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GIS based solutions for management of public building and infrastructure assets: a review of state of the art and research trend analysis

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Highlights:

This literature review on the subject of GIS solutions for the management of public buildings and assets has the following highlights which are of value to researchers and practitioners.

- A systematic literature review of GIS technologies is presented for Public Asset Management.
- Trend analysis using keyword co-occurrence is performed including analysis from related fields.
- A new gap analysis tool is presented for identifying research gaps using Word2Vec NLP models.

Abstract: Building asset management is a complex endeavor that involves development, operation, maintenance and disposal of large-scale costly assets that serve one or more significant functions. Recent and continuing developments in Geographical Information Systems (GIS) offer solutions to the significant challenges of integrating and visualizing asset management data, choosing development proposals, cost assessment, risk assessment and maintenance strategies. Furthermore, GIS data is a common element among many types of projects, buildings and infrastructure assets. GIS technologies can therefore have a significant and broad impact. Navigating GIS developments can be difficult and unclear. To this end, this study performs a literature review on state-of-the-art and emerging GIS technologies as they apply to public asset management. The aim is to provide public authorities with a means to understand the potential and the challenges of these GIS technologies in order to support more informed decision making. The main opportunities that these technologies provide to AM are examined. These include data integration, optimization of resource use, risk assessment and improved decision making from reactive to proactive. In addition, a new Word2Vec K-means based keyword gap analysis tool is proposed to aid in the visualization of keywords in the literature corpus by sorting the keywords into meaningful subject focused categories. This study will help make adoption choices of GIS technologies more informed and coherent, which will allow the reduction benefits in costs, energy and environmental impacts to be more easily leveraged.

Keywords: geography information systems; public assets; asset management; building information modeling; literature review; digitization; natural language processing (NLP); Word2Vec; K-means

1. Introduction

Asset management is the longest and most costly phase of built assets' life cycle, which can account for up to 80% of the overall cost of the assets [1]. Public organizations such as municipalities and government agencies face the challenge of maintaining their built assets as well as managing the public good amidst budgetary constraints, which are often interrelated with other budgetary needs and, as a rule, limited. In addition to deferred maintenance, greenhouse gas emissions can add further pressures to already tight budgets. The spatial component of many assets is often a big factor in their health and usage. However, it is a component that is difficult to grasp without supporting technology. GIS technology can solve many of the spatial challenges associated with asset management such as site assessment [2], monitoring [3], prioritization of rehabilitation [4], risk assessment [5], inventory [6] and cost and emissions analyses [7]. GIS can also be used to visualize and communicate data to both technical and non-technical audiences and support decision making and foster better understanding between collaborating parties. However, GIS is a vast multidisciplinary field that can be very difficult to navigate for those who do not have expertise in the area. Therefore, this study intends to present a guide to traversing the wide ranging and highly applicable body of research in GIS.

The aim of this research is to explore the current state of the art for GIS applications for public asset management. The main objective is to collect information on GIS technologies that is the most relevant and that covers a wide range of asset types including building and infrastructure assets. A keyword search is performed using the Scopus database. Key developments and their applications are summarized, and research gaps are identified based on trends in the literature. This research is an extension of an earlier work by the authors [8]. The work has been expanded with the additions of an in-depth review of more research studies, trend and gap analysis and a proposed tool for keyword gap analysis per subject category of a research field.

The rest of the paper is organized as follows. Section 2 describes the methodology for performing the literature review. Section 3 goes into trend analysis using keyword networks and proposes an additional keyword network tool, going into the trend results. Section 4 presents the findings of the in-depth study of the most significant works that were found using the methodology. Section 5 summarizes the findings and concludes the review.

2. Methodology

A systematic literature review (SLR) was conducted to find relevant scientific papers on GIS for public asset management. The process used a key word search followed by a title and an abstract screening to select papers for more in-depth review. The SLR was done chiefly using the Scopus database. This database was chosen after other options gave too many non-relevant results or too few relevant results. The field of GIS intersects with many other domains and removing less relevant sources was important in order that the focus of the work remain on GIS spatial data technologies.

Figure 1 summarizes the details of the process. The general approach was modified due to the emerging categories of papers which corresponded to the different types of assets that were being managed with the methods.

Step 1 was a keyword search in the Scopus database. The first search of:

- "GIS" "public asset management" 2010–2024 (six results, four Journal Papers) yielded too few results. The phrase "public asset management" was too narrow. It was replaced with "municipal" OR "public" with "asset management." Subsequent searches yielded results in the tens of thousands of results. After numerous different queries with different criteria refinement the following query was selected in step 2:
- municipal OR public "GIS" "asset management" AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP")) (778 results, 476 Journal Papers) 476 journal papers were retained for further review.

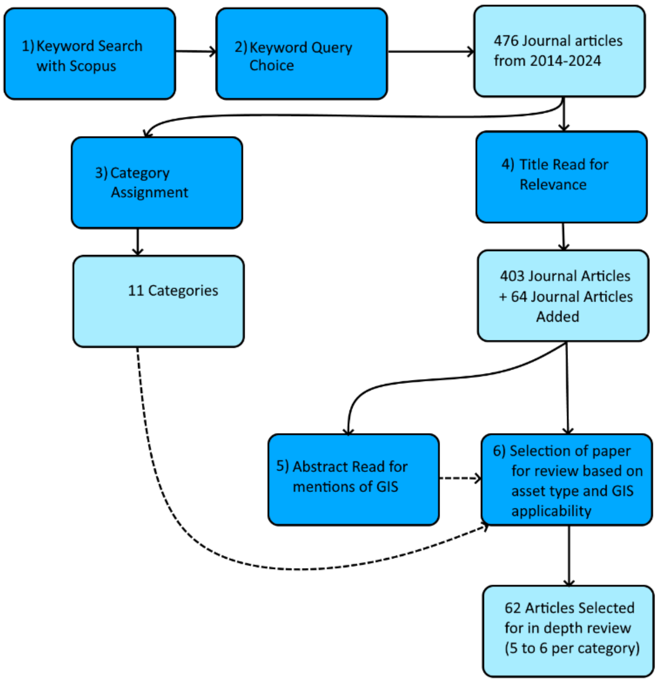

Figure 1. SLR flow chart.

Steps 3 and 4 were conducted simultaneously and consisted of a title read for relevance and asset categorization. Asset types considered by the studies were identified when possible. Eleven categories of assets were identified, and 403 articles were retained as relevant once the literature reviews not identified earlier were removed along with articles focusing on different research. This process was then repeated to extend the literature review to encompass more works published in the last several years with a focus on 2024. An additional 64 articles were retained as relevant.

Steps 5 and 6 were also conducted simultaneously and were respectively abstract reading for mentions of GIS, and selection of articles per asset category, respectively.

Five to six most relevant articles were chosen per asset category for most categories for a total of 62 selected works. Decisions were carried out per asset category with articles mentioning GIS in the abstract being favoured. Additionally, a quick perusal of each article was done to confirm that the results had significant spatial data. Based on these factors, the most relevant articles were retained per asset category. Selected works had to have a strong emphasis on GIS technologies and make use of spatial data. To this end, works whose focus diverged too much from spatial data were excluded. This included works that focused on information management in construction, process management, user adoption studies, among others, where the focus was on subjects other than utilizing spatial data to gain useful results. Studies were then selected for in-depth analysis based on their novel approaches, perceived usefulness, and reported results.

Sixty-two (62) total key papers were selected for in-depth review of the SLR. The results of the in-depth study are presented in section 4.

3. Keyword trend analysis

A SLR was conducted to find relevant scientific papers on GIS for public asset management. The process used a key word search followed by a title and an abstract screening to select papers for a more in-depth review.

In addition to performing the in-depth analysis a keyword co-occurrence analysis was performed to analyze general trends in the research field. The main steps and results of the keyword trend analysis are summarized in the chart below. This trend analysis was conducted in part with a new proposed keyword clustering tool based on an NLP Word2vec model. This was done to overcome some existing limitations of the keyword co-occurrence analysis and its workings are described in a later section.

Keyword co-occurrence networks are excellent ways to visualize the interconnectedness of keywords within a large corpus of bibliometric data. These networks are built using tools such as VOSViewer. Networks were built with VOSViewer on the corpus obtained from the following three research queries:

- GIS and Public Asset Management Query (core query used in in depth study):

  municipal OR public “GIS” “asset management” AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “COMP”)) AND (LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”))

- GIS and Civil Engineering Query (broader related research field query):

  “GIS” AND “CIVIL ENGINEERING” AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “COMP”)) AND (LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”))

- Public Asset Management Query (broader related research field query):

  municipal OR public “asset management” AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, "“COMP”)) AND (LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”))

By analysing the co occurrence networks for these 3 queries, general trends in the research fields could be observed. Additionally, gaps could be identified in the GIS and Public Asset Management field.

A graph of approximately 40 keywords was built for the GIS and Public Asset Management query (Figure 2).

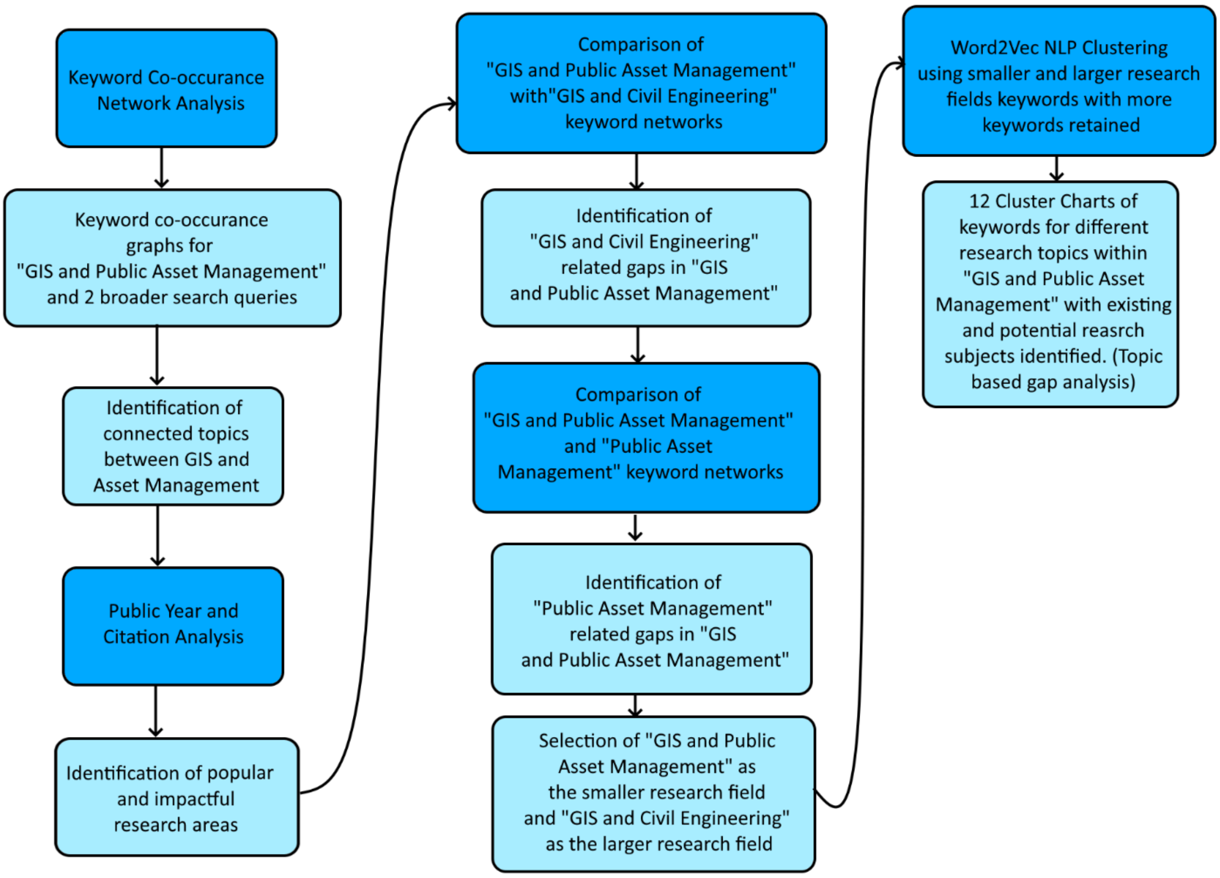

Figure 2. Keyword trend analysis flow chart.

The asset management connected terms are: optimization, Building Information Modeling (BIM), GIS, pavements, highway administration, highway planning, roads and streets, road, maintenance, cost, information systems, budget control, investments, infrastructure, water supply, decision making, decision support systems, machine learning, AI, risk assessment, risk management, sustainability, sustainable development, life cycle, information management, information theory, architectural design, office buildings, construction, project management and construction industry. The GIS connected terms are the same. This indicates that no terms that were related to only GIS, or only Asset Management, were retained, which makes categorization irrelevant because all terms are connected to all other terms. This limits analysis to high level generalization because many more specific terms were not retained. The network can also be visualized in terms of average publication year (Figure 3) and average number of citations (Figure 4).

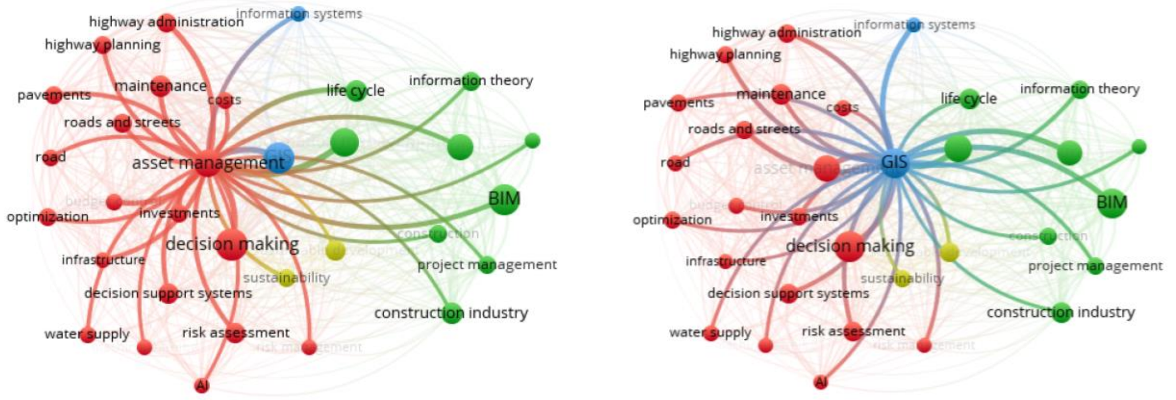

Figure 3. Keyword co-occurrence network for GIS and Public Asset Management search query.

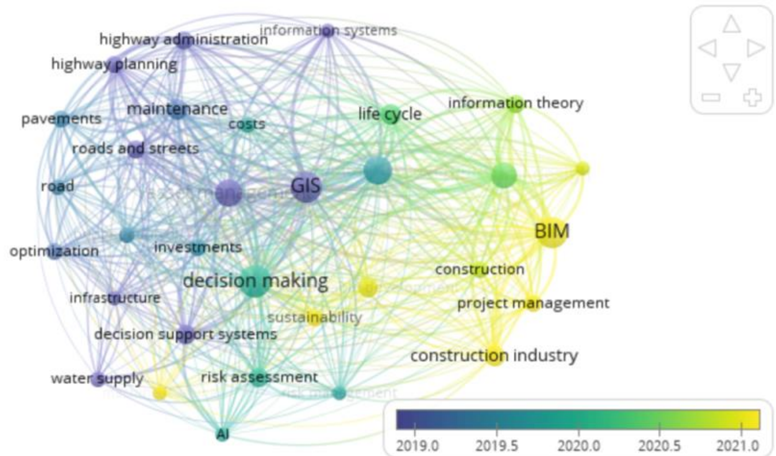

Figure 4. Keyword co-occurrence network for GIS and Public Asset Management with average publication year per subject.

These trends suggest that individual asset type related research is becoming less popular. Information technology related research is becoming more popular. There seems to be a gap in using information technology for specific asset types. Research in the field appears to be of most interest if it deals with BIM and digital technologies at a high level. AI and machine learning being of lower impact supports this notion because these terms become more specific and technical. This highlights the fact that while there is interest in digitalization technologies the practical understanding still needs to grow to match the interest at the higher level.

This keyword network was compared to the network created from the broader research field query of GIS and Civil Engineering (Figure 5). This network also used approximately 40 words and can be seen below.

There is a gap in GIS and Public Asset Management research for remote sensing, land use, urban growth and forecasting. These areas do not have analogous terms in the GIS and Public Asset Management co-occurrence keyword network. Also, while floods, landslides, earthquakes and disasters all fall under the purview of risk assessment, it could be very helpful to explore these fields individually and with more focus in the field of GIS for Public Asset Management. It should be noted that both GIS and Civil Engineering connect to all other terms which suggests that only the most interrelated terms were retained and terms that were more categorical were omitted, which again limits this analysis to a very high level.

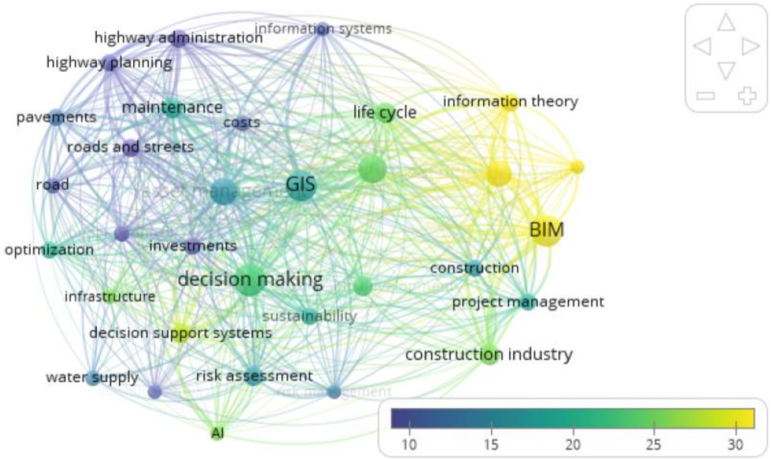

Figure 5. Keyword co-occurrence network for GIS and Public Asset Manage with average number of citations.

The Public Asset Management query was also used to create a co-occurrence keyword network (Figure 6). This network also retained approximately 40 words and enabled comparisons with the broader field of public asset management.

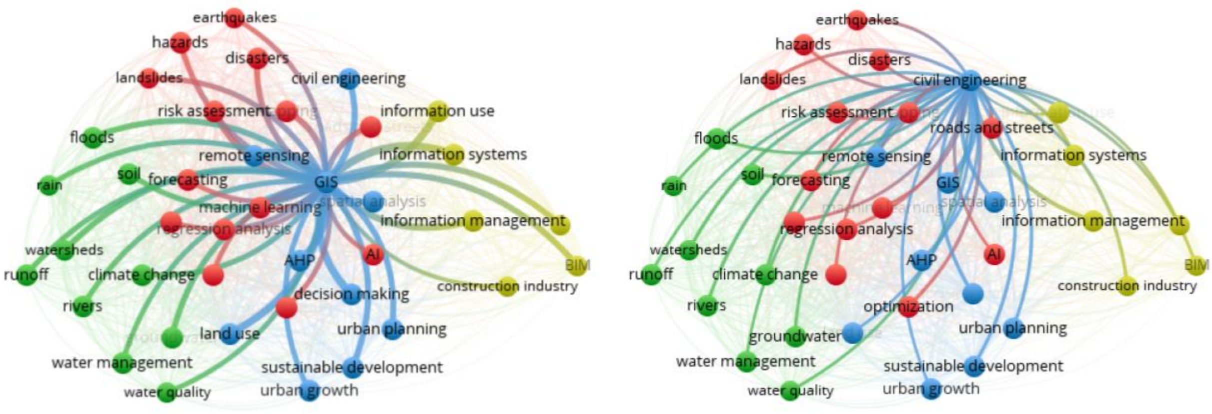

Figure 6. Keyword co-occurrence network for GIS and Civil Engineering search query.

A gap exists in using the Internet of Things (IoT) in GIS for Public Asset Management, as it has already been used within the broader asset management research field. The same can be said of forecasting and blockchain. It is also interesting that GIS is not a key term related to asset management. This suggests that there is an overall research gap in using GIS for asset management which echoes the findings in the other analysis of this review.

The keyword analysis using VOSViewer revealed the interconnectedness of the GIS for Public Asset Management research field along with some interesting research trends and gaps. The keyword trend analysis also revealed that there are some significant drawbacks with using these types of keyword maps. These keyword maps are limited to only the top keyword terms and expanding them further with more keywords quickly leads to cluttered and unreadable graphs. Many useful terms could be lost. There also needs to be better control over how words are grouped. It is natural for example to group different types of disasters or AI/optimization methods together; however, these would sometimes be separated into different clusters in the keyword co-occurrence networks. In order to address these drawbacks, a new keyword-based visualization and gap analysis method is proposed.

Word2Vec k-means keyword gap analysis method

A new gap analysis method for keywords is proposed based on combining VOSViewer keyword extraction, Word2Vec NLP, and k-means clustering. Word2Vec is a natural language processing model that takes a corpus of text and creates vector representations for the contained words. Related words show up closer together within the vector representations then words that are dissimilar. K-means clustering is a vector clustering algorithm that groups vectors into clusters based on their weighted presence in the vector space and thereby creating separations of these vectors into coherent groups. By combining both methods, it is possible to group keywords from search queries. The keywords within these groups can then be delimited by their presence within different search queries. The Word2Vec k-means gap analysis tool can be made available, along with the data used to generate the keyword clusters displayed in this section, upon reasonable request.

The procedure for the method is detailed in Figure 7

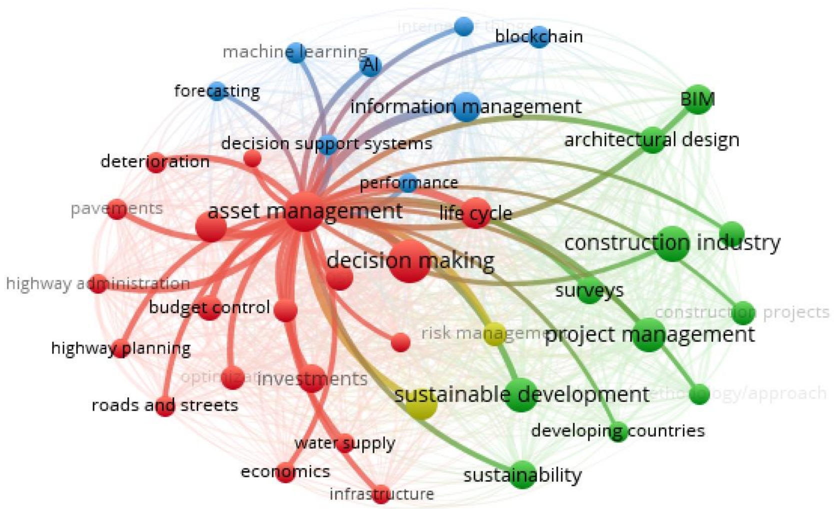

Figure 7. Keyword co-occurrence network for Public Asset Management search query.

As seen in Figure 8, the procedure is done partially in VOSViewer and partially in Python. The yellow steps require human intervention, and the green steps can be automated with scripting. For this work "GIS and Public Asset Management" was identified as the specific research field, and "GIS and Civil Engineering" was selected as the broader research field. Around 350 important keywords were retained from the VOSViewer analysis. Words were retained based on an occurrence threshold in the abstract and keyword corpus of the broader research field. This threshold was set to 100 occurrences in our work, but it must be set based on reviewer judgement in order to have sufficient terms for the subsequent clustering. The keywords were then analyzed for their appearance in the specific research field. In step 8, the terms were organized with specific research field terms first in descending order of occurrence followed by the terms that only appear in the broader research field in ascending order of occurrence in the broader research field.

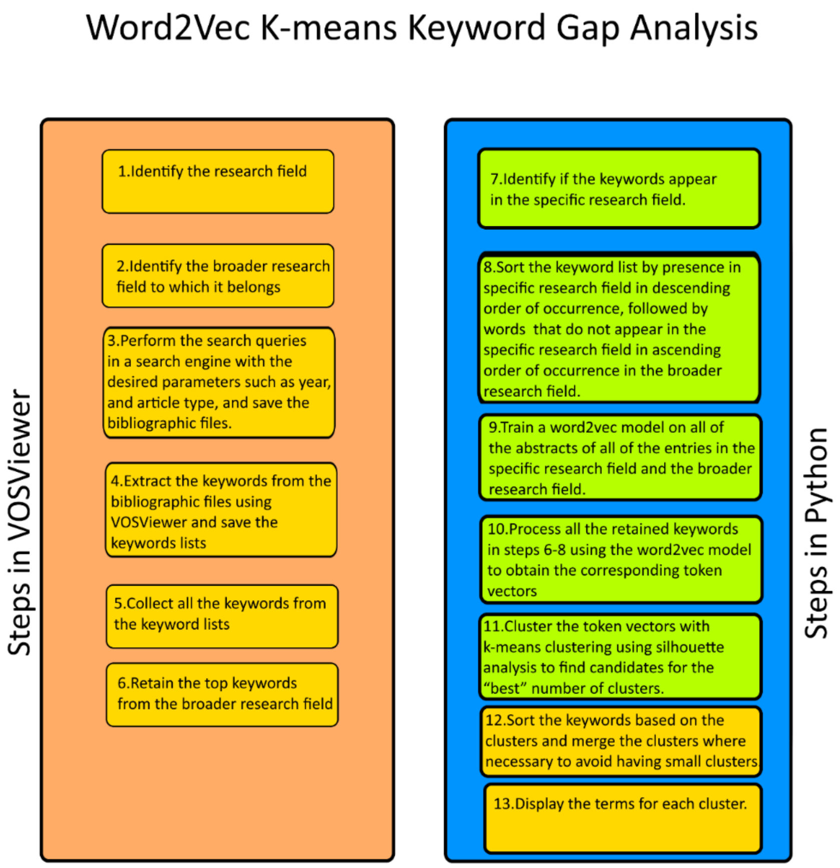

Figure 8. Word2Vec K-means Keyword Gap Analysis Method. The left orange side indicates steps that are done in VOSViewer, and the right blue side indicates steps that are done in Python. Yellow steps require human intervention, green steps can be scripted.

In step 12, the clusters should be merged according to user discretion to avoid having clusters that are too small or too specific. For example, AI/optimization related keywords may only need one cluster containing 10 terms rather than two clusters of five terms. This is up to the discretion of the researcher. Clusters should contain at least five-six terms and all clusters containing one term should be merged into larger clusters. When visualizing, the clusters keywords already present in the specific research field should have a different colour than terms that only appear in the broader research field.

Roughly 350 words were extracted and grouped into 12 clusters. The clusters are Water Distribution Systems and Resources, Road Infrastructure, Project Management, Risk Assessment, AI/Optimization, Modeling and Visualization, Urban Planning, Decision Support, Physical Environment, Information Management, Imaging and Remote Sensing, and Life Cycle Assessment. Some clusters were the results of merging smaller groups of keywords. The resulting gap analysis charts can be seen below for each cluster. Figure 8 to Figure 20 show the clusters for each of the keyword groups. Red boxes show topics that have already been applied within GIS and Public Asset Management. Blue boxes show topics that do not yet appear within the research literature for GIS and Public Asset Management and that have potential for future research and future application to the research field. Please note that not all keywords were properly grouped and outliers exist in some categories. However, the keywords were generally grouped into very useful categories.

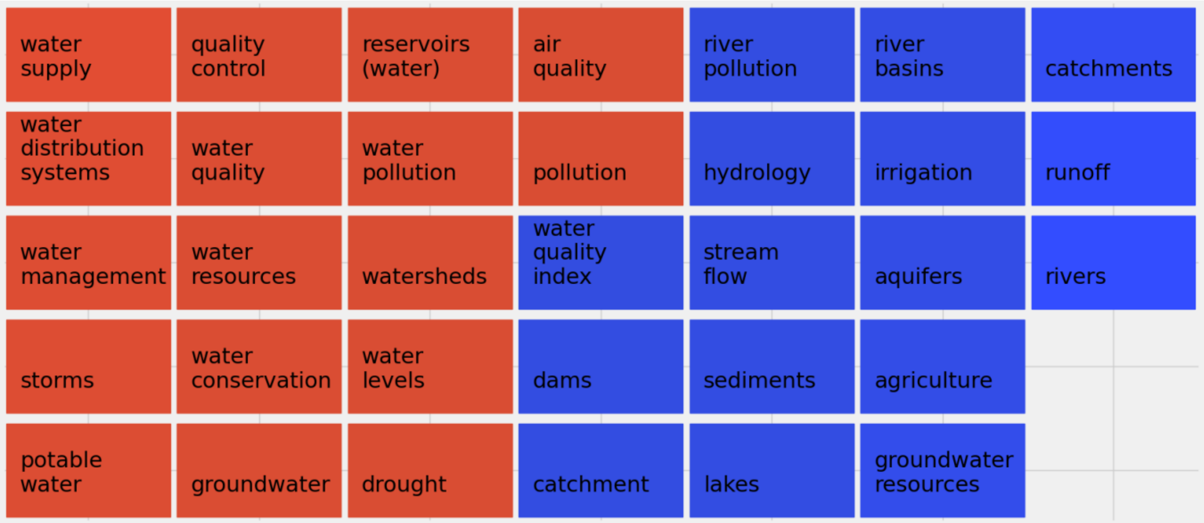

Figure 9. Cluster 1: Present (red) and potential future (blue) topics in water distribution systems and water resources.

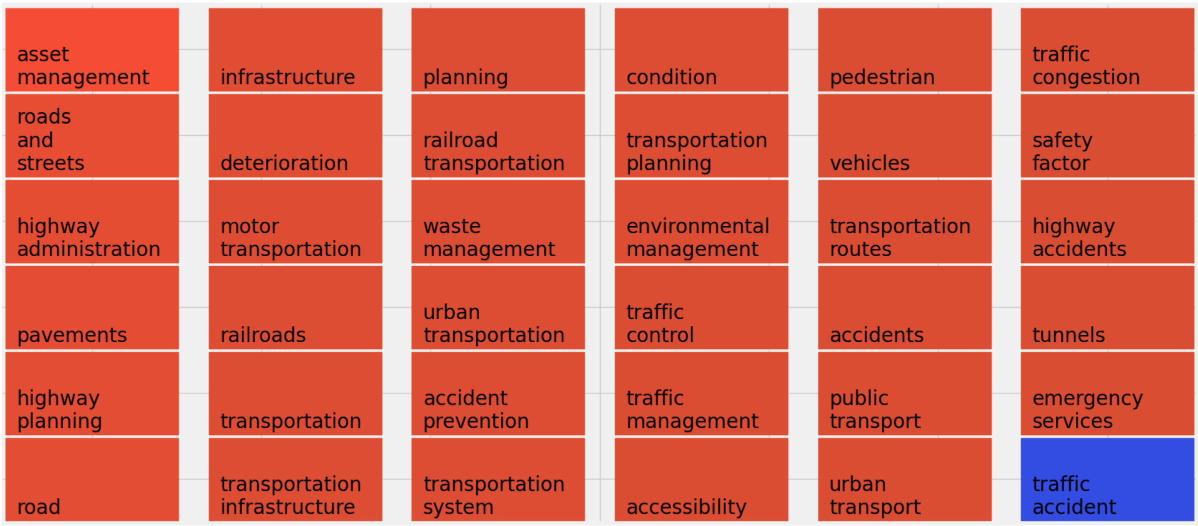

Figure 10. Cluster 2: Present (red) and potential future (blue) topics in road infrastructure.

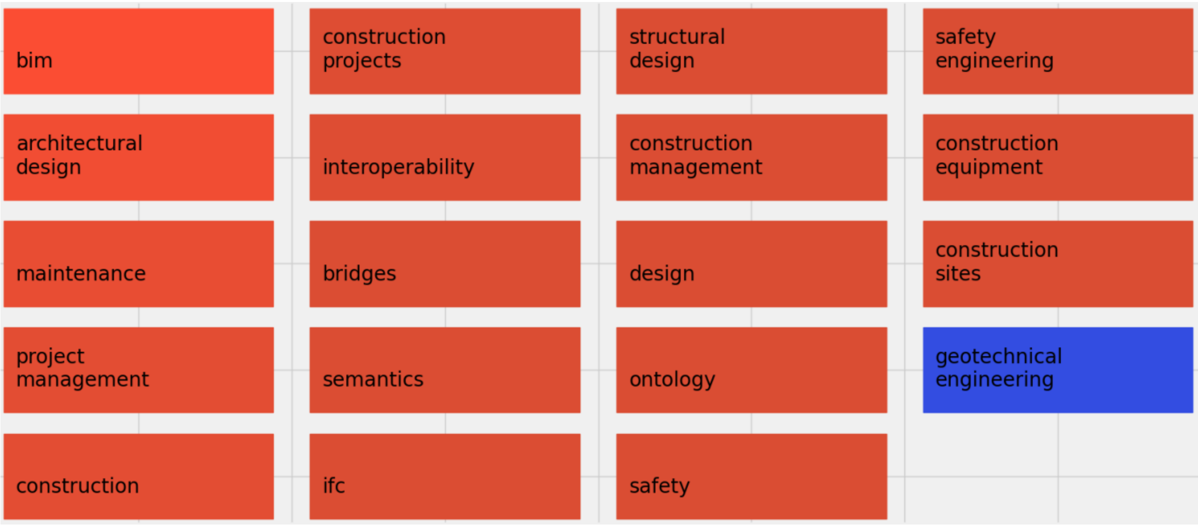

Figure 11. Cluster 3: Present (red) and potential future (blue) topics in project management.

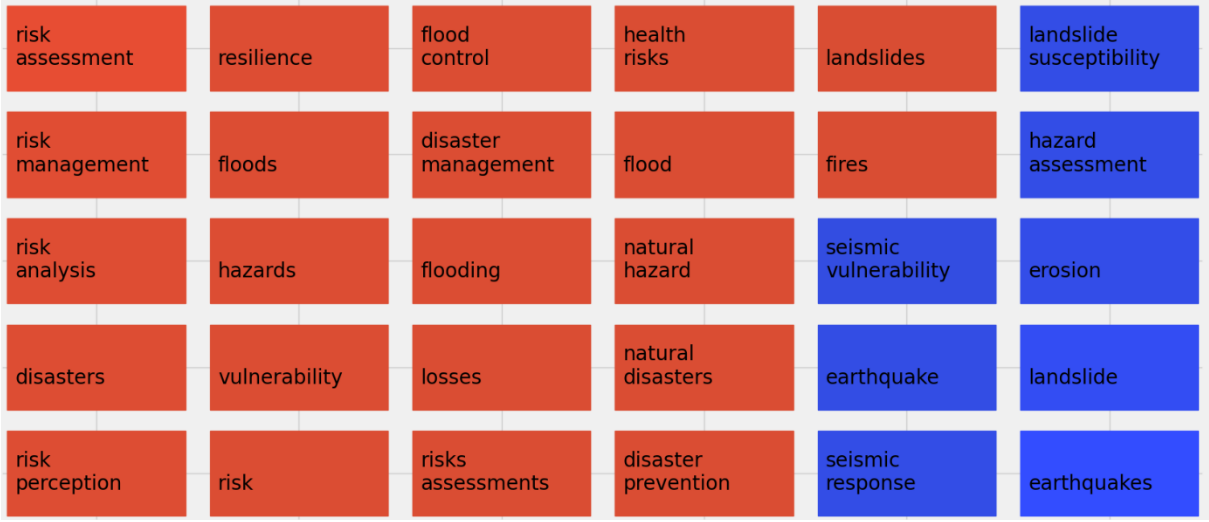

Figure 12. Cluster 4: Present (red) and potential future (blue) topics in risk assessment.

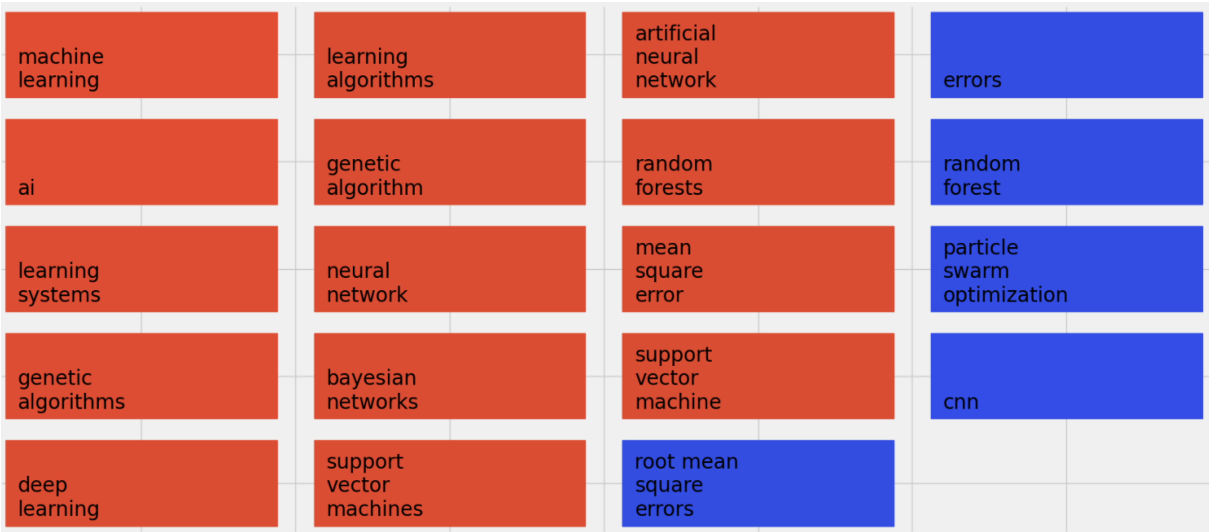

Figure 13. Cluster 5: Present (red) and potential future (blue) topics in AI/optimization.

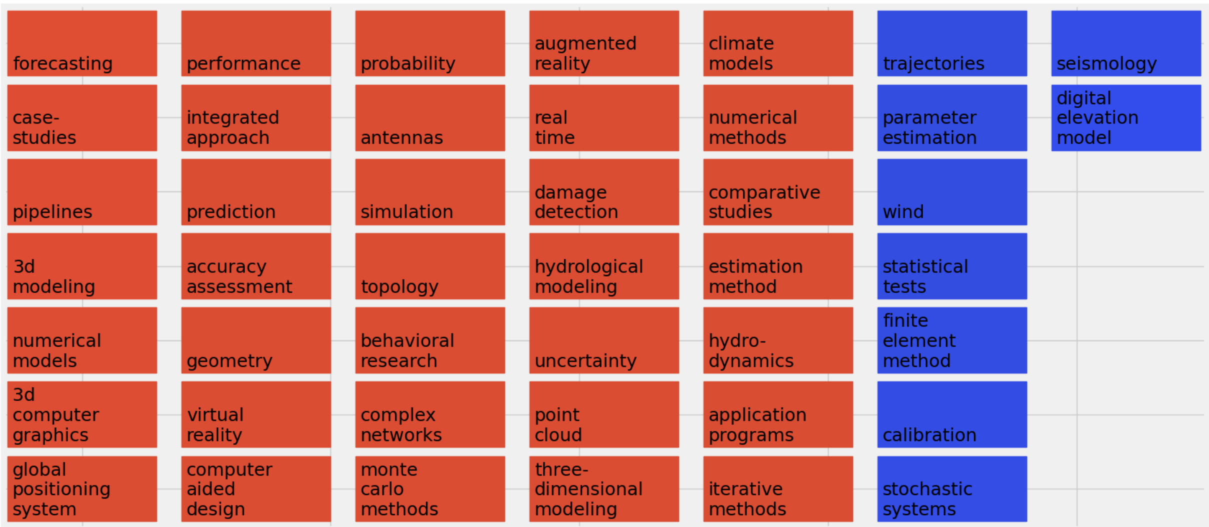

Figure 14. Cluster 6: Present (red) and potential future (blue) topics in modeling and visualization.

Figure 15. Cluster 7: Present (red) and potential future (blue) topics in urban planning.

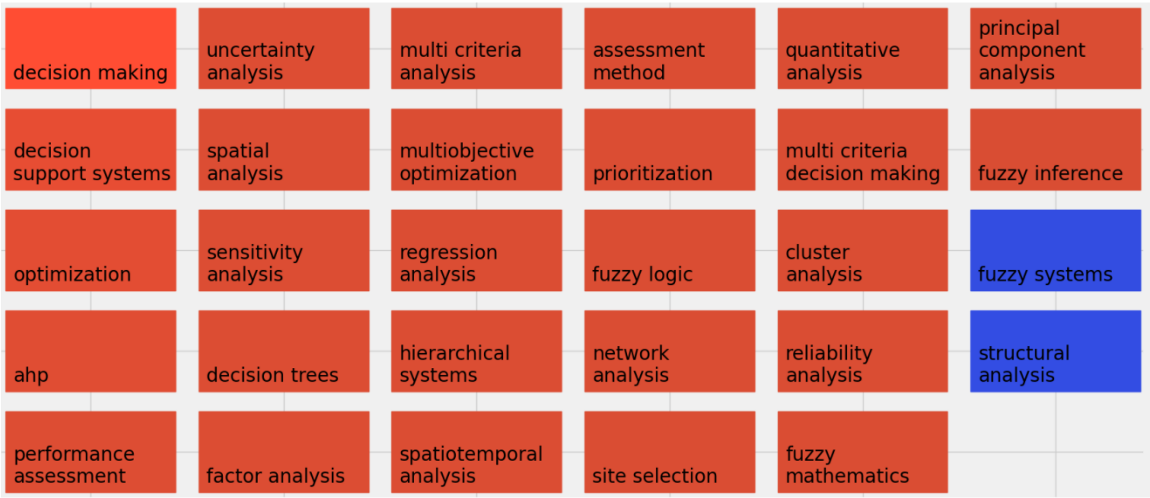

Figure 16. Cluster 8: Present (red) and potential future (blue) topics in decision support.

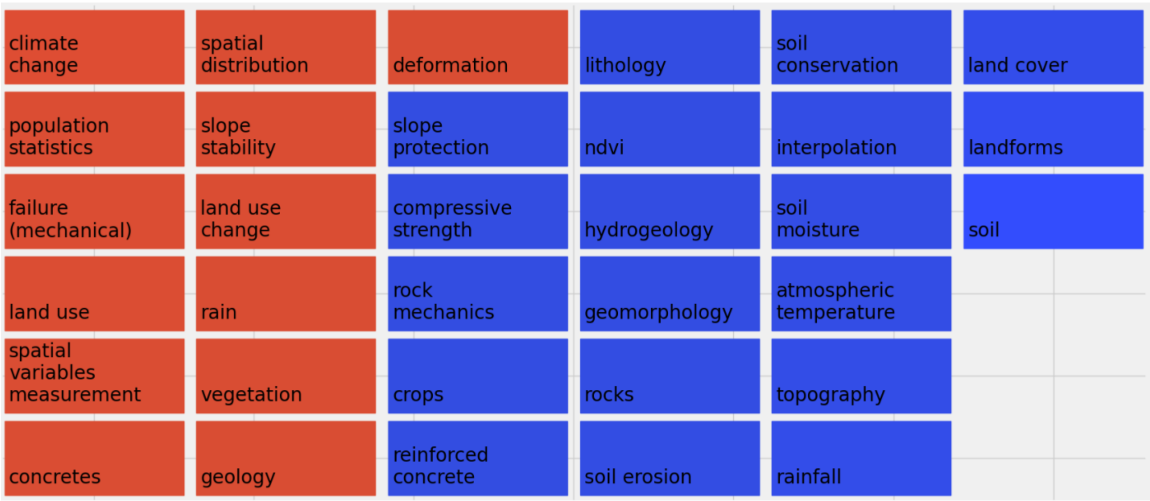

Figure 17. Cluster 9: Present (red) and potential future (blue) topics in physical environment.

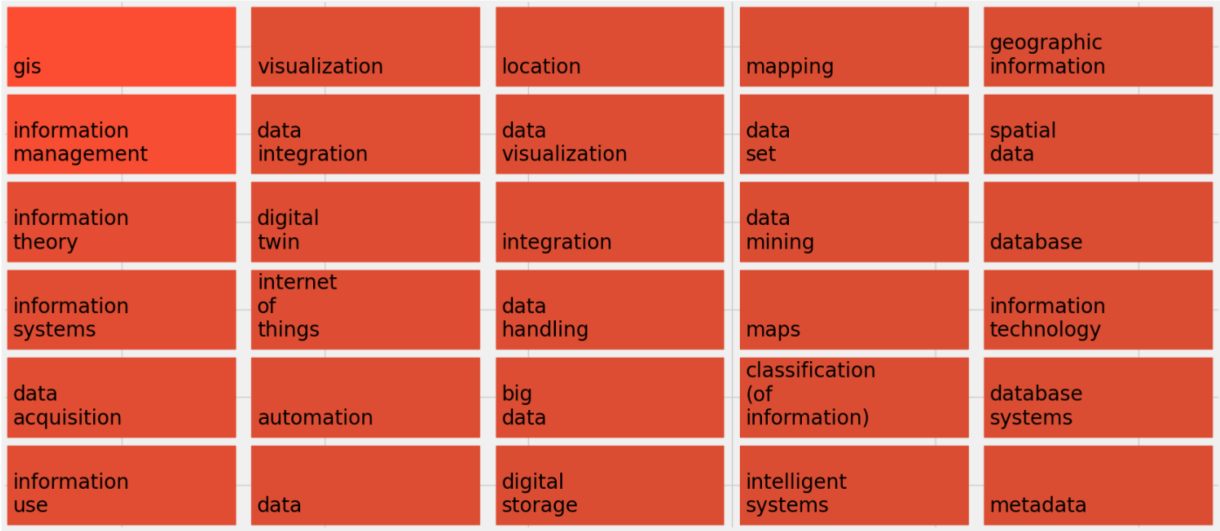

Figure 18. Cluster 10: Present (red) and potential future (blue) topics in information management.

Figure 19. Cluster 11: Present (red) and potential future (blue) topics in imaging and remote sensing.

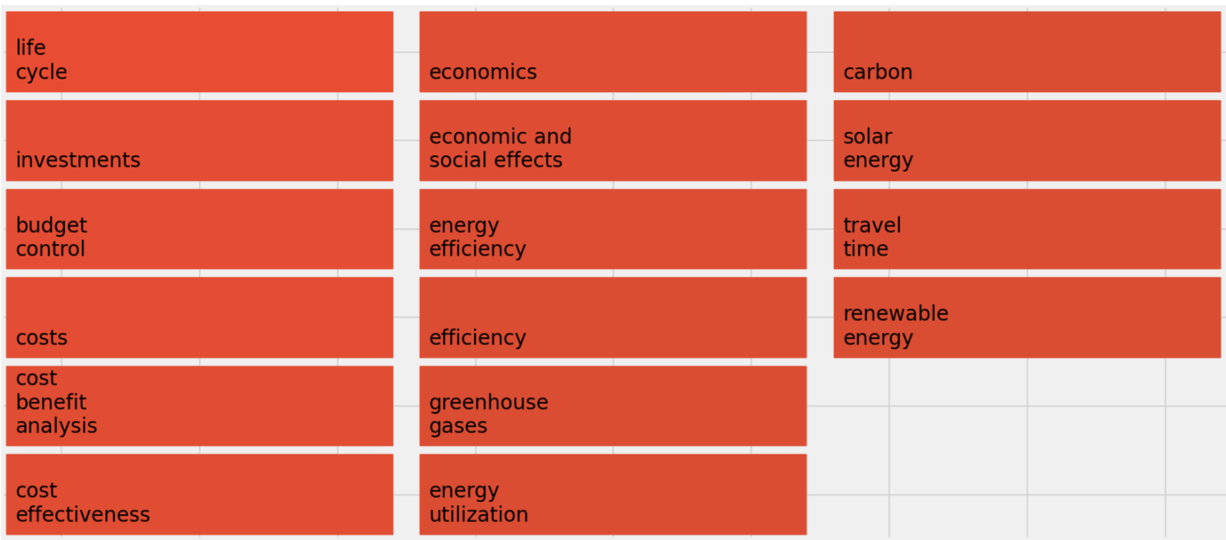

Figure 20. Cluster 12: Present (red) and potential future (blue) topics in life cycle assessment.

The above charts in Figure 8 to Figure 19 indicate areas where novel research can likely be done based on 12 different categories. The largest areas of opportunity are in Water Resources, Risk Assessment, Physical Environment and Imaging and Remote Sensing, where methods and techniques present in the GIS and Civil Engineering research field have yet to be applied to GIS and Public Asset Management. Furthermore, within AI and optimization methods, Convolutional Neural Networks (CNNs), which are commonly used for computer vision, have as yet to be used enough. This is a good opportunity for future work because map data can be transformed to images which can be very well classified or processed using CNNs. Using this method allows for very useful category specific gap analysis which can facilitate the identification of more specialized and more applied research directions according to professional research interest.

In addition to the findings themselves, the visual presentation of the keyword graphs is a significant improvement over keyword co-occurrence networks. The categorical gap analysis charts that were produced present the information in a much clearer and subject focused way. This method overcomes the problems of having too many keywords cluttering the visuals and lacking good categories for grouping together related terms.

4. Results

After completing the systematic literature review, the number of relevant studies selected for using GIS in public asset management was 62. These articles were grouped by asset category with approximately four-five per category. The following table and charts gather the findings on the works in terms of asset type and method summary (Table 1) and study characteristics such as type of problem solved and data availability (Figure 21 to Figure 23).The charts have corresponding tables in the appendix with all of the works listed. In addition, a co-authorship network has been made with these 62 studies with Vosviewer to visualize collaborations between authors.

Table 1. Summary of methods and assets considered.

Study	Type of asset	Method description
[9]	Roads and highways	Used the GIS data of roads, schools, hospitals, bridges and other infrastructure data to predict the impact of climate change on a road network in terms of infrastructure risk and adaptation cost.
[7]	Roads and highways	Used geocoded videos and U-net Convolutional Neural Network to detect clusters of cracks in pavement in a road network.
[10]	Roads and highways	Used a rule-based methodology make near optimal decision strategies for pavement rehabilitation by combining critical areas with less critical areas into more cost-effective work zones.
[11]	Roads and highways	The condition of stone pavements is evaluated with accelerometers on bicycles and cars and the data is aggregated and visualized in a GIS.
[5]	Roads and highways	Used a GIS to assess vulnerability in a road network which incorporated seismic, volcanic and hydro meteorological hazards, as well as user defined start and end locations for important transportation routes.
[12]	Roads and highways	Flood simulations were performed on road networks using GeoAI to explore resilience strategies and their impacts on road network performance and cost optimization.

Table 1. *Cont.*

Study	Type of asset	Method description
[13]	Roads and highways	Smart Objects were used to visualize sensor and survey data in a georeferenced 3D BIM model for road maintenance.
[14]	Roads and highways	Valuation of road networks was performed using GIS data in order to assess asset value for public private partnerships.
[15]	Public buildings/ roads and highways	A digital twin of a highway construction project was built in a game engine using sensor data, geospatial data and 3D models for risk assessment and remote monitoring.
[16]	Roads and highways, bridges	Used GIS road network information to select relevant Interferometric Synthetic Aperture Radar data for road and bridge network monitoring.
[17]	Bridges	Used the GIS data of bridges in a road network along with deep reinforcement learning to prioritize bridge maintenance to reduce costs and risk of failure.
[18]	Bridges	Used geospatial and BIM data along with a rendering algorithm to improve visualization and rendering of bridges in 3D GIS.
[19]	Bridges	Made a 3D model of a bridge from a 3D point cloud obtained from Unmanned Aerial Vehicle, a structural model and sensor data which allows for virtual remote site inspections, and on-site inspections that are augmented with geolocation data and visualizations on a mobile device.
[20]	Bridges	A BIM-GIS integrated framework is proposed which uses UAV point clouds and allows for virtual bridge inspections.
[21]	Bridges	Prioritization plans of bridge repair in flood scenarios are created that minimize cost and ensures equitable prioritization of economically vulnerable areas using deep learning and a Markov Decision Process.
[22]	Bridges	Study uses GIS data and satellite images to monitor bridge asset condition during a conflict to create improved resilience strategies for rebuilding post conflict.
[23]	Railway	Semi automated method for generating georeferenced 3D models of railway lines using GIS data and asset management data.
[24]	Railway	Used geospatial and architectural data of Roma Termini train station in Rome, Italy, to make a digital twin capable of predicting crowding risks and proposing mitigation measures.
[25]	Railway	Used a ConOps study, which is a user-requirements process which determines development strategy, to propose five new GIS applications to address gaps between existing adopted technology and GIS technology needs of a large commuter rail service.
[26]	Railway	3D BIM model was built from geospatial data with data attributes being modeled by smart objects for inspection and maintenance planning.
[27]	Railway	GIS data is used alongside a 3D model of a railroad track in order to create a BIM model for modeling the rehabilitation of a railroad with such functions as construction task simulation and material estimation.
[4]	Electrical and gas utilities	Used GIS data and the Hungarian algorithm to make an electrical network repair plan in the event of an emergency outage situation with downed substations.
[28]	Electrical and gas utilities	Used GIS to model cost and CO2 emissions of installing heat pumps that connect to electric grid versus heat pumps that connect to a gas grid, and associated grid maintenance.
[29]	Infrastructure and urban planning/ electrical and gas utilities	A ventilation study is done of a city using GIS data, Wind Ventilation Analysis, 3D building models, and pollution emittance calculations to identify zones of concern where mitigation measures should be used.

Table 1. *Cont.*

Study	Type of asset	Method description
[30]	Infrastructure and urban planning	GIS data of road and storm water networks is used to evaluate interdependencies with a multilayer graph network model in order to identify flood risk zones.
[31]	Infrastructure and urban planning	GIS Data and AI models are used to predict 2D growth and height growth in buildings around a new transit station and to visualize the result in a 3D city model.
[32]	Infrastructure and urban planning	Remote sensing data, GIS data, google earth and machine learning were used to pinpoint flood zones. The impact of different factors was evaluated.
[33]	Infrastructure and urban planning	A decision framework is proposed that uses GIS data to evaluate earthquake risks by combining data on regional risk areas, demographic and economic data, and resilience capabilities, using entropy weighting.
[34]	Infrastructure and urban planning	Used GIS data to coordinate maintenance of road, water and sewer assets with a trilevel framework and genetic algorithms.
[2]	Infrastructure and urban planning	GIS data and Multi Criteria Decision Making processes were used to determine potential sites for an Eco Industrial Park for brownfield rehabilitation.
[35]	Heritage	Surveyed how GIS was used for making preservation strategies for water heritage assets, by allowing inventory and risk assessment among other analyses, which resulted in educational campuses, a green corridor and a public park.
[36]	Heritage	Used GIS to make a cataloguing system of Portuguese glazed tile heritage sites and the comprising tiles for safeguarding and tourism purposes.
[37]	Heritage	Used BIM, scheduling databases, energy billing data and weather information to model energy usage in a building and provide decision support information for running the HVAC system to reduce energy waste.
[38]	Heritage	Geographic and building information were used to help evaluate the impact of an adaptive reuse of a heritage building.
[39]	Heritage	Used GIS data to create a 3D georeferenced model of a historic site to plan out conservation and intervention activities.
[40]	Heritage	3D city model is built using GIS to support urban planning, maintenance and intervention strategies on historical region of a city.
[3]	Public buildings	Implemented a construction site monitoring system using progressive updates of a site model with frequent laser scanning with a UAV resulting in point clouds which were processed by an octant algorithm which dramatically reduced computation time.
[41]	Public buildings	Used GIS and demographic data for aging adults to come up with social housing plans by solving a graph transportation network problem.
[6]	Public buildings	Used GIS to estimate buildings stock in a city which allows the prediction of housing demand, new construction material demand, waste generated from construction and greenhouse gas emission.
[42]	Public buildings	A GIS database of Public Open Spaces in Private Developments is developed for the city of Hong Kong to promote revitalization, awareness and equitable use, and to analyze accessibility of the sites.
[43]	Public buildings	Displacement of walls was measured using image photogrammetry and the planning and data collection was done using GIS. Results were compared to onsite measurements.

Table 1. *Cont.*

Study	Type of asset	Method description
[44]	Public buildings/ hospitals	Framework that uses BIM and GIS to support facility management was made, which has linking scripts that synchronize BIM-GIS data.
[45]	Hospitals, airports, and universities	Used a digital twin for facility management of a hospital facility by incorporating BIM and sensor data.
[46]	Hospitals, airports, and universities	Used Permanent Scatterer Interferometric Synthetic Aperture Radar data to monitor the structural health of an airport and validated the results with onsite data from borehole measurements.
[47]	Hospitals, airports, and universities	Climate and geographic location data are used to make an energy model of a building using the BIM 6D methodology which allows for simulation of improvement actions resulting in reduced energy use.
[48]	Hospitals, airports, and universities	BIM and GIS data were integrated to create an asset management system for a university which was then used to simulate fire emergencies for risk assessment.
[49]	Hospitals, airports, and universities	A georeferenced digital twin was made of a building on a university campus using UAV and laser scanning. The digital twin provided anomaly detection in pipes, temperature monitoring, maintenance optimization and energy planning.
[50]	Hospitals, airports, and universities	A BIM-GIS integrated system was created for supply chain monitoring with GIS supporting spatial analysis in the supply chain logistics. Case study on a nursing school.
[51]	Hospitals, airports, and universities	GIS and MCDM methods were used for site selection for hospital taking into account socio environmental factors.
[52]	WDS	Clustering and random forest models were used on water main data to predict watermain failures and 17roducing risk maps.
[53]	WDS	GIS data of water main network is used to create a graph network with spatial clustering which is then used by regression models to predict pipe breaks.
[54]	WDS	Used GIS data to improve pipeline rehabilitation plans for Water Distribution Systems by finding optimal placement of digital metered areas and pressure valves which resulted in less leakage.
[55]	WDS	Used GIS to model Infrastructure Leakage Indices for regions of a water network along with other economic factors to determine if a region should invest in leakage maintenance.
[56]	WDS	Spatial patterns of customer problem reporting in a WDS were identified and then compared against technical system performance during regular operation and during emergency situations using GIS data and spatial auto correlation.
[57]	WDS, sewer	Used GIS data and a mathematical model for coordinated maintenance of watermain, sewer, drain, and pavement assets in city.
[58]	Sewer	Used GIS data and a Bayesian network to evaluate probability of failure, based on pipe characteristics, and consequence of failure, based on the proximity of important city amenities, of a sewage network.
[59]	Sewer	Used GIS and Bayesian Network to evaluate renewal complexity and consequences of pipe failure in a sewer network.

Table 1. *Cont.*

Study	Type of asset	Method description
[60]	Sewer	GIS data and physical characteristics of sewer pipes were used to predict pipe conditions using a range of machine learning models.
[61]	Sewer	Risk assessment is performed blocked sewer pipes using GIS data on gradient and physical characteristics for minimum gradient necessary for self cleansing.
[62]	Sewer	A risk assessment framework is presented that uses GIS data, fuzzy logic and multi criteria decision making to assess risk of failure in a sewer network.
[63]	Dams	Made a GIS system that can use both GIS and BIM data while retaining and editing the respective file formats by maintaining links to two databases simultaneously and converting relevant information when it is needed.
[64]	Dams	Used GIS and spatial analysis to determine site locations for hydro dams for pumped hydro energy storage as a method for storing electrical energy by repurposing existing hydro dam assets.

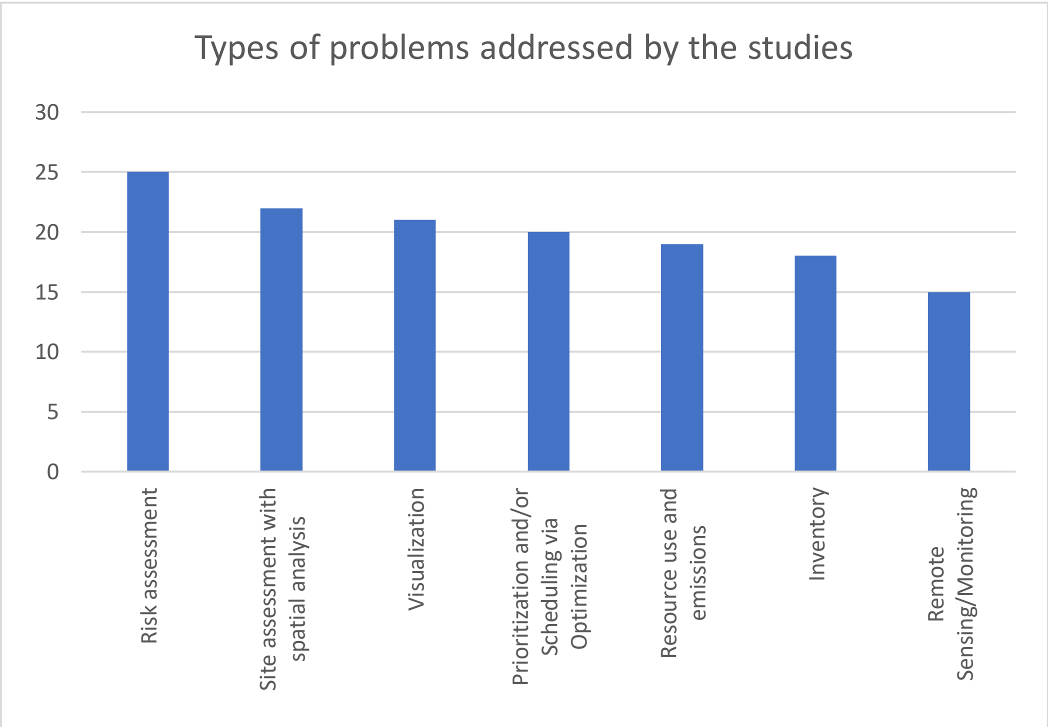

Figure 21. Types of problems addressed by the studies (corresponding table available in Table 2. Types of problems addressed by the studies).

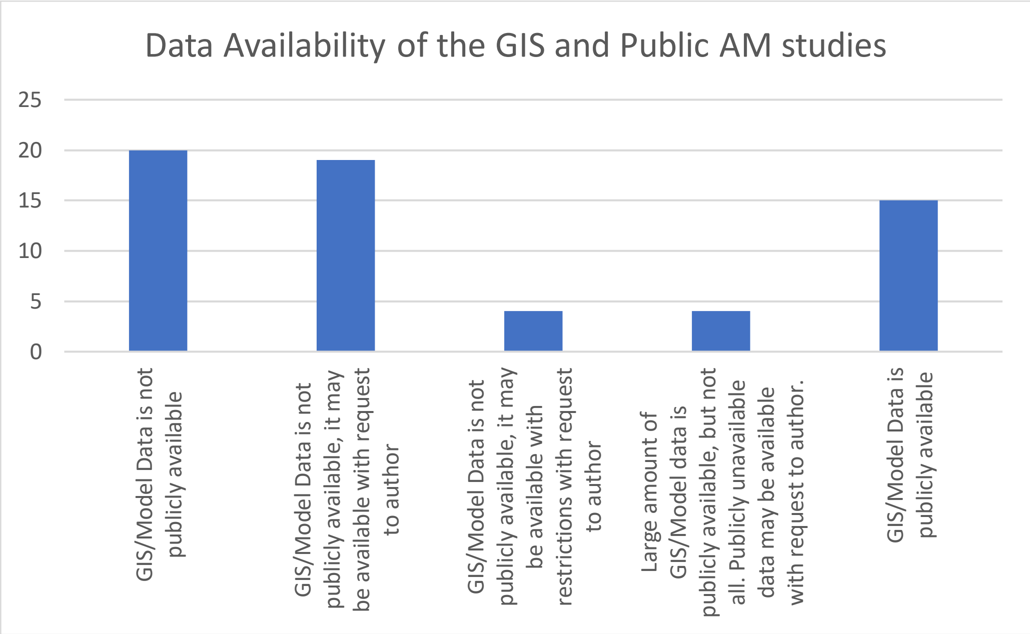

Figure 22. Dataset availability for the considered studies (corresponding table available in Table 3).

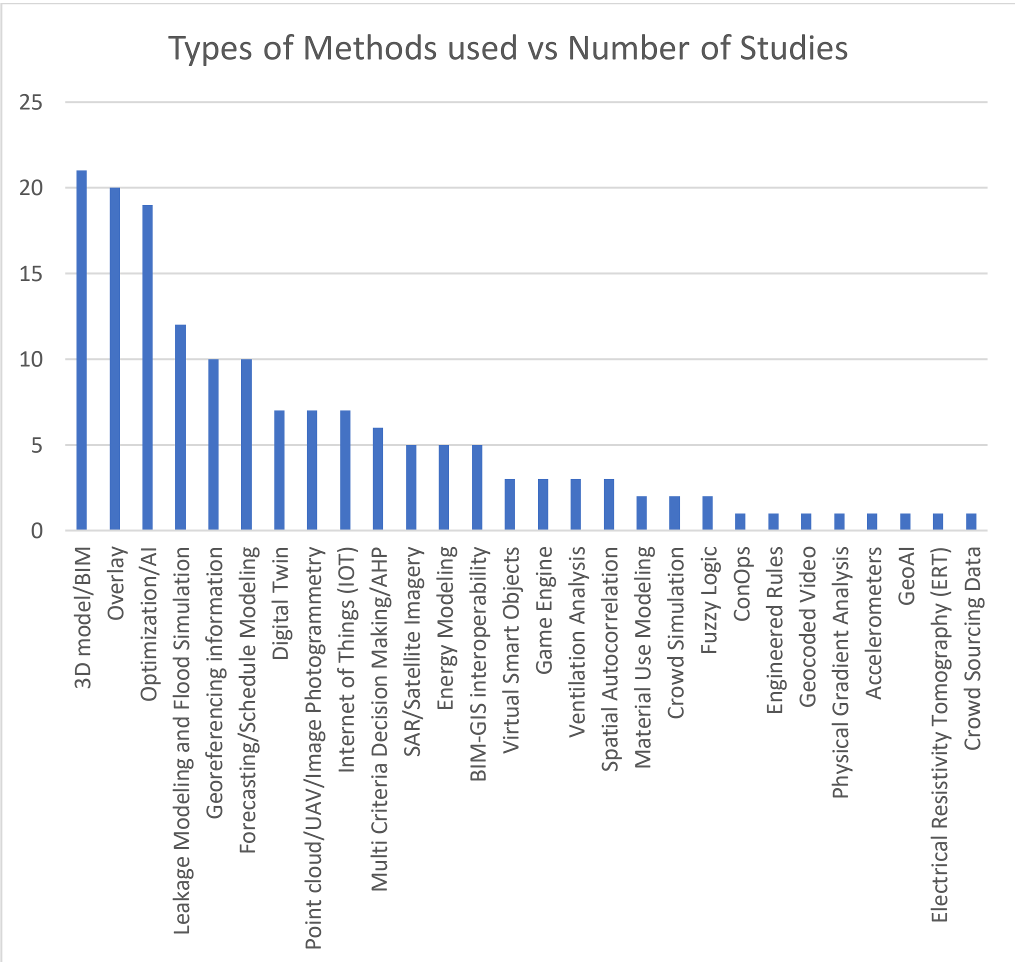

Figure 23. Methods used in studies (corresponding table available in

Table 4).

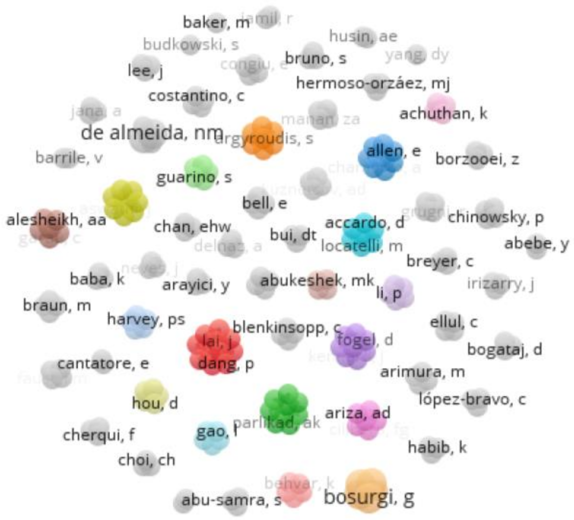

Figure 24. Co-authorship network between authors of works selected for in-depth study.

5. Discussion

GIS technology has been applied in a range of public asset management tasks to perform remote sensing, risk assessment, budget prioritization, carbon emission calculation and other useful analyses. The above table and those in the appendix can be used by public authorities for quick perusal or in-depth study on the potential of GIS technology in the resolution of management challenges for a wide variety of assets.

The in-depth study of the literature has also revealed some interesting research gaps. There is a trend to manage existing assets as opposed to constructing new assets in these studies. It would be of value to see more GIS studies for site planning and remote sensing of new construction projects, particularly since public assets such as transportation networks for roads and rail can be quite large. GIS for public asset management has seen considerable research interest for linear assets such as roads and sewer pipes. Point asset analyses such as dams, hospitals, individual public buildings and airports are less common. There is an opportunity for further research in terms of variety of asset type. For example, there are different types of hospitals located on different terrain. There are also different types of public heritage buildings experiencing different environmental pressures. These are some examples of asset management areas that can benefit from GIS. Exploring the benefits that GIS brings for site analysis, monitoring and cost reductions will help gain a broader knowledge of how GIS can be used for asset management.

Furthermore, despite it being a very visual medium, the question of how to visualize the data remains open. Several studies were focused on researching improvements in visualization [3], [18], [63], which suggests that there is a usability gap that still remains with existing technologies. Any improvement in visualization and rendering will address the problems of lag as well as interpretability which are inherent when mapping large areas in GIS. Computational load will continue to be a challenge especially when studied areas get larger. Any improvement in the computation of GIS data will certainly be welcomed in the research community. This was only addressed in a few studies that were considered in this review, which indicates another potential opportunity for future work. In relation to both visualization and computational load, the nature of the workflows of these methods needs improvement. Some methods use several disjoint software in their workflow which undoubtedly adds complexity and error potential to the processes. Unified software solutions that apply GIS analyses in one platform will be a welcome improvement over data streams coming from different software platforms. This not only applies to GIS-BIM integration but to all other sources of data such as seismic, hydraulic and electrical to name a few.

Another research need for the field is data. Data is often difficult and costly to collect, leading to an understandable reluctance from practitioners to make it publicly available. By observing the results in Table 3 one can see that the majority of data used in the considered studies is either unavailable or only available with direct request from the authors, which is subject to their consideration. Having more publicly available data will allow the research community to verify and build upon the discussed methods and will facilitate a greater exchange of ideas that will be beneficial for all parties. Limitations on data availability pose a major challenge for replicability in the research field. Having at least a portion of the data being available as open access will allow practitioners to replicate findings and verify the usefulness of new methods. The presented methods also need more case studies to verify their generalizability. Currently, most studies with case studies only perform the analyses on one or two areas or locations. More areas need to be studied with these methods to reveal what kind of particularities can emerge from different asset types and locations. This will build confidence in these methods and facilitate adoption.

Some interesting trends emerge when the studies are grouped by methods used. There is considerable interest in 3D models and BIM. However, BIM-GIS interoperability has considerably less research activity. This presents an opportunity for further research that will aid in GIS technology adoption by practitioners. Furthermore, while there is interest in digital twins (*i.e.*, digital replica of a physical asset), there are only a few studies that explicitly use the method. Digital twin is a natural extension of a 3D model and presents a good future research direction to use this technology for decision making. Additionally, SAR and Point Cloud technologies are sensing and visualization tools that could be further leveraged across more studies. Interest in using AI and optimization techniques is considerable and is used roughly in a third of the studies reviewed suggesting that data science techniques are quite applicable to the field. There is also a healthy diversity of singular methods which speaks to the variety of applications and ideas. In addition, from the adoption point of view, technological readiness is an important factor. Some of the studies considered have only implemented a portion of the key features of the methods such as the work of Massafra *et al*. [37], other studies such as Kizner *et al*. [25] only present work in the planning phase. Building on existing methods and completing the implementation of the planned key features is needed in order to show the full benefits of GIS technology in public asset management. Advancing the technology readiness level of prior work in the field will attract more adopters.

There is also a gap in terms of collaboration. The co-authorship network in Figure 24 shows that the research field is very siloed with all research groups publishing solely with member contributors. However, this also suggests that all significant research within GIS and Public Asset Management has potential to become breakout research. Collaboration will however lead to new opportunities to drive research works further and address the challenges of implementation of GIS projects. The effort involved is typically quite large and collaboration will help better distribute the effort among more qualified researchers, which will result in works that are more advanced and ready for adoption for practitioners in industry and government.

Practical applications of GIS in Public Asset Management

This discussion section will now conclude with important highlights of practical applications of GIS technologies for the management of public assets.

Using GIS has shown promising results for condition assessment and proactive planning. Condition assessment has been done in Asada *et al*. [7] which detected pavement cracking using AI and geo-coded videos, in Macchiarulo *et al*. [16] which used InSAR and GIS data to monitor road conditions, and Bosurgi *et al*. [13] which used Smart Objects to visualize road maintenance survey data for rehabilitation planning, among others. These studies confirm that GIS can be very useful for identifying deterioration zones, which enable the optimization of rehabilitation strategies which reduce costs. These inherently data driven approaches align well with research interests in applying AI for asset management. Practitioners are invited to consult the sections on Site Assessment, Visualization, Prioritization and/or Scheduling via Optimization, and Remote Sensing/Monitoring in Table 2 for more methods that use condition assessment, as well as Table 1, which summarizes all methods studied based on category of asset.

GIS is a critical visualization and planning tool for disaster resilience and risk assessment. Chamorro *et al*. [5] used GIS to evaluate the vulnerability of road networks to seismic, volcanic and flooding events. Electrical grid repairs were prioritized using GIS in the work of Guarino *et al*. [4]. The work of Schweikert *et al*. [9] used GIS data of roads and public infrastructure to assess climate change impacts in terms of risk and adaptation costs. Taherkhani *et al*. [21] made bridge repair prioritization plans in flooding scenarios using GIS data and deep learning, which ensured equitable prioritization of economically vulnerable areas. These are some of the applications for disaster resilience among the studies that were reviewed. More related works can be found in the risk assessment, site assessment/selection with spatial analysis, and remote sensing/monitoring sections of Table 2 as well as the leakage/impact modeling/flood simulation section in Table 4. The keyword gap analysis revealed that a research gap exists for disaster-specific risk modeling as well as a strong interest in digital technologies. This suggests that there is ample opportunity for future work to combine resilience studies with GIS data and sensor data to improve disaster preparedness and emergency response.

The findings of the review showed that GIS-enabled digital twin technology is useful for visualization, decision support and predictive analysis, and is of significant interest to public authorities. Padovano *et al*. [24] made a twin of a train terminal capable of predicting and aiding in mitigating passenger crowding. Ellul *et al*. [15] made a digital twin of a highway construction project for risk assessment and remote monitoring. Other works have developed a digital twin for bridges for virtual and augmented site inspections such as the work of Fotia *et al*. [19], and improved rendering of bridges to allow for better and faster visualization such as in the research of Wu *et al*. [18]. Despite ongoing interest with practical applications of GIS in the area of digital twin, full scale digital twin applications need significant further development. Kizner *et al*. [25] is a thorough work describing many organizational benefits for a public authority in managing rail assets; however, it was only in the conceptual stage at the time of publication. For more studies pertaining to digital twin, practitioners and interested researchers can refer to the 3D model/BIM and Digital Twin sections of Table 4. The gap analysis of this review as well as the impressions from the in-depth study suggest that applying these technologies to more case studies with different asset types will be invaluable in improving the visualization, analytics and decision support capabilities of these technologies, and encourage adoption by practitioners and public authorities.

6. Conclusion

A systematic literature review was performed for applying GIS technologies to Public Asset Management. A high-level keyword-based analysis was performed using co-occurrence networks which revealed gaps for remote sensing, land use, urban growth and forecasting. Furthermore, specific types of risks such as floods, landslides, earthquakes and disasters appear to be under-studied. There is also a general need for more GIS studies in the field of Public Asset Management. The general trends suggest that individual asset related research is becoming less popular, whereas information technology related research connecting to general far-reaching technologies such BIM, machine learning, and AI, is becoming more popular.

There were drawbacks to this keyword co-occurrence trend analysis. Using too many terms created cluttered and difficult to read networks. However, eliminating the less prevalent terms removes many important research areas are of interest for further study. The drawbacks of the keyword co-occurrence analysis were addressed by doing category-based keyword gap analysis to inform on which areas within GIS and Public Asset Management have been understudied compared to the broader research in GIS for Civil Engineering. This analysis was done with a new proposed tool based on the NLP Word2Vec model and k-means clustering. The proposed Word2Vec K-means Keyword Gap Analysis tool can be used more broadly in other research areas as well. It will be made available in the supplementary materials of this publication. The tool will aid researchers in organizing the overwhelming amount of data that is present in multirole and multiapplication research topics such as GIS and Public Asset Management. The categorical keyword gap analysis showed that there are further research gaps in Water Resources, Risk Assessment, Physical Environment, Imaging and Remote Sensing, and in applying Convolutional Neural Networks for data processing.

An in-depth study was performed on 62 works that were selected from the systematic literature review. The methods were described, categorized based on asset type, and sorted in terms of methods applied and dataset availability. This was done to aid public authorities and researchers to navigate the field and select technologies in terms of application and situation. Some of the main research gaps found were related to using GIS for new asset planning as opposed to existing asset planning, the need for improved visualisation, unified software solutions, the need for more dataset availability for comparative and repeatable studies and the need for more case studies to boost confidence in new technologies. Regarding using GIS for new asset planning, there is more of a gap for point assets (building and building complexes), as opposed to linear assets (roads and pipes). There is also a need for more GIS studies on specific types of assets. Finding a study for a specific asset type that has a case study, a dataset and a fully implemented solution can be difficult. Despite the lagging popularity of individual asset-based research these types of works are of the most practical use for practitioners and for public authorities. More GIS based studies for specific types of assets will increase technological readiness and attract further adoption.

Public authorities face multiple different challenges when managing public assets. GIS technologies can be adopted in the management processes for applications including monitoring, site assessment, inventory, prioritization of rehabilitation, cost and emission reduction, among others. These technologies can support decision making and have a very positive impact on budgetary needs. Navigating the research field of GIS can be complex. This study can be used as an initial step for deciding which technology can be applicable to which management challenge. Furthermore, it can be used as a guide for an in-depth study on the subject because it shows a broad range of specific assets and asset management problems. This systematic literature review is a way of approaching the decisions for asset management technology in an organized way. It can be used by both academia and practitioners to focus their research efforts.

Dataset and Word2Vec Keyword Analysis Tool availability

The authors confirm that the dataset and the developed Word2Vec keyword analysis tool can be made available upon reasonable request.

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Authors' contribution

Pavel Popov: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review & editing, Visualization. M. Hamed Mozaffari: Conceptualization, Methodology, Data analysis, Writing—review & editing, Visualization. Seyedreza Razavialavi: Conceptualization, Methodology, Data analysis, Writing—review & editing. Farzad Jalaei: Conceptualization, Methodology, Data analysis, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

Authors disclose that they have no conflicts of interest.

References

[1] Cavka HB, Staub-French S, Pottinger R. Evaluating the alignment of organizational and project contexts for BIM adoption: a case study of a large owner organization. *Buildings*, 2015, 5 (4):1265–1300.

[2] Nuhu SK, Manan ZA, Alwi SRW, Reba MNM. Integrated modelling approach for an eco-industrial park site selection. *J. Clean. Prod.* 2022, 368:133141.

[3] Rada AO, Kuznetsov AD, Zverev RE, Timofeev AE. Automation of monitoring construction works based on laser scanning from unmanned aerial vehicles. *Nanotechnol. Constr.* 2023, 15(4):373–382.

[4] Guarino S, Oliva G, Di Pietro AD, Pollino M, Rosato V. A Spatial Decision Support System for Prioritizing Repair Interventions on Power Networks. *IEEE Access*. 2023, 11:34616–34629.

[5] Chamorro A, Echaveguren T, Pattillo C, Contreras-Jara M, Contreras, M *et al.* SIGeR-RV: A Web-Geographic Information System-Based System for Risk Management of Road Networks Exposed to Natural Hazards. *Transp. Res. Rec.* 2023, 2677(12):754–769.

[6] Mollaei A, Ibrahim N, Habib K. Estimating the construction material stocks in two canadian cities: A case study of Kitchener and Waterloo. *J. Clean. Prod.* 2021, 280:124501.

[7] Asada T, Ha TV, Arimura M, Kameyama S. A Novel Approach for Urban Road Network

Maintenance Plans Using Spatial Autocorrelation Analysis and Roadside Conditions: A Case Study of Muroran City, Japan. *Sustainability* 2022, 14(23):16189.

[8] Popov P, Mozaffari MH, Razavialavi S, Jalaei F. GIS Based Solutions for Management Of Public Building and Infrastructure Assets: A Review of State of the Art and Emerging Technologies. In *2024. Transforming Construction with Off-site Methods and Technologies (TCOT)*, New Brunswick, Canada, June 26, 2024.

[9] Schweikert A, Espinet X, Goldstein S, Chinowsky P. Resilience versus risk: Assessing cost of climate change adaptation to California's transportation system and the City of Sacramento, California. *Transp. Res. Rec.* 2015, 2532(1):13–20.

[10] Mizutani D, Nakazato Y, Lee J. Network-level synchronized pavement repair and work zone policies: Optimal solution and rule-based approximation. *Transp. Res. Part C Emerg. Technol*. 2020, 120:102797.

[11] Bruno S, Vita L, Loprencipe G. Development of a GIS-based methodology for the management of stone pavements using low-cost sensors. *Sensors* 2022, 22(17):5650.

[12] Rezvani SMHS, Silva MJF, de Almeida NM. Urban Resilience Index for critical infrastructure: A scenario-based approach to disaster risk reduction in road networks. *Sustainability* 2024, 16(10):1–41.

[13] Bosurgi G, Pellegrino O, Ruggeri A, Rustica N, Sollazzo G. Customized approaches for introducing road maintenance management in I-BIM environments. *Sustainability* 2024, 16(15):6530.

[14] Wang X, Li Y, Zhang R, Liu J, Gao L. Comprehensive network-level urban road asset valuation method integrating physical and social values. *J. Transp. Eng. Part A Syst.* 2024, 150(7):1–14.

[15] Ellul C, Hamilton N, Pieri A, Floros G. Exploring data for construction digital twins: Building health and safety and progress monitoring twins using the Unreal gaming engine. *Buildings*. 2024, 14(7):2216.

[16] Macchiarulo V, Milillo P, Blenkinsopp C, Giardina G. Monitoring deformations of infrastructure networks: A fully automated GIS integration and analysis of InSAR time-series. *Struct. Health Monit.* 2022, 21(4):1849–1878.

[17] Yang D. Deep reinforcement learning–enabled bridge management considering asset and network risks. *J. Infrastruct. Syst*. 2022, 28(3):04022023.

[18] Wu J, Zhu J, Zhang J, Dang P, Li W, *et al*. A dynamic holographic modelling method of digital twin scenes for bridge construction. *Int. J. Digit. Earth*. 2023, 16(1):2404–2425.

[19] Fotia A, Barrile V. Viaduct and bridge structural analysis and inspection through an app for immersive remote learning. *Electronics* 2023, 12(5):1220.

[20] Achuthan K, Hay N, Aliyari M, Ayele YZ. A digital information model framework for UAS-enabled bridge inspection. *Energies* 2021, 14(19):6017.

[21] Taherkhani A, Mo W, Bell E, Han F. Towards equitable infrastructure asset management: Scour maintenance strategy for aging bridge systems in flood-prone zones using deep reinforcement learning. *Sustain. Cities Soc*. 2024, 114:105792.

[22] Mitoulis SA, Argyroudis S, Panteli M, Fuggini C, Valkaniotis S, *et al.* Conflict-resilience framework for critical infrastructure peacebuilding. *Sustain. Cities Soc.* 2023, 91:104405.

[23] Li P, Tang Y, Zheng Z, Wang Z, Zhuang Y. Semiautomated railway line information modeling based on asset management data. *J. Constr. Eng. Manag.* 2024, 150(10):1–16.

[24] Padovano A, Longo F, Manca L, Grugni R. Improving safety management in railway stations through a simulation-based digital twin approach. *Comput. Ind. Eng.* 2024, 187:109839.

[25] Kizner T, Perez H, Robayo M, Alfelor R, Ferguson D, *et al*. Geographic information system concept of operations as a first step toward total enterprise asset management: Metro-North commuter railroad case study. *Transp. Res. Rec.* 2016, 2540(1):111–124.

[26] Bosurgi G, Pellegrino O, Ruggeri A, Sollazzo G. Railway condition information modelling in a BIM framework for maintenance applications. *Int. J. Rail Transp.* 2024:1–21.

[27] Neves J, Sampaio Z, Vilela M. A case study of BIM implementation in rail track rehabilitation. *Infrastructures* 2019, 4(1):8.

[28] Kisse JM, Braun M, Letzgus S, Kneiske TM. A GIS-Based planning approach for urban power and natural gas distribution grids with different heat pump scenarios. *Energies* 2020, 13(16):4052.

[29] Budkowski S. The Use of Geodata in the Process of the Ventilation of the City of Krakow. *Geomatics Environ. Eng.* 2023, 17(4):53–76.

[30] Kays HMI, Sadri AM, Muraleetharan KK, Harvey PS, Miller GA. Exploring the Interdependencies Between Transportation and Stormwater Networks: The Case of Norman, Oklahoma. *Transp. Res. Rec.* 2024, 2678(5):491–513.

[31] Karmarkar OD, Jana A, Velaga NR. Modelling volumetric growth of emerging urban areas around new transit stations. *npj Urban Sustain.* 2024, 4(1):34.

[32] Kazemi M, Mohammadi F, Nafooti MH, Behvar K, Kariminejad N. Flood susceptibility mapping using machine learning and remote sensing data in the Southern Karun Basin, Iran. *Appl. Geomatics* 2024, 16(3):731–750.

[33] Rezvani SMHS, Falcão Silva MJ, de Almeida NM. The Risk-Informed Asset-Centric (RIACT) Urban Resilience Enhancement Process: An Outline and Pilot-Case Demonstrator for Earthquake Risk Mitigation in Portuguese Municipalities. *Appl. Sci.* 2024, 14(2):1–34.

[34] Abu-Samra S, Ahmed M, Amador L. Asset Management Framework for Integrated Municipal Infrastructure. *J. Infrastruct. Syst.* 2020, 26(4):1–17.

[35] López-Bravo C, Peral López J, Mosquera Adell E. The management of water heritage in Portuguese cities: Recent regeneration projects in Évora, Lisbon, Braga and Guimarães. *Front. Archit. Res.* 2022, 11(1):73–88.

[36] Santos B, Gonçalves J, Almeida PG, Martins-Nepomuceno AMT. GIS-based inventory for safeguarding and promoting Portuguese glazed tiles cultural heritage. *Herit. Sci.* 2023, 11(1):1–14.

[37] Massafra A, Costantino C, Predari G, Gulli R. Building Information Modeling and Building Performance Simulation-Based Decision Support Systems for Improved Built Heritage Operation. *Sustainability* 2023, 15(14):11240.

[38] Amro DK, Sukkar A, Yahia MW, Abukeshek MK. Evaluating the Cultural Sustainability of the Adaptive Reuse of Al-Nabulsi Traditional House into a Cultural Center in Irbid, Jordan. *Sustainability* 2023, 15(17), 13198.

[39] Simou S, Baba K, Nounah A. Preserving Historic Structures: Advancing Conservation Practices Through Building Material Analysis and Mapping. *Civ. Eng. Archit.* 2024, 12(1):312–325.

[40] Lasorella M, Cantatore E. 3Dcitymodels To Support Technical Knowledge and Management of Historic Built Environments. A Semantic Citygml-Based Model for the Ancient Core of Carovigno (Br), Italy. *Scires-It.* 2023, 13(1):101–116.

[41] Bogataj M, Bogataj D, Drobne S. Planning and managing public housing stock in the silver economy. *Int. J. Prod. Econ.* 2023, 260:108848.

[42] Jian I, Chan E, Yao T. ICT as a solution for the revitalization of public open space in private

developments. *Built Environ. Proj. Asset Manag.* 2020, 11(3):440–453.
[43] Choi CH, Han J, Hong G. Applicability of Digital Image Photogrammetry to Rapid Displacement Measurements of Structures in Restricted-Access and Controlled Areas: Case Study in Korea. *Appl. Sci*. 2024, 14(12):5295.
[44] Congiu E, Quaquero E, Rubiu G, Vacca G. Building Information Modeling and Geographic Information System: Integrated Framework in Support of Facility Management (FM). *Buildings* 2024, 14(3):610.
[45] Demirdöğen G, Işık Z, Arayici Y. BIM-based big data analytic system for healthcare facility management. *J. Build. Eng.* 2023, 64:105713.
[46] Pooja B, Oommen T, Sajinkumar KS, Nair AG, Rajaneesh A, *et al*. Correspondence of PSInSAR monitoring and Settle3 modelling at Cochin International Airport, SW India. *Appl. Geomatics*. 2021, 13(4):735–746.
[47] Montiel-Santiago FJ, Hermoso-Orzáez MJ, Terrados-Cepeda J. Sustainability and energy efficiency: BIM 6D. Study of the BIM methodology applied to hospital buildings. Value of interior lighting and daylight in energy simulation. *Sustainability* 2020, 12(14):45731.
[48] Meschini S, Pellegrini L, Locatelli M, Accardo D, Tagliabue LC, *et al*. Toward cognitive digital twins using a BIM-GIS asset management system for a diffused university. *Front. Built Environ.* 2022, 8:959475.
[49] Lu Q, Parlikad AK, Woodall P, Ranasinghe GD, Xie X, *et al*. Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. *J. Manag. Eng.* 2020, 36(3):05020004.
[50] Irizarry J, Karan EP, Jalaei F. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Autom. Constr.* 2013, 31:241–254.
[51] Zandi I, Pahlavani P, Bigdeli B, Lotfata A, Alesheikh AA, *et al*. GIS-Enabled Multi-Criteria Assessment for Hospital Site Suitability: A Case Study of Tehran. *Sustainability* 2024, 16(5):2079.
[52] Delnaz A, Nasiri F, Li S. Prediction of water–main failures and management of the associated risks using integrated predictive analytics approach. *Saf. Reliab.*, 2024, 43(4): 1–24.
[53] Chen T, Guikema SD. Prediction of water main failures with the spatial clustering of breaks. *Reliab. Eng. Syst. Saf.* 2020, 203:107108.
[54] Laucelli DB, Enriquez LV, Ariza AD, Ciliberti FG, Berardi L, *et al.* A digital water strategy based on the digital water service concept to support asset management in a real system. *J. Hydroinformatics*. 2023, 25(5):2004–2016.
[55] Nahwani A, Husin AE. Water network improvement using infrastructure leakage index and geographic information system. *Civ. Eng. Archit.* 2021, 9(3):909–914.
[56] Tiedmann HR, Sela L, Stephens KK, Faust KM. Leveraging water utility customer reporting for resilient operations and management. *Sustain. Cities Soc.* 2024, 101:105087.
[57] Qasem A, Jamil R. GIS-Based Financial Analysis Model for Integrated Maintenance and Rehabilitation of Underground Pipe Networks. *J. Perform. Constr. Facil.* 2021, 35(5):04021046.
[58] Ghavami SM, Borzooei Z, Maleki J. An effective approach for assessing risk of failure in urban sewer pipelines using a combination of GIS and AHP-DEA. *Process Saf. Environ. Prot.* 2020, 133:275–285.
[59] Abebe Y, Tesfamariam S. Underground sewer networks renewal complexity assessment and trenchless technology: A Bayesian belief network and GIS framework. *J. Pipeline Syst. Eng. Pract.* 2020, 11(2):1–17.
[60] Van Nguyen L, Bui DT, Seidu R. Comparison of machine learning techniques for condition assessment of sewer network. *IEEE Access*. 2022, 10:124238–124258.
[61] Baker M. Sewer risk management: Reducing pollution using minimum gradient and GIS.

Proc. Inst. Civ. Eng. Munic. Eng. 2016, 169(1):31–37.
[62] Roghani B, Tabesh M, Cherqui F. A fuzzy multidimensional risk assessment method for sewer asset management. *Int. J. Civ. Eng.* 2024, 22(1):1–17.
[63] Zhang S, Hou D, Wang C, Pan F, Yan L. Integrating and managing BIM in 3D web-based GIS for hydraulic and hydropower engineering projects. *Autom. Constr*. 2020, 112:103114.
[64] Ghorbani N, Makian H, Breyer C. A GIS-based method to identify potential sites for pumped hydro energy storage - Case of Iran. *Energy*. 2019, 169:854–867.

Appendix

Table 2. Types of problems addressed by the studies.

Type of problem	Applicable studies	Number of studies
Risk assessment	[16] [24] [7] [17] [40] [57] [55] [58] [34] [9] [59] [5] [35] [30] [48] [61] [12] [21] [52] [15] [43] [32] [33] [62] [29]	25
Site assessment/selection with spatial analysis	[46] [64] [28] [25] [19] [41] [35] [30] [2] [42] [51] [14] [21] [31] [52] [43] [32] [62] [29] [56] [50][33]	22
Visualization	[18] [39] [40] [63] [25] [36] [19] [3] [20] [48] [27] [42] [49] [14] [13] [26] [31] [23] [15] [44] [50]	21
Prioritization and/or scheduling via optimization	[24] [4] [7] [17] [10] [57] [58] [34] [59] [54] [41] [5] [60] [53] [12] [21] [22] [52] [62] [50]	20
Resource use and emissions	[7] [17] [10] [45] [37] [39] [6] [57] [55] [34] [64] [28] [9] [54] [47] [27] [49] [21] [33]	19
Inventory	[45] [39] [40] [6] [25] [36] [35] [11] [48] [42] [49] [38] [14] [13] [43] [56] [50][44]	18
Remote sensing/monitoring	[16] [45] [25] [19] [3] [11] [20] [22] [26] [31] [23] [15] [44] [43] [32]	15

Table 3. Dataset availability for the considered studies.

Data availability	Applicable studies	Number of studies
GIS/model data is not publicly available.	[4] [7] [10] [39] [40] [55] [58] [25] [19] [5] [3] [20] [47] [53] [27] [42] [61] [49] [15] [56]	20
GIS/model data is not publicly available. It may be requested from the author.	[18] [17] [45] [37] [57] [59] [36] [54] [41] [11] [2] [38] [51] [14] [21] [22] [44] [32][50]	19
GIS/model data is not publicly available, it may be requested, with restrictions, from the author.	[13] [26] [23] [62]	4
Large amount of GIS/model data is publicly available, but not all. Publicly unavailable data may be requested from the author.	[16] [34] [43] [29]	4
GIS/model data is publicly available.	[24] [6] [46] [63] [64] [28] [9] [35] [30] [60] [48] [12] [31] [52] [33]	15

Table 4. Methods used in studies.

Method	Studies using the method	Number of studies
3D model/BIM	[27] [48] [47] [20] [19] [63] [40] [39] [37] [45] [18] [24] [49] [13] [26] [31] [23] [15] [44] [29][50]	21
Overlay	[61] [2] [30] [35] [5] [59] [9] [64] [16] [51] [14] [12] [21] [23] [52] [32] [29] [56] [50] [33]	20
Optimization/AI	[53] [60] [3] [5] [41] [54] [59] [64] [34] [58] [57] [17] [7] [4] [12] [21] [31] [52] [32]	19
Leakage/impact modeling/flood simulation	[54] [9] [58] [55] [59] [5] [30] [12] [21] [52] [32] [62]	12
Georeferencing information	[42] [11] [35] [36] [40] [39] [38] [51] [14] [33] [56]	10
Forecasting/schedule modeling	[27] [41] [9] [34] [55] [6] [21] [22] [44] [50]	10
Digital twin	[48] [45] [24] [19] [49] [26] [15]	7
Point cloud/UAV/image photogrammetry	[20] [3] [19] [49] [23] [15] [43]	7
Internet of Things (IOT)	[24] [37] [45] [48] [49] [15] [50]	7
Multi criteria decision making/AHP	[2] [64] [58] [4] [51] [62]	6
Synthetic aperture radar/satellite imagery	[46] [16] [13] [22] [31]	5
Energy modeling	[47] [28] [37] [49] [29]	5
BIM-GIS interoperability	[48] [20] [63] [44] [50]	5
Virtual smart objects	[13] [26] [23]	3
Game engine	[19] [18] [15]	3
Ventilation analysis	[37] [47] [29]	3
Spatial autocorrelation	[7] [30] [56]	3
Material use modeling	[27] [6]	2
Crowd simulation	[48] [24]	2
Fuzzy logic	[2] [62]	2
ConOps	[25]	1
Engineered rules	[10]	1
Geocoded video	[7]	1
Physical gradient analysis	[61]	1
Accelerometers	[11]	1

Table 4. *Cont.*

Method	Studies using the method	Number of studies
GeoAI	[12]	1
Electrical Resistivity Tomography (ERT)	[43]	1
Crowd sourcing data	[22]	1