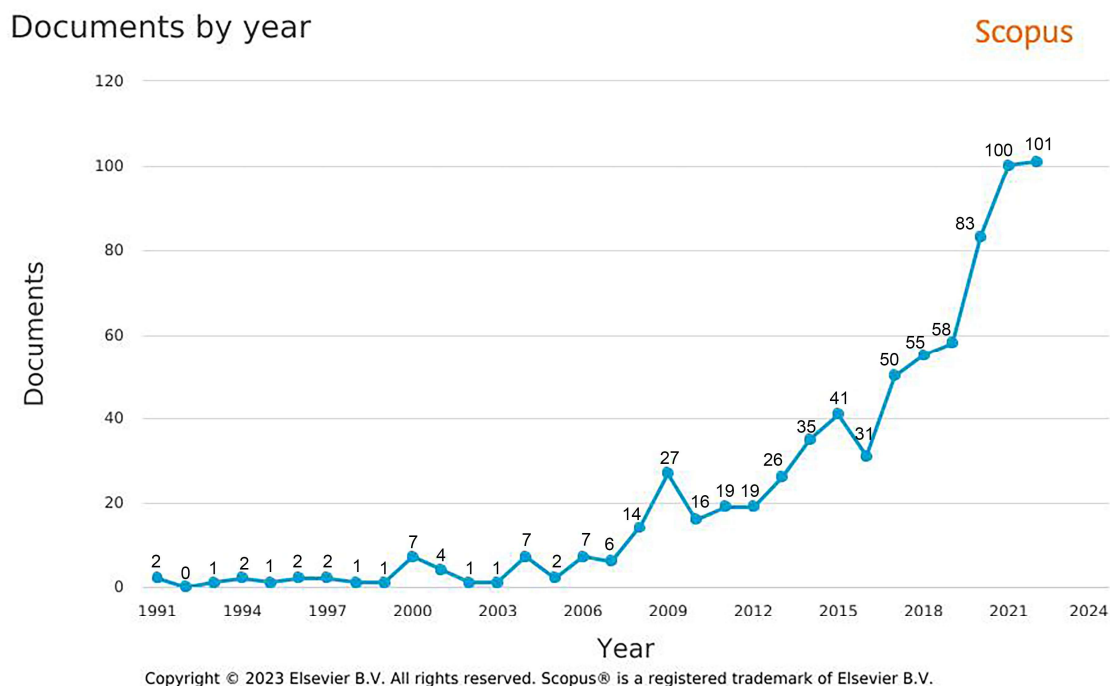


Figure 12. Yearly Number of Papers about Digital Cultural Heritage 1991 to 2022

4.1.3. Results of Country-based Citation Analysis of Digital Cultural Heritage

The landscape of DCH unfolds as a dynamic field shaped by research endeavors across various countries. To illuminate the country-specific impact within the literature, a citation analysis was conducted. The resulting scientometric map provides a visual representation of the country-based influence (Figure 13). Six distinct clusters emerged from the analysis, each contributing to the intricate tapestry of DCH research. Upon scrutiny of the data encapsulated in Table 1, it becomes apparent that the United States, England, and Germany stand out as the foremost contributors, publishing prolifically in the realm of DCH. The total connection strength metric serves as an indicator of the robustness of country-based research connections with other nations. In this context, the United States, Germany, and France emerged as the top three countries, boasting the highest total connection power values. A closer examination of the research activities within these leading countries reveals a notable inclusion of computer simulations, emblematic of modern technological tools. Furthermore, these nations actively engage in

studies pertaining to excavations in the Tanzania region, showcasing the diverse and multidimensional nature of their contributions to DCH research.

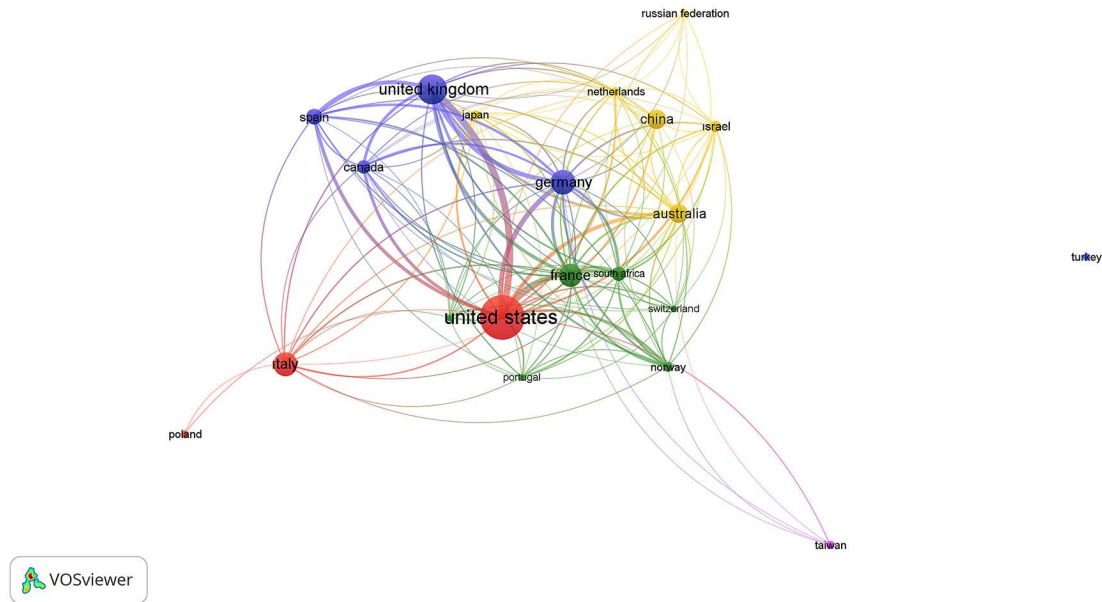


Figure 13. Network Visualization Map of Country-based Citation Analysis in the Research Field of Digital Cultural Heritage

Table 1. Country-based Citation Analysis in the Research Field of Digital Cultural Heritage

Cluster	Link	Total Link Strength	Document Numbers	Average Published Year	Average Citation	Average Normalized Citation
Research Region 1						
Belgium	14	59	10	2009,40	62,50	0,94
France	18	370	60	2014,22	30,52	1,71
Norway	17	170	17	2015,14	24,29	1,40
Portugal	14	66	10	2015,40	26,80	1,15
South Africa	17	235	30	2015,37	45,70	1,64
Switzerland	14	49	10	2012,80	30,30	1,56
Research Region 2						
Australia	18	251	45	2014,51	50,60	2,19
China	14	68	47	2014,53	11,55	0,82
Israel	15	89	21	2014,00	52,86	1,49

Japan	16	100	15	2011,00	46,87	1,46
Netherlands	15	97	14	2013,57	50,71	2,10
Russian Federation	9	13	11	2015,09	5,91	0,90
Research Region 3						
Canada	16	191	27	2011,67	45,52	1,41
Germany	18	526	66	2015,67	21,91	1,34
Spain	15	269	33	2015,85	24,82	1,58
United Kingdom	17	728	87	2013,56	42,22	1,81
Research Region 4						
Italy	15	80	63	2014,00	13,08	0,84
Poland	2	3	11	2016,27	11,36	0,49
United States	19	899	158	2012,92	45,46	1,66
Research Region 5						
Taiwan	5	9	14	2013,64	4,29	0,37
Research Region 6						
Turkey	0	0	12	2012,25	24,75	0,27

4.1.4. Results of Country-based Bibliographic Coupling Analysis of Digital Cultural Heritage

Bibliographic coupling serves as a valuable metric to discern the interconnectedness of scholarly works through the examination of overlapping reference lists. When two publications share a common reference, they are bibliographically coupled, and the common reference number acts as a quantitative indicator of the strength of this coupling relationship (van Eck and Waltman, 2014). In the context of country-based research, a bibliographic coupling analysis was executed to unravel the intricate web of connections between countries. The outcome of this analysis materialized into the network visualization map depicted in Figure 14. The map showcases five distinct clusters, each denoted by a different color, signifying the diverse thematic foci of the coupled publications. Within this visual representation, each circle corresponds to a country, and the links between these circles, along with their respective distances, unveil the publishing relations between pairs of countries. The map thus provides a

comprehensive overview of the bibliographic coupling relationships among nations in the scholarly landscape

The outcomes of the country-based bibliographic coupling analysis are presented in Table 2, offering insights into the intricate network of publication relationships among different nations. The total link strength value within the table serves as a quantitative measure, indicating the robustness of publication connections between any two countries. Upon examination, the three countries exhibiting the highest total link strength values emerge as the United States, Germany, and the United Kingdom. Notably, these countries stand out as the primary contributors to the literature concerning the integration of technology in DCH. The scholarly works from these nations showcase a diverse array of technological methodologies employed in the field of DCH. While the studies from these countries include investigations into excavation sites in Tanzania, there is also a significant focus on preserving CH within their respective national boundaries. Specifically, academic inquiries delve into the use of computer simulations to ensure the continuity of CH, employing UAVs and remote sensing technologies for accurate and comprehensive archaeological evidence.

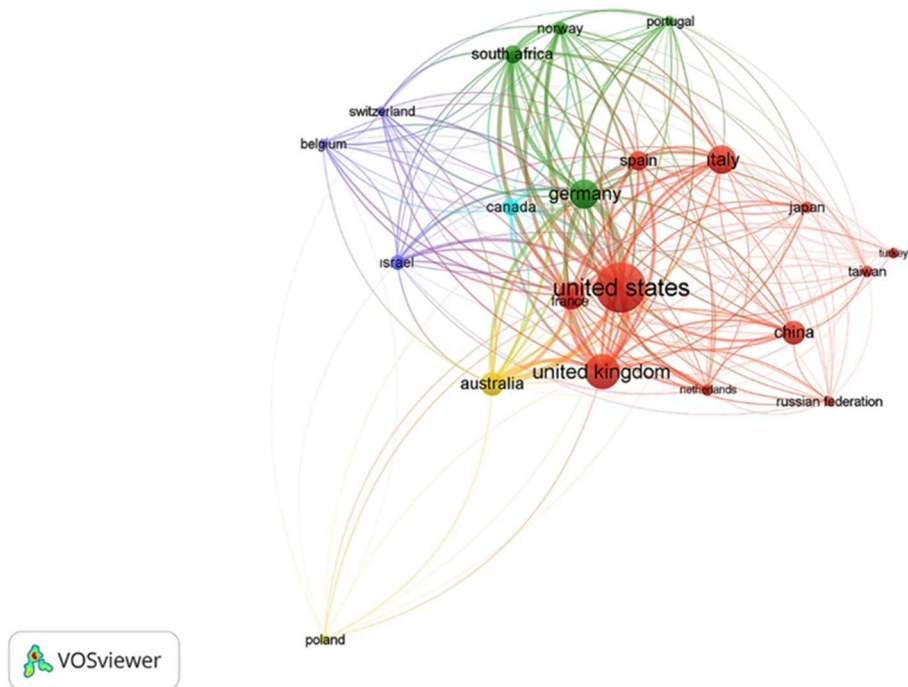


Figure 14. Network Visualization Map of Country-based Bibliographic Coupling Analysis in the Research Field of Technology Use in the DCH

Table 2. Country-based Bibliographic Coupling Analysis in the Research Field of
Digital Cultural Heritage

	Link	Total Link Strength	Document Numbers	Average Publication Year	Average Citation	Average Normalized Citation
Research Region 1						
China	20	5865	47	2014,53	11,55	0,82
France	20	28777	60	2014,22	30,52	1,71
Japan	20	11116	63	2014,00	13,08	0,84
Netherlands	19	2500	15	2011,00	46,87	1,46
Russian Federation	19	1274	11	2015,85	24,82	1,58
Spain	20	11160	33	2015,85	24,82	1,58
Taiwan	18	649	14	2013,64	4,29	0,37
United Kingdom	20	29660	87	2013,56	42,22	1,81
United States	20	48218	158	2012,92	45,46	1,66
Turkey	17	157	12	2012,25	24,75	0,27
Research Region 2						
Germany	20	35337	66	2015,67	21,91	1,34
Norway	19	13354	17	2015,24	24,29	1,40
Portugal	19	5262	10	2015,40	26,80	1,15
South Africa	19	24071	30	2015,37	45,70	1,64
Research Region 3						
Belgium	18	3486	10	2009,40	62,50	0,94
Israel	20	6897	21	2014,00	52,86	1,49
Switzerland	19	5010	10	2012,80	30,30	1,56
Research Region 4						
Australia	20	19837	45	2014,51	50,60	2,19
Poland	11	207	11	2016,27	11,36	0,49
Research Region 5						
Canada	19	9637	27	2011,67	45,52	1,41

4.1.5. Results of Document-based Citation Analysis of Digital Cultural Heritage

The visual representation of the network, derived from the citation analysis of documents focused on DCH using Vosviewer software, is illustrated in Figure 15. The intricacies of the relationships between documents are conveyed through the lines, colors, and distances between circles, symbolizing the mutual citations and associations between pairs of documents. The size of the circle, along with the font, serves as an indicator of the document's substantive contribution to the research area-larger circles denote a more significant contribution. Table 3 provides detailed insights into the links, citations, normalized citations, and publication years resulting from the comprehensive analysis of the documents. Link values in the table signify interconnected publications, while the citation count indicates how frequently a publication is referenced as a source in documents authored by various researchers.

As depicted in Figure 14, a network of 23 emerging documents is observed to be interconnected through links. The domain of DCH is inherently extensive, necessitating diverse expertise across various domains. The apparent independence of research in the analyzed documents suggests that these specialized areas have somewhat constrained collaborative spaces where interdisciplinary cooperation may be limited.

Table 3. Documents in the Research Field of Digital Cultural Heritage

Documents	Link	Citation	Normalized Citation	Publication Year
Barkai et al., 2003	1	101	3.08	2003
Bonano et al., 2000	0	49	1.14	2000
Chase et al., 2012	1	98	3.83	2012
Eren et al., 2015	1	48	1.97	2015
Evans et al., 2013	1	121	5.05	2013
Galvan et al., 2014	0	43	1.77	2014
Gravina et al., 2005	0	70	3.17	2005
Harmand et al., 2015	0	294	12.06	2015
Holen et al., 2017	0	68	6.99	2017
Iovita, 2011	0	66	4.25	2011
Kohler et al., 2005	0	71	3.22	2005
O'Connor et al., 2014	0	42	1.73	2014
Ofli et al., 2016	0	50	3.33	2016
Ott et al., 2011	0	54	3.48	2011

Pappu et al., 2011	0	102	6.57	2011
Perrault., 2012	0	41	1.60	2012
Sadier et al., 2012	0	55	2.15	2012
Schibille et al., 2011	0	42	2.71	2011
Torres et al.,2007	0	45	0.32	2007
Tryon et al., 2002	0	92	2.92	2002
Valladas et al., 2013	1	42	1.75	2013
Wang et al., 2012	1	52	2.03	2012
Yilmaz et al., 2007	0	111	0.79	2007

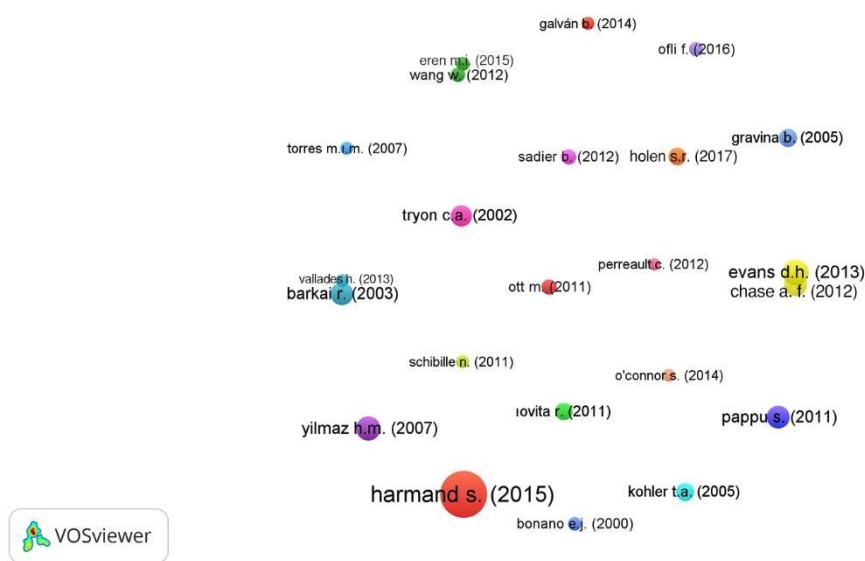


Figure 15. Network Visualization Map of Document-based Citation Analysis in the Research Field of Digital Cultural Heritage

The three most cited documents are “Harmand et al., 2015”, “Evans et al., 2013”, and “Yilmaz et al., 2007” (Figure 14 and Table 3). In the study by Harmand et al., 3D scanner technology was employed to create a comprehensive digital model of the historical area. The article by Evans et al. utilized LIDAR technology to capture the 3D topography of the historical area beneath canopy cover. Absolute location information was obtained using a Global Positioning System (GPS) antenna. The integration of LIDAR and GPS data into ArcGIS software facilitated the creation of a detailed 3D representation of the area. Yilmaz et al. emphasized the significance of technology in the certification stage, a critical aspect of the restoration process for historical buildings. In

their case study, Photogrammetry methods were employed to collect data from the field. Images of a historically significant building, damaged in a fire in Konya, were captured using Digital Close-Range Photogrammetry (DCRP). The mathematical equations applied to the DCRP images resulted in a 3D model through the use of Photomodeler software. This approach ensures permanent access to information even if the documents suffer damage for any reason.

The chronological order of the development of the field of DCH, as indicated by keyword co-occurrence analysis results, is presented in Table 3. VR emerges as the most prevalent topic in DCH literature. VR technology enables the seamless integration of the real-world environment with digital representations of unbuilt structures, offering an immersive experience without significant resource expenditures. This technology allows remote access to historical sites through visually integrated representations of the real-world environment. Remote sensing technologies play a crucial role in capturing data from CH without compromising its historical integrity, serving as a valuable method for evidence collection. Photogrammetry methods are prominently utilized in CH restoration, facilitating the digitization of physical CH information. The combination of photogrammetry and laser applications yields 3D models of CH structures. The recent integration of technology has significantly contributed to the enduring preservation and storage of CH knowledge. Research indicates that these technologies, although extensively studied, are not widely implemented in practice, and ongoing efforts aim to bridge this gap. The adoption of environmental technologies, prompted by environmental concerns such as pollution, climate change, and ecosystem shifts, is becoming prevalent. The historical environment, susceptible to these challenges, is now a focal point for researchers striving to apply these technologies. Environmental technologies offer benefits such as reduced material inputs and energy consumption, aligning with sustainability goals. The use of technological methods ensures cost-effective historical research while minimizing environmental impact.

4.1.6. Results of Keyword Co-occurrence Analysis of Digital Cultural Heritage

Scientometric mapping, a method adept at analyzing bibliometric data inclusive of authors, journals, and articles, can be generated based on co-occurrence data utilizing VOSviewer. Keywords assume a pivotal role in unraveling crucial facets of research. Scientometric maps, as innovated by van Eck and Waltman (2014), unveil the intricate relationships between research topics and the organizational structure of information. Co-occurrences furnish a means to extract data regarding articles wherein keywords appear in conjunction. In this context, bibliometric data was leveraged to craft a map that visually depicts keyword associations (Figure 16). The colors ascribed to keywords denote their clustering, discerned through Keyword Co-occurrence Analysis. The outcomes of the analysis lay bare the segregation of keywords into six distinct clusters:

1. Facility Management for Built-Heritage (red-coded)
2. Remote Sensing Technologies for Heritage Areas (green-coded)
3. Cultural Heritage Sustainability (blue-coded)
4. Digital Reconstruction (yellow-coded)
5. Digital Heritage Countries (purple-coded)
6. Visualization of Cultural Heritage Areas (turquoise-coded)

Keywords are visually depicted using circles in the analysis, with the size of each circle corresponding to the relative importance of the associated word. The distance between two keywords on the map reflects the degree of semantic relatedness between them. Table 4 showcases six clusters of keywords, presenting only the most robust connections among them. The link value, a positive numerical indicator, signifies the collective strength of connections between two keywords, denoting the number of articles in which these keywords co-occur.

The meanings of the column headings in Table 4 are elucidated below:

Number of Links: Quantifies the degree to which a keyword is associated with other keywords.

Total Link Strength: Measures the overall strength of a keyword's associations with other keywords.

Table 4. Co-occurrence of Author and Index Keywords in the Digital Cultural Heritage

Keywords	Link	Total Link Strength	Occurrence Frequency	Average Publication Year	Average Citation	Average Normalized Citation
Cluster 1-Facility Management for Built-Heritage (red-coded)						
Artificial intelligence	12	19	11	2016,36	24,82	0,91
Building Information Modelling	13	17	5	2020,80	7,20	1,62
Database Visualization	10	16	5	2010,60	58,20	1,13
Database Systems	11	14	5	2000,00	54,00	0,74
Decision Making	18	24	10	2016,30	13,60	0,85
Environmental Technology	8	9	5	2017,80	4,40	0,57
Heritage Buildings	24	42	13	2017,38	14,54	1,56
Historic Preservation	31	59	16	2018,06	14,00	1,39
ICT	9	11	7	2017,29	16,57	0,77
Information Management	17	19	10	2014,20	5,11	0,55
Information Technology	27	38	20	2011,25	20,85	0,79
Internet	15	20	10	2011,40	5,50	0,40
Internet of Things	16	22	11	2020,00	8,91	1,43
Preventive conservation	10	14	5	2020,00	14,40	2,16
Restoration	16	18	7	2016,43	13,71	0,95
Visualization	31	44	12	2012,25	37,33	0,95
Cluster 2-Remote Sensing Technologies for Heritage Areas (green-coded)						
Egypt	7	7	5	2016,40	19,40	3,39

Experimental Technology	8	17	16	2012,06	50,75	1,18
GIS	40	102	57	2013,18	16,04	0,76
Lidar	17	32	14	2016,79	27,79	1,13
Mapping	12	15	6	2012,67	6,00	0,33
Remote Sensing	41	108	55	2015,00	21,69	1,04
Reverse Engineering	6	8	5	2010,60	13,80	0,64
Satellite Data	8	17	5	2014,60	20,20	0,90
Satellite Imaginary	19	41	13	2012,08	24,00	0,66
South Africa	7	9	5	2011,80	69,20	1,47
Spatial Analysis	23	37	12	2015,83	13,50	0,88
Technology	36	77	85	2013,59	21,64	0,89
Technology Adoption	6	9	12	2016,83	17,67	1,03
Turkey	16	21	8	2012,25	28,00	0,82
United States	13	20	11	2012,36	18,45	0,91
Cluster 3-Cultural Heritage Sustainability (blue-coded)						
China	23	41	18	2016,56	13,72	0,75
Cultural Heritage	62	225	120	2017,08	10,37	0,87
Economic Development	16	18	6	2016,00	18,00	1,12
Energy Efficiency	15	26	7	2017,29	17,86	1,63
Energy Utilization	15	31	8	2017,62	18,00	1,34
Heritage Conservation	25	46	13	2019,00	6,54	0,80
Heritage Tourism	14	25	7	2016,71	13,71	1,29
Optimization	19	26	6	2015,83	17,33	1,13
Spatial data	13	19	5	2012,20	41,60	2,28
Sustainability	24	46	17	2019,89	4,72	0,83
Sustainable Development	33	70	19	2018,42	9,00	0,91
Technology Transfer	15	18	10	2018,42	9,00	0,91
UNESCO	26	39	11	2014,55	11,45	0,81
World Heritage Site	32	56	15	2013,47	21,33	1,07

Cluster 4-Digital Reconstruction (yellow-coded)

3D Printing	5	8	6	2020,67	2,33	0,69
Algorithm	15	22	7	2011,86	37,43	1,23
Automation	12	18	6	2014,00	54,17	2,36
Computer-Aided Design	23	30	7	2008,43	44,00	1,28
Computer Simulation	27	36	13	2013,08	26,15	0,97
Data Acquisition	37	55	14	2012,43	14,71	1,20
HBIM	5	7	5	2020,20	21,80	5,18
Laser Applications	17	22	6	2012,17	22,00	1,37
Laser Scanning	16	22	7	2018,86	5,43	1,04
Photogrammetry	41	85	50	2017,28	10,10	1,22
Reconstruction	14	18	9	2015,22	17,22	1,00
Three-Dimensional Modelling	38	75	26	2014,50	21,81	1,46
UAV	11	17	7	2019,29	21,57	1,79

Cluster 5-Digital Heritage Countries (purple-coded)

Aerial Photography	17	24	7	2010,14	15,00	0,64
Archeological Site	13	17	6	2013,83	31,83	0,75
Data Processing	21	30	6	2012,17	10,50	0,54
Digital Photogrammetry	15	22	6	2013,50	8,67	0,70
Eurasia	34	70	16	2007,69	43,25	1,19
Europe	26	54	16	2009,38	31,00	0,89
Italy	27	52	18	2015,06	11,33	0,83
Jordan	8	11	5	2017,20	3,60	0,20
Southern Europe	13	25	5	2007,80	32,20	0,74
Spain	17	21	5	2007,80	32,20	0,74
United Kingdom	11	16	7	2011,43	22,71	1,57

Cluster 6-Visualization of Cultural Heritage Areas (turquoise-coded)

3D Reconstruction	9	16	6	2018,67	9,50	1,07
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Augmented Reality	19	40	18	2016,44	12,94	1,09
Digital Technologies	12	16	8	2019,38	3,75	0,52
Heritage Sites	20	30	9	2013,44	7,22	0,31
Image Analysis	20	28	7	2007,88	24,50	0,45
Image Reconstruction	20	28	7	2008,86	33,29	0,84
Virtual Archeology	10	21	10	2015,50	37,10	1,54
Virtual Reality	42	89	48	2014,98	15,92	1,12
Virtual Reconstruction	8	13	5	2018,60	4,60	0,88

In Pearson correlation analysis, the statistical values include the correlation coefficient (r) representing the relationship between measurement indicators. The significance of the correlation is measured by the p-value, with values below 0.001 and 0.05 indicating a statistically significant correlation. If the p-value exceeds 0.05, the correlation is considered statistically insignificant. The same statistical values and rules apply to Table 7 for the correlation analysis of keywords. Table 5 examines the relationship between quantitative factors, revealing a highly positive correlation ($r = 0.794$) between total link strength and keyword occurrence. Table 5 demonstrates the independence of average citation and average normalized citation from occurrence frequency and total link strength. Additionally, the relationship between average citation and average normalized citation is found to be not significant (Table 5).

Table 5. Pearson Correlation Analysis of the Measurement Factors for Keyword Co-Occurrence Analysis.

Measurement Items	Statistic al Values	Number of Links	Total Link Strength	Occurrence Frequency	Average Citation	Average Normalized Citation	Average Year Published
Number of Links		1					
Total Link Strength	r	0,766333	1				
	p - value	<0.001					
Occurrence Frequency	r	0,639991	0,794181	1			
	p - value	<0.001	<0.001				
Average Citation	r	0,038784	0,104389	0,090831	1		
	p - value	.303	.345	.422			
Average Normalized Citation	r	0,071498	0,025547	0,051177	0,451122	1	
	p - value	.179	.254	.422	.001		
Average Year Published	r	0,063492	0,0311	0,009743	0,65199	0,03608	1
	p - value	.588	.868	.543	<0.001	.072	

Number of Links in Co-occurrence keywords in the Digital Cultural Heritage:

The 'Number of Links' functions as a metric indicating the degree of interconnectedness of a keyword with other keywords within the research domain. Notably, the keyword 'Cultural Heritage' (62) demonstrates the highest number of connections, followed by 'Virtual Reality' (42), 'Photogrammetry,' and 'Remote Sensing' (41) in the field of research on Novel Technology used for the Digital Transformation of CH. The substantial number of links associated with these keywords emphasizes their central role in the digitization of CH and their crucial contribution to supporting CHKM. Conversely, keywords like 'Virtual Reconstruction' (8), 'Egypt' (7), and 'Reverse Engineering' (6) display lower numbers of connections, respectively. This observation can be attributed to the relatively limited research focus on 'Virtual Reconstruction' and 'Reverse Engineering' within the context of CH, suggesting that these areas have not yet received extensive scholarly attention. The application of Novel Technologies in CH holds the potential to create a Digital Heritage Twins (CH Digital Twins), introducing innovative platforms to strengthen CHKM.

Total Link Strength in Co-occurrence keywords in the DCH:

The keywords 'Cultural Heritage' (225), 'Remote Sensing' (108), and 'GIS' (102) emerge as the top three terms in 'Total Link Strength.' It is noteworthy that 'Cultural Heritage' not only possesses the highest 'Total Link Strength' but also exhibits the highest

occurrence frequency, indicating an increased utilization of Novel Technology for the Digital Transformation of CH. Subsequently, 'GIS' ranks as the second most prominent keyword. The data harnessed through Geographic Information Systems (GIS) play an integral role in amalgamating with other technologies, facilitating the digitalization of CH elements. As a result, GIS finds widespread and effective utilization across diverse research domains. Furthermore, 'Remote Sensing' claims the highest 'Total Link Strength.' The proficiency of remote sensing technologies in rendering CH in a precise and environmentally benign manner underscores its status as one of the most sought-after and extensively explored technologies in this domain. On the other hand, keywords such as 'Environmental Technology' (9), '3D Printing' (8), and 'HBIM' (7) exhibit relatively lower link counts. These areas necessitate further examination regarding their contributions to production and development in the future.

Occurrence Frequency in Co-occurrence keywords in the DCH:

The Occurrence Frequency metric serves as an indicator of the emphasis placed on a word within the research domain. The term 'Cultural Heritage' (120) boasts the highest value. It is crucial to note that the bibliometric search includes 'Cultural Heritage' as an essential keyword, hence its prominence in this regard. Subsequently, 'GIS' (57) emerges as the second-highest keyword. GIS technology plays a pivotal role in the storage and analysis of geographic data, making it a significant component of research in this field. 'Remote Sensing' (55) ranks third, reflecting the efficacy of remote sensing technologies in the collection of data about CH. Conversely, keywords such as 'HBIM' (7), 'Energy Efficiency' (7), and 'Optimization' (6) exhibit notably lower 'Occurrence Frequency' values, indicating a substantial research gap in these areas. Bridging this gap could potentially lead to the development of more sustainable practices within CHKM.

Average Citation in Co-occurrence keywords in the DCH:

The keywords 'South Africa (69.20),' 'Database Visualization (58.20),' and 'Database Systems (54.00)' have demonstrated the highest values. These findings underscore the vital role of Information and Communication Technologies (ICT) in the digitalization of CH data. Through the utilization of ICT, CH data can be efficiently visualized and structured into databases, rendering them readily accessible. The notable

increase in the 'Average Citation' value across these keywords is indicative of the active utilization of these technologies within the field of CH research. Keywords such as 'Virtual Reconstruction (4.60),' 'Digital Technologies (3.75),' and 'Jordan (3.60)' exhibit considerably lower values. This suggests an existing research gap within these specific domains, warranting further attention and exploration.

Average Normalized Citation in Co-occurrence keywords in the DCH:

The keywords 'HBIM (5.18),' 'Egypt (3.39),' and 'Automation (2.36)' have surfaced as the top three terms, boasting the highest 'Average Normalized Citation' values. The integration of nD (n-Dimensional) information into the HBIM platform assumes paramount significance in preserving the sustainability of CH data. This synergy between nD information and the HBIM platform allows automation within historical contexts, leveraging the potential of digital technologies. 'Mapping (0.33),' 'Image Analysis (0.31),' and 'Jordan (0.20)' exhibit notably lower 'Average Normalized Citation' values. This observation underscores the necessity for further exploration and research in these areas, where the potential for scholarly engagement remains untapped.

Average Publication Year in Co-occurrence keywords in the DCH:

Keywords such as '3D Printing (2020.67),' 'HBIM (2020.20),' and 'IoT (2020.00)' have gained prominence in the field of CH. 3D printing serves as a valuable tool for assessing interventions in CH preservation by recreating physical artifacts, with a focus on sustainability through the use of recyclable materials. HBIM enables the digital modeling of CH, bridging the gap between historical assets and the digital realm. IoT technology has become increasingly significant due to its real-time data collection capabilities via embedded sensors in physical structures. This upsurge in research activity aims to establish a DCH platform, offering real-time data and enriched digital representations. This growing research trajectory points to a promising future for the field, with expectations of further advancements soon.

VR is a predominant technology in CH research, enabling immersive experiences of historical sites without the need for physical construction, and extending remote access to a broad audience. Remote sensing technologies are pivotal for non-invasive data acquisition, preserving the physical integrity of CH assets. Photogrammetry is

instrumental in digitally capturing physical CH information. The integration of novel technologies has contributed to preserving interdisciplinary knowledge and consolidating expertise on a single platform. However, the practical implementation of these technologies is still evolving.

4.2. Scientometric Analysis and Mapping of Cultural Heritage Ontology

4.2.1. Bibliometric Search of Cultural Heritage Ontology Research

To refine the search results and emphasize high correlation with the combined research keywords, a Boolean search methodology was employed, systematically eliminating irrelevant outcomes. To enhance clarity and precision, limitations were strategically applied to the bibliometric search, as depicted in Figure 17. The initial search yielded 698 articles, and subsequent restrictions, including narrowing the document type to journals, refining the scope within specific fields of science, and further restricting to journal articles, led to a curated set of 220 results. Recognizing the predominant use of English in academic publications, the search was further confined to English language articles following the recommendation of Butler and Visser (2006), resulting in 208 articles. The investigation was then further confined to keywords within the specific subject areas of CH and Ontology, ultimately yielding a focused set of 177 articles, as illustrated in Figure 18. This systematic approach not only ensures relevance but also establishes a robust foundation for a more in-depth exploration of the selected articles.

TITLE-ABS-KEY({ontology} AND {cultural heritage} OR {built-heritage} OR {ancient city} OR {ancient site}) AND (LIMIT-TO(SRCTYPE, "J")) AND (LIMIT-TO(SUBJAREA, "COMP") OR LIMIT-TO(SUBJAREA, "SOCI") OR LIMIT-TO(SUBJAREA, "ARTS") OR LIMIT-TO(SUBJAREA, "ENGI") OR LIMIT-TO(SUBJAREA, "DECI")) AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(EXACTKEYWORD, "Ontology") OR LIMIT-TO(EXACTKEYWORD, "Semantics") OR LIMIT-TO(EXACTKEYWORD, "Semantic Web") OR LIMIT-TO(EXACTKEYWORD, "Ontologies") OR LIMIT-TO(EXACTKEYWORD, "CIDOC CRM") OR LIMIT-TO(EXACTKEYWORD, "Metadata") OR LIMIT-TO(EXACTKEYWORD, "Ontology's") OR LIMIT-TO(EXACTKEYWORD, "Linked Data") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Based Systems") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Management") OR LIMIT-TO(EXACTKEYWORD, "Interoperability") OR LIMIT-TO(EXACTKEYWORD, "Data Handling") OR LIMIT-TO(EXACTKEYWORD, "Information Retrieval") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Representation") OR LIMIT-TO(EXACTKEYWORD, "CIDOC-CRM") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Base") OR LIMIT-TO(EXACTKEYWORD, "Linked Open Data") OR LIMIT-TO(EXACTKEYWORD, "Open Data") OR LIMIT-TO(EXACTKEYWORD, "Linked Open Datum") OR LIMIT-TO(EXACTKEYWORD, "Ontology Evaluation") OR LIMIT-TO(EXACTKEYWORD, "Virtual Reality") OR LIMIT-TO(EXACTKEYWORD, "Data Integration") OR LIMIT-TO(EXACTKEYWORD, "Digital Storage") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Acquisition") OR LIMIT-TO(EXACTKEYWORD, "Semantic Enrichment") OR LIMIT-TO(EXACTKEYWORD, "Semantic Web Technology") OR LIMIT-TO(EXACTKEYWORD, "Semantic-Web") OR LIMIT-TO(EXACTKEYWORD, "User Experience") OR LIMIT-TO(EXACTKEYWORD, "Visualization") OR LIMIT-TO(EXACTKEYWORD, "Artificial Intelligence") OR LIMIT-TO(EXACTKEYWORD, "Augmented Reality") OR LIMIT-TO(EXACTKEYWORD, "Data Structures") OR LIMIT-TO(EXACTKEYWORD, "HBIM") OR LIMIT-TO(EXACTKEYWORD, "Mapping") OR LIMIT-TO(EXACTKEYWORD, "Natural Language Processing") OR LIMIT-TO(EXACTKEYWORD, "Ontology Development") OR LIMIT-TO(EXACTKEYWORD, "User Interfaces") OR LIMIT-TO(EXACTKEYWORD, "Computational Ontology") OR LIMIT-TO(EXACTKEYWORD, "Data Mining") OR LIMIT-TO(EXACTKEYWORD, "Deep Learning") OR LIMIT-TO(EXACTKEYWORD, "Information System") OR LIMIT-TO(EXACTKEYWORD, "Internet Of Things") OR LIMIT-TO(EXACTKEYWORD, "Knowledge Graph") OR LIMIT-TO(EXACTKEYWORD, "Learning Systems") OR LIMIT-TO(EXACTKEYWORD, "Linked Datum") OR LIMIT-TO(EXACTKEYWORD, "Linked Open Data (LOD)") OR LIMIT-TO(EXACTKEYWORD, "Maps") OR LIMIT-TO(EXACTKEYWORD, "Metadata Interoperability") OR LIMIT-TO(EXACTKEYWORD, "Natural Language Processing Systems") OR LIMIT-TO(EXACTKEYWORD, "Ontological Analysis") OR LIMIT-TO(EXACTKEYWORD, "Ontology Design Patterns") OR LIMIT-TO(EXACTKEYWORD, "Ontology Engineering") OR LIMIT-TO(EXACTKEYWORD, "Ontology Matching") OR LIMIT-TO(EXACTKEYWORD, "Open Datum") OR LIMIT-TO(EXACTKEYWORD, "RDF" ...

Figure 17. Bibliometric Search Input

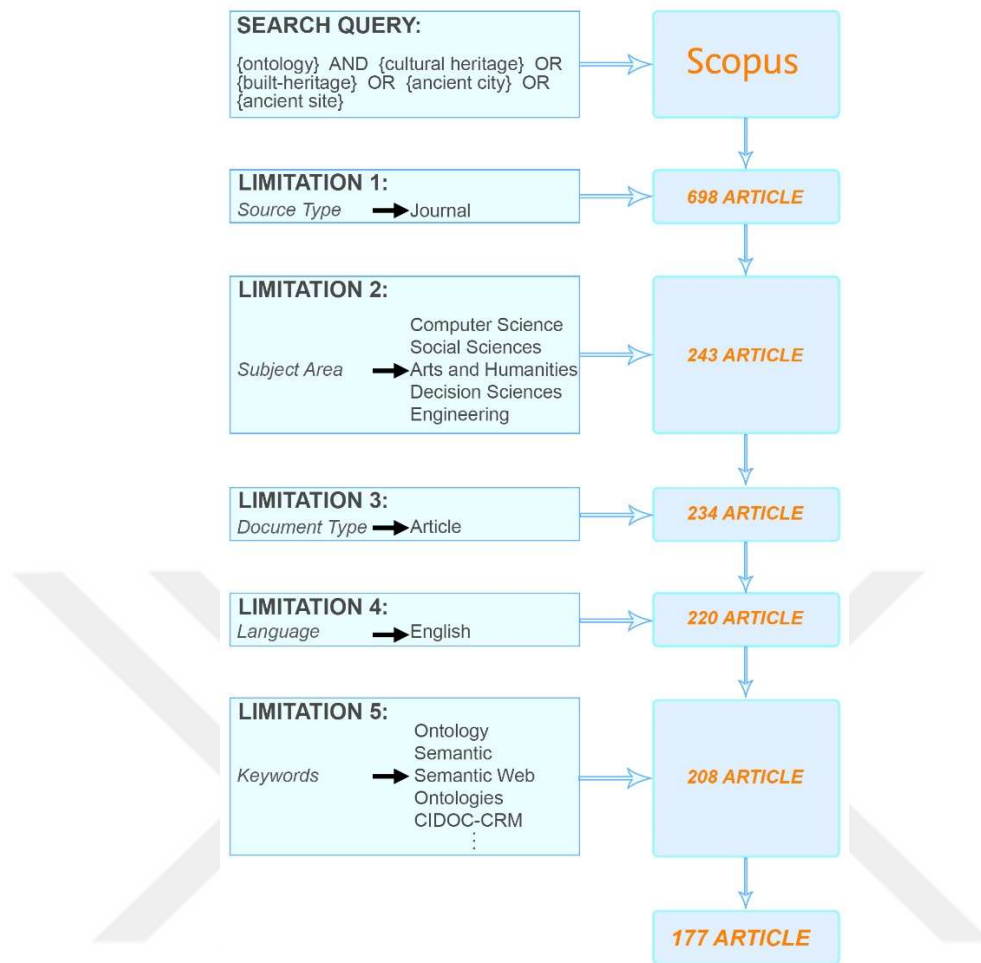


Figure 18. Bibliometric Search Limitations

4.2.2. The Literature Sample Size

The annual publication trends of articles dedicated to CH Ontology Research span the years 2002 to 2023 (inclusive of articles published until the conclusion of April 2023). Notably, there is a discernible surge in the number of articles, particularly in 2021, signifying a significant uptick in research output. From 2016 to the end of June 2023, an average of 25.33 articles were published annually, showcasing a substantial increase compared to the average of 5.70 articles annually between 2002 and 2021. This surge in publications may be attributed to the recent advancements in Semantic Web Technologies, indicating a noteworthy escalation in CH Ontology Research (Figure 19).

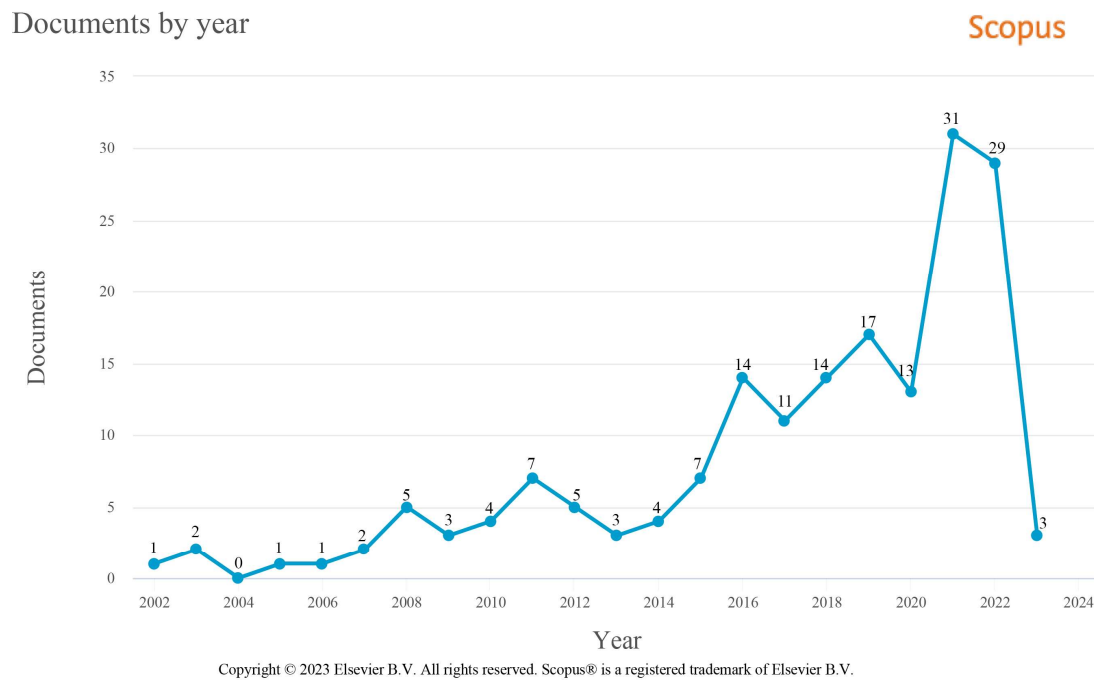


Figure 19. Yearly Number of Papers about Ontology Researches in Cultural Heritage Literature from 2002 to 2023 (The number of papers in 2023 is 3 and represents the published papers up to June 2023)

The graphical representation in Figure 20 delineates the distribution of ontology research within the CH domain across various academic disciplines. Notably, Computer Sciences constitute the predominant sector, accounting for 34.8% of ontology research. Social Science and Arts and Humanities follow closely, contributing significantly with percentages of 18.9% and 15.9%, respectively. Engineering holds a noteworthy share at 9.2%, while Material Science, Physics and Astronomy, Chemical Engineering, Business, Management, Accounting, Chemistry, Decision Sciences, and other disciplines contribute to the overall landscape with varying percentages ranging from 1.6% to 6.5%. It is evident from the graph that the primary domains for research studies in CH are Social Sciences and Arts and Humanities. Concurrently, ontology studies find a robust foundation within the field of Computer Science, as indicated by their prominent representation in the graph. This distribution underscores the imperative for interdisciplinary collaboration in ontology studies within the CH domain, as these three leading fields collectively form the cornerstone of research activities in this context.

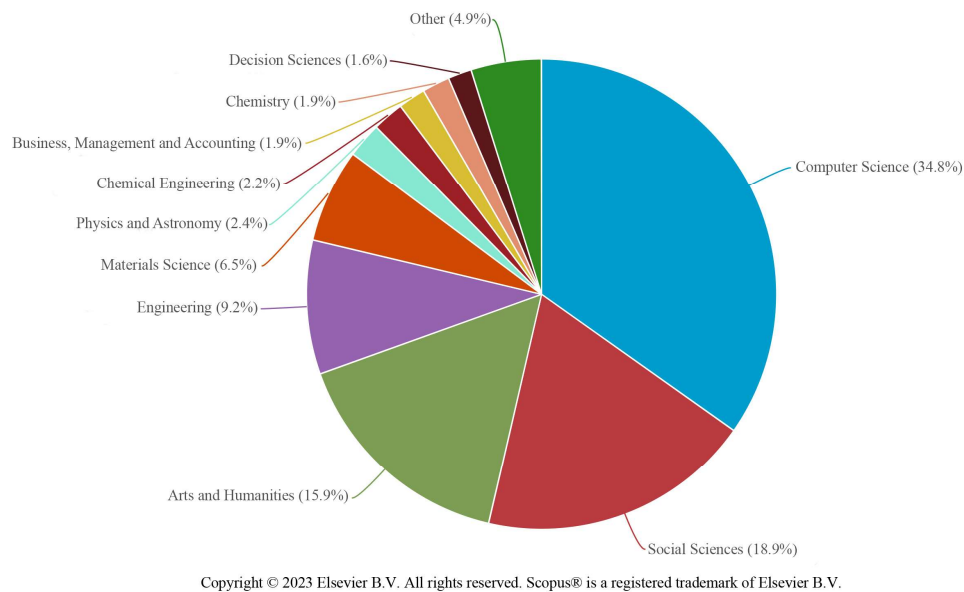


Figure 20. The Contribution of Research Fields to Cultural Heritage Ontology Literature

4.2.3. Results of Keyword Co-Occurrence Analysis of Cultural Heritage Ontology Research

Keywords are assumed to delineate essential facets of research (Su and Lee, 2010; He et al., 2017). The exploration of relationships between keywords is facilitated through VOSviewer, leveraging NLP algorithms and text mining methods. VOSviewer employs clustering techniques to construct a keyword network (van Eck and Waltman, 2014). Some databases incorporate index keywords in addition to those specified by authors, encompassing terms potentially overlooked by the authors themselves. This research incorporates both author-specified and index keywords to comprehensively capture the nuances of the articles under scrutiny. The filtration of all examined articles enables the determination of the frequency of keywords, with the recurrence of a keyword in an article indicative of the article's thematic scope. The manifestation of keyword occurrences in the title, abstract, or article keywords is denoted by the respective count. Figure 20 showcases the co-occurrence network of keywords, delineating the interconnected

landscape through the analysis of bibliometric data. The map was generated with consideration for the combination of at least 3 keywords. Out of the 1211 keywords initially identified, 101 met or exceeded the threshold of 3 occurrences. Subsequently, the keywords underwent a meticulous curation process, resulting in the tabulation of 45 keyword data (Table 6). This approach ensures a nuanced exploration of the research landscape, capturing the interplay and significance of diverse keywords in the realm of CH Ontology Research.

The intricate keyword network depicted in Figure 21 underwent a meticulous clustering and color-coding process leveraging the VOS clustering technique (van Eck and Waltman, 2014). This technique proficiently organizes and categorizes keywords into distinct clusters, each encapsulating a specific research area. To enhance visual clarity, clusters are discernibly named based on their corresponding research domains. The vivid spectrum of colors employed in the visualization serves as a key identifier, distinctly associating each keyword with its respective cluster. This methodological approach not only elucidates the intricate relationships between keywords but also provides a structured representation, affording a comprehensive insight into the diverse and interconnected facets of CH Ontology.

The six clusters are listed below:

- 1) Ontology Lifecycle (red)
- 2) Semantic Knowledge Management (green)
- 3) AI-Based Knowledge Generation (blue)
- 4) Semantic Search (yellow)
- 5) Semantic Web Technologies for IoT (purple)
- 6) Semantic Interoperable Information Management (turquoise)

Ontology development	13	18	4	9,00	0,37	2012,00
Ontology evaluation	10	14	6	4,50	1,33	2021,33
Semantic annotation	3	4	3	27,33	1,61	2016,33

Cluster 2: Semantic Knowledge Management (green-coded)

Built heritage	8	13	3	30,67	2,95	2020,00
Data integration	11	15	5	7,40	0,63	2019,20
Data mining	10	12	3	18,67	1,21	2018,00
Data structures	12	15	4	123,25	1,46	2015,25
Knowledge based systems	22	52	13	16,00	1,37	2016,77
Knowledge graph	5	6	3	21,33	1,62	2020,00
Knowledge management	15	30	11	14,00	1,29	2015,09
Linguistics	10	14	3	16,00	3,19	2016,00
Natural language processing	14	17	4	23,50	1,38	2016,00
Ontology matching	7	9	3	9,00	0,87	2015,33
Semantic interoperability	11	14	3	16,67	0,85	2015,00

Cluster 3: AI-Based Knowledge Generation (blue-coded)

Artificial intelligence	9	9	4	3,75	0,62	2014,25
Deep learning	10	11	3	23,00	1,66	2019,33
E-learning	11	12	3	19,67	1,09	2016,67
HBIM	3	5	4	5,00	1,20	2021,50
Information systems	4	5	3	4,33	0,39	2017,33
Learning systems	5	7	3	12,33	0,91	2014,00
Semantic enrichment	18	26	5	18,80	1,83	2015,40
User experience	12	20	5	29,20	1,60	2018,80

Cluster 4: Semantic Search (yellow-coded)

Data handling	16	43	9	9,33	0,60	2017,56
Linked data	23	65	15	6,07	0,66	2018,67
Linked open data	18	36	7	14,86	1,42	2018,14
Open data	16	34	7	9,43	0,83	2019,86
Search engines	16	39	9	19,78	1,04	2013,22
Semantic technologies	12	18	3	18,00	0,76	2014,67
Semantic web	26	104	38	16,79	1,25	2018,45

Cluster 5: Semantic Web Technologies for the IoT (purple-coded)

Digital libraries	17	42	13	9,38	0,94	2015,46
Internet of things	8	10	3	7,67	1,02	2019,00
Semantic integration	4	7	3	3,33	0,23	2020,00
Semantic network	5	6	3	9,33	0,68	2017,33
Semantics	37	144	46	25,87	0,94	2016,33

Cluster 6: Semantic Interoperable Information Management (turquoise-coded)

Information retrieval	17	9	9	22,00	1,10	2011,56
Interoperability	17	10	10	66,00	1,85	2014,40
Ontology engineering	4	3	3	24,33	1,99	2014,67

In Figure 21 and Table 6, keywords are visually represented through circles and corresponding labels. The size of each circle and its accompanying tag is intricately determined by the weight of the respective keyword, establishing a direct proportional relationship. The weight of a keyword is assessed based on two key characteristics: the number of links it holds and its total link strength. These interconnected keywords and links collectively form the dynamic keyword network. Within this network, the spatial arrangement of keywords is strategically determined, signifying the relationships between

them. The distance separating keywords serves as a metric to gauge the intensity of their relationship. Keywords that share a robust connection are positioned nearby, underscoring the strength of their association. Conversely, keywords with a more subdued relationship are situated at a greater distance from each other, visually representing the nuanced degrees of association within the intricate keyword network. This visual representation not only offers a comprehensive overview of the thematic landscape but also provides nuanced insights into the interplay and relational dynamics among keywords in CH ontology research.

Table 6 enumerates the most robust connections among keywords within the six clusters. The strength of these connections is denoted by positive values, with a higher magnitude signifying a more potent association and a lower magnitude indicating a comparatively subdued link. The link strength is reflective of the frequency with which two keywords co-occur in scholarly articles. Consequently, a higher link strength value implies a more frequent and robust collaboration between the associated keywords, while a lower value signifies a less pervasive or intensive connection. To elucidate the information presented in Table 3, the column headings hold specific meanings, as delineated below for clarity and comprehension. This systematic approach not only facilitates a nuanced understanding of the strength of connections but also provides a detailed exploration of the collaborative dynamics among keywords within the six identified clusters in the field of CH Ontology research.

Table 7. Pearson Correlation Analysis of the Measurement Factors for Keyword Co-occurrence Analysis.

Measurement Items	Statistical Values	Number of Links	Total Link Strength	Occurrence Frequency	Average Citation	Average Normalized Citation	Average Year Published
Number of Links	<i>r</i>	1					
		0,90525					
Total Link Strength	<i>p - value</i>	<0.001	1				
Occurrence	<i>r</i>	0,853784	0,983627				
Frequency	<i>p - value</i>	<0.001	<0.001	1			
	<i>r</i>	0,057624	0,05436	0,03537			
Average Citation	<i>p - value</i>	.305	.348	.424	1		
Average	<i>r</i>	0,09399	0,11195	0,08775	0,306879		
Normalized Citation	<i>p - value</i>	.182	.256	.424	.042	1	
Average Year	<i>r</i>	0,0758	0,065133	0,051845	0,21261	0,182465	1
Published	<i>p - value</i>	.588	.869	.545	<0.001	.075	

Table 7 outlines the results derived from the Pearson correlation analysis conducted on the six factors outlined in Table 6, with the objective of evaluating the quantitative interconnections between these factors. The findings provide compelling insights into the nature of these associations. Total link strength demonstrates a highly positive correlation of 0.983 with the frequency of keyword occurrence, signifying a robust and consistent relationship between the cumulative strength of links and the prevalence of keywords in scholarly articles. Additionally, total link strength displays a significant positive correlation of 0.905 with the number of links associated with keywords, emphasizing the coherence between the overall strength of links and the extent of keyword connections. The number of links exhibits a noteworthy positive correlation of 0.853 with the frequency of keyword occurrence, affirming a substantial association between the number of links and the recurrence of keywords in research studies. In contrast, the average citation shows a relatively moderate positive correlation of 0.306 with the average normalized citation of keywords, suggesting a discernible but not overwhelmingly strong connection between these two metrics. Table 7 elucidates that average citation, average normalized citation, and average publication year remain largely independent of the number of links, total link strength, and frequency of keyword occurrence in research studies. Furthermore, the relationship between the average normalized citation and the average year of publication is deemed statistically insignificant based on the correlation coefficients. These nuanced correlation analyses contribute to a comprehensive understanding of the intricate relationships between key quantitative factors in the context of CH Ontology research.

Number of Links of Cultural Heritage Ontology Research:

The interconnection among keywords within the ontology is established through the number of links. In the context of the ontology-focused search, the term "ontology" (42) takes precedence, closely followed by another crucial term, "cultural heritage" (40). Subsequent keywords exhibiting substantial links include "semantics" (37), associated with Semantic Web Technologies, as well as "semantic web" (26) and "linked data" (23), both correlated with Semantic Search. The prominence of these top five keywords underscores their relevance to the development of CH Ontology and the semantic enrichment of the developed ontology. The third-highest linked term, "semantics," which

signifies the infusion of Semantic Web Technologies into ontology studies within the CH literature. This integration, facilitated by Semantic Web Technologies, plays a pivotal role in completing the CHKM cycle, offering a comprehensive platform for the collection, processing, storage, and dissemination of CH information. Consequently, there is a widespread adoption of Semantic Web Technologies in CH Ontology Research. Conversely, keywords such as "learning systems" (5), "semantic integration" (4), and "HBIM" (3) exhibit comparatively lower connection numbers. This suggests a limited volume of research in CH Ontology concerning Artificial Intelligence (AI) technologies and their integration with HBIM platforms. Addressing this research gap holds significant potential, particularly in terms of the positive contributions CH Ontologies could make to the tourism and education sectors. Therefore, future endeavors should prioritize comprehensive integration efforts between ontology, AI, and Semantic Web Technologies to further enrich CH research in these domains.

Total Link Strength and Occurrence Frequency of Cultural Heritage Ontology Research:

Keywords that demonstrate elevated values in both total link strength and occurrence frequency are considered highly influential within the scholarly discourse. As outlined in the results of the scientometric analysis presented in Table 6, the keyword "Ontology" stands out as the most impactful, boasting the highest total link strength (279) and occurrence frequency (116). Following in descending order of influence are keywords such as "Cultural Heritage" (183 and 73), "Semantics" (144 and 46), and "Semantic Web" (104 and 38). Significant terms like "Linked Data," "Knowledge-Based Systems," and "Data Handling" also secure positions as keywords with substantial total link strength values, indicating their potential significance in upcoming research endeavors. The prominence of these terms suggests that they are likely to play important roles in shaping future research trajectories within the field.

On the contrary, specific keywords, including "Knowledge Graph" (6 and 3), "Semantic Network" (6 and 3), "Information Systems" (5 and 3), "HBIM" (5 and 4), "Semantic Annotation" (4 and 3), and "Ontology Engineering" (3 and 3), reveal significant gaps in both total link strength and occurrence frequency. These areas present intriguing opportunities for future discussion and exploration within the scholarly

landscape. Addressing these gaps could contribute to a more comprehensive understanding of CH ontology research and potentially unveil novel dimensions for exploration and analysis in the future.

The central focus of this study is the exploration of Ontology and Semantics keywords within the context of CH. The intricate nature of CH knowledge, marked by variations across diverse scientific fields, poses formidable challenges for KM. Addressing these challenges involves establishing an interdisciplinary KM platform through the development of a semantic model for CH knowledge utilizing Ontology. A KG model is crafted by interlinking data across the web to the Ontology model established through Semantic Web Technologies. This interconnected model facilitates machine-enabled reading and editing of knowledge, paving the way for human-computer interaction with CH elements to shape a CH Digital Twins. It is noteworthy that the term "Digital Twins" did not emerge in the analysis results, presenting an intriguing observation. Despite the emergence of virtual museums and digital libraries leveraging Semantic Web Technologies to create new platforms for tourism and education, there remains a prevalent lack of mutual interaction among these entities. The full integration of AI technologies, Semantic Web Technologies, and the HBIM platform holds the potential to create a comprehensive CH Digital Twins. Such integration would establish a robust platform for the management of interdisciplinary CH knowledge, fostering enhanced interaction and understanding within the realm of CH.

The application of HBIM provides a platform for the 2D and 3D visualization of semantic and parametric elements. Despite its capabilities, HBIM faces challenges in effectively managing semantic data, particularly concerning historical context. The integration of Semantic Web and Ontology emerges as a crucial bridge to address these knowledge gaps within HBIM. However, the analysis results highlight a notable scarcity in the adoption of HBIM within CH Ontology research. Primarily, CH Ontology research has focused on constructing KG for CH, fostering information exchange through developed KG, IoT, and Semantic Web technologies. These integrated systems enable Information Retrieval processes to automatically discern information with precision and significance. It is noteworthy that the incorporation of HBIM in Ontology research remains relatively limited, indicating a potential avenue for further exploration. The collaborative integration of these systems has the potential to enhance learning processes

by providing comprehensive information from nD models, thereby contributing to more efficient and informed practices within the CH domain.

Average Citation of Cultural Heritage Ontology Research:

Terms like "Data structures" (123.25), "Interoperability" (66.00), "Built heritage" (30.67), "User experience" (29.20), and "Semantic annotation" (27.33) emerge as noteworthy with the highest average citation values. The design of data structures is aimed at encapsulating diverse facets of CH, facilitating the organization and analysis of CH data. The emphasis on interoperability in CH contributes to the seamless sharing of data among databases or systems, streamlining the integration of CH information from various sources and fostering collaboration and information sharing. The incorporation of built heritage data into the CH Ontology enhances the documentation and understanding of physical CH, leading to the development of user-friendly interfaces for an enriched user experience. The provision of efficient search capabilities and meaningful visualizations contributes to improved accessibility of CH information for researchers, historians, and visitors. Additionally, the utilization of semantic annotation helps enrich CH data with ontology-related concepts and relationships. By associating CH elements with pertinent concepts and relations from the ontology, semantic connections are established, creating a cohesive framework for understanding the various elements within the realm of CH.

The subsequent phase of CH Ontology Research necessitates a focus on practice-based investigations. By harnessing big data semantic technologies inherent in CH, comprehensive datasets can be consolidated onto a unified platform. The application of Ontology Engineering has proven instrumental in establishing efficient processes for organizing, sharing, and utilizing CH knowledge. The integration of deep learning algorithms provides a valuable avenue for augmenting ontology through the analysis of CH data. Implementing deep learning techniques, particularly in the image analysis of physical CH items, enables the automatic recognition and classification of these items, fostering a visual relationship within the CH Ontology and enhancing the overall representation of CH. Incorporating NLP techniques facilitates the extraction of information from diverse sources such as historical documents, museum archives, and scientific articles. This enrichment of the ontology with contextual information and

relationships between different CH entities contributes to a more nuanced understanding of CH. The adoption of advanced analytical capabilities and user-centric platforms becomes feasible through the application of deep learning and NLP techniques to CH Ontology. These techniques empower Ontology to process substantial volumes of big data, recognize visual and textual elements, and extract valuable information, aligning with the prevailing trend in Ontology studies within CH literature towards the development of user-centric interfaces. Nonetheless, there remains a discernible gap in areas such as 'ontology evaluation' (4.50), 'information systems' (4.33), 'artificial intelligence' (3.75), 'semantic integration' (3.33), and 'inference' (3.00). Addressing these gaps will be crucial for advancing the field and fostering a more comprehensive understanding of CH Ontology studies.

Average Normalized Citation of Cultural Heritage Ontology Research:

"Linguistics (3.19)," "built heritage (2.95)," "ontological analysis (2.60)," "ontology engineering (1.99)," and "ontology design pattern (1.99)" emerge as pivotal keywords with substantial significance in CH Ontology literature. Research employing these keywords holds profound implications for shaping the landscape of CH Ontology. Although these keywords exhibit the highest average normalized citation values, they do not necessarily boast the highest total link strength or occurrence frequency. The average normalized citation, calculated based on the actual number of citations relative to genre, publication year, and citation rate of articles on the subject, underscores their scholarly impact. CH Ontology Research has evolved significantly with the infusion of AI and Semantic Web Technologies. Given the novelty of these studies, the total link strength value remains relatively low. The primary objective of CH Ontology research revolves around the organization of complex CH information, contributing to the development of resources for conservation management. However, the integration of new technologies becomes imperative for achieving effective CHKM. Certain areas, such as "ontology development (0.37)," "inference (0.24)," and "semantic integration (0.23)," have received limited attention in research endeavors, signaling areas with untapped potential for exploration and advancement within CH Ontology studies.

Average Published Year of Cultural Heritage Ontology Research:

In recent years, terms such as “HBIM (2021.50)”, “Ontology Evaluation (2021.33)”, “Built Heritage (2020.00)”, “Knowledge Graph (2020.00)”, and “Semantic Integration (2020.00)” have emerged as focal points in ontology research within the CH literature. A chronological examination reveals a discernible trend among researchers, with a notable inclination toward developing integrated systems that amalgamate Ontology studies and HBIM. Although there is a growing emphasis on the development of Ontology studies, the overall landscape suggests a scarcity of research, particularly in the realms of restoration and conservation management. The potential for the comprehensive CHKM domain is promising, particularly through HBIM-based processes. The exploration of open data, ontological analysis, and deep learning represents relatively novel avenues in research endeavors within this field.

4.3. Cultural Heritage Ontology Development

4.3.1. Scope Definition

The delineation of the scope and goals plays a pivotal role in establishing the boundaries and focus of an ontology. CH Ontology is directed toward the consolidation of knowledge from diverse fields encompassing CH elements onto a singular platform. This platform, in turn, facilitates efficient KM processes tailored specifically for CH. The formation of ontology classes is predicated on the data gleaned from an extensive literature review, with expert consultations pivotal in the determination of these classes. Drawing from insights provided by art historians, the conceptualization of CH at this juncture involves a dichotomy: immovable and movable. Movable CH encapsulates artistic and sociological data spanning literature, painting, folklore, and music. In contrast, immovable CH comprises tangible elements such as ancient cities and historical buildings. Subsequently, the categorization and determination of concepts for both movable and immovable CH classes are delineated in alignment with the specified scope.

This thoughtful structuring, guided by expert opinions and an extensive literature base, contributes to the precision and relevance of the CH Ontology.

Defined within the ontology's ambit is the scope that centers on CH elements. In alignment with the delineated scope of the CH Ontology, a preliminary exploration is undertaken encompassing the entity, subject headings associated with the entity, and the interrelations among these subjects. The focal points within the specified target and scope include:

- (a) Facilitating the provision of information regarding CH resources through the establishment of a common language and standardized terms. This initiative aims to enhance the efficiency of searches and information retrieval across ontologies and data classes, whether defined within the same or different ontologies;

- (b) Managing the knowledge pertinent to CH, including activities such as editing, structuring, and enriching, with an additional emphasis on fostering the sharing of ontologies to advance CH initiatives;

- (c) Serving as the foundational framework for the development of intelligent systems.

These systems, designed to assist in information comprehension and decision-making within the CH domain, aspire not only to acquire data but also to establish semantic associations, thus providing more comprehensive and nuanced results. This delineation outlines the multifaceted objectives inherent in CH Ontology's specified scope, emphasizing its role in advancing information retrieval, KM, and the development of intelligent systems within the CH.

4.3.2. Enumeration of Domain Ontology

During the Data Acquisition phase, data aligned with the predetermined area, aim, and goal identified in the Scope Definition stage were procured. These acquired data serve the purpose of representing concepts and relationships within the CH Ontology. The diverse sources contributing to the data encompass CH-specific dictionaries, terminologies, expert judgements, databases, web resources, and APIs. The acquisition

process employed a combination of manual and semi-automatic methodologies. Initiating the process, a comprehensive literature review was conducted to explore CH-related data. Key thematic areas were discerned by soliciting expert opinions from the body of data identified in the literature review.

To commence the process, a literature review was undertaken, scouring available data on CH. The identification of foundational thematic areas was accomplished by integrating expert opinions derived from the literature review. An expert panel comprising professionals from diverse fields, including archaeologists, art historians, civil engineers, architects, restorers, and computer engineers, was assembled to foster a comprehensive and interdisciplinary approach including heritage site visits (Figure 22). This collaborative effort not only enhanced the data collection process but also revealed a multifaceted perspective crucial to the development of the CH Ontology.

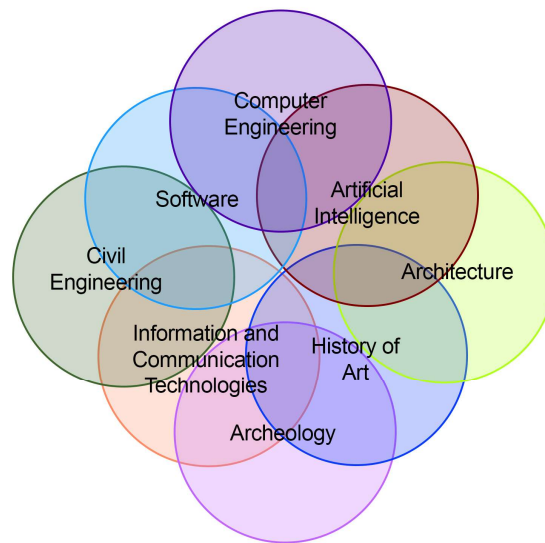


Figure 22. Interdisciplinary Areas for Experts

In the manual data collection phase, information was systematically acquired through search engines. Given the uncertainty regarding the accuracy of information obtained from these sources, a validation process ensued, involving consultation with domain experts. The manually collected data were organized in text form across different

files. The ontology creation process unfolded by categorizing concepts into classes through ongoing consultations with experts. For instance, in the initial stage, an organizational framework for research was established by categorizing CH into distinct classes, such as movable and immovable CH artifacts.

4.3.3. Defining Class and Hierarchy

Within the domain of computer science and programming, classes serve as fundamental concepts, providing a framework to express objects sharing identical properties within a specified set. In the creation of the CH Ontology, terminology about CH is sourced from existing ontologies' dictionaries and augmented with novel terms as deemed necessary. Once the ontology and the anticipated standard terms are identified, the pertinent classes are systematically generated. Even in instances where detailed information about each class is not available, the utilization of lexical databases, such as Wordnet (2010), streamlines access to lower and upper classes within the CH Ontology. The intricate web of ontologies encompasses semantic relations not only among classes but also between classes. These relations elucidate the purpose behind the interconnection of classes and correspond to the predicates found in natural language expressions. During the configuration phase, the structuring of the CH ontology is undertaken, guided by these principles and leveraging semantic web technologies. At this juncture, the collected ontology and standard terms of the data undergo a pairing process. Subsequently, these previously independent ontologies are seamlessly amalgamated semantically. The Neo4J linear database supports these processing methods, playing a crucial role in the synthesis of the CH Ontology. The ultimate goal of this phase is to generate well-defined classes and relations for the CH Ontology through the application of Neo4J.

The classification of classes for the CH Ontology was established based on gathered information through a manual review. The process involved seeking expert opinions to ensure precision in determining the classes. CH was categorized into two fundamental classes: movable and immovable CH. Subsequently, terms contributing to the formation of subclasses were nested under these primary classes. These child terms, referred to as hyponyms, and their corresponding parent terms, designated as hypernyms, were

identified. The initial classes formulated for the ontology, guided by expert insights, are presented in Figure 23.

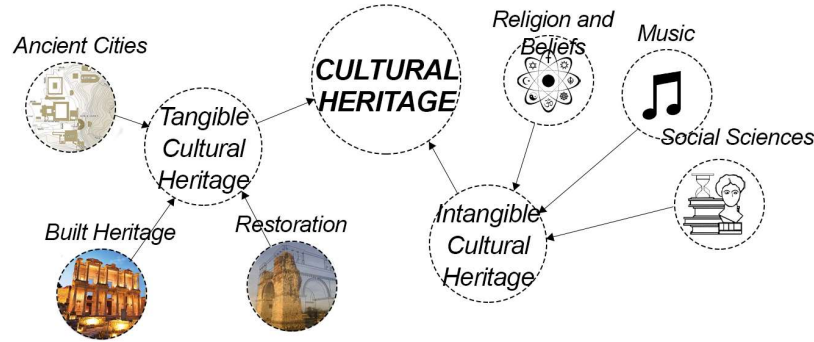


Figure 23. The First Version of Cultural Heritage Ontology Study Prepared by Taking Expert Opinions

In order to visually represent this data using Neo4J, definitions for class, relation, and property were introduced, and an illustrative depiction was generated by scripting the appropriate code. Below is a summary of the code created to prepare the CH Ontology model in Neo4J:

```
create(immovable_cultural_heritage:immovable_cultural_heritage{title:"immovable
cultural heritage"})
create(movable_cultural_heritage:movable_cultural_heritage{title:"movable cultural
heritage"})
create(historical_artifacts)-[:consistOf{title:"consist of"}]-
>(immovable_cultural_heritage)
create(historical_artifacts)-[:consistOf{title:"consist of"}]->(movable_cultural_heritage)
create(historical_artifacts)-[:present]->(professions)
create(historical_buildings:historical_buildings{title:"historical buildings"})
create(ancient_city:ancient_city{title:"ancient city"})
create(management_techniques:management_techniques{title:"management
techniques"})
create(installation_principles:installation_principles{title:"installation principles"})
create(formation:formation{title:"formation"})
create(urban_planning:urban_planning{title:"urban planning"})
create(urban_development:urban_development{title:"urban development"})
create(functions:functions{title:"functions"})
create(immovable_cultural_heritage)-[:include]->(ancient_city)
```

4.3.4. Defining Properties

The formalization of an ontology entails the representation of its concepts, categories, relationships, and constraints using a precise formal language or syntax. The initial step in this process involves the careful selection of a language or syntax that aligns with the ontology's objectives and the intended audience. Subsequently, the chosen syntax is employed to define the concepts and categories within the ontology. The relationships between these concepts are also elucidated within this syntax and language framework. A critical phase involves testing the ontology to ensure its correctness and accurate representation of the designated field. The formalization of an ontology serves to enhance the comprehensibility and manipulability of systems and algorithms. The overarching objective of the formalization process is to guarantee the accuracy of the ontology and its seamless alignment with the requirements of the target audience. Through formatting, ontology becomes a more accessible and effective tool for understanding and navigating complex systems, contributing to its utility and relevance within the intended domain (Figure 24).

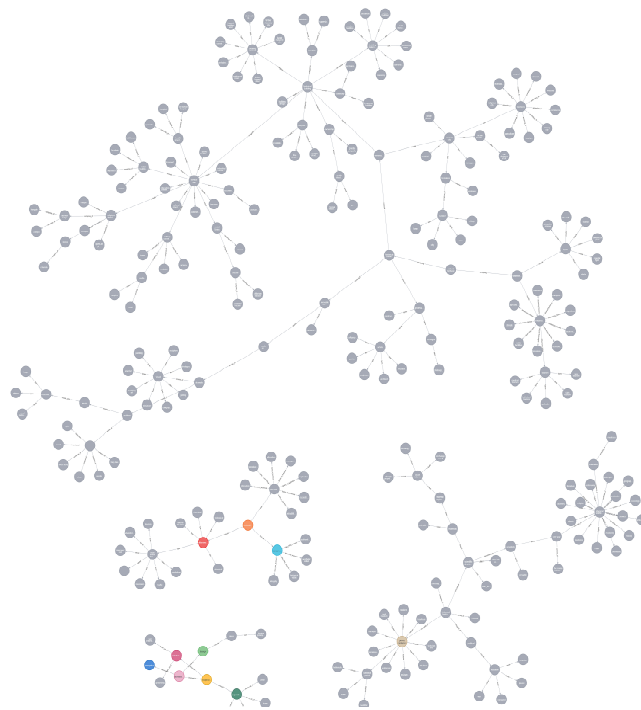


Figure 24. Cultural Heritage Ontology

4.3.5. Evolution

The outcome of the initial structuring underwent a reassessment by an interdisciplinary expert team prior to the integration of semantically related ontologies. This stage aims to format the terms within associated ontologies, ensuring their alignment with the project scope. Unnecessary terms are excised, and any absent but essential terms are introduced to the CH Ontology. Given that classes convey limited information without their accompanying properties, the incorporation of unique features indicative of each class becomes imperative. Consequently, this phase necessitates the addition of class properties to the ontology, thereby refining and finalizing its structure. The consideration and inclusion of these properties contribute to the comprehensive and definitive form of the CH Ontology, ensuring its coherence and relevance within the specified project framework. This iterative and expert-guided process underscores the importance of precision in the representation of terms and properties, further enhancing the ontology's utility and effectiveness.

4.4. Cultural Heritage Knowledge Graph Generation via Semantic Enrichment

KG stands as a systematically structured representation of knowledge, embodying entities, relationships, and attributes. This format ensures the availability of information in a machine-readable form, facilitating efficient and flexible retrieval. In the realm of KM, KGs prove invaluable for illustrating relationships between diverse cultural artifacts, historical events, and cultural practices (Wang et al., 2020). Given the multifaceted nature of CH, which draws from varied sources, ontologies emerge as a fitting tool for semantically representing and sharing different data types (Sureephong et al., 2008). In the pursuit of semantic modeling for CH data, this research employs ontologies, particularly focusing on CH ontology. To imbue conceptual richness, the CH ontology undergoes semantic enrichment via the aggregation of data from diverse sources (Benabdellah et al., 2021). For instance, the knowledge about 'Ephesos Ancient City' under the umbrella concept of 'Built Heritage' is integrated into the CH ontology. This integration involves accessing reliable information sources on the web, resulting in the

semantic augmentation of information concerning the 'Ephesos Ancient City' within the KG. This approach exemplifies a strategic use of ontologies and KGs to enhance the semantic depth and breadth of CH data (Figure 25).

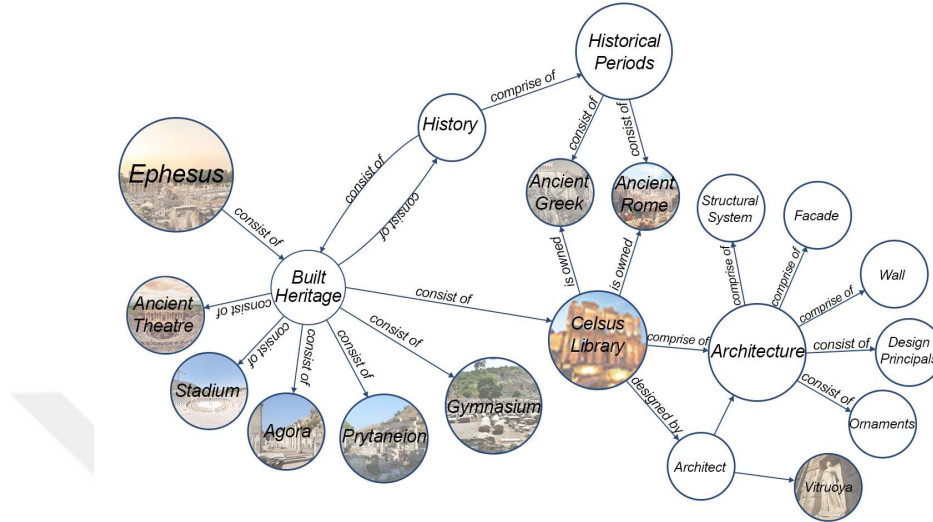


Figure 25. Ontology and Knowledge Graph Representation of the Cultural Heritage Entity

4.4.1. Semantic Enrichment with Existing CH Ontologies

The foundational structure for this research lies in ontology, a framework delineating the structure and relationships of terms and concepts within a specific field of knowledge. KG plays a pivotal role in representing information generated through an ontological approach in a manner comprehensible and processable by computers. This approach allows for the representation of information by associating it with real-world counterparts, such as Ephesus representing the semantic entity conceptually defined in the ontology, such as Built Heritage. This representation extends beyond mere entities, encompassing properties and the intricate relationships existing between them. Consequently, accessing interconnected information becomes feasible through the exploration of KG. This approach not only addresses basic queries regarding CH entities, such as "what is it?" but also enables the derivation of inferences concerning the relationships interlinking these entities. The outcome is a more expansive and nuanced

understanding, enhancing the capacity to glean comprehensive insights from the represented information.

KG encompasses both structural and semantic data, constituting Knowledge Graphs (KGs) comprising entities and relationships intricately linked to reliable data sources. These KGs express information both structurally and semantically and are grounded in their respective ontologies, leveraging the Web Ontology Language (OWL), specifically utilizing the `owl:equivalentClass` (<https://www.w3.org/TR/owl-ref/>) construct. Class-level matching is facilitated through the `#equivalentClass-def` feature, while individual-level matching is achieved using the `owl:sameAs` (<https://www.w3.org/TR/owl-ref/#sameAs-def>) feature. Furthermore, alignment was established with common and domain-specific classes found in existing CH ontology studies documented in the literature. This strategic matching approach ensures that the information graph derived from the CH ontology remains interoperable, enabling seamless querying without necessitating additional transformations. The utilization of OWL constructs and cross-referencing with established ontologies enhances the robustness and compatibility of the CH ontology, fostering accessibility and integration within broader knowledge frameworks.

KGs encompass both structural and semantic data. However, a substantial portion of web and local system data resides in tabular/structured databases. Despite the structured nature of data within these databases, it lacks the ontological structures necessary for semantic representation. The schemas in these databases primarily define data columns without establishing semantic relationships among these columns. For example, CH data is commonly stored in such databases linked to CH systems, prompting the need for a transformation of this data into a KG. To achieve this transformation, the properties of entities within the database are utilized, and relationships are established by interpreting them as connections in ontological triples. This process results in the enrichment of KGs, aligning the data with semantic structures along with insights available at <http://d2rq.org/> (Sahoo et al. 2009; Jang et al. 2007; Türkmen and Can, 2022). These collective efforts emphasize the significance of converting structured databases into information graphs to bridge the semantic gap inherent in tabular data, particularly relevant in the context of managing CH data.

Figure 26. SparQL Query Web Page (<https://dbpedia.org/sparql>)

Within the framework of semantic enrichment of the CH Ontology, the boundaries of the CH Ontology were broadened through the aggregation of data from diverse sources. For example, to access information about individuals categorized under the "Ancient City" class in the CH Ontology, queries were directed to verify the existence of an information box associated with any ancient city on Wikipedia. Upon confirmation of an information box, a comparative analysis was conducted to match the relationships within the box with those outlined in the CH Ontology. Upon detecting a relationship match, subsequent inquiries were made through the Dbpedia Sparql Endpoint to ascertain the existence of sub-individuals related to the encompassing class (Figure 26). SparQL provides standard querying for Linked Open Data or RDF triple stores on the web. It allows users to query information from databases or any data source that can be mapped to RDF. Those individuals identified were subsequently incorporated into the CH Ontology, aligned with the appropriate class designation. Furthermore, data from both structural and semantic sources underwent semantic alignment processes at the ontology level, allowing for the integration of data not originally present in our CH knowledge base. Platforms such as DBpedia and Wikidata, with their KGs and ontologies, played a pivotal role in this integration, facilitated within the Neo4j environment. The objective was to retrieve hyponym and hypernym data for classes directly from infoboxes. SparQL queries were crafted by scrutinizing the contents of infoboxes, with the overarching goal of seamlessly incorporating pre-existing CH Ontologies. Table 8 includes queries that sent to SparQL and Query results.

Table 8. SparQL Queries and Results

Queries	Results
<pre> prefix dbp: <http://dbpedia.org/property/> select ?Concept where {?Concept dbp:type "Ancient Greek settlement"@en} </pre>	http://dbpedia.org/resource/Caesarea_(Mazaca) http://dbpedia.org/resource/Blaundus http://dbpedia.org/resource/Ephesus
<pre> prefix dbp: <http://dbpedia.org/property/> prefix dbo: <http://dbpedia.org/ontology/> select ?concept where {?concept rdfs:subClassOf dbo:Settlement} </pre>	http://dbpedia.org/ontology/City http://dbpedia.org/ontology/CityDistrict http://dbpedia.org/ontology/Town http://dbpedia.org/ontology/Village http://dbpedia.org/ontology/HistoricalSettlement
<pre> prefix dbp: <http://dbpedia.org/property/> select ?Concept where {?Concept dbp:type "Ancient Greek settlement"@en} </pre>	http://dbpedia.org/resource/Caesarea_(Mazaca) http://dbpedia.org/resource/Blaundus http://dbpedia.org/resource/Ephesus
<pre> prefix dbp: <http://dbpedia.org/property/> prefix dbo: <http://dbpedia.org/ontology/> select ?concept where {?concept dbp:type dbo:Historical Settlement} </pre>	No results.
<pre> prefix dbo: <http://dbpedia.org/ontology/> prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> SELECT ?city ?person ?name WHERE { ?city a dbo:City; rdfs:label ?name. ?person a dbo:Person; rdfs:label ?name. } </pre>	Resulted with links from Dbpedia for city, person and name.
<pre> prefix rdf:<http://www.w3.org/1999/02/22-rdf-syntax-ns#> select ?settlement where {?settlement rdfs:label "Hierapolis (Phrygian Pentapolis)"@en} </pre>	http://dbpedia.org/resource/Hierapolis_(Phrygian_Pentapolis)

4.4.2. Semantic Enrichment with Text Data

Utilizing CH data from both web resources and texts sourced from historical records in the region, this study incorporates deep learning techniques for semantic enrichment (Kertkeidkachorn and Ichise, 2017; Rincon and Senatore, 2022; Zhong et al., 2023). The initial step in the deep learning phase involved the meticulous curation of texts containing CH knowledge by field experts, resulting in a carefully selected and reliable text set. Co-reference resolution was then applied to this text set, a process essential for identifying expressions referencing a specific entity and linking relative pronouns to the corresponding entity. Following co-reference analysis, the named entity binding stage aimed to extract and connect all named entities to a designated knowledge base.

Named entity linking, a crucial facet of this process, addresses the challenge of ascertaining the meaning of entities. This step plays a pivotal role in aligning entities in the texts with those in the existing information graph. Once the named entity linking process was completed, the subsequent task involved determining the relationships between these entities, known as relationship extraction. These identified relationships were subsequently integrated into the KG, establishing connections between entities and enhancing the KG with the new information.

To operationalize these tasks on text data, Python application was employed, featuring code designed to transform sentences structured as Subject, Verb, and Object into Ontology language. This facilitated the seamless integration of texts into the CH Ontology, marking a significant achievement in aligning text data with the established ontology structure (Figure 27 and Table 9).

Text example: *Ephesus was an ancient Greek city, an important Roman city. It is hosted by the Romans, the Byzantine Empire, the Ottoman Empire and many Anatolian principalities. It is a port city. It is located on important trade routes in history. It was founded by female warriors. It got its name from Arzawa. Arzawa is translated as the Mother Queen City. It was developed in Roman period. It has Artemis Temple, Celsus Library, Ancient Theater, Agora Square, Domitian Temple, Kuretler Street, Heracles Gate in the Ancient City of Ephesus. It is famous for Turkey. It was an important commercial and political center. It was included in the UNESCO World Heritage List in 2015. It has been a residential area for Turks in 1300s. It was the capital of the Province of Asia in 27 BC.*

```
text_file = open("ephesus.txt", "r")
text = text_file.read()
def coref_resolution(text):
    """Function that executes coreference resolution on a given text"""
    doc = nlp(text)
    # fetches tokens with whitespaces from spacy document
    tok_list = list(token.text_with_ws for token in doc)
    for cluster in doc._coref_clusters:
        # get tokens from representative cluster name
        cluster_main_words = set(cluster.main.text.split(' '))
        for coref in cluster:
            if coref != cluster.main: # if coreference element is not the representative element of that cluster
                if coref.text != cluster.main.text and bool(set(coref.text.split(' ')).intersection(cluster_main_words)) == False:
                    # if coreference element text and representative element text are not equal and none of the coreference element words are in representative element. This was done to handle nested coreference scena
                    tok_list[coref.start] = cluster.main.text + \
                        doc[coref.end-1].whitespace
                    for i in range(coref.start+1, coref.end):
                        tok_list[i] = ""
    return "".join(tok_list)

ENTITY_TYPES = ["state", "natural process", "territorial entity", "artificial entity",
                "legal form", "separate legal entity", "structure", "location",
                "administrative territorial entity of a single country", "first-level administrative country subdivision",
                "measurable space", "group of physical objects", "geographic entity", "legal form",
                "city with millions of inhabitants", "individual entity", "municipal administration", "human-geographic territorial entity",
                "historical geographic location", "historical administrative division",
                "geographic location", "natural geographic entity", "landform",
                "interaction", "transport route", "road transport infrastructure", "trade route", "historic road"]
```

Figure 27. The Code Taken as Reference for Co-Reference Resolution

Table 9. The Output of Executed Code

<i>Source</i>	<i>Target</i>	<i>Type</i>
Ephesus	Ancient theatre	Consist of
Ephesus	Agora	Consist of
Ephesus	Stadium	Consist of
Ephesus	Library	Consist of
Byzantine Empire	Historical period	Comprise of
Ottoman Empire	Historical period	Comprise of

5. DISCUSSION

5.1. Digital Cultural Heritage Research

5.1.1. Challenges and Tendency of Digital Cultural Heritage

While the adoption of Novel Technology for DCH research showed promising developments in 2007, 2013, and 2016, a significant increase in research activities emerged after 2018, as depicted in Figure 1. Novel technologies offer the potential for sustainable practices within CHKM. However, their adoption presents multifaceted challenges in the environmental, social, and economic realms. Environmental challenges are linked to the production of technological devices, with potential adverse impacts on natural resources and biodiversity. Social challenges encompass issues of equitable internet access and transparent decision-making processes. Economic challenges revolve around the need to account for the comprehensive costs of digital technologies, including potential drawbacks (Dimitrijević, 2018).

5.1.2. Discussions of Country-based Citation Analysis

Numerous nations prioritize initiatives focused on the preservation of CH knowledge, actively contributing scholarly discourse on this crucial subject. Elements of CH serve as invaluable markers that unveil the intricate developmental trajectories of societies. Previously arduous and time-consuming processes have undergone a paradigm shift towards enhanced efficiency with the continual advancement of technology. Nations, recognizing the potential of DCH have augmented their investments in this domain. The United States emerges as a notable leader in this endeavor, not only in the preservation efforts within its archaeological sites but also in collaborative initiatives spanning diverse countries. The discernible employment of computer simulation,

especially, signifies a concerted global effort toward formulating enduring and sustainable methodologies for heritage conservation. Innovations like computer simulation and 3D modeling present promising avenues that hold the potential to safeguard CH permanently, ensuring its seamless transmission across successive generations.

The tourism sector stands as a significant magnet for CH enthusiasts and is important in the economic development of nations. The economic impact of tourism is undeniable, fostering both economic and cultural advancements in countries. Research initiatives focusing on CH not only contribute to economic prosperity but also enrich the cultural fabric of nations. There is a prevailing perspective that innovative technological methods may pave the way for the creation of novel employment opportunities within the tourism sector. While the integration of DCH processes necessitates initial investments, it can be asserted that the substantial potential this investment holds within the tourism sector is instrumental in driving overall national development.

The Republic of Türkiye, encompassing the remnants of diverse civilizations from the past, has witnessed a rich CH that spans various periods. Additionally, numerous works dating back to the era of the Ottoman Empire's ascendancy contribute to this cultural tapestry. Collaborative endeavors with countries that share historical ties within the Ottoman Empire's former borders present an opportunity to unveil and preserve these treasures for future generations through the application of technology and knowledge transfer. Notably, despite the abundance of CH assets, there is a noticeable scarcity of studies exploring the potential of technology. Examination of existing research reveals that technological methods, such as photogrammetry and laser technology, are employed in only a limited number of studies, primarily focusing on the archaeological sites and historical structures within the country. Given Türkiye's historical significance as the host of numerous civilizations, there is substantial potential for tourism and economic development. However, the scarcity of comprehensive studies in this domain highlights a significant gap in the existing literature. Bridging this gap and ensuring the sustainability of cultures can be achieved through a more extensive integration of technological methods in research.

5.1.3. Discussions of Country-based Bibliographic Coupling Analysis

The adoption of technologically developed methods has demonstrated significant advantages in the field of CH. Nations have initiated diverse initiatives in this domain, aiming to enhance the efficiency of CHKM processes. Through these efforts, it has become evident that technology offers varied potentials across different sectors. For instance, in the tourism industry, the utilization of technology allows access to CH sites from various countries, potentially introducing a new dimension to the tourism sector. Moreover, technology opens up opportunities for innovative educational approaches, blending learning with enjoyment and firsthand experiences.

Observations reveal that countries commonly derive mutual benefits from each other's research, often generating new publications through collaborative efforts in bibliographic coupling. The limited emphasis on DCH in the literature suggests a relatively minor focus on this aspect. Economic constraints, particularly the high costs associated with technological advancements, may pose a limitation on research activities. Therefore, the economic status of countries plays a crucial role in influencing the progress of studies. An analysis of research endeavors indicates that countries are advancing technological developments through collaborative publications and leveraging each other's research outcomes.

Turkiye finds itself among the countries with relatively fewer publications, particularly in the domain of technological approaches to the CHKM. The scarcity of publications contrasts with Turkiye's rich CH, presenting an opportunity for the nation, given its sizable young population, to explore new employment avenues through DCH. The potential for utilizing technological tools is evident in pre-restoration analysis processes for buildings and document collection fields, indicating that their application could see increased prominence in future studies.

5.1.4. Discussions of Document-based Citation Analysis

The extensive history of CH has given rise to numerous sub-specialties, each with its distinct focus. Technological advancements have significantly impacted research within the CH research domain, leading to the emergence of specialized areas dedicated to the CHKM. These specialized areas operate independently, resulting in a fragmented landscape that complicates the comprehensive examination of CHKM. Notably, technology-driven tools primarily serve the purpose of acquiring evidence from heritage sites, with limited efforts directed toward consolidating data on a unified platform. Embracing platforms like BIM, developed through technology, holds the potential to enhance the aggregation and organization of diverse and disparate data sources in a more cohesive manner.

5.1.5. Gaps and Trends in Digital Cultural Heritage Research

The scientometric analysis of keyword results has unveiled that the most substantial impact and connections are evident in the domains of 'Facility Management for Built-Heritage,' 'Remote Sensing Technologies for Heritage Areas,' and 'Cultural Heritage Sustainability' within the existing body of research. This conclusion is derived from the total link strength, occurrence, and average normalized citation values, as displayed in Figure 11 and Table 1. Nevertheless, the results also highlight existing gaps in the domains of 'Digital Reconstruction,' 'Digital Heritage Countries,' and 'Visualization of Cultural Heritage Areas' research.

Facility Management for Built Heritage:

CH items represent a global treasure that enriches exhibitions, museums, archaeological sites, and monuments. The sustainability of CH relies on effective conservation, KM, and knowledge sharing. The judicious utilization of novel technologies has the potential to catalyze advancements in CHKM. The proliferation of ICT has spurred numerous innovations in CH, fostering a closer integration between the physical and digital realms (Belhi et al., 2019; Ott and Pozzi, 2011; Albourae et al., 2017).

ICT not only broadens access to information but also offers sustainable methods for CHKM (Ott and Pozzi, 2011). It transcends the constraints of time and space, opening new avenues for research. The role of ICT, particularly in technology-assisted learning, remains a prominent subject of investigation. Learning models and methodologies contribute significantly to the broader dissemination of CH knowledge. Moreover, ICT allows for real-time monitoring of CH elements.

Remote Sensing Technologies for Heritage Areas:

CH illuminates the social, cultural, economic, and technological trajectories of the past, offering valuable insights into the historical evolution of societies. Consequently, the evidence derived from CH research holds significant value. The integration of novel technologies has ushered in practical, cost-effective, and non-invasive methods for acquiring CH data. Technology finds broad application in various aspects of documentation preparation, with GIS, remote sensing technologies, and laser scanner tools emerging as the most frequently employed innovations. The application of remote sensing technologies has contributed to the exploration of previously uncharted areas while minimizing environmental impact (Chase et al., 2011). The convergence of remote sensing technologies with ICT promises to enhance interoperability and data integration.

Cultural Heritage Sustainability:

Built heritage significantly contributes to the urban landscape, acting as a magnet for tourists and enhancing environmental quality within urban environments. Therefore, legal safeguards are often implemented to preserve their visual appeal. The integration of modern materials and construction techniques into CH architecture during physical restoration is essential. Equally significant is the transition to sustainable energy systems and the renewal of the city's building stock, which is crucial in terms of environmental and energy considerations. Renovation encompasses the restoration of architectural, structural, and technical facets while taking into account environmental factors. The HBIM platform facilitates the integration of energy data into the digital representation of historical structures, providing valuable insights (Bruno et al., 2018; Piselli et al., 2020). The concept of sustainability concerning CH extends beyond environmental considerations to encompass sociological and cultural dimensions. Technological

advancements facilitate the digital transformation of structures, ushering in an era of CHKM. Simultaneously, technology breaks down barriers of distance and time, promoting innovative approaches to cultural tourism.

Digital Reconstruction:

With the continuous advancement of technology and increased accessibility to sophisticated tools, photogrammetry, laser scanning, and 3D printing have gained more widespread usage in CH. Recent years have witnessed significant developments in both hardware and software for photogrammetry, laser scanning data processing, and the transformation of 2D images into 3D representations (Davis et al., 2017). The domain of Novel Technologies continues to evolve, offering fresh prospects for CHKM. The challenge of 3D visualization for expansive and intricate CH sites has gained prominence with the advent of novel technologies. The integration of 3D reconstruction tools and visualization technologies has the potential to yield unique, visually compelling, and aesthetically pleasing environments. This development paves the way for the accessibility of ancient and remote sites to a wider audience (Aguilera and Lahoz, 2010). Despite the increasing use of digital reconstruction in CH research, scientometric analysis reveals a paucity of studies focused on data visualization and digital reconstruction integration. The linkage among digital reconstruction studies appears limited, indicating an existing research gap within the CH field.

Digital Heritage Countries:

The tourism sector significantly leverages the appeal of CH. The economic contribution of tourism to national development is undeniable, with CH research in countries catalyzing both economic and cultural progress. It is posited that technology-driven innovations may open new avenues for employment in the tourism industry. While harnessing Novel Technologies for CH entails investments, the sector holds substantial potential for bolstering a country's development (Ozturk and Ozen, 2020). Several nations, including Italy, Spain, and the United Kingdom, have embarked on the use of digital technologies as a means to preserve and promote their CH. Initiatives often commence with technologies like digital photogrammetry and aerial photography, laying the groundwork for the digitalization of CH assets and data.

Visualization of Cultural Heritage:

CH holds a special place in society's collective memory and serves as focal points in cities with their iconic architecture. They significantly contribute to the local economy by sustaining the tourism sector. Therefore, there is an increasing need for contemporary CHKM supported by today's technologies. These components often face deterioration due to factors like natural disasters and conflicts, underlining the importance of comprehensive documentation studies (Albourae et al., 2017). The relationship between technology and CH is intricate and often dialectical. Innovative technological applications and location-based services offer opportunities for aesthetically preserving CH and advancing the CHKM approach (Chianese et al., 2015). Virtual technologies hold great tourism potential, as they overcome distance barriers, making them crucial for the future. These technologies offer valuable educational platforms for students and scholars (Fast-Berglund et al., 2018). Research findings reveal that Novel Technology Use for Digital Transformation of CH covers a broad spectrum of topics. VR technology is expected to gain prominence in future research due to its ability to store CH items in virtual environments, providing access without geographic constraints (Figure 15 and Table 4).

5.2. Cultural Heritage Ontology

5.2.1. Challenges and Tendency of CH Ontology Research

A discernible upsurge in CH Ontology research has become apparent, particularly post-2020 (Figure 18). Initially, the integration of emerging technologies into CH research primarily focused on the physical conservation aspect. However, this emphasis posed challenges in achieving a comprehensive preservation of CH knowledge. The conceptualization and development of CH Ontology have emerged for CHKM. Despite the recognized importance of CH Ontology, the existing literature displays a relative scarcity of research in this domain. The process of developing CH Ontology encounters fundamental challenges in various ontology-related tasks, encompassing design,

structuring, and evaluation. These challenges contribute to the complexity of CH Ontology research, underscoring the intricacies involved in the ontology development process. The interdisciplinary nature of CH data presents an additional obstacle to CH Ontology research. The flexible semantics required for CH Ontology must accommodate diverse data types (Cacciotti, 2015; Belhi et al., 2019). These diverse data types can be seamlessly integrated into the CH KG through the process of semantic enrichment applied to CH Ontology.

5.2.2. CH Ontology Research Gaps and Trends

A thorough examination of the existing literature reveals that CH Ontology studies have exerted a substantial influence, particularly in the domains of "Ontology Life-cycle," "Semantic Search," and "Semantic Web Technologies for the Internet of Things (IoT)." This influence is evident through their prominent connections, as evidenced by the findings of scientometric analysis (Table 6 and Figure 20). However, when subjected to metrics such as Total Link Strength, Occurrence Frequency, and Average Normalized Citation values, significant gaps emerge within the domains of "Semantic Knowledge Management," "AI-Based Knowledge Generation," and "Semantic Interoperable Information Management" studies (Table 6 and Figure 20).

Ontology Life-Cycle:

CH encapsulates the tangible and intangible aspects of a culture, transcending time and passed down from the past to the future. Ontology, through the development of structured knowledge representations, provides a mechanism to efficiently organize, retrieve, and search for CH resources. The CH Ontology serves as a framework for structuring CH information, introducing an innovative approach to knowledge representation. It facilitates the creation of structured models that encapsulate the historical context and cultural significance of CH elements, offering a solution for information access and enabling the generation of semantic representations of CH knowledge (Zalama and García, 2020; Tibaut and Oliveira, 2022; Araújo et al., 2017). The ontology life-cycle encompasses three interconnected phases: knowledge

acquisition, ontology development, and ontology evolution. This cycle involves the continuous capture of knowledge, its representation in an ontology, quality evaluation, and necessary improvements. Through this iterative process, information retrieval and data integration are enhanced by creating ontologies that accurately and effectively capture domain-specific knowledge. The CH Ontology Lifecycle has emerged as a focal point of research interest due to its potential to represent the concepts, relationships, and features inherent to CH Ontology.

The CH Ontology operates as a structured framework designed to capture and depict the intricate concepts, relationships, and properties associated with CH. An essential aspect of enhancing the understanding of CH artifacts lies in semantic enrichment. Through semantic annotation, specific metadata customized to CH resources is integrated, enabling the representation of the nuanced meanings of CH (Tibaut and Oliveira, 2022; Pramatha, 2018; Schreiber et al., 2008). Another avenue for improving the usability and comprehensibility of the CH Ontology involves the application of Ontology Design Patterns. These patterns play a facilitative role in integrating and exchanging data across diverse systems and databases, fostering consistency and coherence in the representation of CH information, thereby simplifying CHKM (Isa et al., 2020). Ontological Analysis provides an additional method for promoting integration with existing ontologies for the CH Ontology. By employing ontological analysis, interoperability and knowledge sharing can be achieved across distinct domains, contributing to a more holistic understanding of CH. Despite these methods, which aim to enhance the semantics and interoperability of the CH Ontology, having seen limited application, there exists substantial potential for their increased adoption, promising advancements in the future of AI-based CHKM. The ongoing development and implementation of these methodologies could establish a robust foundation for AI-based CHKM initiatives.

Semantic Knowledge Management:

The CH Ontology unfolds as a structured framework crafted for the representation of CH knowledge. Within the domain of CHKM, semantic interoperability emerges as a potent catalyst for Semantic KM, fostering the seamless integration and sharing of knowledge. The essential integration of semantic web technologies with the CH Ontology

facilitates the organization, representation, and management of information related to CH artifacts, applications, and contexts. Knowledge-based systems play a pivotal role in semantic CHKM, laying the groundwork for decision-making and analytical mechanisms in the realm of CH. For instance, Natural Language Processing (NLP) can analyze textual CH data, contributing to the semantic enrichment of the CH Ontology by facilitating natural language interfaces. The effectiveness of data structure and integration occupies a crucial place in Semantic KM, promoting semantic interoperability and knowledge sharing. Standardizing CH data structures proves instrumental in ensuring consistency in knowledge representation, thereby facilitating semantic interoperability. The integration of data plays a key role in amalgamating CH data from diverse sources, fostering the development of comprehensive and holistic perspectives for CHKM (Simeone et al., 2019; Alivizatou et al., 2017; Gürbüz et al., 2018; Tanasijević & Pavlović-Lažetić 2020; Goryunova & Wei, 2021). Knowledge-based Systems emerge as a prominent focus in research, primarily due to their support in enabling access to CH knowledge through Semantic KM. The incorporation of data into the CH Ontology strengthens semantic interoperability, enhancing the efficiency of CHKM. Additionally, the integration of previously established CH Ontologies can be achieved through Ontology matching, significantly contributing to the semantic enrichment of the CH Ontology. Despite these advancements, there is a notable gap in research areas such as ontology matching and knowledge graphs within the current literature. A surge in research efforts in these areas could yield numerous advantages for the CH Ontology, encompassing decision support, semantic enrichment, data sharing, and interoperability.

AI-Based Knowledge Generation:

The multifaceted and interdisciplinary nature inherent in CH has traditionally posed challenges in terms of accessibility and comprehension. In order to ensure the preservation and effective transfer of CH knowledge for cultural and social sustainability, the integration of AI technologies emerges as a transformative approach to enhance the CH Ontology. These technologies encompass a spectrum of capabilities, including semantic enrichment, automatic knowledge acquisition, intelligent data integration, recommendation systems, data management, and knowledge representation. Semantic enrichment plays a pivotal role in refining the representation of CH knowledge by

seamlessly integrating detailed and semantic information into the CH Ontology. AI-based deep learning applications, in particular, contribute significantly by automatically annotating CH elements based on visual data, thereby aiding in their classification. HBIM provides a robust platform for representing multi-dimensional information related to built-heritage sites. The integration of the CH Ontology with HBIM holds immense potential for advancing CHKM and fostering knowledge sharing (Li et al., 2022; Dhombres et al., 2021; Nurfarani et al., 2020; Casillo et al., 2022). AI and semantic web technologies extend their influence to the development of educational platforms, thereby enhancing the accessibility of the CH Ontology. Through the augmentation of text data with additional visual information, AI technologies facilitate comprehensive learning experiences. The convergence of HBIM, CH Ontology, and AI technologies plays a pivotal role in making CH information more comprehensible to a broader audience. Present research endeavors primarily focus on topics such as semantic enrichment, user experience, and e-learning. However, noteworthy gaps persist in the domains of HBIM and learning systems. A dedicated surge in research within these areas has the potential to significantly contribute to the sustainability of CHKM.

Semantic Search:

The Semantic Web assumes structuring, interconnecting, and imbuing meaning into web content. Particularly within the context of CH, the adoption of Semantic Web standards, such as Uniform Resource Identifiers (URIs), Resource Description Framework (RDF), and Web Ontology Language (OWL), facilitates the precise definition of objects and their interrelationships. This adoption enables the seamless connection and integration of CH data from diverse sources. By enriching web content with semantic data and adhering to linked data principles, search engines gain the capability to discern and interpret intricate relationships between disparate data sets. The structured data encapsulated within the CH Ontology proves invaluable to search engines, ensuring improved accuracy and efficiency in users' access to information (Iadanza et al., 2019; Yang et al., 2019; Knoblock and Szekely, 2015). The infusion of Semantic Web technologies contributes significantly to the linkage, organization, and enhanced accessibility of CH information. Through the semantic enrichment of the CH Ontology, CH resources are intricately woven into a broader data network. In contrast, search

engines further amplify the accessibility of CH information by presenting it to users in a contextual and meaningful manner. The existing body of literature primarily focuses on the development of a more comprehensive CH Ontology, emphasizing the role of Semantic Web technologies. The integration of Semantic Web technologies with CH Ontology holds the potential to empower search engines to deliver more efficient and contextually relevant results. Consequently, this amalgamation augments the discoverability and accessibility of CH information in digital environments through search engines.

Semantic Web Technologies for IoT:

Semantics, as applied to CHKM, delves into the scholarly exploration of the meaning and interpretation of CH knowledge. Establishing a shared and comprehensive understanding of CH knowledge is crucial for its effective reuse, preservation, renewal, and further development within the realm of CHKM. Digital libraries play a pivotal role in the conservation and accessibility of CH information by aligning with the structured framework offered by CH Ontology. This structured framework ensures the systematic organization and retrieval of CH resources, facilitating their discovery and scholarly exploration. The IoT emerges as an efficacious technological asset for fostering sustainability and disseminating CH knowledge. IoT technologies stimulate intelligent navigation and the creation of interactive CH platforms, particularly within the domain of museums (Ranjgar et al., 2022; Moraitou et al., 2019; Liang et al., 2023; Melro et al., 2021). Through the integration of IoT, interactive models can be developed to enhance CHKM, resulting in enriched user experiences. IoT technologies also offer the potential to establish dedicated platforms for educational and tourism purposes, thereby introducing novel approaches for the presentation and evaluation of knowledge structures.

Semantic Interoperable Information Management:

Ontology engineering enables the development and management of the CH Ontology. Simultaneously, Information Retrieval functions as a pivotal tool for the systematic storage, organization, and retrieval of CH information. In the process of developing the CH Ontology, the utilization of information retrieval techniques becomes

imperative for the integration and exchange of heterogeneous CH information, ultimately fostering seamless access to and sharing of CH data. The development of the CH Ontology further promotes semantic interoperability within the CH domain, enhancing the effective dissemination and collaborative exploration of CH data, while mitigating the loss of valuable information (Tibaut and Oliveira, 2022; Amali et al., 2022; Wei et al., 2021). Ontology engineering, in a broader context, provides vital support for the advancement of the semantic web, linked data initiatives, and innovative technologies. The creation and implementation of the CH Ontology have the potential to significantly enrich experiential learning in the realm of CH. Furthermore, the CH Ontology lays the groundwork for the development of cutting-edge technologies, including chatbots and Digital Heritage Twins (CH Digital Twins) systems, promising novel and transformative approaches to understanding and preserving CH. Importantly, this infrastructure facilitates the ethical and secure management of CHKM.

5.3. Goals of Development of Cultural Heritage Ontology and Cultural Heritage Knowledge Graph Generation Via Semantic Enrichment

CH encompasses both tangible and intangible elements that are intrinsic to human social and cultural activities. The diverse and conceptual nature of CH includes societal practices such as food, clothing, celebrations, and beliefs, reflecting the multifaceted tapestry of civilizations (Kalita & Deka, 2020). This inherent complexity necessitates an interdisciplinary knowledge-based approach spanning various scientific fields. Collaborative efforts among researchers from diverse disciplines have the potential to enhance the efficiency of CH research (Hellmund et al. 2018). Ontologies serve as catalysts for organizing and reusing knowledge. The ontology model proposed in this study is tailored to streamline CH research by consolidating it onto a unified platform. Through ontology, a shared vocabulary and a mutual comprehension of the field are established, essential for effective KM. The integration of the intricate and extensive CH model with the proposed CH Ontology establishes a robust foundation for CHKM. Simultaneously, the proposed ontology ensures a semantic representation of CH information, contributing to the development of an ontological model within the context

of CH. This approach democratically facilitates access to CH information, fostering inclusivity and accessibility for all.

CH knowledge exhibits variations influenced by species, temporal factors, and geographical origins, rendering it intricate and context-dependent. The process of Semantic Enrichment applied to the CH Ontology serves to enhance the comprehensibility of CH concepts and relationships. Through Semantic Enrichment, intricate details, classifications, and nuanced relationships are incorporated into the CH Ontology, augmenting its depth and sophistication. The resultant creation of CHKG via semantic enrichment facilitates broad access to CH information, catering to a diverse user base. Leveraging Semantic Web Technologies further democratizes access to CH information, ensuring that even those without technical expertise can engage (Yeh et al., 2021; Collado et al., 2021; Pellegrino et al., 2022). This increased accessibility not only fosters collaboration in CHKM but also establishes a shared platform for interdisciplinary CH researchers. Additionally, the integration of the developed CHKG with AI technologies holds promising prospects, not only for CHKM but also for the dissemination of CH information. The CH Ontology and CHKG, emerging from this study, collectively form a robust foundation for the integration of AI technologies within the realm of CH.

5.4. Limitations of the Thesis

The application of DCH involves keyword and author analysis based on Scopus data. Additionally, a comprehensive examination of journals, institutions, and countries through metrics like citations, common citations, and bibliographic coupling provides in-depth insights into the field. Certain limitations merit consideration in this bibliometric inquiry. Firstly, the inclusive approach incorporating all languages ensures global coverage but may introduce language-specific biases. Furthermore, the study relies solely on data from the Scopus database, lacking integration from other databases. Future research endeavors could enhance comprehensiveness by incorporating data from multiple sources. The static nature of this research, confined by a specific date range, underscores the necessity for a dynamic system enabling continuous data updates in

future studies. Despite the enormous potential of technology for CHKM, the study primarily maintains a theoretical focus, with limited exploration of practical applications. The development of a robust platform supporting knowledge exchange, information sharing, and interoperability is crucial for fostering more effective CHKM in future research.

The examination of gaps and emerging trends in the literature on CH Ontology is conducted through a comprehensive analysis of keywords within the field, utilizing data sourced from Scopus. However, to deepen insights into CH Ontology research, fellow scholars can further elucidate their findings by delving into the realms of citation, co-citation, co-authorship, and bibliographic congruence across articles, authors, academic institutions, and countries. The scope of bibliometric inquiry can transcend linguistic barriers, casting a wider net to glean perspectives from global studies. The primary focus of this investigation is on journal articles. Nevertheless, it should be noted that supplementary and pertinent information regarding ongoing projects may be accessed through conference proceedings and other relevant sources. An inherent limitation of this study pertains to the exclusive utilization of data drawn from the Scopus database. To foster a more expansive and holistic understanding of the CH Ontology landscape, future research endeavors may contemplate aggregating data from diverse databases, consolidating multiple instances of each article to yield a more comprehensive panorama of the subject matter.

The intricacies and multifaceted nature inherent in CH knowledge have introduced challenges in the development of ontologies. CH information is dispersed across diverse digital and physical environments, posing a challenge in terms of data availability. To address the issue of data scarcity, insights were gleaned from experts. While being valuable, this approach proves insufficient for ensuring the comprehensiveness of the ontology. The ongoing evolution and enhancement of the ontology are imperative to surpass the confines of scope limitations. The resulting CH Ontology serves as a reflection of the prevailing state of literature. Notably, the testing of the CH ontology did not involve the engagement of end-users. The incorporation of users into the testing processes holds paramount importance for enhancing the usability of the CH Ontology. Recognizing the significance of user perspectives can contribute to refining and optimizing the ontology's effectiveness in accommodating diverse user needs and

ensuring broader applicability within the CH domain. An essential aspect of the semantic enrichment of the CH Ontology involves querying and incorporating classes from DbPedia using SparQL. For instance, the "Museum" class information was obtained and integrated into the CH Ontology through querying. However, it's noteworthy that when querying a different class via DbPedia, it was possible to access data linked to the "Museum" class. Additionally, there were classes not cataloged in DbPedia. Due to the time-consuming nature of conducting comprehensive research on these classes, it was not feasible to integrate some of them.

5.5. Suggestions for Future Studies

An observable surge is evident in the adoption of Semantic Web and AI technologies within the CH Ontology literature. These technologies represent prominent and dynamic areas of inquiry in the literature, particularly in the context of advancing CHKM. The development of the CH Ontology has been instrumental in achieving semantic interoperability and effective representation of CH knowledge. The assimilation of Semantic Web Technologies into the CH Ontology framework has the potential to foster interdisciplinary interoperability across diverse domains. Furthermore, the strategic amalgamation of Semantic Web Technologies and AI illuminates the path toward novel digital platforms for CH related industries. The integration of these technologies can give rise to user-centric information-sharing platforms, where the CH Ontology functions as a foundational infrastructure for chatbot-based services. This synergy not only augments the accessibility of CH knowledge but also enhances the user experience. Additionally, the convergence of technologies, including the IoT, may act as a catalyst for the development of the Digital Heritage Twin (CH Digital Twins), ushering in new dimensions of engagement and understanding in the realm of CH.

KG offers a structured representation of real-world entities and relationships. The creation of a CHKG facilitates reasoning across diverse information sources. Large Language Models (LLM), extensively trained on vast text datasets, demonstrate the capability to generate articulate and coherent text through concise commands. LLMs also empower various applications, including conversational AI. However, their informational

scope is confined to learned patterns from training data, lacking true comprehension. Despite their reasoning limitations, such models fall short of making logical inferences or synthesizing facts from multiple sources. The integration of CHKG provides a semantic framework for interdisciplinary CH data from varied sources. Consequently, within the proposed Digital Heritage Twins (CH Digital Twins) model, users can access precise information for their queries from dependable sources.

The acquisition of CHKG involves the enhancement of the CH Ontology through the incorporation of both structured and unstructured data. Primary sources for semantic enrichment encompass classes acquired via queries in DBpedia and natural language texts procured from reputable sources. However, the study encountered limitations due to the restricted availability of Dbpedia and text data. To overcome these limitations and expand the scope of the CH Ontology, LLM can be used. Classes within the purpose-built CH Ontology underwent querying in both DbPedia and Bard.ai which is a LLM. The resulting class numbers are detailed in Table 10. In instances where the Bard.ai query yielded an overwhelming number of classes, it is denoted as "none" to signify the impracticality of counting. Extension values within the table indicate the growth potential of the CH Ontology through LLM integration. To ensure the reliability and accuracy of the data obtained from Bard.ai, a validation process can be conducted using the Ministry of Culture and Tourism dataset. Higher extension values suggest substantial potential for the advancement of CHKG with the incorporation of LLM.

Table 10. Subclasses in DBpedia and LLM

Class Name	DBpedia	Bard.ai	Extension
Mosque	476	82.693	475,89 %
Fortress	114	3.000	2.526,32 %
Museum	131	552	322,14 %
Settlement	733	35.000	4682,01 %
Stadium	77	200	159,74 %
Fountain	55	None	Cannot be calculated
Sculpture	159	None	Cannot be calculated
University	108	65.000	59.974,07 %

The CH Ontology functions as a tool for the semantic representation of CH knowledge. By incorporating data from the web into the CH Ontology through Semantic Web Technologies, a KG can be formulated. The complete semantic enrichment of the CH Ontology for generating the CHKG faced limitations due to its reliance on manual and semi-automatic processes. LLM, particularly adapt at tasks such as text creation and question answering, can facilitate automatic enrichment of the CH Ontology. Enhancing LLM's performance through Retrieval-Augmented Generation (RAG) proves beneficial, enabling LLM to draw information from external sources for more insightful responses. Future research endeavors could explore the development of a RAG mechanism connecting LLM and the CH Ontology. This approach would foster the creation of a dynamic CHKG Model that remains continuously nourished and updated.

The CHKG introduces a novel dimension to human-computer interaction in the CH domain, empowering machines to comprehend and manipulate CH knowledge. This interactive dynamic fosters seamless communication between the digital and physical realms, giving rise to the conception of Digital Heritage Twins (CH Digital Twins) (Figure 28). The foundational infrastructure for the envisioned Digital Heritage Twins (CH Digital Twins) is laid by the CH Ontology and CHKG. Realizing Digital Heritage Twins (CH Digital Twins) involves the development of a chatbot that integrates seamlessly with CHKG, serving as the digital manifestation of CH. Additionally, the creation of nD HBIM, encapsulating visual and textual data of CH structures, contributes to the comprehensive integration of systems. Achieving full integration entails connecting the established CH Ontology with the HBIM Ontology, enabling information exchange across various levels through the synthesized system. The incorporation of Distributed Ledger Technology (DLT) not only ensures information security but also regulates access control within the system. While the proposed system is initially tailored for ancient cities, its adaptability extends to modern cities, offering potential applications in the development of smart city initiatives.

The Digital Heritage Twins (CH Digital Twins), operating as a semantic platform, emerges as a pivotal conduit for effective CHKM and knowledge dissemination. Encompassing assets such as museums and ancient cities, Digital Heritage Twins (CH Digital Twins) has the transformative potential to serve as prototypes, breathing life into numerous historical values. Their applications transcend various disciplines, including

architecture, archaeology, civil engineering, anthropology, history, and philosophy, significantly enriching educational processes. Facilitating access to CH knowledge not only eases learning within these disciplines but also ensures the enduring sustainability of CH knowledge, providing long-lasting benefits. Beyond its educational ramifications, Digital Heritage Twins (CH Digital Twins) can play a vital role in bolstering the country's economy. Their contribution to the tourism sector can through distinct online and on-site applications exert a tangible influence on the economic landscape. Moreover, they can harbor the potential to furnish database services to academics, catering to specific needs across various research fields. The versatile applications of Digital Heritage Twins (CH Digital Twins) underscore their paramount importance in both academic and practical domains.

Figure 28 delineates the sequential steps essential for the creation of a Digital Heritage Twin (CH Digital Twins). This thesis undertook the development of the CH Ontology, a foundational element for the subsequent derivation of the CHKG through semantic enrichment. The establishment of this infrastructure laid the groundwork for the eventual realization of Digital Heritage Twin (CH Digital Twins). Moving forward in the Digital Heritage Twin (CH Digital Twins) creation process, the subsequent steps involve the generation of HBIM with nD information on it (instead can be a Point Cloud Model as a data model rather than a 3D representation), the development of chatbots, and the seamless integration of these distinct systems. The ultimate goal is the comprehensive amalgamation of these components, culminating in the presentation of an integrated and user-centric Digital Heritage Twin (CH Digital Twins). This holistic approach aims to foster the creation of user-interactive CH platforms, facilitating enriched engagement and interaction with CH resources.

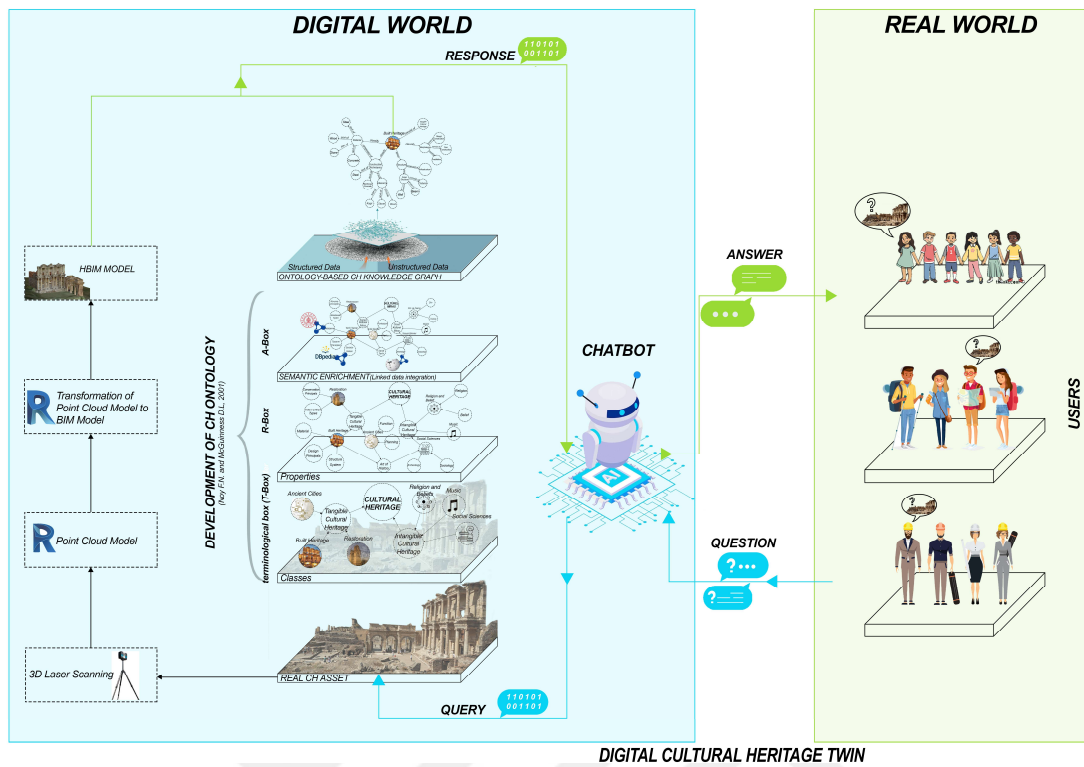


Figure 28. Digital Heritage Twin (CH Digital Twins) Suggestion for Future

6. CONCLUSION

Recent advancements in Digital Cultural Heritage (DCH) have brought forth innovative methodologies within the field of Cultural Heritage Knowledge Management (CHKM). The objective of this study is to establish a unified CHKM platform through the development of CH Ontology and the implementation of Semantic Enrichment, leading to the creation of a Knowledge Graph. To achieve this goal, a comprehensive approach involving bibliometric research and scientometric analysis was undertaken via the Scopus interface, focusing on the literature pertaining to DCH technologies.

The findings of the analysis reveal a predominant concentration of studies within the CHKM domain, with a notable scarcity of integration studies. In response to these insights, a subsequent scientometric analysis was conducted to pinpoint gaps and emerging trends in the literature related to CH Ontology studies. This analysis highlighted the potential for innovative CHKM platforms through the integration of CH Ontology studies with Semantic Web and Artificial Intelligence (AI) technologies.

Building upon the outcomes of the bibliometric search and scientometric analysis, a CH Ontology was meticulously developed. The semantic enrichment of this ontology facilitated the creation of a platform for AI-based CHKM. The study acknowledges certain limitations, including the exclusive reliance on journal articles for literature searches, language restrictions to English, the multifaceted nature of CH information, and the incomplete digitization of certain data.

The integration of LLM presents an avenue for expanding the scope of CHKG. Leveraging LLM enables the automatic enrichment of the CH Ontology. The RAG empowers LLM to glean information from external sources, thereby enhancing its ability to provide informed responses. This augmentation allows LLM to access up-to-date, domain-specific information, paving the way for the potential development of a Digital Heritage Twin (CH Digital Twins) through the integration of the evolved CHKG with AI-based chatbots in the future.

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ACADEMIC PUBLICATIONS

1. ARTICLE

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2. CONFERENCE PROCEEDING

Ozturk G.B., & Ozen B. (2022, 20-22 October). Major Research Areas in Smart Factory Research. International Project and Construction Management Conference 2022, Istanbul, Turkey.

3. BOOK CHAPTER

Ozturk G.B., & Ozen B. (In press- April 2024) Artificial Intelligence Enhanced Cognitive Digital Twins for Dynamic Building Knowledge Management, Zhihan Lv (Ed.), Handbook of Digital twins, CRC Press.