remote sensing

Review

BIM–GIS Integrated Utilization in Urban Disaster Management: The Contributions, Challenges, and Future Directions

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Abstract: In the 21st Century, disasters have severe negative impacts on cities worldwide. Given the significant casualties and property damage caused by disasters, it is necessary for disaster management organizations and the public to enhance urban disaster management. As an effective method, BIM (Building Information Modeling)–GIS (Geographic Information System) integration can significantly improve urban disaster management. Despite the significance of BIM–GIS integration, there is rarely the adoption of BIM–GIS integration in urban disaster management, which significantly hinders the development of the quality and efficiency of urban disaster management. To enhance urban disaster management and reduce the negative impact caused by disasters, this study is developed to perform a systematic review of the utilization of BIM–GIS integration in urban disaster management. Through the systematic review, the capabilities of BIM–GIS integration in disaster prevention and mitigation, disaster response, and post-disaster recovery are reviewed and analyzed. Moreover, the data acquisition approaches, interoperability, data utilization and analysis methods, and future directions of BIM–GIS integrated utilization in the disaster management process are also discussed and analyzed. Through this study, the public and urban disaster managers can effectively familiarize themselves with and utilize the capabilities of BIM–GIS integration in urban disaster management, thereby improving the urban disaster management efficiency and the survival rate of disaster victims worldwide. For BIM and GIS software developers, this study can support them to familiarize themselves with the methods and trends of BIM–GIS integrated utilization in urban disaster management and thus optimize the development of software for BIM and GIS.

Keywords: building information modeling; geographic information system; urban disaster management; urban hazard management

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Citation: Cao, Y.; Xu, C.; Aziz, N.M.; Kamaruzzaman, S.N. BIM–GIS Integrated Utilization in Urban Disaster Management: The Contributions, Challenges, and Future Directions. *Remote Sens.* **2023**, *15*, 1331. https://doi.org/10.3390/rs15051331

Academic Editors: Pingping Luo, Ahmed Elbeltagi, Reza Hassanzadeh, Van-Thanh-Van Nguyen and Baofu Li

Received: 15 January 2023
Revised: 19 February 2023
Accepted: 22 February 2023
Published: 27 February 2023

1. Introduction

Disasters cause serious negative impacts worldwide. According to the Global Assessment Report on Disaster Risk Reduction 2022 [1], the number of medium and large disasters recorded each year was between 350 and 500 between 2001 and 2020. In 2021, the number of deaths caused by natural disasters and the number of those affected by natural disasters worldwide were 10,492 and 104.1676 million, respectively [1].

Given the significant losses caused by disasters, it is significant to enhance disaster management in urban areas. As an effective approach, Building Information Modeling (BIM)–Geographic Information System (GIS) integration can significantly contribute to disaster management [2–5]. According to Zhu and Wu [6], BIM–GIS integration is defined as the joint utilization of BIM and GIS for resolving practical issues. With the integration of BIM and GIS, it can integrate the advantages of both BIM and GIS to maximize their performance, thus enhancing their capability to resolve urban-related issues (such as urban disaster management) [5]. From the perspective of BIM–GIS integration, BIM can provide information about buildings and their internal conditions, while GIS can complement geospatial information and assist stakeholders through its powerful analytical capabilities [6]. BIM is a shared digital representation method generated from and based on the target project's physical information and functional characteristics [7]. Based on BIM capabilities, BIM can assist the stakeholders in achieving 3D modeling and visualization, decision-making assistance, knowledge storage and management, environmental simulation, cost estimation, and clash detection [8–11]. GIS is the digital approach for mapping and analyzing objects and events that occur on Earth [12,13]. Compared to the traditional approaches, GIS can combine the visual presentation and spatial analytical advantages of maps with typical database functions (including query and statistical analysis) [14–16].

Given the functional complementation between BIM and GIS, the integrated utilization of BIM and GIS is deemed an effective approach to enhancing urban disaster management. Multiple studies pointed out the significant capacities of BIM–GIS integration in disaster management [6,8,17–20]. BIM–GIS integration can not only effectively simulate and display the interior and surroundings of a building but also provide geospatial information about the holistic urban areas from both macroscopical and microscopical perspectives [21]. However, although BIM–GIS integrated utilization can provide non-negligible contributions to urban disaster management, the adoption of BIM–GIS integration for urban disaster management is not widespread worldwide. A notable reason for this deficiency is the stakeholders' insufficient familiarity with the capabilities of BIM–GIS integration in urban disaster management. According to the authors' retrieval in WoS (Web of Science) and Scopus, there are rarely comprehensive reviews that aim to review the BIM–GIS integration utilization in urban disaster management. Given the insufficient comprehensive review of BIM–GIS integration in urban disaster management, the promotion and development of BIM–GIS integrated utilization in the urban disaster management field are relatively unsatisfactory.

To bridge the abovementioned research gap and enhance the urban disaster management capability to reduce the negative impact caused by disasters, this study aims to perform a systematic review of the utilization of BIM–GIS integration in urban disaster management. To complete this systematic review, the following research objectives are formulated in this review:

1. Identify the capabilities of BIM–GIS integration in urban disaster management.
2. Discuss and analyze the data acquisition method, interoperability, and data process and utilization methods of BIM–GIS integration in urban disaster management.
3. Discuss and summarize the advantages and challenges of BIM–GIS integrated utilization in urban disaster management.
4. Identify the future directions of BIM–GIS integrated utilization in urban disaster management.

This study can develop a comprehensive overview and detailed exploration of the capabilities of BIM–GIS integration in urban disaster management. From the perspective of disaster management personnel, this research can assist them in comprehensively understanding the BIM–GIS integrated capabilities in urban disaster management, which can facilitate the promotion and development of BIM–GIS integrated utilization in urban disaster management. For urban managers and residents, this study can improve the quality of urban disaster prevention, disaster responses, and post-disaster reconstruction to minimize the physical damage and the loss of people caused by disasters. Moreover, it can also assist urban managers in optimizing their disaster management decisions. For the BIM and GIS software developers, this research can support them in becoming familiar with the methods and trends of BIM–GIS integrated utilization in urban disaster management so they can develop and optimize BIM and GIS software accordingly.

2. Methodology

This study is a systematic review. Compared to the traditional review, there are multiple benefits to a systematic review. The systematic review can assist researchers in disclosing the prospective theory or rules, verifying the developed methodology or procedure, and evaluating the divergences between multiple research outcomes [22–25]. In addition to these, scholars can utilize systematic reviews to explore the directions for future studies and compile guidelines for making decisions [22,26,27]. To achieve the research aim and objectives, the authors adopt the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach as the main article search and screen procedure. PRISMA is the guidance procedure that can provide regulations and criteria for article searching and screening, data retrieval, and performing qualitative and quantitative information analysis in the systematic review process [28,29]. In this study, the authors implemented a three-phase literature search and screening procedure based on PRISMA, as in other multiple systematic review studies [9,30–32]. The research framework of this study is presented in Figure 1.

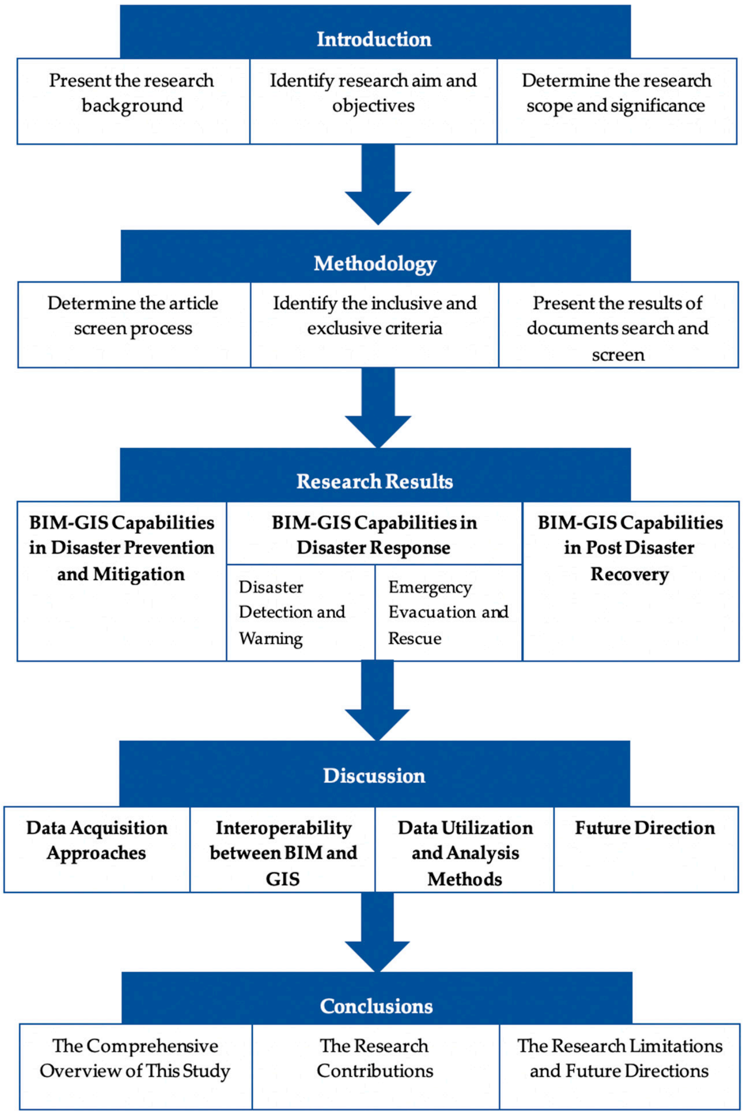

Figure 1. The Research Framework of This Study.

The first phase is the formulating phase. In the formulating phase, the authors determine the adopted databases, keywords, and article inclusion and exclusion criteria. To guarantee that the retrieved articles are qualified, WoS (Web of Science) and Scopus are determined as the databases in this systematic review. Furthermore, the following items are adopted to advance the keywords for the initial articles search: "Building Information Modeling", "Geographic Information System", "Smart City" "Disaster", and "Hazard". From the perspective of document types, the documents that do not belong to articles, conference papers, and reviews are excluded from the process of the article search. Moreover, the inclusion and exclusion criteria are presented in Table 1. Through the initial article search, 5835 documents were retrieved from the data repositories. The search strings and documents search results are presented in Table 2.

Table 1. Inclusion and Exclusion Criteria.

Primary Criteria		Secondary Criteria	
Inclusionary	**Exclusionary**	**Inclusionary**	**Exclusionary**
Journal articles, reviews, and conference papers that can be searched in the databases of WoS or Scopus	Duplicated papers	The papers that can assist the authors in obtaining urban disaster-related knowledge and disaster management approaches	Articles that are not helpful in achieving the following objectives: 1. Obtain urban disaster-related knowledge and disaster management approaches. 2. Identify the capabilities of BIM–GIS integration in urban disaster management. 3. Discuss and analyze the data acquisition method, interoperability, and data process and utilization methods of BIM–GIS integration in urban disaster management. 4. Discuss and summarize the advantages, challenges, and future directions of BIM–GIS integrated utilization in urban disaster management.
	Invalid articles (articles that cannot provide the online version of the full-text content)	The documents that can assist the authors in identifying the BIM–GIS capabilities in urban disaster management	
		The documents that can assist the authors in discussing and analyzing the data acquisition method, interoperability, and data process and utilization methods of the BIM–GIS integration in urban disaster management	
		The documents that can assist the authors in discussing and summarizing the advantages, challenges, and future directions of BIM–GIS integrated utilization in urban disaster management	

Table 2. Search Strings and Documents Search Results.

Search Engine	Search String	Results
WoS	TS = ((“Building Information Modeling” OR “Geographic Information System“ OR “BIM–GIS”) AND (“disaster” OR “hazard” OR “flood” OR “fire” OR “landslide” OR “earthquake” OR “storm” OR “hurricane” OR “evacuation” OR “rescue” OR “escape”) AND (“prevention” OR “mitigation” OR “response” OR “recovery” OR “rescue” OR “escape” OR “evacuation”))	1260
	Document Types: Articles or Proceeding Papers or Review Articles	1258
Scopus	TITLE-ABS-KEY ((“Building Information Modeling” OR “Geographic Information System“ OR “BIM–GIS”) AND (“disaster” OR “hazard” OR “flood” OR “fire” OR “landslide” OR “earthquake” OR “storm” OR “hurricane” OR “evacuation” OR “rescue” OR “escape”) AND (“prevention” OR “mitigation” OR “response” OR “recovery” OR “rescue” OR “escape” OR “evacuation”))	4779
	AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “re”)	4577
Sum of the papers = 5835		

The second phase is the article screening phase. In the second phase, the retrieved documents are screened according to the inclusion and exclusion criteria presented in Table 1. In the first step, the retrieved documents are screened based on their titles and keywords. Moreover, duplications and invalid papers are also excluded in this step. There were 5377 articles excluded from this step. After the initial step of the documents' exclusion, the remaining 458 articles were subjected to abstract screening. Through the abstract screening, 296 articles were excluded. From their abstracts, these articles do not include BIM–GIS capabilities in urban disaster management, or these excluded documents do not help to achieve the research aims or objectives. A total of 162 articles remained after the abstract screen. Then, the author performed the full-content review of these remaining articles. A total of 56 articles were excluded from the full-content review process.

The third phase is the review phase. In this stage, the remaining 106 articles are subjected to a systematic review to identify the capabilities of BIM–GIS integration that can be utilized in urban disaster management. After the BIM–GIS capabilities are identified, they are classified according to the methods and capabilities of BIM–GIS integration in exerting their effects in urban disaster management. The detailed process of the articles' classification development is presented in Table 3. Moreover, the flowchart of the article screening process in this study is shown in Figure 2.

Table 3. The Detailed Process of Classification Development.

Conduct a full-text review of the remaining articles in this study.
Identify the capabilities of BIM–GIS integration that can be utilized in urban disaster management.
Organize the similar capabilities of BIM–GIS integration together.
Develop the classification based on the methods of BIM–GIS capabilities in exerting their effectiveness in urban disaster management.
Check for consistency by referring to other studies.
Verify the developed classifications in this study.

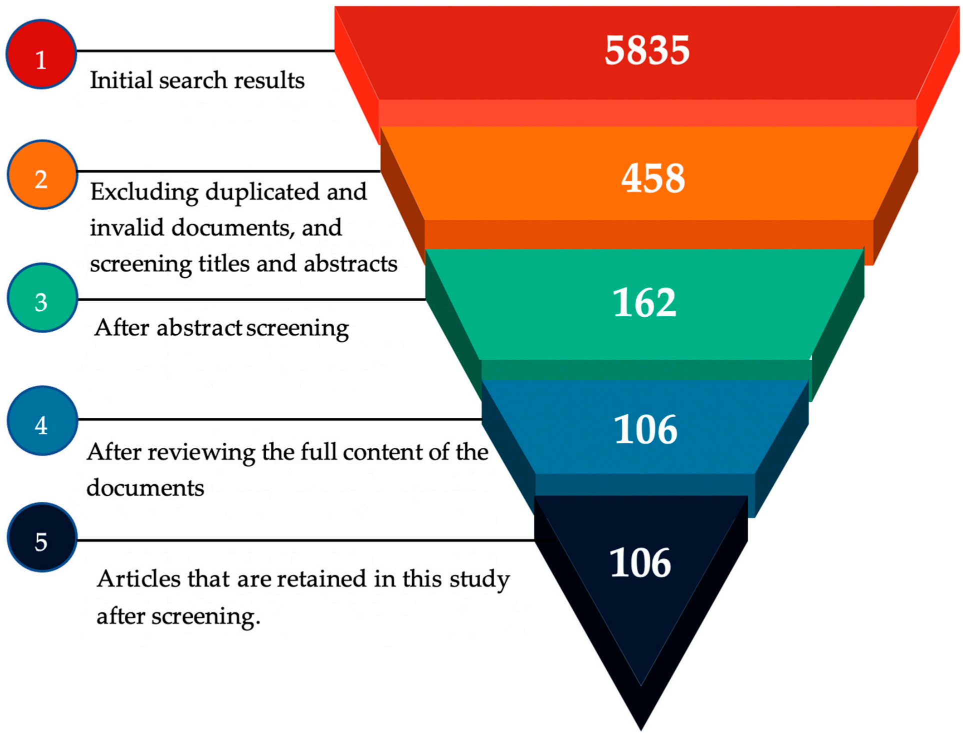

Figure 2. Article Screening Process in This Study.

3. Results

3.1. Descriptive Analysis

There are 106 studies reviewed in this study. According to Figure 3, it can be determined that the research on the capabilities of BIM–GIS integration in urban disaster management is generally on a rapidly developing upward trend. Figure 3 demonstrates that although the number of reviewed articles published each year does not always exceed the publication quantity in the previous year, the comprehensive trend shows a significant and substantial increase in the number of papers on BIM–GIS integrated utilization in urban disaster management from 2002 to 2022, and the increased amplitude is still constantly augmenting. The earliest reviewed article was published in 2002. Moreover, 2002–2012 can be regarded as the initial phase of this field. During this period, although studies on BIM–GIS integrated utilization in urban disaster management gradually warmed up, research into the BIM–GIS integrated utilization did not form a prominent trend in the disaster management domain. Between 2014 and 2017, the capabilities of BIM–GIS integration received increasing attention from scholars, and the contribution and potential of BIM–GIS integrated utilization in urban disaster management and emergency responses were recognized by an increasing number of disaster management authorities. During this period, the number of reviewed studies published increased obviously. Since 2018, there has been a spurt in the number of studies on the capabilities of BIM–GIS integration in the urban disaster management domain (from 6 in 2018 to 27 in 2022). This phenomenon can also demonstrate that the research on BIM–GIS integrated utilization in disaster management is flourishing and that BIM–GIS integration is gradually becoming a mainstay of urban disaster prevention and responses.

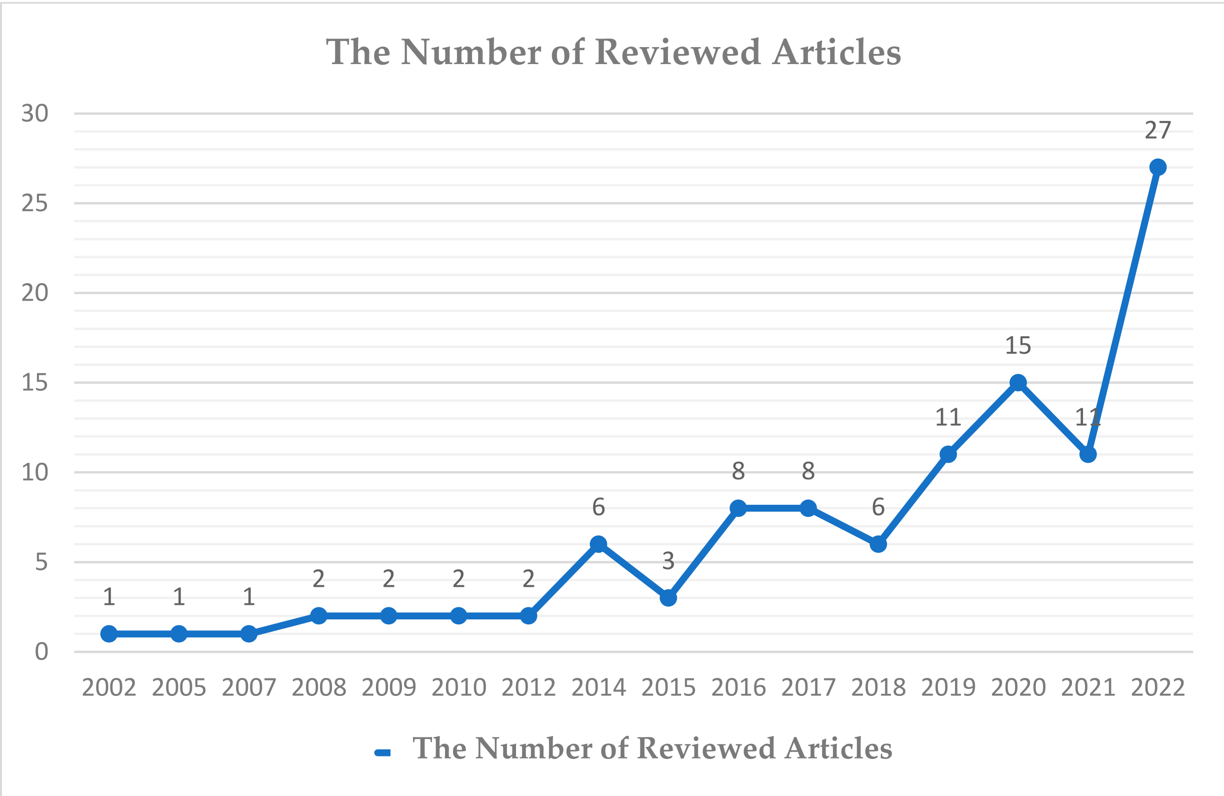

Figure 3. The Number of Reviewed Articles Published Per Year.

Figure 4 presents the number of reviewed documents published per source. Considering space limitations, only the top 12 journals in terms of the number of reviewed documents published are listed in Figure 4: Automation in Construction (10); Remote Sensing (8); Sustainability (5); Science of The Total Environment (3); Buildings (3); Advanced Engineering Informatics (3); ISPRS International Journal of Geo-Information (IJGI) (3); Water (2); Sensors (2); International Journal of Disaster Risk Reduction (2); International Journal of Digital Earth (2); Computers, Environment and Urban Systems (2).

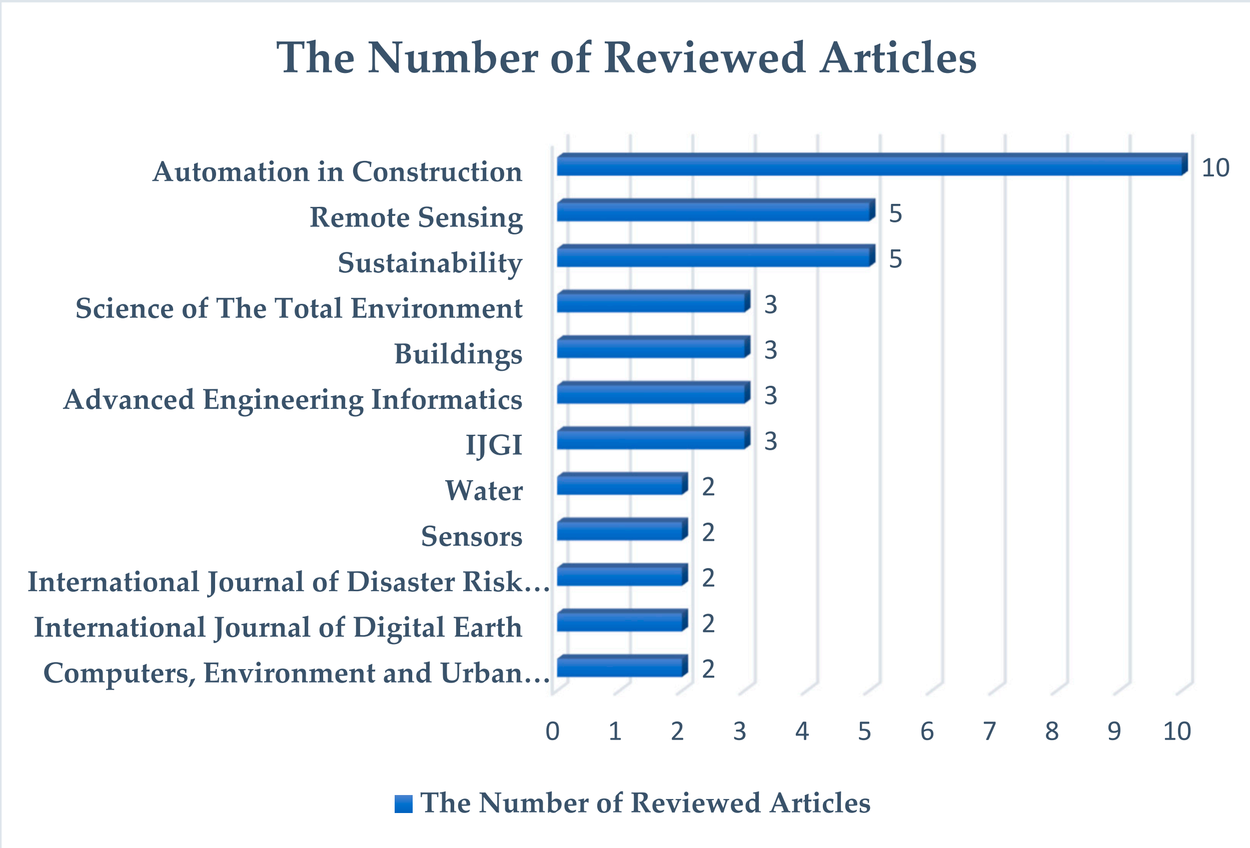

Figure 4. The Number of Reviewed Articles Published Per Source (only the top 12 journals).

Figure 5 demonstrates the number of reviewed documents published per country. In this study, the authors adopt the first-ranked affiliation of the first author as the criterion for determining the country or region in which the article was published. According to the rank based on the number of reviewed articles published, the top 9 countries or regions in this study are shown below (Due to space constraints, this article only lists the top 9 countries or regions in terms of the number of articles published): China (42), the USA (13), Australia (7), Italy (5), Malaysia (5), the United Kingdom (4), Iran (4), Turkey (3), and Belgium (3). According to Figure 5, scholars in China and the USA attach significant importance to the application of BIM–GIS integration in disaster management. Both countries are among the world leaders in terms of the quantity of reviewed articles in this study contributed by their research institutions and universities. Furthermore, the universities and institutions in Australia (7), Italy (5), Malaysia (5), the United Kingdom (4) and Iran (4) also provide distinguished contributions to BIM–GIS integrated capabilities in disaster management and have developed substantial theoretical guidance and knowledge assistance for the optimization of BIM–GIS applications for urban disaster management. In addition to these, scholars from Turkey (3) and Belgium (3) have also produced excellent research and made conspicuous contributions to the field. Moreover, the percentage of reviewed articles published per continent is presented below and in Figure 6: Asia (58%), Europa (22%), North America (13%), and Oceania (7%).

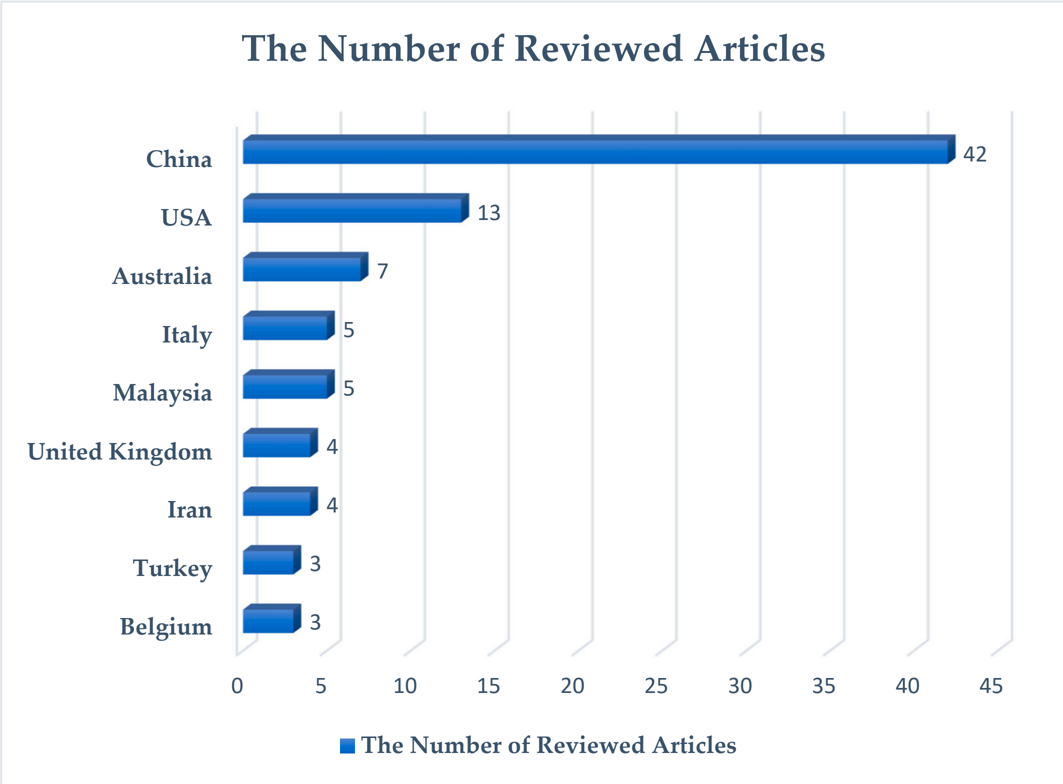

Figure 5. The Number of Reviewed Articles Published Per Country or Region.

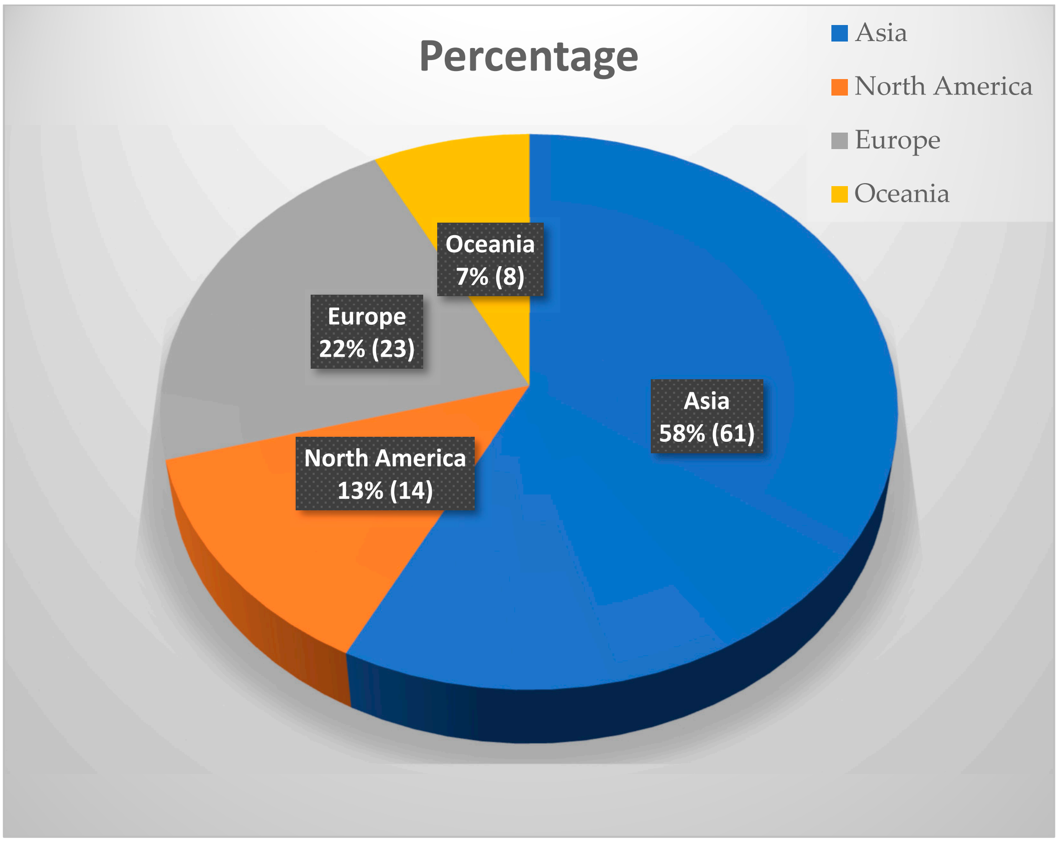

Figure 6. The Percentage of Reviewed Articles Published Per Continent.

3.2. Results Analysis

After the document retrieval and screening, the authors conducted a full-text review of the contained studies. Through the review, it can be concluded that the capabilities of BIM–GIS integration can be performed in the following disaster management stages: disaster prevention and mitigation, disaster response, and post-disaster recovery.

3.2.1. Disaster Prevention and Mitigation

From the perspective of disaster prevention and mitigation, it is essential to achieve disaster forecasting and early warning. According to Lyu et al. [33], the following classes of methods can be utilized to achieve disaster prediction and forecasting: GIS–RS (remote sensing) integration disaster detection and scenario-based disaster analysis; multi-criteria analysis (MCA); historical record-based disaster statistics.

BIM–GIS-based scenario simulation is an essential method for optimizing disaster prevention and mitigation. Based on BIM-based simulation capabilities and 3D spatial environmental demonstration in GIS, the BIM–GIS integrated application can effectively simulate disaster scenarios with different intensities [34]. This assists stakeholders in performing disaster damage assessments and predicting the affected areas, thus assisting the stakeholders in performing disaster damage assessments and delineating the expected disaster areas. Flooding has always been a serious threat to the safety of urban areas [35–39]. These threats are caused by both the physical damage to urban infrastructure/people and the additional poisoning of affected people by pollutants in the flood [40–43]. From the perspective of BIM–GIS integration-based flood scenario simulation and visualization, BIM can be responsible for providing building/facility/utilities-related information, and GIS can effectively provide flood-related parameters [18]. To achieve the three-dimensional scenarios of flood disasters establishment, Rong et al. [20] proposed the BIM–GIS integration-based 3D flood dynamics simulation model to simulate the inundation scenarios of specific areas with different intensities of floods by adopting high-altitude and -resolution UAV photography as a third-party auxiliary device. In the BIM–GIS-based flood inundation simulation method developed by Rong et al. [20], BIM and GIS can effectively provide internal information about the building structure with the aid of aerial photography-based technology. The method utilizes the UAV-based multi-camera approach to perform image capture to generate ground truth data measured by the real-time kinematic (RTK) system and compares it to the resulting digital model to determine the margin of error [20]. Based on the resultant 3-D digital maps, the planar hydrodynamic model based on shallow water equations (SWEs) and a 3-D hydrodynamic model based on the 3-D Reynolds-averaged Navier-Stokes (RANS) equations were constructed [20]. In the process of flood inundation simulation, the two-dimensional hydrodynamic model is utilized to detect/estimate the inundation area initially, the affected buildings, the flow depth distribution, the depth-average velocity, and the average flow pressure of the flood inundation space [20]. Through the 2D hydrodynamic model, the disaster management personnel can achieve the approximate identification and delineation of the affected area and the initial estimation of potential casualties/property damage by comparing it with residential areas and infrastructure [20]. The 3-D model is used to perform simulations of the interaction between the complex geometry of the ground surface and the flooding fluid (the simulation also identifies the axial velocity and vortex structure of the flood), thus improving the accuracy and precision of the simulation [20]. Based on the 3D hydrodynamic simulation model, the precise identification and measurement of inundated buildings, the flow depth distribution, the depth-average velocity, and the average flow pressure can be completed. After the 2D/3D hydrodynamic simulation results are generated, the stakeholders can compare these two simulation results to achieve the high-accuracy identification of flooded areas, affected buildings, and flood flow paths [20].

Moreover, Yang et al. [5] put forward the BIM–GIS–DCEs (domain-specific computational engines) integration-based vulnerability evaluation method to examine the flood resilience of urban infrastructure. In the BIM–GIS–DCEs integrated vulnerability assessment, through the prior identification of the category of flood-sensitive building data in the IFC file, BIM can be utilized to extract the related information about buildings/facilities/components/materials that might be affected by urban flooding [5]. DCEs are adopted to perform the physics-based simulation of utility performance, including runoff from underground pipes, surface stormwater runoff, hazardous traffic properties, and their negative impacts [5]. In the simulation of rainwater flow, the stormwater flow path in the tube is represented by a one-dimensional linear model, and the flood flow is present through two-dimensional shallow water equations [5]. After the data preparation and simulation from BIM and DCEs are complete, GIS can be utilized to extract and integrate the data from BIM, DCEs, and other sources and conduct geospatial analysis to develop the appropriate urban flood response measures [5].

To achieve the precise flood damage assessment for a single building, the BIM–GIS integration-based microscale flood damage assessment approach was developed by Amirebrahimi [17]. This building-level flood damage evaluation approach includes four phases: information preparation, physical flood damage assessment, economic loss estimation, and report generation [17]. In the information preparation stage, the GIS is adopted to provide the elevation model, and BIM is utilized to provide building-related data, including information on building interior spaces and building components (quantities, materials, replacement/repair costs, and so on) [17]. In the process of physical flood damage assessment, stakeholders can utilize the projected flood infiltration and the houses' area provided by the BIM to estimate the interior inundation depth [17]. Based on the building component information provided by BIM/GIS, stakeholders can assess the flood loads of individual building components and examine whether the flood loads to the components are subjected to exceeding the limit state [17]. With the above assessment, the economic losses caused by flooding can be estimated based on the data provided by BIM/GIS regarding the repair costs of each component (including the damage status, repair method, replacement decision, and unit cost of each affected component). In the assessment report generation phase, BIM–GIS integration can visualize the damage extent to individual units by the different color presentations of each component [17].

In BIM–GIS integrated utilization, data integration is always a significant technical barrier to be overcome. To enhance the information transcription and integration of BIM–GIS integrated utilization in the flood damage assessment process, the specific data integration approach between BIM and GIS was put forward by Amirebrahimi et al. [18]. During the geometric information conversion process, the IFC elements from the BIM are transitioned to the ESRI geodatabase feature classes (with the format of GenericCityObject) via the ArcGIS Interoperability Extension [18]. Each unit is assigned the corresponding TAG property. Furthermore, the building-related information (including the classification, material, and cost) is extracted from the exported XML version of the IFC file [18]. Once the abovementioned information is extracted, the semantic and geometry information can be matched correspondingly [18].

From the perspective of earthquake scenario simulation, Quinay et al. [44] put forward the BIM–GIS-based earthquake scenario establishment method to evaluate earthquake damage through the integration of earthquake-related parameters such as maximum interstory drifts. In the earthquake scenario formulation, the authors constructed a framework for the simulation and evaluation of earthquake scenarios based on a grid of line elements using the finite element method [44]. Through this method, the researchers identified the geological faults that cause high-intensity earthquakes in Manila and determined the interaction relationship between the maximum interstory drift (ISD) and the building height and structural plan area [44]. BIM–GIS integration is utilized in the earthquake simulation process to provide the building information and environmental information necessary for seismic simulation and analysis. In this process, the data from GIS and BIM are adopted to generate Model A and Model B, respectively. Model A (generated based on GIS data) includes the geometric information of the building structures, which can be utilized to present the building envelope [44]. The data provided by GIS are presented in polygon format, and the points are located by latitude and longitude. Model B (generated based on BIM data) can provide the building detailing information (e.g., structural frame characteristics, material attributes, quantity/category/performance of components) [44]. It can effectively complement the structural details that are lacking in Model A.

To simulate the building conditions in the fire situation and to implement correspondence precautions, the FDS (Fire Dynamics Simulator developed by NIST) model can be adopted to simulate the fire scenario [34]. Stakeholders can utilize the FDS-embedded combustion product extrapolation framework to simulate the toxic gases scenario in indoor fire disasters. In addition, the thermal resistance and flame resistance of the building's interior structure and components are also integrated into the framework to simulate the intensity of heat radiation during the fire disasters [34]. In addition, to simulate the multiple disasters' impact on specific sites and compare the damage between various disasters, the BIM and GIS-based city information model (CIM) was put forward by Lu et al. [45]. In the CIM disaster scenario simulation process, the high-resolution fire scenario modeling based on thermal radiation and heat plume mechanisms can simulate fire spread paths under different weather conditions and between multiple categories of building complexes [45].

From the perspective of hurricane evaluation and prevention, the contribution of BIM–GIS integration is also significant. In the BIM–GIS-based wind hazard modeling proposed by Nofal et al. [46], stakeholders can achieve the highly precise simulation and assessment of the hurricane impact on communities through BIM, GIS, and a numerical wind tunnel based on Computational Fluid Dynamics (CFD). In this process, stakeholders collect information about the footprint of the buildings (including the buildings' geometry, the number and height of storeys, the roof shape, and foundation details) and input these data into the GIS shapefile [46]. Based on the information in the GIS shapefile, the community-level 3D BIM–GIS integration-based model can be developed [46]. The model includes the 3D model of each building in the community, which was converted from the building footprints in the GIS shapefile by the geometry library embedded in Revit Dynamo [46]. Then, through the integration of 3D models and geographical and environmental information, the three-dimensional BIM/GIS integration-based model at the community level can be generated [46]. Based on the information provided by the BIM–GIS community modeling, stakeholders can effectively simulate aerodynamic-based wind interactions to effectively conduct digital computing wind engineering (community-level aerodynamics interference modeling) [46]. With the BIM–GIS integration-supported wind modeling described above, stakeholders can obtain a comprehensive understanding of the wind flows' direction and the intensity of the envelope of buildings, the spacing between buildings, and the field behind the buildings during the wind hazards.

In addition to the BIM–GIS-based scenario simulation, the disaster-related historical records can also provide significant contributions to urban disaster prevention and mitigation [47–56]. Disaster-related historical records can demonstrate the type, frequency, intensity, and affected area of disasters that happened in the past, thus assisting stakeholders in deducing the risks of various disasters and the potential areas affected [33]. In the case study of Black and Burns [57], the researchers discuss the nine longest peak-over-threshold (POT) river hydrological surges that caused floods in Scottish history and model the frequency of POT for each river based on this study. Based on the results of the abovementioned study, the flood inducements for each river in the region were derived, and the flood risk for each region was analyzed [57]. In the analysis of the spatial and temporal patterns of heavy rainfall and flooding in China prepared by Hu et al. [58], the researcher summarized the frequency and spatial distribution of flooding caused by heavy rainfall in China's county-level administrative regions from 1984 to 2007, as well as the human casualties and property damage caused by flooding, through the utilization of data provided by the Meteorological Bureau and the Bureau of Statistics. Through the analysis of the rainfall-caused flood, the researcher successfully achieved flood hazard risk analysis and early warning for the lower Yangtze River Basin, the middle and lower reaches of the Pearl River Basin, and the Huai River Basin in China [58]. Moreover, based on the above analysis, suitable flood disaster prevention and mitigation guidance was developed based on the extreme precipitation, elevation, and river network density statistics in each region [58].

From the perspective of historical record-based disaster statistics, the information management capabilities in BIM and GIS can effectively store and classify the historical record of hazard conditions through manual input, document storage, internet retrieval, and IoT transmission [59]. By combining the information management of BIM with the spatial visualization of GIS, stakeholders can effectively access the disaster history of different areas based on zoning and thus optimize the Chinese urban disaster prevention and mitigation schemes.

In addition to these, the BIM–GIS integrated utilization can also provide essential contributions to safety training from the perspective of disaster prevention and mitigation. In the case study of Chen et al. [60], the fire department used BIM–GIS integration-based disaster response aids to perform optimal rescue path generation, damage area identification, and trapped people positioning during fire rescue drills. Furthermore, with the mutual combination of BIM, GIS, VR (Virtual Reality), and AR (Augmented Reality), participants can immerse themselves in simulated scenarios to perform safety training and escape drills. VR is the superexcellence method of learning based on constructivism. It can assist participants in gaining a deeper understanding and knowledge of the training experience and enhances the interestingness/attractiveness of the safety training [61]. According to Kanak et al. [62], in the evacuation drill process through BIM/GIS-based VR, VR can provide the three-dimensional immersive visualization of hazardous areas and dangerous objects (such as the columns and beams in earthquake scenarios and gas tanks, ovens, and other flammable appliances in fire disaster scenarios) to the participants in the drill. In this BIM–GIS–VR-based crisis preparedness, data in CityGML format (from GIS) provide urban-level information (e.g., street distribution, building location, infrastructure layout) [62]. The data in IFC format (derived from BIM) mainly provide information on the internal environment and components of a building (e.g., doors, windows, beams, and fire-fighting equipment). To establish the connection between the IFC elements and the CityGML elements with identical definitions, the authors used the proposed shell ontology to achieve the one-to-one correspondence between the synonymous elements of the IFC format and the CityGML format [62]. Furthermore, the information on the built environment in BIM–GIS integration is divided into the following four categories: hazardous areas/objects/elements, safety zones/objects, fire/rescue equipment, and evacuation routes [62]. These data are defined as crucial elements and are used in the data simulation during the crisis preparedness process to achieve the VR demonstration with high precision and accuracy [62].

3.2.2. Disaster Response

1. Disaster Detection and Warning

Through the simulation and visualization of BIM capabilities, stakeholders can effectively simulate the micro-level internal structure of individual buildings, and GIS can demonstrate the macroscopic landscape and layout of the entire urban area [63]. With the integration of BIM and GIS, the stakeholders can develop an accurate positioning of the disaster and the corresponding 3D demonstration [64]. In the BIM–GIS risk management system designed by Peng et al. [65], the designer can utilize the building heat source information and the distribution of flammable materials stored in the BIM–GIS approach to deduce the fire-prone areas, thus performing the targeted installation of smoke detectors and thermal detectors with heat resistance attributes. Based on the above-mentioned capabilities, the BIM–GIS integrated risk management system can assist stakeholders in locating the explosive areas and assessing their intensity in a three-dimensional model through real-time monitoring and air quality detection [66,67]. Furthermore, the information exchange and management capabilities in the BIM–GIS integrated system can significantly contribute to disaster detection.

In the BIM–GIS-based information management system, the internal communication network can contain both the local area network (LAN) and the wide area network (WAN) [65]. The interoperability between BIM, GIS and third-party devices/technologies is essential [68,69]. The LAN can be linked to sensors in sensitive components (e.g., heating, ventilating and air-conditioning, gas pipes) to transmit the data that are required to be analyzed in the management terminal for the automatic identification and timely identification of the hazards [70]. In the BIM–GIS-based cyber-physical systems, it is possible to decentralize the arrangement of monitoring instruments and integrate them into a mature network via the network communication technology (such as wired/wireless local area network) [71]. Based on sensors, actuators, embedded computing, and LAN communication, stakeholders can perform corrosion monitoring, crowd activity sensing, thermal imaging, and multi-dimensional structural health detection [72–74]. In turn, the BIM–GIS integration-based disaster management software can utilize intelligent algorithms to conduct the control and status feedback of building structures in multiple categories of disasters, providing early warning as structures' hazards arise [71,75]. Through the WAN in the BIM–GIS integration-based risk management system, the cross-platform data exchange with external assistance organizations (e.g., weather bureau, earthquake bureau, fire service, rescue team, etc.) through the information crossover medium can be achieved [43,64,65]. Based on the combination of network, BIM, and GIS, the stakeholders can transmit the collected data to the disaster management department without omission and obtain the requested knowledge to achieve potential hazard identification and warning [76–79].

By integrating with third-party equipment and software, BIM and GIS can promptly detect potential hazards or ongoing disasters. In the GIS-based risk detection method formulated by Hussain et al. [80], this integrated approach can assist disaster management departments in the acquisition of morphological information on the topography of a mountain structure and the execution of time-delayed seasonal monitoring by the utilization of aerial photographic reconnaissance from the Unmanned Aerial Vehicle (UAV). By importing the data into the GIS adopted and BIM–GIS integrated approaches for modeling and simulation, the probability and locations of landslides or mudslides occurring on the specific mountain at different dates can be concluded [81–83]. In the case study of Agliata et al. [81], the researchers utilized BIM and GIS to retrieve information related to susceptibility assessment indicators and to visualize and model the target area at macroscopic and microscopic levels to assess the susceptibility of specific areas in the floods, landslides, and mudslides, respectively. Through remote sensing, field research, and web-based information retrieval, GIS databases can integrate geo-referenced graphical data (vector information and orthophotos) with building character indicators for the area [81]. Based on the GIS, stakeholders can retrieve and summarize the indicators related to vulnerability assessment (including the structural condition; the quantity of building storeys; the number of facades with large openings; the orientation of constructions; and the maintenance condition) [81]. BIM can establish an individual building model to visualize their building geometry and interiors. Once the modeling of an individual building has been completed, the model is assigned a unique ID for integration into the overall HBIM model of the area once all modeling has been completed [81]. HBIM is integrated with GIS through the online usBIM platform, which matches the multidimensional BIM model of each building to its geographic location in GIS through building ID identification [81]. The HBIM–GIS integration contains all five vulnerability-related indicators of each building. Moreover, the researcher also performs the literature review to assign weighting factors to each susceptibility assessment indicator in the susceptibility assessment equations for different hazards (including flood, debris flow, and landslide) [81]. Based on the abovementioned procedure, disaster management personnel can utilize the appropriate equation (the Weighted Linear Combination Method is recommended by the researchers for performing risk evaluation) to perform the susceptibility assessment, thus completing the evaluation of the resilience and susceptibility of each building in the selected area in floods, landslides, and debris flow [81].

Based on the massif-related data collected by UAV, the finite element modeling can be completed by adopting the modeling function of the BIM–GIS integration, which can assist the disaster management personnel in conducting further geotechnical analysis to evaluate the stability of risky mountains [84,85]. From the perspective of fire emergency responses, to improve the speed of the disaster response, Li et al. [86] developed a BIM-based meta-heuristic algorithm to optimize the distribution of sensors. This algorithm utilizes BIM to integrate and present the geometric data of the sensing area as a basis for calculating the spatial division of mass, which can support the optimization of the sensor arrangement based on different buildings' layouts [86]. According to statistics, the abovementioned meta-heuristic algorithm can reduce sensor requirements by an average of 32.1% compared to conventional sensor placement solutions and can guarantee 87.1% accuracy in locating trapped persons [86].

Moreover, machine learning is also an essential characteristic of the risk identification process. In the case study of Arabameri et al. [87] and Hakim et al. [88], the researchers collated 18 landslide susceptibility factors and used the random forest method to determine the relevance of different landslide susceptibility factors in the assessment of landslide susceptibility. The proposed landslide susceptibility model can assist the stakeholders in matching the mountain conditions to the previous landslides' cases stored in Case-Based Reasoning through the machine learning function of BIM and GIS to identify hazards and reduce landslides' destructive power promptly [87,89–91].

From the perspective of earthquake detection, Bertello et al. [92] and Lévy et al. [93] performed seismometers to record and derive the first resonant frequencies of seismic noise recordings and summarize the resonant frequencies that tend to cause the collapse of load-bearing columns in buildings during earthquakes based on the collected data. Through the connection with seismometers, the BIM and GIS can assist the hazard management system in collecting and managing the monitored seismic noise to achieve early earthquake warning and detection by automatically comparing it with stored resonant frequencies that tend to collapse buildings [80,94]. Furthermore, to achieve the precise early warning of geological disasters, the REST 3D geo-hazard monitoring platform was developed by Liu et al. [95]. In REST, geographic information presentation modules (including map layering data and data required for digital elevation modeling and digital orthophoto mapping), geographic information services modules (data collected at monitoring points can be customized and provided to stakeholders), and client interfaces are integrated to present monitoring data with a high resolution and conduct timely warning in a three-dimensional manner [95]. In addition, remote sensing (RS) and permanent scatter interferometry synthetic aperture radar (PSInSAR) can also provide significant contributions to BIM–GIS-based geological hazard monitoring [33]. The integration of RS and PSInSAR with BIM–GIS enables the effective identification of subsurface objects, discontinuities, underground faults' displacement, and their movement trends to identify the areas with potential geological hazards (such as landslides and earthquakes) for early warning [96–98].

To reduce flood damage, the prompt flood risk identification and warning are essential in disaster management [99,100]. In flood risk identification and warning, BIM–GIS integration is deemed a fundamental approach to solving the challenges in hazard identification [33,101]. Subways and underground plazas are possibly heavily exposed to flooding in urban areas [102–105]. In the case of urban flooding due to heavy storms, the intensity of the flooding depends mainly on the following influencing factors: the precipitation in a specific period; the layout of the metro system; the distribution of underground pipes; the spatial configuration of the drainage system; and the materials adopted in road construction [104]. In the urban flooding hazard analysis performed by Lyn et al. [104], GIS is used to manage and describe the geospatial information of urban areas (including their elevation, slope, and layout and characteristics of the river network). With the multiple-buffer operator in ArcMap, it is possible to simulate flooding areas due to the metro system effectively [104]. These flooding areas include both areas flooded due to their low-lying and regions affected by flooding due to the metro impacting the drainage capacity of the underground drainage network. Moreover, Lyn et al. [104] also pointed out that the BIM can provide essential assistance in establishing the "sponge city" to enhance the flood prevention capability of urban areas. Compared to conventional cities, "sponge cities" can significantly improve their stormwater storage and drainage capacity during heavy rainfall through their high-density drainage network systems and water storage facilities [104]. The BIM–GIS integration can provide urban-level geospatial information on the location and attributes of the pipeline system layout and water storage facilities [104]. It can assist urban disaster managers in developing targeted disaster prevention schemes based on the abovementioned information. In addition, BIM–GIS can provide pipeline distribution for underground construction activities to mitigate their negative impact on the capacity of the drainage system [104]. For the underground spaces under construction, disaster prevention departments can perform the dynamic monitoring and management of the 3D spatial positioning of machinery based on BIM–GIS integration by installing GPS (Global Positioning System) receivers on large construction machinery to assess the risk to people and equipment in the vicinity when flooding occurs [106].

In addition to these, in the case study of Lyu et al. [33], the authors utilized the Interval Analytic Hierarchy Process (I-AHP) to assign weights to the influences that could lead to flood damage and thus assess the flood risk level of individual spaces within the metro and underground premises. Based on the regional flood rating determination, BIM and GIS risk identification software was used to develop risk level maps to assess the risk of flooding in selected subsurface areas for adequate early warning [33]. The groundwater inflow assessment can also be carried out by the detection and early warning of flooding [107]. In the comparative study of Hassani et al. [107], based on the hydrogeology, geotechnical conditions, and tunnel geometry, the researcher deduced the steady-state groundwater inflow by the SGR (Sample Generation by Replacement) empirical method and conducted a finite element analysis of groundwater inflow to achieve the timely flood identification and response. Moreover, the potential threat of flash floods is nonnegligible for the cities around the mountains and valleys. To achieve an efficient response to mountain torrents, Elkhrachy [108] modeled and visualized the contours of the river surface using a GIS–GPS-based hydrological analysis application to model mountain torrents disasters in preparation for the rapid positioning of flash flood inundation areas.

2. Emergency Evacuation and Rescue

The BIM–GIS integration can effectively support evacuation and rescue. As a complementary approach, the 3D building model can effectively supplement the environmental information inside the building for the GIS-adopted evacuation and rescue method [109]. Through the utilization of BIM–GIS integration, emergency management personnel can effectively perform personnel positioning, automatic route planning, and rescue scheme formulation.

From the perspective of personnel positioning, with the spread of indoor monitoring and sensors in urban areas, BIM–GIS integration approaches can locate the trapped people in time to provide the necessary information for rescue organizations [110–112]. Furthermore, ultra-wideband (UWB) can also provide an essential assistance to BIM–GIS-integrated indoor positioning. Based on the time difference of arrival (TDoA) and angle of arrival (AoA), UWB can support stakeholders in performing highly accurate indoor positioning [113]. In the indoor positioning approaches developed by Akcan and Evrendilek [114] and Chandra-Sekaran et al. [115], the researcher utilized interactive radio nodes to detect targeted personnel and then performed the estimation of people's location through the Monte Carlo and Unscented Kalman Filter methods, thus achieving real-time positioning with room-level accuracy. In addition, through the UWB-BIM integrated personnel tracking and positioning technology based on WLAN (wireless local area network) or RFID (radio-frequency identification) developed by Kaya et al. [116], Khoury and Kamat [117], and Ruppel et al. [118], it is possible to achieve personnel positioning the accuracy in the allowable range by attaching readers and positioning wearable beacons through backward ray-tracing algorithms that analyze the angle of arrival (AOA), time of arrival (TOA), and signal power. With the connection of the abovementioned tools and

BIM–GIS emergency management applications, it can facilitate not only the positioning of people in indoor and outdoor environments but also the 3D model establishment of selected people, their located buildings, and the surrounding environment [86].

For high-rise buildings with multiple floors, wireless-based floor identification (BWFP), barometric pressure-based floor positioning (BPFP), and targeted people activities detection can be integrated into the BIM–GIS combination positioning system to implement the floor position identification for people trapped by the disaster [119]. This method can achieve a less than 1% error rate in locating the floor of a trapped person, thus providing reliable data assistance for rescuers [119]. In addition, given the widespread popularization of smartphones, it is highly feasible to locate people via smartphones and other radio frequency equipment [8]. In the study of Li et al. [8,86], the Bluetooth device was integrated with BIM–GIS software to locate and demonstrate the position of the selected person in the building model [8,86]. Furthermore, Li et al. [86] also proposed an indoor-centric localization algorithm based on the above research results to optimize the beacon layout design to improve the accuracy of positioning and the response efficiency and reduce the disaster response-related expenditure. In the process of disaster relief, the effective positioning and route planning represent the significant optimization of rescue organizations' efficiency and the remarkable improvement of the affected people's survival probability [120–122]. To optimize positioning accuracy, the EASBL (Environment Aware Sequence-Based Localization) algorithm was developed by Li et al. [86] to establish a temporary RF communication system and locate trapped persons. This method proposes a spatial partition quality assessment framework, deployment placement criteria, and the majorization path to the objective function that balances the trade-offs between the above objectives to provide rescue support to first responders [86].

Route planning and automatic pathfinding are also essential BIM–GIS integrated capabilities for disaster rescue and evacuation. From the perspective of disaster response, route planning and automatic pathfinding are essential to enhancing rescue efficiency and reducing casualties [123]. In the process of BIM–GIS integration utilization in route planning and automatic pathfinding in disasters, BIM can be performed to demonstrate the structural conditions and affected areas inside the buildings through its 3D modeling, simulation, and information management capabilities to effectively develop escape routes and identify available shelters [77,106]. GIS can be utilized to present the urban macroscopic layout to suggest the most optimized course for the rescue teams [2,66,124]. To familiarize the firefighters with the internal structure, external environment, and rescue routes of the affected buildings, the 3D Indoor Emergency Spatial Model (IESM) was developed dy Tashakkori et al. [125]. To improve the efficiency of the simulation, IESM disregards non-target-related IFC information and extracts the building information necessary for mission execution, including the interior information of buildings, outdoor emergency response-related information, and dynamic and semantic building data [125]. Through the Data Interoperability extension in ArcGIS, the BIM-derived data and GIS-derived data can achieve format matching and integration [125]. Furthermore, through the integration of IESM and ArcScene, stakeholders can utilize GIS to locate and highlight elements of a specific type through specific semantic strings [125]. Based on the integrated BIM–GIS application, IESM also enables the simulation of the interactive effects of indoor and outdoor environments [125]. During the fire response process, IESM can effectively identify hazardous substances, flammable objects, fire-fighting equipment, diversion areas, and surrounding traffic routes to simulate their possible interacted impacts and utilization options [125].

Compared to the traditional 2D route planning method, BIM–GIS route planning in 3D allows for a better consideration of geometric elements [126,127]. Based on the dynamic analysis of the geometric elements, structural elements, overall layout, and information retrieved by sensors in indoor and outdoor environments, BIM–GIS integration can assist stakeholders in identifying and locating the potential risks during the evacuation [128,129]. This enables hazard avoidance through the multiple geometrical views provided by the

3D analysis. From the perspective of disaster response and emergency route planning, the BIM–GIS-adopted multi-purpose geometric network model (MGNM) is also a practical approach. By extracting information about the building in BIM, stakeholders can retrieve the data needed in the route planning formulated process, including corridor footprints, spatial footprints, and centroids of opening elements [130]. Based on the above data, the MGNM can be generated and integrated into the GIS as the feature class. Moreover, the MGNM plugged the transitional element (the transfer arc, an arc that links the entrance of constructions to the outdoor road) to automatically bridge the BIM-derived road network within the building and the outdoor traffic routes in the GIS by identifying transfer arcs that do not encounter the building and its indestructible components, such as the transfer arcs at entrances, doors, and windows that can be opened [130]. The seamless indoor–outdoor path planning can be effectively achieved, thus improving the efficiency of the rescue and escape. Compared to the conventional route planning method, the MGNM can consider all passable elements instead of including only exits and entrances, which can assist stakeholders in identifying the shortest and safest escape/rescue routes [130]. In addition, MGNM allows the complexity of the model to be rationalized for different areas, thus improving the efficiency of emergency route planning [130].

To avoid trampling during the evacuation process, the evacuation navigation framework based on BIM and GIS was proposed by Xu et al. [131]. This framework utilizes the collection of route data generated by ArcGIS for BIM as the data source to identify distinction points of different areas and then connect adjacent points to formulate the evacuation networks [131]. Based on the abovementioned results, the Triangulated Irregular Network-based optimization algorithm is conducted to provide optimal escape routes for each individual trapped in the crowd [131,132]. This method avoids trampling during the evacuation and minimizes the duration required to complete the evacuation [132–134]. To decrease the time needed for fire response and rescue, Isikdag et al. [135] integrated the location information of each fire station in BIM and GIS, thus automatically selecting the nearest fire station to the fire location to minimize the rescue journey. Moreover, identifying breakable structures is also an effective method of optimizing evacuation and rescue efficiency. In the fire rescue simulation approach formulated based on a 3D geometric network model (GNM) and BIM, the method can implement the fire scenarios simulation and shortest safety route planning based on geographical information and fire conditions collected through GIS [60]. The GNM is established on polygon layer data. In the polygon layer data, the nodes of the rooms and staircases are determined at the centroids of the polygons, and the vertical heights originated from the elevation maps [60]. The route of the corridor is generated based on medial axis transformation (MAT). In this process, BIM can provide all the data required for the fire simulation and the rescue of the target building from the early design phase to the operation/maintenance/alteration/refurbishment phase [60]. In the GIS, spatial features are defined by vector and raster data models, and the buildings, roads, and fire-fighting equipment are the features of polygons, lines, and points, respectively [60]. Furthermore, the Fire Dynamics Simulator (FDS) can effectively simulate the smoke density and temperature in each space based on the internal structure, the external building layout, the materials utilized in the building, and the flammable and explosive objects in the building provided by BIM and GIS [60]. Based on the building geometry provided by the GNM and the smoke density and combustion conditions provided by the FDS, the disaster response personnel can use the Dijkstra algorithm to generate the shortest safe path for rescue, escape, and evacuation [60].

In addition, with the integration of BIM and GIS in Smart City, metropolitan-level route planning and automatic pathfinding can be achieved. Through this integration, disaster management personnel can model the topology of urban information into a BIM–GIS approach to enable metropolitan-wide facility management [66,136]. Based on the abovementioned BIM–GIS disaster management approach, stakeholders can locate police stations, fire stations, civilian rescue services, hospitals, military bases, and disaster areas throughout the metropolitan area to achieve minute-level hazard responses and disaster rescue mobilization [136].

3.2.3. Post-Disaster Recovery

In the post-disaster recovery process, it is vital to evaluate the extent of damage to buildings and structures in the post-disaster period. Multiple evaluation methods were developed to perform the damage evaluation in the post-earthquake period. To achieve an accurate assessment of post-earthquake building damage, Xu et al. [137,138] developed a framework for post-earthquake building condition assessment based on Building Information Modeling (BIM) and FEMA P-58 (FEMA represents the Federal Emergency Management Agency). Through model mapping and information interactive transmission, earthquake damage simulations from FEMA P-58 can be imported into BIM and used as the data foundation to perform post-disaster reconstruction/refurbishment expenditure estimation [138]. In addition, with the combination of BIM's Time-History Analysis (THA), the GIS's spatial presentation capabilities, and the vulnerability curves, BIM–GIS integration can support the post-disaster reconstruction participants in assessing the damage status of components within the building and the spatial distribution of damaged components [138]. Moreover, the earthquake damage assessment approach put forward by Rad et al. [137,139] also adopted FEMA P-58 to perform the earthquake damage prediction and post-disaster renovation cost evaluation by incorporating the drift degree and acceleration at different floors as the assessment factors in the framework. In the case study of Ramírez Eudave and Ferreira [140], the authors utilized the coordination of BIM and historical BIM models (HBIM) to identify the factors relevant to the vulnerability evaluation of historic buildings in disasters such as earthquakes. BIM–GIS-based remote sensing technologies are utilized to take post-disaster photographs of buildings and import them into the GIS data repository in CityGML format to produce the high-resolution post-disaster model [140]. After the factors' identification and GIS-based model establishment are accomplished, the vulnerability evaluation-related factors can be integrated into the established model to evaluate the available ancient buildings' vulnerability [140]. For bridges in earthquake-affected areas, to enhance the accuracy of bridge damage assessment in earthquake disasters and the safety of post-disaster aid engineers, the BIM and UAV-based post-earthquake bridge condition detection framework was proposed by Zou et al. [141]. Following the algorithmically optimized route, the drones can carry out aerial photography of damaged bridges and earthquake-affected areas at high altitudes. The digital multidimensional model of the specific earthquake-related damaged bridge is then generated and visualized through an interactive interface [141].

Given that post-disaster reconstruction/repair works require the approval of the corresponding authorities, the traditional reconstruction/renovation approval process in some countries significantly delays the commencement of reconstruction works due to its inefficiency. To mitigate the inefficiencies of the conventional post-disaster reconstruction approval process, the BIM-based Virtual Permitting Framework (VPF) for the approval of post-disaster reconstruction/repair activities was developed by Messaoudi and Nawari [137,142]. This method stores the condition of the damaged building in the BIM-based information storage and classifies the damaged buildings according to the severity of their damage [142]. Then, the stakeholders can utilize VPF to automatically match the suitable repair/reconstruction schemes to earthquake-affected buildings and compare the schemes with corresponding legislation and regulations to accelerate the approval process [142].

After extraordinarily serious natural calamities (e.g., an earthquake measuring 8 on the Richter scale), it is necessary to perform reconstruction and repair for the entire city. The BIM–GIS adopted smart management system put forward by Assem et al. [143] is deemed as an effective approach to improving the post-disaster reconstruction efficiency. This smart management system incorporates the GIS server, the building information model, the MySQL database, and Google Maps as its data sources [143]. Based on the scalability, positioning capabilities, and geospatial analysis of GIS, the GIS-level database in the smart management system can support stakeholders in the search and management of building repairs/reconstruction at the city/community/region level [143]. With data from BIM, GIS, and the web level, the intelligent management system enables the identification of the building category (priority attention is paid to monuments, high-value buildings, buildings in danger, and buildings in need of repair), maintenance/reconstruction schedule, and hazard areas [143]. BIM is conducted for building-level reconstruction progress management and three-dimensional visualization [143].

Furthermore, LIDAR (laser imaging, detection, and ranging) is also an important tool for the BIM–GIS integrated application from the perspective of post-disaster recovery. In the road detection and parametrization method developed by Barazzetti et al. [144], the LIDAR stored data can be categorized into the following classifications: ground, trees, and buildings. These data can be converted into vector layers in the BIM–GIS integrated model to achieve the enrichment of the model with parametric elements related to facilities and vegetation [144]. In the road renovation process, the renovation personnel can utilize the tilt photography approach to capture the surrounding environmental conditions to create ultra-simulated maps of the terrain, topography, hydrology, and surrounding traffic network for the BIM–GIS model [145]. The construction organizations can perform the traffic capacity assessment of multiple transportation planning schemes based on the utilization of 3D visualization in BIM and overall comprehensive planning maps in the motorway renovation/reconstruction process [145].

For the retrofitting and renovation of historical buildings, based on the historical and multi-modeled complexity of historic buildings, the BIM–GIS integrated Jeddah Historic Building Information Modeling process (JHBIM) was proposed by Baik et al. [146] to provide stakeholders with the necessary knowledge management assistance. In the process of JHBIM utilization, the enriched semantic models in BIM can be conducted to provide the required information, including materials utilization, repair/refurbishment records, and buildings' historical backgrounds [146]. The 3D GIS in JHBIM is operated to provide three-dimensional geometric modeling of historic buildings and to generate vector data for road grids and raster data for ground images [146].

4. Discussion

In Section 3, the authors review the capabilities of BIM–GIS integration in urban disaster management. From the articles reviewed in Section 3, it can be concluded that the capabilities of BIM–GIS integration can be utilized in the following aspects of urban disaster management: disaster prevention and mitigation, disaster response, and post-disaster recovery. Based on the research results in Section 3, the capabilities of BIM–GIS integration in urban disaster management are discussed and analyzed in Section 4. The discussion and analysis reveal the characteristics of BIM–GIS integrated utilization in urban disaster management. In Section 4, the authors discuss and analyze the reviewed capabilities of BIM–GIS integration from the perspective of data acquisition methods, the interoperability between BIM and GIS, and data utilization/analysis. Moreover, the challenges and future directions of BIM–GIS integration in urban disaster management are investigated in this section.

4.1. Data Acquisition

The BIM–GIS integration has multiple data sources in its utilization process in urban disaster management (as presented in Figure 7). Through the article review in Section 3, it can be revealed that multiple studies adopted third-party devices or plug-ins as the primary data acquisition approach. From the perspective of landslide prevention, flood disaster management, and post-earthquake recovery, the UAV is recommended as an efficient data collection device. Through the integration of UAVs with high-altitude photography, stakeholders can obtain high-resolution, accurate information on the mountains' structural condition, flooded areas distribution, and post-earthquake scenes [20,80,84,85,141].

Through the combination of drone patrols and overhead photography technology, disaster management organizations can achieve the prompt identification of potential disaster risks and disaster responses. In addition, the high-resolution photograph can provide the high-precision original shape of affected buildings/structures for post-disaster reconstruction [141,147]. Compared to other third-party data collection devices, UAV-based photography can achieve high-resolution and massive area imaging [148]. In addition, compared to other ground-based detection methods, UAVs can effectively access treacherous mountains or floodplains without unnecessary detection-related hazards [85,149,150].

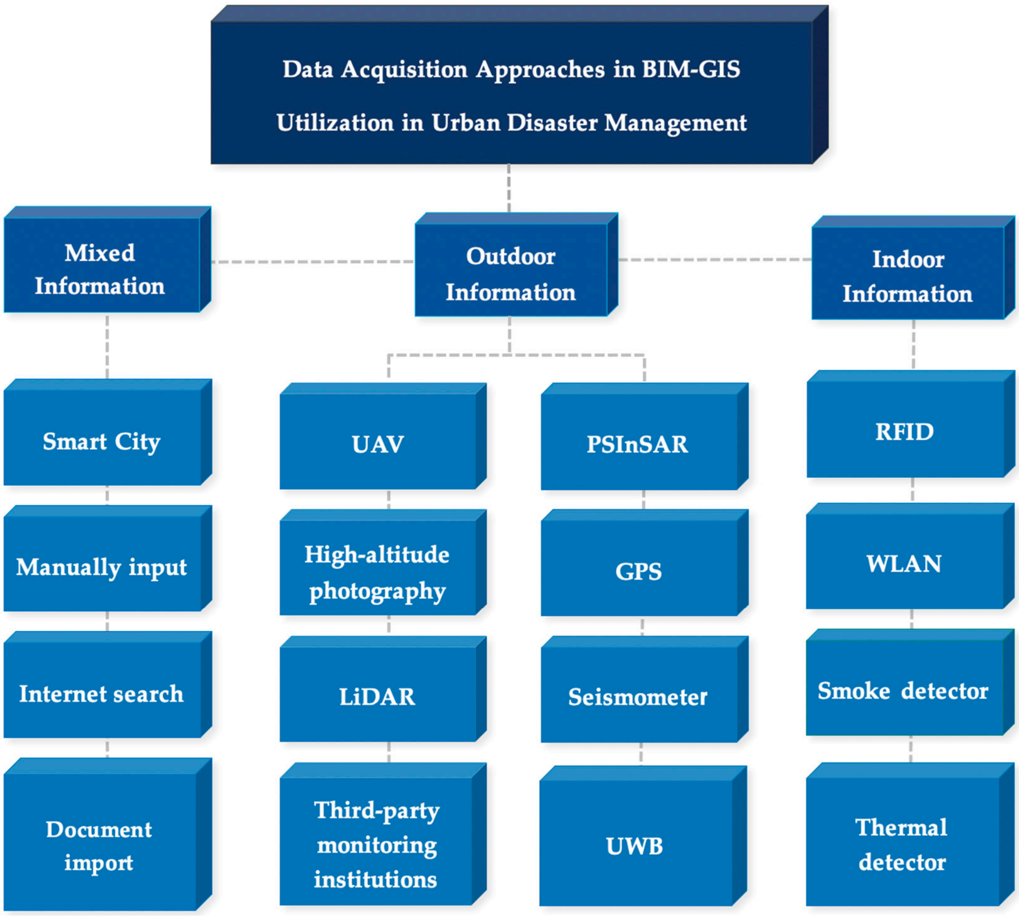

Figure 7. Data Acquisition Approaches in BIM–GIS Utilization in Urban Disaster Management.

Moreover, the combination of UAV and LiDAR is another data acquisition method for formulating the high-resolution digital elevation model in BIM–GIS integration urban disaster management. With LiDAR mounted on a UAV, the UAV can transmit a pulsed laser at the target objects and assess the distance and altitude of the selected object by evaluating the differences in the time and wavelength of the pulsed laser reflections [151]. Based on this, LiDAR-UAV can provide the data needed to create a multi-dimensional digital scenario simulation [151].

Despite the notable performances of the UAV-based data acquisition approach, there are still some limitations to UAV utilization. Safety regulatory authorities in multiple countries have strict restrictions on the areas where UAVs can be used and the altitudes at which UAVs can hover, so UAV-adopted data acquisition method utilization in partial countries should obtain official permission [152,153]. In addition, the endurance of Medium-Altitude Long-Endurance UAVs is generally within 48 h [154]. So, insufficient battery capacity is another inevitable barrier for data acquisition tasks that long-term mountain surface monitoring or flooded areas' aerial patrol is required to perform. Moreover, the efficiency of drone data collection can be affected sensitively by weather conditions. Adverse weather can cause severe damage to UAV components, given that the cooperation of high-resolution cameras or camcorders is required for UAVs to perform high-altitude data acquisition activities, and adverse weather can damage or wear out the camera elements [153,155]. In addition, low visibility conditions can also have a negative impact on the operator [153].

Moreover, the instant detection of seismic noise and earth crust shaking is a practical approach to achieving the early warning of seismic disasters and reducing casualties. In earthquake-related data acquisition, the seismograph and permanent scattering interferometric synthetic aperture radar (PSInSAR) are used as the primary third-party equipment to detect the required data [33]. Compared to the conventional Synthetic Aperture Radar (SAR) tool, PSInSAR can effectively overcome weak signals and the inability of individual interferogram-based stratigraphic deformation identification [97,156], thus accomplishing highly accurate topographic and geological monitoring and presentation [97,156]. Furthermore, PSInSAR can be conducted to compare the monitoring of topographic and geological environmental data at multiple timepoints to identify ground subsidence and liquefaction conditions and the distribution of surface fractures before and after earthquakes [97,157].

In terms of the aspect of early warning and evacuation, third-party sensors make significant contributions to the data acquisition process. The positioning system is essential in the disaster management system for enabling timely disaster alerts, rescues, and escapes. For field regions or extensive area regions, by integrating the GPS into the BIM–GIS model, rescue teams can achieve trace-related and positioning-related information acquisition for affected human beings [106,158]. In the indoor rescue and evacuation process, radio frequency devices and Bluetooth equipment can be tracked as signal sources to identify rooms and floors where trapped people are located through RFID identification or WLAN positioning [117,118]. To achieve the no-omission data exchange between the BIM–GIS integration disaster management framework and third-party devices, multiple studies adopt Local Area Network (LAN), Wide Area Network (WAN), and Internet as the information transmission intermedium [65,68]. During the operation process of the RF devices, the received signal strength (RSS) of multiple access points (APs) for the devices can be measured and compared [117]. Depending on the strength of the received signal at each AP, the stakeholder can determine the target person's location by utilizing the corresponding proprietary algorithm (such as Multilateration, Bayesian Inference, the Monte Carlo Method, and the Unscented Kalman Filter Method) [117,159].

Although RFID, WLAN, and other positioning-related data collection technologies can be utilized to effectively perform the location identification in the BIM–GIS-based disaster management framework, there are still some barriers in their utilization process. The RFID-based and WLAN-based positioning systems are significantly influenced by the building's structure and layout during the indoor positioning process [159,160]. Given the attenuation effect of walls or other obstacles on the signal, the accuracy of the positioning might be relatively reduced [159]. Moreover, response collisions between multiple sensors might lead to negative interference between the sensors, thus reducing the efficiency and accuracy of the position [161]. In addition to these, with the widespread use of RF devices, the invasion of people's privacy by positioning systems using RF devices is a challenge that needs to be addressed [162].

Besides the abovementioned third-party devices, the smart city is also an influential trend in BIM–GIS utilization in urban disaster management. Smart cities can provide macro-level data to the stakeholders, including the location and structure of affected buildings, the distribution of hospitals, police stations, and fire brigades within the city, and the urban area's road planning and traffic conditions [66,136]. Through the smart city utilization in the urban disaster management phase, data on the absolute locations (longitude and latitude), relative locations, and descriptive locations (e.g., building name, postcode, street, district) of buildings in the urban space can be provided [163]. According to Long [164], it has been determined that China is in the leading position regarding smart cities' quantity and scale. Furthermore, the smart cities in the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration have been widely diffused and promoted [164].

It provides technical support and data assistance for the integration and application of BIM–GIS and smart cities in urban disaster management in China.

In addition, manual input and document import can be deemed as the simplest and most rudimentary data acquisition methods in the BIM–GIS utilization process in urban disaster management. In the case studies of Black & Burns [57] and Hu [58], researchers used historical records of natural hazards and weather- and climate-related data from the meteorological bureau to perform risk predictions for natural hazards. Manual input and document import have an inferior technical barrier. However, compared to other data acquisition approaches, the manual method is inefficient. So, the stakeholders are preferred to adopt it as the supplemental measure of data collection in the BIM–GIS integrated utilization in disaster management. Besides these, multiple studies have retrieved the necessary environmental information through the accessed monitoring agencies (e.g., seismological bureau, weather stations, etc.) to perform urban disaster management [165,166]. These documents and data can be stored and categorized as information in the BIM database, allowing stakeholders to effectively utilize BIM's knowledge management capabilities to perform data retrieval, data analysis, and information extraction [10,11,167].

4.2. The Interoperability between BIM and GIS

The integrations of BIM and GIS include three primary integration modes: BIM-led (BIM is responsible for creating multi-dimensional digital models and providing database storage; GIS is responsible for supplementing additional required information); GIS-led (GIS generates spatial environment visualization and provides the data of each element in the target area; BIM serves additional functions to import BIM); BIM and GIS are equally co-led (the effective integration of building information and data related to the overall environment of the selected area can be achieved) [168]. Although each of these above-mentioned BIM–GIS integration modes has its unique characteristics and advantages, it is necessary to sustain the satisfactory interoperability between BIM and GIS to achieve the effective application of BIM–GIS integration capabilities in the field of urban disaster management. Multiple studies have been developed to enhance the interoperability between BIM and GIS. According to Kang [169], the interoperability between BIM and GIS is mainly achieved or enhanced through the following approaches:

1. Ontological modeling (interoperability through semantic transformation formulas or frameworks that are based on ontology models)
2. Web service-based interoperability framework (access to information using the internet or local area network)
3. Data mapping (converting BIM models to other formats)
4. Expansion based on current data exchange models

In the ontological modeling-based semantic translation method that Karan and Irizarry [170] proposed, the researcher translates the model into (resource description framework) RDF triples, defining and standardizing information in incompatible semantic networks through ontologies in the structural and spatial domains, as required. In semantic-based BIM–GIS data integration, BIM and GIS data can be transformed into a third-party transition format to enable data interaction and integration. In the BIM–GIS integration method developed by Hor et al. [171], both BIM-generated data (IFC format) and GIS-generated information (CityGML format) with identical concepts are exported/serialized to RDF graphs to achieve ontologies merging [171]. The newly generated RDF graph will be adopted to refer to the corresponding BIM elements and GIS elements. Based on the generated RDF graphs, the Integrated Geospatial Information Model (IGIM) can be developed to achieve the integration, mapping, and utilization of BIM/GIS data into a single platform [171].

From the perspective of data mapping, mapping the frames and data from the initial model to the chosen model using the EXPRESS-X mapping model is an effective method [169,172]. Through the foundation of the Flexible Instance Oriented Partial Exchange Environment (FIOPE), the interoperability of the IFC data framework is effectively optimized [172]. Furthermore, to enhance the expansion based on current data exchange models, the Open-Source Approach (OSA) was developed to lubricate the mutual information exchange between BIM (IFC) and GIS (shapefile) [173]. This method utilizes IFC-Tree to identify the graphical information in the BIM digital model and transforms it into a GIS-readable document using an algorithmic framework based on automatic multi-patch generation (AMG) [173]. Moreover, based on the Open-Source Approach (OSA), the enhanced OSA (E-OSA) framework has also been established to further enhance the interoperability of IFC format documents with shapefile-based data [174]. In the development of the E-OSA, the authors designed the Enhanced Automatic Multi-Block Generation (E-AMG) algorithm to convert geometry information in BIM multidimensional models into a boundary representation (BRep) without any data omission to improve the reliability of mutual information exchange [174]. Moreover, linking information in IFC format to data stored in GIS through semantic mapping and then performing the loose coupling and code compliance audits on independent third-party platforms is also a crucial potential trend from the perspective of BIM–GIS data integration [175].

In addition to enhancing the seamless integration of BIM and GIS, maintaining the appropriate interoperability of BIM–GIS with third-party devices and applications is also an important prerequisite to ensuring their performance in urban disaster management. From the perspective of the interoperability between UAV and BIM–GIS, the consistency check is performed on the acquired data since the data are captured by the UAV, and the automated BIM updating or the automated in-BIM documentation can be performed based on the conformity results and the update/filing requirements [176]. From the perspective of smart city utilization in urban disaster management, Open CASCADE technology can convert IFC format information into shapefile-based data [127,177]. From the perspective of smart city utilization, Open CASCADE technology can convert IFC format information into shapefile-based data and transform the IFC-type geometry data to CityGML format files by converting them into an intermediary format (e.g., Wavefront OBJ) [127,177]. It can effectively enhance the integration of smart city and urban disaster management. Moreover, from the perspective of GIS-AR integration enhancement, the WebVRGIS Hybrid program can utilize the P2P structure to achieve the multiple dimensional scenarios/models transmission and index the information in GIS/AR data repositories through hash values [178]. Based on these abovementioned measures, the spatial visualization of GIS and the immersive and user-friendly interaction of VR can be seamlessly integrated [178,179].

In addition to these, it is crucial to ensure information security in the information exchange process. In the BIM–GIS integration-based crisis preparedness approach developed by the researcher, the ontology storage data and IoT stream information are encrypted/decrypted via the Hardware Security Module (HSM) [62]. Moreover, authorized users are required to enter a randomly generated One-Time-password (OTP) to access the database [62].

Despite multiple studies being developed to optimize the interoperability between BIM and GIS, some barriers still need to be solved to enhance the interoperability of BIM–GIS in the urban disaster management process. Data omission in the semantic mapping process between BIM and GIS is a challenge that needs to be addressed urgently [124]. The IFC format contains more abundant attribute categories than the CityGML format, so it is inevitable that information omissions will happen in the data transformation process from the BIM dataset to GIS [177]. In addition, the absence of information related to the geographic location in the BIM model (e.g., latitude and longitude of the building, etc.) can also cause hindrances in the data exchange process [177]. Furthermore, the transformation between multiple categories' 3D geometries (e.g., geometrical information conversion between Constructive Solid Geometry and b-rep) is a BIM–GIS interoperability-related issue that needs to be addressed [4,180]. Given that the LODs of the BIM models and GIS files to be integrated may differ, the mutual adaptability of mutual LODs is also a significant issue to which importance must be attached [4,180]. From the visualization perspective, given the abundant semantic attributes in BIM models and the excessive quantity of data that far exceeds conventional GIS files' data storage, the visual demonstration of BIM models might not be satisfactorily implemented in the BIM–GIS integration utilization due to insufficient rendering power [63,181].

4.3. Data Utilization and Analysis

Through the systematic review of the capabilities of BIM–GIS integration in urban disaster management in Section 3, it can be determined that the BIM–GIS integration can provide contributions from the pre-disaster prevention phase to the post-disaster recovery phase. In the integration utilization of BIM and GIS, BIM is adopted to provide detail-level information about the building structure and to perform data processing and analysis using the information management, modeling, simulation, and collaboration capabilities in BIM [63]. GIS can provide stakeholders with city-level environmental demonstration and knowledge assistance based on the data collected [63]. Through the BIM–GIS utilization in the urban disaster management process, BIM can assist stakeholders in processing the building elements, geometrical and topological relationships, and structural properties [5]. GIS is responsible for reflecting the spatial relationship between assets and their surrounding sites [5]. The contributions of BIM–GIS integration capabilities in urban disaster management in this study are summarized in Table 4.

Table 4. The Capabilities of BIM–GIS Integration in Urban Disaster Management.

	Scenario Simulation and Visualization	Scenario Analysis	Positioning	Route Planning and Automatic Pathfinding	Data Analysis
Flood	[2,17,18,20,33,64,102–104,109,110,145]	[2,5,17,18,20,33,101,102,104,108]		[133]	[5,17,18,59,81,101,103,105,107,108,140]
Landslide	[2,83–85,95,109,110,145]	[2,83–85,88,90,91,95,96]			[59,81–83,87–96]
Fire	[2,34,45,60,62,68,109,110,112,125,135,145]	[2,34,45,65,67,125,129,135]	[60,64,74,75,112,114–119,131]	[60,64,112,118,119,121,125,129–131,133,134]	[45,59,62,67,73,94,111,125,135,140]
Earthquake	[2,45,62,64,67,68,95,98,109,110,138,141,145]	[2,44,45,67,95,97,98]	[8,64,74,114,115,117,131]	[131,133]	[44,45,59,62,67,81,82,94,95,98,138–141]

Based on the reviewed articles, it can be concluded that the BIM–GIS-based scenario analysis and demonstration are essential characteristics of the urban disaster management process. From the scenario visualization perspective, the GIS aims to provide stakeholders with a visual representation of the affected area, the intensity of the disaster, and the hills or riverbanks at risk. The BIM can reflect the hazard-influenced space within the assets and the damaged situation to the buildings. Furthermore, by utilizing VR and AR technologies for the demonstration of disaster scenarios, users can immerse themselves in a simulated disaster and visually identify the hazards source and elements that caused the risks of the disaster.

According to Table 4, it can be determined that the disaster scenario visualization and simulation capabilities in BIM–GIS integration are widespread in multiple categories of hazards. Moreover, the disaster scenario visualization and simulation of each disaster category have been proposed in multiple corresponding studies by scholars. The disaster scenario visualization and simulation can provide stakeholders with a high-fidelity and multi-dimensional representation of the indoor layout and outdoor environment, thereby effectively improving the quality and efficiency of disaster management for each disaster category. Furthermore, disaster scenario visualization and simulation can be regarded as the basis for multiple BIM–GIS integration capabilities (as shown in Figure 8). Based on the visualization and data supplement provided by disaster scenario visualization and simulation, the scenario analysis, positioning, and automatic pathfinding can be effectually performed.

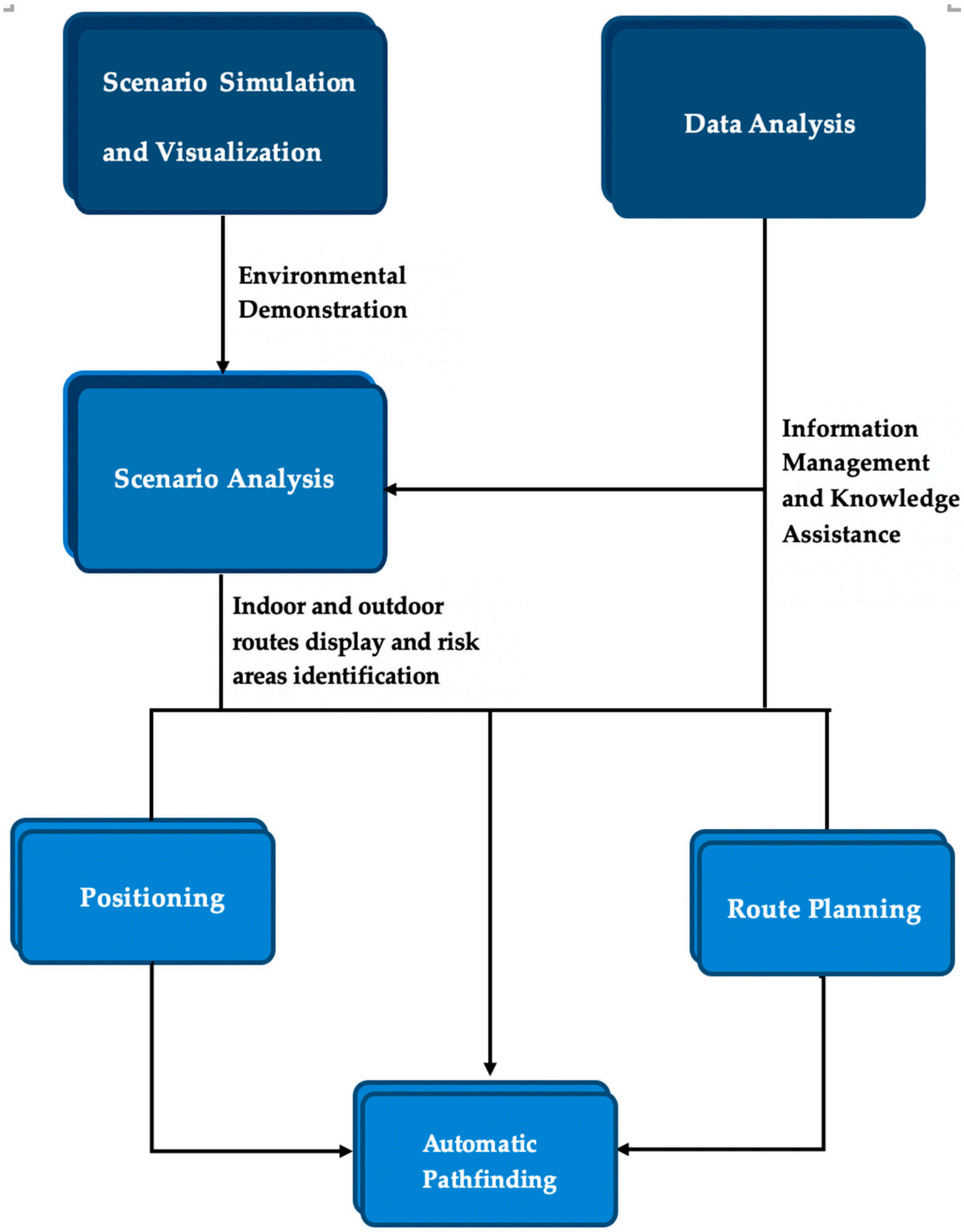

Figure 8. Relationship between Various Types of BIM–GIS-Based Capabilities in Urban Disaster Management.

Moreover, multiple studies pointed out that the BIM–GIS scenario analysis can significantly contribute to disaster risk identification in urban disaster management. Through the integration of corresponding algorithms/models with BIM–GIS, the potential geological risks, the flood levels, and the interaction between buildings, infrastructure, flooding, and geology are effectively analyzed. Regarding fire scenario analysis, BIM–GIS provides information on the distribution of flammable materials in the building, the thermal resistance of building materials, the location of doors, windows, escape ladders, and fire-fighting equipment, the weather, and the building's surroundings based on data from sensors. Stakeholders can use BIM–GIS fire scenario analysis and simulation to identify the fire spread space, the heat radiation intensity, the distribution and density of toxic gases, and the available safe shelters for trapped people.

In addition to the abovementioned contributions, disaster-related data analysis is also a significant capability of BIM–GIS integration in urban disaster management. According to Table 4, many reviewed articles explored the data analysis capabilities of BIM/GIS in disaster management. Table 4 also indicates that the BIM–GIS-based disaster data analysis can provide significant contributions to the prevention, emergency response, and post-disaster renovation/reconstruction of almost all disasters. Based on the collected seismic noise recordings, crustal resonance frequencies, hydrological attributes, and barometric variations, the BIM–GIS-based disaster detection application can assist the stakeholders in achieving prompt earthquake/flood identification and response.

Based on the abovementioned disaster scenario visualization, scenario analysis, and data analysis, BIM–GIS integration can effectively assist the stakeholders in performing the positioning, route planning, and automatic pathfinding functions during the rescue evacuation process (as shown in Figure 8). According to Tashakkori et al. [125], in the disaster response process, the following information is necessary for first responders to optimize the response efficiency and to protect affected people: indoor environment-related data; dynamic and semantic information (e.g., occupants' quantities in the selected asset at different times, the dynamic movement of people in the building, spatial accessibility); outdoor disaster response-related information (road layout, traffic conditions, transportation load, locations of rescue service organizations, distribution of surrounding facilities). The retrieval, management, and provision of this required information can be effectively achieved without omissions and mistakes by the BIM–GIS-based disaster scenario demonstration and analysis function mentioned above. Based on the established disaster scenario model, rescue organizations can locate people in distress by using RFID, GPS, WLAN, and other sensors. Depending on the different LoDs in models, detection methods, and sensors distribution, the positioning can be accurate to specific coordinates or only contain the serial number of the room/floor where the person is trapped. With the aid of positioning systems, disaster scenario modeling, and route planning, automatic pathfinding can be implemented to help the people afflicted by natural disasters and rescue teams determine the most unobstructed and non-hazardous route (as shown in Figure 8). In addition, BIM–GIS integration can also assist disaster victims in identifying potential hazards and available escape aids in their paths. Moreover, multiple scholars pointed out that navigation optimization can be achieved by identifying breakable structures (such as breakable windows or doors) through the BIM–GIS-based disaster management applications to improve the rescue efficiency and survival rates.

According to Table 4, the vast majority of the reviewed BIM–GIS studies on indoor positioning and automatic pathfinding are concentrated on fire emergency management and earthquake disaster responses. In the site selection and layout planning stages for buildings, most stakeholders prefer to locate buildings in areas that can avoid the negative impact of flooding and mudslides. However, it is challenging to avoid earthquakes and fires through the preparation in the early site selection, which, to some extent, indirectly leads to the extensive focus on BIM–GIS-based indoor positioning and automatic pathfinding during fires and earthquakes.

4.4. Future Directions

According to Shkundalov and Vilutienė [181], the deficiency of the unified format that can be applied to BIM and GIS is the leading cause of semantic mapping and geometric transformation obstacles in BIM–GIS integration. So, it is necessary to develop the BIM–GIS adapted formats and data transformational standards to enhance the interoperability between BIM and GIS in urban disaster management. The formalization of AEC ontologies is deemed an effectual approach to enhancing BIM–GIS interoperability [69,182]. Based on this method, the unified protocol can be constructed for typical applications across multiple ontologies. The data management patterns of AEC ontologies formalization can be either centralization or decentralization [182,183]. To optimize the quality of BIM–GIS integration, three potential BIM–GIS integration approaches are proposed for other researchers to explore: Loose Integration (BIM and GIS are both operated independently, only combined in partial functional fields); Tight Integration (both BIM and GIS are integrated as subsections, within the more comprehensive geographic information science framework); Data Source Hypothesis (BIM is responsible for data identification and collection, and GIS is responsible for information analysis) [77].

In addition to the interoperability of BIM and GIS, the optimization of in-building presentation in BIM digital models within the Web environment deserves the attention of researchers [181]. Given that most research related to BIM–GIS integration has focused on the application of BIM and GIS in one area, it is also a promising future research direction to develop a comprehensive BIM–GIS integration framework that can be worked in multiple fields (including urban disaster management) [66]. Moreover, the historical disaster record is a crucial disaster prevention method that can provide essential assistance to urban disaster management departments. Other researchers could focus their efforts on developing BIM–GIS modules for the automatic retrieval and management of historical disaster records to optimize the efficiency of historical disaster records utilization in the field of BIM–GIS-based urban disaster management. Furthermore, inappropriate sensor distribution and weak sensor signal strength are also considerable challenges in applying BIM–GIS to urban disaster management. So, other researchers can propose corresponding studies on optimizing the sensors' indoor distribution and enhancing the signal strength of WLAN/RFID to reduce the whole life cycle expenditure of building disaster management systems and improve disaster response efficiency.

Moreover, the files or protocols in BIM–GIS are often developed by stakeholders delegated by multiple organizations, and many BIM–GIS models are produced through multiple stakeholders' collaboration [59]. Consequently, the contributions of all participants in the process are integrated into single or multiple models/documents, and there are no clear legal boundaries between the contributions of different participants [184,185]. So, it is indispensable for other scholars to conduct corresponding research to overcome IPR issues in the integrated use of BIM–GIS.

5. Conclusions

Many cities suffer casualties and severe economic losses due to disasters. To reduce the disasters' damage to buildings and property and increase the affected people's survival rate, it is necessary to optimize disaster management capabilities in urban areas. BIM–GIS integrated utilization is deemed an effective method to improve urban disaster management capabilities. Through the utilization of BIM–GIS integration in urban disaster management, real-time visualization, information management, and scenario simulation at the macroscopical urban level and microscopical buildings level can be achieved. Considering the prominent potential and advantages of BIM–GIS integration in disaster management, it is necessary to promote and enhance BIM–GIS integration in the urban disaster management field. To achieve the abovementioned proposal, this study is developed to perform a systematic review of the capabilities of BIM–GIS integration in urban disaster management.

Through the systematic review in this study, it can be identified that the capabilities of BIM–GIS integration can provide significant contributions to disaster prevention and mitigation, disaster responses, and post-disaster recovery in urban management disasters. From the perspective of disaster prevention and mitigation, based on scenario visualization, risk-based scenario analysis, historical disaster records, and data storage/management capabilities in BIM and GIS, BIM–GIS integration can support the stakeholders in identifying the potential hazards and in the hazards prevention/mitigation schemes preparation. From the viewpoint of urban disaster responses, hazard detection and early warning can be effectually accomplished with the assistance of BIM–GIS integration. Through positioning, automatic pathfinding, and route planning functions based on BIM–GIS integration, the emergency escape, evacuation, and rescue efficiency in urban disasters can be effectively optimized. For post-disaster recovery, the disaster management authorities and personnel can utilize the multi-dimensional visualization of the post-disaster environment and the structural analysis of buildings conducted by BIM–GIS integration to significantly improve the quality and efficiency of post-disaster reconstruction. In addition, the data acquisition methods and interoperability of the BIM–GIS utilization process in urban disaster management are discussed in the discussion section. Moreover, the data analysis methods and future research directions are also analyzed.

There are some limitations in this study that are required to be overcome by further studies:

1. The interoperability issue between BIM and GIS is the primary challenge of BIM–GIS utilization in urban disaster management. Although some articles aiming to solve interoperability issues are reviewed and discussed in this study, it is still necessary for other researchers to perform relevant studies to eliminate the interoperability deficiencies.
2. Third-party devices, software, and institutions are important data acquisition approaches in the utilization of BIM–GIS integration in urban disaster management. Due to space limitations, this study does not review all the devices, plug-ins, and institutions that can provide the required data for BIM–GIS utilization in the urban disaster management phase. It is recommended that other scholars develop further studies to supplement the omissions.
3. Constrained by space limitations, most of the reviewed articles are mainly concentrated on BIM–GIS-based urban disaster management in floods, fires, landslides, and earthquakes. However, the articles about other disasters (such as snowstorms and hailstones) are rarely reviewed in this study. Other researchers can develop relevant articles to fill this gap.

In conclusion, this study performs a comprehensive review and critical analysis of the capabilities of BIM–GIS integration in urban disaster management. Through this study, the public and urban disaster managers can be effectively familiar with and apply BIM–GIS integration in urban disaster management, thus improving the urban disaster management efficiency and victims' survival rate.

Author Contributions: Y.C. wrote the original draft and conducted the data curation and formal analysis; Y.C. was responsible for the article selection and evaluation; Y.C., C.X., N.M.A. and S.N.K. were responsible for the review and conceptualization; C.X., N.M.A. and S.N.K. were responsible for the supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: We express our gratitude to Mingru Cao and Yan Zhang. Their insightful comments inspired us to improve our thinking and raised the caliber of our work.

Conflicts of Interest: The authors declare no conflict of interest.

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