A review on the GIS usage in spatio-temporal risk assessment in asset management

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Abstract. Risk assessment for asset management is a process to analyse the potential risk that could affect the efficiency of operating assets. An effective risk assessment strategy depends on high-quality data and effective data analysis. To do so, risk assessment should take into consideration the spatial and temporal aspects of risks of physical assets in asset management for a data-driven decision-making. Failure to incorporate the spatial and temporal aspects in risk, when the risk possess spatio-temporal correlation, could lead to a defective estimation of assets risks. GIS can be used to analyse multidimensional information which includes 3D GIS, and spatio-temporal data (2D+t and 3D+t). Due to its superiority in handling multidimensional data, GIS is often a preferable tool to collect, manage, manipulate, and visualize spatio-temporal data to allow an accurate and informed analysis. The aim of this study is to uncover the use of GIS for risk assessment in asset management when spatial and temporal data are concerned. This study conduct a thorough review of previous research to look into the current development of asset management that utilizes a spatio-temporal approach for data collection, analysis, and 3D visualization for risk assessment. At the end of this study, we found that physical assets are affected by risk that possess spatio-temporal correlation. Several GIS techniques for data collection, analysis and visualization are found to provide a more effective analysis for assessing spatio-temporal risks. This paper concludes by providing a workflow that can be used by asset managers to assess risk spatio-temporally based on the findings of this study.

1. Introduction

Asset management is a series of activities that are done systematically by several departments that work collectively to manage their assets optimally and as sustainably as possible [1]. Asset management activities that are done competently will provide asset-intensive organizations with multifold advantages such as reduced operational costs, increased revenues, increased efficiency, and the ability to provide clients with a high level of service. Asset management is outlined by the asset life cycle which describes the key stages that asset managers need to pay attention to when managing their assets [2]. Perhaps, the most important stage of the asset life cycle is the operation and management (O&M) stage as this stage constitutes most of the ages of the assets [3]. The useful age of the assets could be well defined by how asset managers approach managing their assets in this stage. Thus, asset managers need to take the necessary steps to manage their assets effectively during the O&M stage to increase the longevity of the assets.

Assets must be maintained periodically to ensure the assets can operate in the best condition possible. The best possible method for asset maintenance is preventive-based rather than reactive-based which relies on identifying the imminent risk to identify the appropriate maintenance action that needs to be done [4]. Reactive maintenance that depends on risk assessment can avoid significant asset downtime as the oncoming risk can be avoided or the effect of the risk towards the assets and daily operation can be significantly reduced by taking the necessary action to rectify the cause of the risk. Hence, this method of asset maintenance relies on accurate and informed risk assessment to ensure faultless diagnostic of risk to avoid adverse effects on assets and the daily operation of any asset-intensive organizations.

The risk that could affect any asset may be caused by various factors and some may have interdependencies between spatial and temporal factors. The spatial value of the risks is related to the location of the assets and the potential location of the risk. The temporal value of the risks is most associated with the frequency of the risk, the time the risk will happen, and the time the risk happened. These spatial and temporal factors of the risk need to be correlated and quantified to provide meaningful analysis for risk assessment. Assessing the space-time aspects represents the geographic location of the asset, the spatial extent of any phenomena and their changes over time [5]. However, the spatial and temporal dimensions of asset failures are typically managed in an isolated way due to a lack of quality data [6] and efficient spatio-temporal databases [7]. Ignoring the interdependencies of space-time aspects of the risk hinders the capability to perform risk prediction for efficient decision-making in asset management.

Geographic Information System (GIS) has been utilized extensively in many applications, and asset management is no exception. GIS has allowed the retrieval of information with large spatial extent relatively easily in a more time-effective manner. Furthermore, GIS is more effective to analyze spatial-related information with the help of numerous geospatial analyses and GIS software to aid in the analytical assessment of asset risk and visualization. Furthermore, adopting 3D GIS for risk assessment allows a more immersive visualization approach to strategize the action for risk mitigation. Asset management can benefit from this advantage by correlating the spatial location of the asset with the temporal factors of asset risk to introduce appropriate analysis to allow efficient predictive analysis. Space-time analysis from an asset management perspective grants the ability for asset managers to manage their assets in a predictive manner allowing them to strategize the most appropriate action for their assets. Conventional ways of assessing risk in asset management based on unidimensional aspects of either space or time rather than both aspects hinders a more valuable analysis in risk assessment. However, this issue can be improved by using GIS approach, as GIS is favorable in managing multidimensional data, which includes spatio-temporal data (2D+t or 3D+t).

Physical assets are exposed to various types of risk. The risks in asset management may have correlation with spatial and temporal aspects and may affect all types of physical assets. These spatio-temporal risks need to be studied to identify the most appropriate approach for assessing risks of physical assets for an effective risk assessment strategy in asset management practice. Therefore, this study provides an insight on the strategy to assessing spatio-temporal risk of physical assets and investigates the use of GIS for assessing risk when spatial and temporal dimensions need to be considered for a well-informed risk assessment.

2. Spatio-Temporal Risk in Asset Management

The risk that could act on any asset varies depending on the factor that caused the risk. These varying risks can be classified into several categories according to the international standard of asset management, ISO 55000:2014 Asset Management - Overview, principles and terminology [8]. The ISO 55000 standard classified risk in asset management into physical failure risk, operational failure risk, natural environment risk, stakeholders' risk, lifecycle risk, and risks that are outside the organizational control [9]. These risks are caused by different factors; however, recent research suggests that only physical risks and natural environments risk are affected by both spatial and temporal factors. The risks can be classified as having spatio-temporal value if it allows spatio-temporal analysis, spatio-temporal visualizations, and are caused by spatio-temporal factors. Physical risks are failure to the asset because of the ageing or deterioration of the assets and the material of the assets. Meanwhile, natural environmental risks are risks due to extreme weather conditions, natural disasters, and surrounding conditions.

2.1. Physical Risks

The physical of the assets may result in ageing and deterioration that will eventually lead to failure and asset breakdown if the necessary maintenance to repair or replace the asset at risk is not undertaken. Maintaining a good level of service could be complicated as a consequence of the assets' poor condition due to neglected maintenance to restore the optimum conditions of the assets [9]. The ageing and deterioration of the assets are inevitable as the condition of the asset will ultimately degrade when the asset goes deeper into its operating life. Hence, any asset requires constant monitoring, and an effective maintenance based on predictive maintenance (PdM) is a necessity to reduce the risk of the asset due to ageing and deterioration.

The prediction of the physical risks of the asset can be made effectively by analyzing the spatial and temporal factors of the asset and the risk [6]. For the purpose of predicting the risk due to ageing and deterioration, the integral information that needs to be acquired are the geographic location of the asset, the age of the asset, and historical information of asset failure. The location of the assets is essential to locate the asset for inspecting and maintenance purposes. The condition of the assets can be predicted by analyzing the trend in asset failure based on past failure information. The trend of past failure may indicate when the asset will suffer failure by looking into the average age of the asset that has suffered from breakdown. Asset managers can cluster the assets that are nearing the average age of breakdown to schedule maintenance activity to repair or replace the asset at risk which will ultimately avoid a more significant asset downtime.

Deteriorating assets due to ageing need extra care as these assets are subjected to a higher possibility of damage and failure due to the longevity of their operating life. The frequency of previous failures needs to be taken into consideration as well as this piece of information provides the patterns of the risk events over time that gives asset managers insight into what risk to expect and when it might occur. The incorporation of both spatial and temporal can reflect the behavior of the risk in both space and time dimensions which grants the ability to foresee the possible location and time of the risk.

2.2. Natural Environment Risks

Natural environment risks from an asset management perspective can be categorized into natural disasters, surrounding conditions and extreme weather. Natural disasters such as earthquakes can be very threatening to infrastructure assets such as buildings as these assets are exposed to natural disasters directly. The effect of these risks can be catastrophic as it may cause partial or total loss of assets and leads to loss of lives. Assets that are at risk of being affected by natural disasters are referred to as being at risk of exposure. Exposure is a spatio-temporal risk as places with a high possibility of suffering from natural disasters change from time to time. Hence, managing the exposure risk needs to be managed dynamically by considering both the spatial and temporal factors of the hazards and the assets [7].

Exposure risks are driven by economic and urbanization factors. People tend to migrate to places that can offer them a stable economy, thus increasing the urbanization of these areas. Buildings are built more rapidly to accommodate larger populations. The exposure risk increases when cities expand, and the risk grows when urbanization is concentrated in disaster-prone cities. Changes in urbanization can be seen as a dynamic entity due to the changes in the spatial extent of urbanization that changes from time to time. Consequently, the risk of exposure will also change over time covering different spatial extent of the cities.

The changes in urbanization can be quantified to predict the risk of exposure in a city. According to [10], specific time series are required for the prediction process. This can be done by analyzing the changes in the urban growth of a city for several years from satellite imagery [11]. Then, the imagery of urban growth over several years can be compared to each other to see the changes in urban growth of a city over time and give authorities to predict the level of threats if any natural disasters will occur at any time in the city. To increase the value of the prediction, spatio-temporal visualization based on hazard maps can be created from the satellite imagery to give an insight into which areas are susceptible to larger consequences of the disasters to prioritize retrofitting work to restore the value of the asset in a case where the disasters have occurred.

According to [7], the risk assessment of exposed assets is a dynamic process as it undergoes different phases throughout the risk assessment strategy. The first phase is the pre-disaster phase to mitigate the adverse effects of exposed assets. Then, exposed assets need an immediate response during the disasters, and finally, the post-disaster phase to recover the condition of the exposed assets. These phases of risk assessment of exposed assets are dynamic and appear at different spatial and temporal scales. It can be linked to the changes of urban growth [11], and mitigation measures such as retrofitting to reduce the impact of disaster risk [12]. Hence, it is evident that the space-time dynamic is crucial for a well-planned risk assessment strategy for disaster-related risk.

With regards to the risk related to surrounding conditions, this risk is caused by factors such as temperature, soil properties, and moisture. These risks have a more adverse impact on buried assets such as pipelines which are exposed to harsh conditions. Accordingly, buried pipelines are subjected to deterioration due to corrosion resulting from the chemical activity acted between the iron pipeline and the properties of the soil. According to [13], the corrosion of pipelines is a spatio-temporal process. The spatial occurrence of the corrosion can be correlated, and corrosion is a time-varying process where the rate of corrosion occurrence changes over time. Failure estimation of the pipeline due to corrosion can be predicted spatio-temporally even in the case of limited historical data of previous failures [14]. The spatio-temporal reliability analysis in the works of [14] has shown that it can predict the future condition of the buried pipeline where the location and the time of future failure can be predicted with good accuracy.

Extreme weather conditions can be harsh towards infrastructure assets, particularly electricity assets. These assets can suffer sudden power outages due to extreme weather such as lightning, and high winds. Power outages could be a costly failure as humans and many essential operations such as healthcare rely on electricity to sustain their daily activities. The information regarding weather conditions appears in different spatial and temporal resolutions. Based on the spatio-temporal information, the assets that are prone to be affected by extreme weather can be identified. However, correlating the spatial and temporal information is imperative before utilizing the spatio-temporal information on a spatio-temporal model [15]. Spatio-temporal correlation has proved to improve the predicting ability of weather-related risks [16].

3. The Role of GIS for Spatio-Temporal Risk Assessment

GIS have prominent role in asset management for assessing the risk of any assets. Various GIS-based data collection method, visualizations approach and analysis can be used to enhance the approach for assessing risk based on spatial and temporal data on top of the conventional method of risk assessment that based on unidimensional aspects of space or time only.

3.1. Data Collection

High-quality data is an important prerequisite for a faultless prognosis of risk in asset management. Good quality data can be obtained from a competent data collection process to avoid data imperfections that could introduce bias to the risk prediction if it is not handled appropriately [6]. The GIS technique is a favoured option to collect spatio-temporal data due to its superiority and advantage in collecting spatial-related information. Spatial information in some GIS approach for data collection may also contain timestamped information that may provide valuable information such as indicating when a certain event happened. Remote sensing, GPS measurement, laser scanning, UAV, and videogrammetry are several GIS techniques that can be implemented for data collection in asset management.

Remote sensing is a process of obtaining information about the Earth remotely without coming into physical contact with the earth’s surface. Remote sensing depends on reflected signals of electromagnetic radiation (EMR) from any object on earth that is emitted actively or passively to obtain information about the earth. The source of the signal is the distinctive factor of remote sensing technology. Passive remote sensing takes advantage of the sun's radiation by recording the reflected signals of sun radiation from the earth's surface. Active remote sensing records the reflected signals that are emitted by the sensors on the remote sensing platform itself. Several remote sensing platforms offer a wide coverage of the earth's surface with a high temporal resolution allowing analysis of the earth's surface at high frequencies.

Remote sensing is a practical approach to obtaining imagery covering a wide area as it relies on satellites to obtain imagery from a high altitude. The use of remote sensing for risk assessment is presented in [11], [17]. The remote sensing approach can be exploited for detecting the change in urban growth as the imagery regarding the previous state of urbanization from several years back can still be obtained from the satellites archive or repositories to be compared with the current urban growth. The information from satellite imagery can be combined with GIS technology to model and predict future urban growth. Based on the temporal evolution of urban growth obtained from the satellite imagery, the risk of exposure on infrastructure assets can be predicted and the information can be reported to local authorities to make necessary decisions to reduce the adverse impact of disasters on infrastructure assets. The information from remote sensing can be further improved by integrating the information with data collection that was obtained on-site [17]. Satellite imagery may have several limitations concerning its quality such as lacking detail and parts of the imagery that were covered by clouds that causes the imagery to need further clarity. In-situ observations may provide the clarity that the satellite imagery needed to come up with worthwhile information.

GPS could provide valuable information as well for a well-informed risk assessment. GPS is a technique in GIS that is used to collect accurate positional information with up to millimeters accuracy. GPS that are used for asset management are typically embedded on other platforms such as remote sensing satellites or vehicles providing the position of any occurrence that concerns any asset. GPS that is embedded in a sensor on a moving vehicle can be used to collect information on road defects while simultaneously providing the location of the defect for further assessment [18]. This could simplify the work of local authorities to locate and rectify the defects on road assets to avoid any risk happening to road users. To provide coordinates with good accuracy consistently, GPS as well as any sensors need to undergo calibration to ensure good quality data can be obtained at all times.

Several pieces of information on assets need to be retrieved rapidly and as accurately as possible. For example, the information on road and railway track profiles for condition monitoring needs to be collected rapidly to cover the large longitudinal extent of the road and railway track while maintaining a good level of accuracy. Laser scanning or LiDAR can be used to meet these requirements as it depends on repeated pulses of light to obtain any information about a surface which is suitable to obtain the profile of any object. The uses of LiDAR for managing assets are shown in research by [18], [19]. Laser scanning for road condition monitoring can be used to obtain the road profile to study the roughness of the roads [18]. The degradation of railway tracks can be predicted by LiDAR-based condition monitoring [19]. Studying the profile of the surface of roads and tracks is important for the assessment of risk as it can be used to provide essential information on surface degradation to predict the rate of degradation. This can help asset managers to predict the future state of the assets and schedule maintenance works to decrease the chances of risk due to deterioration occurring.

Laser scanning platforms such as Terrestrial Laser Scanning (TLS) [20], mobile LiDAR [20], and airborne LiDAR [20], [21] can be used to create a 3D city model of assets that can facilitate visualization for risk inspection. In 3D GIS, 3D city models are a digital representation of physical objects such as buildings in lightweight formats such as GML and JSON. The 3D model will need to be generated from point clouds collected from various laser scanning platform using 3D modelling software before being converted into other formats such as CityGML [22] or CityJSON [23].

Aside from obtaining point clouds directly from laser scanning devices, the point cloud can be generated using an image-based approach. Basically, the images were captured, typically by using airborne platforms such as a UAV [22], [24]. To generate the point cloud, the resultant image captured from UAV needs to undergo image processing using Structure from Motion (SfM) photogrammetric software to reconstruct the two-dimensional image to a three-dimensional view of an object through the generation of point clouds [25]. In some cases, the image generated from UAV does not enough to produce a complete point cloud since the image only shows the top view of the building and lacks information on the building façade. Hence, the UAV approach for 3D modelling requires additional data from a terrestrial laser scanner or close-range photogrammetry technique to produce a complete point cloud of the buildings with both top and façade views of the buildings.

Another possible approach in generating point clouds is by using videogrammetry. Videogrammetry involves creating point clouds through the utilization of sequences of video frames. Positioned within the realm of photogrammetry, this discipline presents appealing functionalities, rendering it a captivating option for 3D data acquisition. Nonetheless, variations in camera inputs and specifications can lead to varying qualities of resulting point clouds [26].

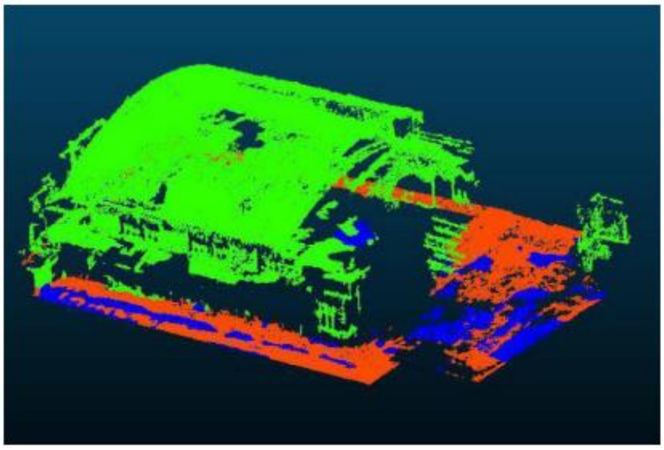

Figure 1. Image-based point cloud from UAV imagery [27]

In videogrammetry, successive videos need to have overlapped for the resultant point clouds of a building to be complete and to facilitate the generation of a detailed 3D model. The quality of the videogrammetry technique relies on the resolution of the video. A more detailed point cloud can be generated from a higher video resolution at the expense of larger point cloud files [26].

The point clouds obtained from all the 3D data collection techniques discussed are suitable for the generation of 3D city models that are suited for urban management applications such as disaster risk management [28].

3.2. 3D Data Modelling

3D modelling is a GIS tool allowing 2D objects to be represented in three-dimension when a height value (Z-coordinate) is added. Adding a height component to a 2D object allows it to be visualized in a more detailed and realistic manner. Due to this, the infrastructure industry has begun to realize the advantage of GIS-based 3D city models for various needs to capture the physical information of any infrastructure assets which are vital for infrastructure projects. In asset management, 3D city model serves as way to provide a more immersive visualization of physical assets virtually for various stages in asset lifecycle, including risk assessment. The 3D city model can be used to facilitate inspection, risk simulation, and indoor navigation for evacuation during risks [29]. A realistic visualization in 3D allows authorities to better understand the asset which leads to better decision-making and ultimately manages to reduce risks of various factors [30].

3D modelling relies on GIS data to generate a 3D model that manages to cover the physical aspects of the objects as accurately as possible. The GIS data that can be used to generate 3D models are image-based data, point cloud data, and an integrated approach of both image and point cloud data [27]. These types of data can be collected through either airborne or terrestrial means.

```
<building>
........
  <lod2Solid>
  ........<gml:surfaceMember>
          <gml:Polygon gml:id="wallSurface4711">
            <gml:exterior>
              <gml:LinearRing>
                <gml:pos srsDimension="3">32.0 31.0 2.5</gml
                ........
              </gml:LinearRing>
            </gml:exterior>
          </gml:Polygon>
        <gml:surfaceMember>
  ...........
  </lod2Solid>
..............
</building>
..............
<building>
...............
  <lod2Solid>
    <gml:surfaceMember xlink:href="#wallSurface4711"/>
  .................
  </lod2Solid>
</building>
```

Figure 2. Excerpt of CityGML file in GML encoding [31]

```
"CityObjects": {
   "id-1": {
       "type": "Building",
       "attributes": {...},
       "children": ["id-2", "id-3"
       "geometry": [{...}]
   },
   "id-2": {
       "type": "BuildingPart",
       "parents": ["id-1"],
       "geometry": [{...}]
```

Figure 3. Excerpt of CityJSON file in JSON encoding [32]

GIS-based 3D city models can be represented in several formats with different data structures, storage capabilities, and visualization approaches. The most discussed 3D city models based on recent development in research are CityGML and CityJSON. The main distinction between these two 3D city models is their encoding, where CityGML is based on GML (see Figure 2), whereas CityJSON is based on JSON encoding (see Figure 3). CityJSON adopts most of the CityGML data models but is improved complexity-wise by using JSON encoding that is easier to parse as compared to GML-encoded CityGML. The adoption of JSON encoding has reduced the size of CityJSON storage significantly [33] and with better interoperability capability [34]. However, both data models are limited in terms of entities relations descriptions or in other words adjacencies among objects [35]. For the application in the real world, CityGML possesses Application Domain Extension (ADE), to extend the core data model of CityGML to allow the addition of more application-specific attributes. The CityGML ADE, have demonstrated its use in disaster risk management [29]. Similar to CityGML ADE, CityJSON has its own method to extend its data model to allow the addition of attributes required for specific applications through CityJSON Extension.

Figure 4. Five Levels of Detail (LoD) in 3d city model and its generalization [36]

3D city models allow the visualization in 3D of the physical objects accurately in five different levels of detail (LoD) allowing authorities to decide the degree of detail that suits the requirement for various applications in the infrastructure industry. LoD 1 to 3 visualizes the exterior of the object with different levels of generalization on the appearance of the exterior structures such as roofs and windows. For example, LoD 2 has a more generalized roof structure, where the appearance of extended roof, if exists, is not noticeable. On the other hand, LoD3 has a more detailed roof structure where the appearance of an extended roof is discernible through visual inspection of the 3D city model in this LoD, as depicted in Figure 4. These three levels of LoD (LoD 1-3) that emphasize exterior visualization are sufficient to study the impact of disaster risks on infrastructures such as buildings. The prediction of the number of buildings that might be affected by disasters such as flooding can be facilitated by the generation of 3D models [37]. LoD 4 is the only LoD that is able to visualize the interior of buildings. LoD 4, which represents the interior of buildings, is the requirement for indoor navigation purposes for emergency response that need fast evacuation of people inside a building in the case of disaster risk [28], [30], [38].

3.3. Spatio-temporal Risk Assessment: Spatial Analysis

Efficient data analysis can be done by exploiting the high-quality and accurate data obtained from GIS data sources. The spatial information retrieved from GIS sources allows spatial data analysis such as spatial autocorrelation to correlate the occurrence of an event with the location. For risk assessment, the event is normally related to the risk event that has or will happen to an asset. Any event is spatio-temporal data according to [39]. Spatial autocorrelation of the risk events can be used as a decision-support tool by relating the risk towards assets in spatial dimensions [18]. It allows authorities to understand the spatial variation of risks towards an asset at a certain location by indicating whether it has a strong spatial correlation or low spatial correlation. The correlation of spatial information of the risks also points out that the location might be the factor of the risk.

Spatial clustering can indicate whether there is a clustering of risk events concerning the assets. The clustering of the risk events can indicate whether the risk is a hotspot to the assets in a certain geographical area. Hotspot analysis is an essential decision support tool for predictive-based risk assessment. Hotspot analysis allows asset managers to predict the future risk of the assets by looking into the previous risk that occurred on the assets derived from hotspot visualization such as hotspot maps. Hence, aside from spatial information on the risk events, the historical information on past risks that have occurred is crucial to investigate the vulnerability of the assets to the same risks in the future.

The risk hotspot can change over time whether it will become a more serious hotspot zone, or it will decrease and turn into a cold spot. The time-varying changes of the hotspot zone can be analyzed using emerging hotspot analysis that incorporate both the spatial (distance between failures) and time information (time interval of failure observation) of the risk events into the analysis [40]. Emerging hotspot analysis identifies the changes in the hotspot zone over time whether it will increase, decrease, or persistent, and able to visualize a risk hotspot map in three dimensions as shown in Figure 5. The third dimension in emerging hotspot maps is the temporal dimension. Emerging hotspot analysis is fundamentally a spatio-temporal clustering due to the incorporation of temporal dimension [39]. Emerging hotspots for risk assessment are popular to predict the hotspot of water main failure [40], [41].

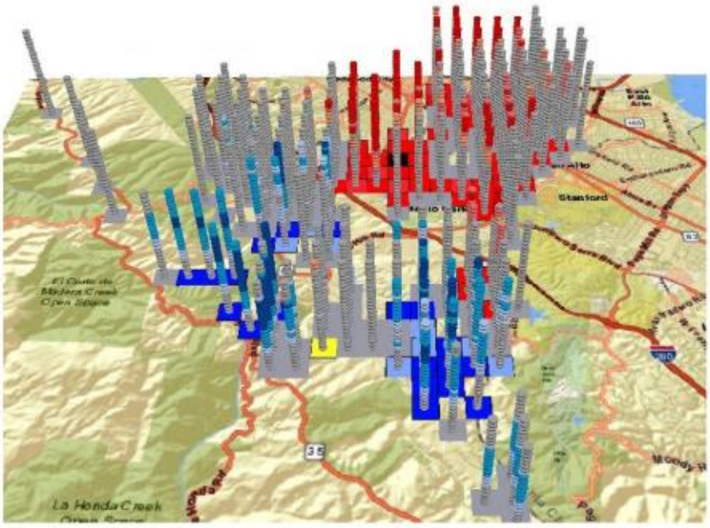

Figure 5. Hotspot map from emerging hotspot analysis on ArcGIS [41]

Getis-Ord Gi* statistics are used in spatio-temporal clustering for emerging hotspot analysis to identify risks with high clustering value (hot spot) and low clustering value (cold spot) by looking into the z-score and p-score resulting from the calculations of the statistics. The Getis-Ord Gi* equation [41] is shown below.

$$G^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S\left(\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}\right)^{1/2}} \quad (1)$$

From the equation, x_j is the failure count, $w_{i,j}$ is the spatial weight between features i and j, and n is the number of failures. The resultant z-score is a standard deviation. A high z-score indicates a more intense clustering of risks occurring in an area. The p-score is the probability that indicates whether the risk is a result of a random process or possesses dependency with external factors. The z-score and p-score are used to suggest whether to accept or reject the null hypothesis (failures are resulted from a random process) based on confidence levels. If the null hypothesis is rejected, the failures possess spatial dependency and are a spatial process based on statistical evidence [41].

Spatio-temporal visualization can be done in two ways either 2D coordinate with temporal information (2D+t) or 3D coordinate with temporal information (3D+t). 2D+t involves planimetric visualization such as maps. In risk assessment, an effective risk assessment involving any type of asset involves the inspection of the asset virtually to model and predict the rate of degradation of the asset in both spatial and time dimensions. However, inspecting the asset solely based on planimetric visualization is strenuous since lacking the detail on the physical characteristics of the objects. Hence, it is more practical to visualize the asset in 3D, where the appearance of the asset virtually resembles the exact appearance of the object in the physical world. The prediction of asset risk can be done accurately and effectively when the 3D model is integrated with the temporal information of the risks.

4. 3D GIS for Risk Assessment

3D GIS works by extending 2D GIS that consists of X and Y components of coordinates with another dimension typically the Z coordinates that contain the height information [42]. Analysts may also substitute the third dimension with other information such as temporal information (2D+t) for the recognition of trends for any phenomenon. Other than that, a 3D model may also consist temporal information (3D+t) for temporal analysis of an object in 3D. A spatio-temporal analysis such as emerging hotspot analysis allows a 3D visualization of risk hotspot occurrences facilitating users and authorities with a better understanding of the pattern of risk hotspots in both space and time dimensions as shown in Figure 5.

Asset management is a key component in Architecture, Engineering and Construction (AEC) domain [43]. Managing assets in 3D is dominated by BIM although several limitations favour 3D GIS for managing assets. Refs [3] highlight that relying on BIM-based analysis and decision-making alone is unable to satisfy the user requirements in the AEC industry which leads to a decrease in quality and inability to decrease the environmental risks. The authors describe that the AEC industry is reliant on spatial and temporal dynamics for many phases in the industry and BIM is not mainly involved in the quantitative analysis of spatio-temporal process. Thus, the management of information needs the integration of 3D GIS for comprehensive modelling and analysis of spatial and temporal data across various phases in the AEC industry.

3D GIS allows a more immersive visualization of any object in three dimensions granting a better understanding of a physical object. Management of building assets information, 3D modelling, spatial queries such as 3D nearest neighbor queries [44] and topological queries [35]. Besides that, precise visualization is also possible with the creation of 3D GIS [45]. Management of infrastructures can be done with increased flexibility through visual interpretation with detailed analysis which supports authorities in the decision-making process and planning.

Among the advantages of 3D City Model such as CityGML is the visualization of a physical objects virtually in a lightweight format. While 3D GIS for asset management is an active subject of research, limited research highlights the importance and practical aspects of 3D GIS for assessing risks using 3D city model visualization. Several research emphasizes the use of 3D city models for disaster risk management [28], [29], [38], [46]. The use of 3D city models in 3D GIS are beneficial for assessing risk as it provides visual representation of infrastructure that are vulnerable to the risk. The 3D model can be combined with other GIS layers such as bathymetry, and topography [47]. Based on the various GIS layer that combined with the temporal factors of the risk, authorities able to conduct a 3D spatio-temporal visualization of the risk to provides authorities with the answer on which assets are susceptible to high level of damage due to risk. Thus, authorities can prioritize any preventive measures to reduce the impact of the risk towards the infrastructure.

Infrastructure assets are vulnerable to disasters and there is a need to evaluate the risk and the impact of the disaster on the asset. Authorities may need to decide the best location to place their assets to minimize the probability of disaster happening to their assets. Besides, placing the assets in the most practical location will ease the service and maintenance process in an effort to reduce the risk that will affect the assets. CityGML is an appropriate solution to these situations. However, CityGML by default lacks the attributes for a specific scenario but it can be improved by sourcing the data from BIM through the development of CityGML Application Domain Extension (ADE) to fetch the domain-specific attributes from IFC, an interoperable format for BIM [29].

The advancement of 3D GIS has made the availability of 3D data storage for the manipulation and integration of 3D city models. The introduction of 3D data storage has eased the data entry and sharing of asset information in 3D. Spatial databases such as PostgreSQL have reduced the barriers for 3D information management permitting centralized storing of asset data and visualization of 3D city models. The adoption of spatial databases allows asset managers to store their assets in 3D city model format for a digital approach to asset inspection for asset condition monitoring [48]. The adoption of digital inspection manages to save a lot of time and allows maintenance scheduling to be done in a more effective approach in a timely manner. Thus, potential risk can be reduced when the assets are maintained appropriately and significantly improved the asset uptime.

5. Case Studies and Applications

5.1. Risk Assessment on Pipelines Asset

Managing pipeline assets is tedious as these assets are hidden underground and authorities do not have a clear visual of what is happening towards the buried pipeline. These assets are needed to be maintained properly as these assets are prone to risk that might affect the operation severely affecting many people. The main problem to manage pipelines based on 2D maps is we cannot easily distinguish the position of the pipes based on two-dimensional positions (X and Y). Thus, the pipes often appear to be overlapped in a 2D map with other underground utilities such as cables [49]. Hence, visualizing the pipes in 3D with additional Z coordinates will enhance the visualization capabilities of the pipes inside a spatial database. In the work of [49], the authors developed a 3D GIS approach to visualize pipelines in a spatial Database Management System (DBMS) and the 3D visualization is developed using CAD software. Their works manage to resolve the complexity to visualize the buried pipeline while also solving the challenges relating to the absence of vertical segments, visualization of the intersection of cylindrical pipes, reconstruction of rectangular pipes and replacement of 3D symbols with 3D symbols for easy interpretation in 3D visualization. The adoption of spatial DBMS allows spatial queries in both 2D and 3D coordinates. Adopting 3D GIS for enhanced visualization manages to clearly visualize the location and the spatial relationship between other buried pipelines in the same vicinity. Hence, in the case of disasters, authorities are able to make quick decision-making for crisis recovery after a disaster happened. Besides, maintenance tasks can be performed safely without worrying any digging activity might damage other pipelines through the development of a 3D visualization, thus significantly reducing the risk of damaged pipes [50].

5.2. Flood Risk Management for Coastal Areas

Flooding is a major concern to coastal areas and poses a great threat to the urban and infrastructures along the coastline. Increasing human activities prompted growing habitation thus increasing the risk of destruction of the buildings and the population in coastal areas. Therefore, predicting the impact of flooding on the coastal areas is imperative for authorities to act suitably and timely to prevent further destruction. The usage of 3D GIS for predicting flood risk has been discussed by several researchers. Refs [47], [51], [52] use DEM for the analysis to determine the effect of varying water surfaces towards flooded areas. The DEM is used to generate a Triangular Irregular Network (TIN) which will facilitate the creation of risk maps to visualize the effect of water level on coastal areas. To achieve an effective analysis of flooded areas, several GIS layers containing bathymetric, topographic and land use need to be acquired. These layers can be utilized to quantify the severity of the flood by predicting the number of infrastructures affected and the areas that will be covered by the flood. The work by [37] manages to predict the number of buildings and the area that will be covered by flood given a certain sea level rise by utilising the GIS layers and 3D GIS modelling of the buildings and other infrastructures. The changes to the coastal areas are dynamic and change rapidly depending on the severity of the flood. Hence, analysing the effect of flooding in spatial dimension alone unable to predict and simulate the changes in the coastal areas due to flooding. 3D spatio-temporal simulation is needed for this reason to study the rapidly changing topography of the area affected by flooding.

5.3. Urban Infrastructure Resilience Effort

Developing urban that are resilient to various risks is a priority for authorities to ensure the urban are aware and well-prepared for any risk and vulnerability to protect important assets. The digitalization of physical objects through 3D GIS technology can be exploited to bridge the assets with any risk factors for a well-informed risk prevention effort through the development of spatial databases to store 3D GIS products and relate them with the spatial information of the risks and hazards. Refs [53] demonstrated the use of 3D GIS products in LoD 0 such as DTM manage to analyse large risk areas and connect them with the geographical, geologic and hazard factors of a risk. A higher level of LoD that represents an infrastructure in 3D form in LoD 2 or higher such as 3D city models is advantageous for risk simulation tools. The main intention of risk simulation is to predict and approximate the level of damage an urban might suffer in the case of risk such as earthquakes and floods in spatial and temporal dimensions. The information from the simulation will inform concerned authorities to be well-prepared and make necessary prevention measures to put focus on developing urban that are resilient and adaptable to the potential risks.

6. Discussion

Physical and Environment risks that affecting physical assets possess correlation between spatial and temporal factors as evident by several research this paper has discussed. The spatial information in 2D of both risks allows authorities to identify the location of the asset and the risk. The uses of temporal information for both risks differs. Temporal information in physical risk contributes to identifying the rate of aging and degradation of the assets with time. Meanwhile, the temporal information of natural environment risks contributes to determining the inclination of risk reoccurrence over time. Both risks provide a more significant information when temporal information is added to the 2D spatial information, that unlocks a more meaningful analysis of the risk through predictive strategy.

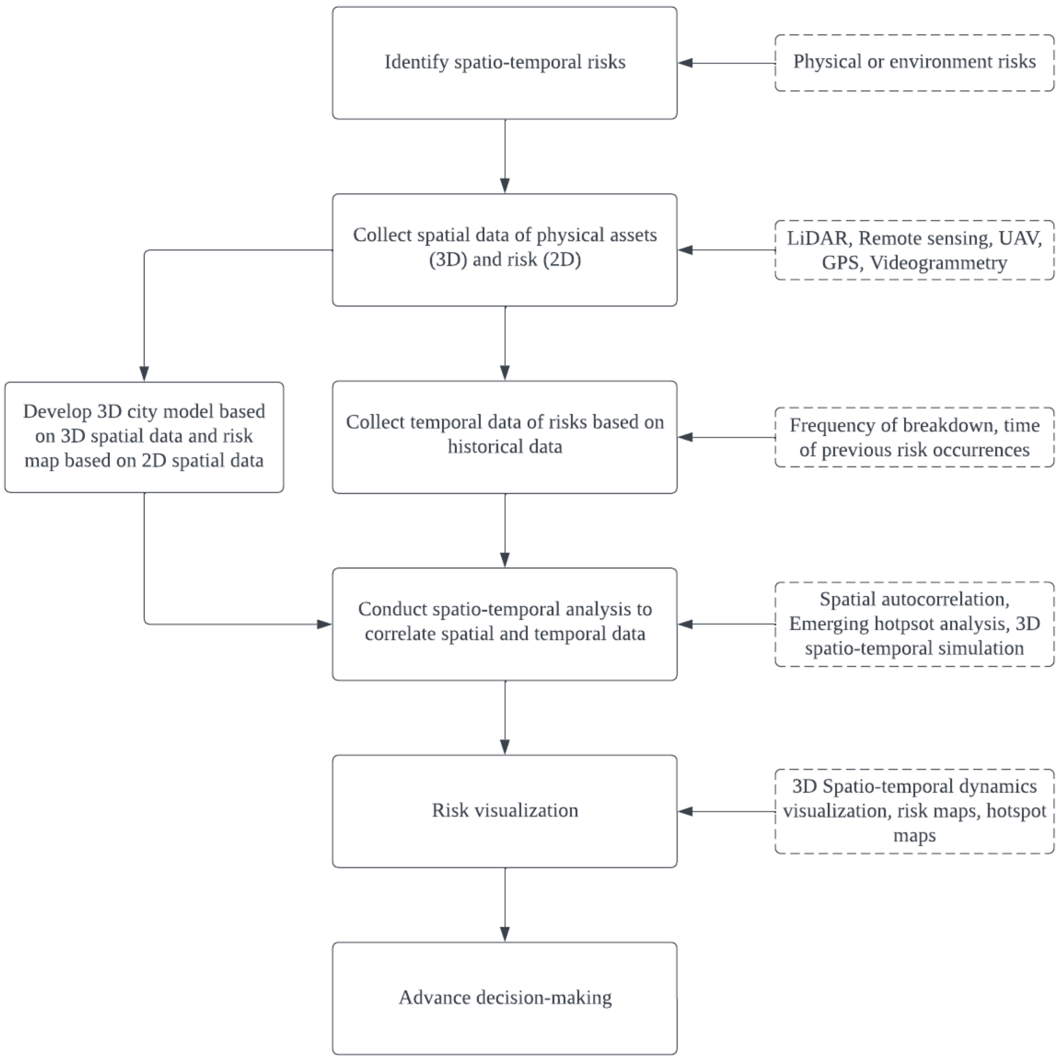

Figure 6. The workflow for spatio-temporal risk assessment

The 2D spatial information when added with height information for a 3D GIS approach, allows a better understanding of the risk affecting the physical assets. Authorities possess the ability to inspect the asset condition in real-time through the creation of 3D model [54], as well as giving information on the future tendency of the assets by understanding the behaviour of the risks and the assets in three-dimension. As demonstrated by [37], the 3D model manages to give authorities understanding on which infrastructure are at risk of flooding when the information regarding the flood is incorporated. Furthermore, the 3D model allows simulation of risks to be made in an effort to create a more useful predictive and preventive analysis to build an urban that are more resilient towards risks that could potentially results in the destruction of infrastructures. To provide a guide for embarking assessing risk spatio-temporally, a workflow for spatio-temporal risk assessment is shown as visualized in Figure 6 to highlight all the important GIS-based data collection tool, analysis, and visualization approach that has been discussed in this study for a successful approach of spatio-temporal risk assessment.

Managing spatio-temporal information is as important as utilizing it for assessing the risk. Spatio-temporal information are heterogeneous in nature [4], thus, need an effective way to manage it. In spatio-temporal asset management research, the scarcity of the focus on how to manage spatio-temporal data is something that needs considerable attention. These include the spatio-temporal data model, and the effective database to manage spatio-temporal information. Highlighting how spatio-temporal information could be manipulated and represented through a data model could provide a more seamless flow of information in a database and ease the interoperability between platforms.

Finally, the overall findings of this study are shown in Figure 7. The approach of various GIS tools has been discussed which allows authorities to utilize the spatio-temporal information for predictive analysis of the risks and allowing predictive maintenance (PdM) to minimize the effect of physical risk towards physical assets.

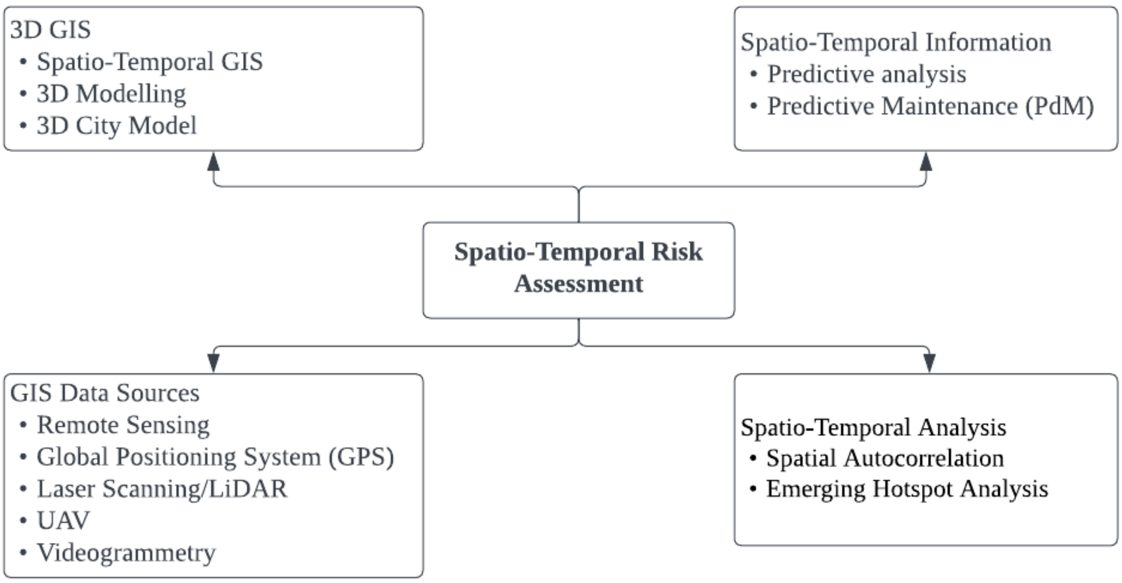

Figure 7. Summary of 3D GIS for spatio-temporal risks assessment

7. Conclusion

To summarize, this article has demonstrated the practicality of assessing risk in asset management spatio-temporally utilizing multiple GIS tools for data collection and data analysis. The aim of this study which is to uncover the use of GIS for spatio-temporal risk assessment have been achieved by emphasizing the data sources, suitable analysis tool, the visualization approach, and how these tools can be exploited to assess risk in asset management that possess spatio-temporal dependency based on GIS approach. The role of spatial information has been highlighted in risk assessment to locate the assets and their risks and to examine whether spatial dependency exists between the risks that occurred on an asset. Adding temporal information has proved to enhance risk assessment towards a predictive-based assessment that provides an advantage in predicting the future tendency of the asset's risks and operation. The historical information in asset management is the main information in temporal dimensions that can be used to predict the future risks of the asset by analyzing the occurrence of past risks on an asset.

Besides that, this article has shown the use of 3D GIS for assessing risk utilizing multi-dimensional information for analysis and visualization. 3D models have been demonstrated to be useful in risk management and the use cases in several applications have been discussed. The use of 3D city models can provide numerous advantages for risk assessment if several limitations can be solved. The limitations are described as the issue regarding data availability and the willingness of the government to adopt 3D city models for urban management [55]. 3D city models are developed mainly for geospatial visualizations [28], [29]; thus, much domain-specific information is inevitably lost. Although the loss of the non-spatial related information is not necessarily a disadvantage to the 3D city model, in some applications, it is advantageous for the 3D city model to possess both spatial and non-spatial attributes to allow a more specific and detailed spatial analysis. Recent research has pointed out that the CityGML ADE can be used to extend the standard data model of CityGML to include more domain-specific information [29]. 3D city models for risk assessment are concentrated on disaster risk management concerning building assets. Hence, for future research recommendation, researchers can investigate the integration of 3D city models for other spatio-temporal risks described in this article other than disaster risks. In addition, the study on data models to facilitate the use of spatio-temporal data in asset management could provide a worthwhile study to assist the integration of spatio-temporal data for various uses in asset management.

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