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INTEGRATION OF BIM, GIS AND WEB
ENVIRONMENTS FOR SOLVING
MULTIFACETED CONSTRUCTION
PROJECT PROBLEMS

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Danylo SHKUNDALOV

**BIM, GIS IR INTERNETO APLINKŲ
INTEGRAVIMAS STATYBOS PROJEKTŲ
DAUGIALYPĖMS PROBLEMOMS SPREŠTI**

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Abstract

Handling real-world data is crucial for addressing various problems and obstacles in the construction industry. Nonetheless, incorporating real-world data is not always achievable. The integration of BIM, GIS, and Web environments is a promising research field that offers numerous benefits in the construction industry for solving this problem. The integration of BIM models, 3D real-world representation, a connection of GIS databases, and geospatial analysis are among the advantages achieved with such integration. The integration process faces many obstacles, e.g., interoperability issues, standardisation, and methods for BIM model processing. Many different techniques and methods to solve the most pressing issues have been proposed in recent years. However, the existing research findings presented in the state-of-the-art are insufficient to cover all issues and gaps in the integration process. This PhD dissertation presents a comprehensive analysis of the revealed issues and gaps, proposes novel methods and techniques for solving the most significant ones, implements the results of the developments in a Web-based spatial decision-support system and solves several fundamental problems in the construction field.

The first section of the dissertation reviews the state-of-the-art using bibliometric analysis to determine the most significant issues and gaps, as well as the main focuses in integrating BIM, GIS, and Web environments. Based on the identified gaps and specified problems, related scientific articles were analysed, revealing and investigating integration and interoperability problems, property attractiveness and building location problems, geospatial analysis, crane selection and operation problems.

The second section presents novel methods and techniques developed in this dissertation aimed at addressing the identified issues and outlines the main research outcomes. This chapter covers multiple developments, including a method for determining relationships between objects in BIM models and recalculating coordinates for improved BIM model processing in a Web environment. The section also proposes a multi-criteria decision-making analysis, a method for visibility analysis based on the mathematical calculation of view, a methodology for crane selection and operation based on the developed visibility analysis, and a methodology for automatic data collection that addresses building location problem and multi-criteria decision-making analysis.

The third section presents an innovative Web-based spatial decision-support system that implements all methods and techniques developed in this dissertation. Its applicability and efficiency are demonstrated by a case study, where multiple problems in the construction field can be solved by the proposed approach of integrating BIM, GIS and Web environments.

Reziumė

Realaus pasaulio duomenys naudojami visuose statybos projekto gyvavimo ciklo etapuose ir yra esminiai užtikrinant racionalių sprendimų priėmimą statybos projektuose. Tačiau ne visada įmanoma įtraukti realiuosius duomenis. BIM, GIS ir žiniatinklio aplinkų integravimas yra vienas iš perspektyvių šių problemų sprendimo būdų. Tokia integracija leidžia susieti BIM modelius, 3D realaus pasaulio vaizdavimą su GIS duomenų baze ir atlikti geoerdvinę analizę. Integravimo procesas susiduria su daugybe kliūčių, tarp kurių yra sąveikos problemos, standartizavimas ir BIM modelių apdorojimo metodai. Moksliniuose tyrimuose siūlomi skirtingi būdai kaip išspręsti svarbiausias problemas. Tačiau šiuo metu esamų tyrimų nepakanka, kad galėtų būti išspręstos visos integracijos problemos ir spragos. Disertacijoje pateikiama išsami literatūros analizė, nustatytų svarbiausių problemų sprendimui siūlomi metodai, tyrimų rezultatai demonstruojami internetinėje erdvinių sprendimų paramos sistemoje ir išsprendžiami kai kurie statybos srities uždaviniai.

Disertacijos pirmojoje dalyje pristatoma literatūros analizė, kurios tikslas – nustatyti svarbiausias problemas ir tyrimų spragas, taip pat BIM, GIS ir žiniatinklio integravimo tendencijas. Nustačius esamų tyrimų spragas disertacijoje analizuotos BIM, GIS ir žiniatinklio aplinkų integracijos ir sąveikumo problemos, aptariami galimi pritaikymai statybų srityje. Skyriuje aptariami naujausi pasiekimai bei taikymo atvejai, susiję su BIM, GIS ir žiniatinklio integracija, nustatomos spragos, apibrėžiama būsimų tyrimų kryptis ir pagrindžiamas tyrimo aktualumas.

Antrojoje dalyje pateikiami disertacijos autoriaus pasiūlyti metodai, skirti spręsti pirmoje disertacijos dalyje nustatytas problemas, taip pat apibūdinami pagrindiniai tyrimo rezultatai. Šis skyrius apima keletą siūlomų naujų rezultatų, įskaitant metodą, skirtą nustatyti ryšius tarp objektų BIM modeliuose ir perskaičiuoti koordinates, kad būtų pagerintas BIM modelių apdorojimas žiniatinklio aplinkoje. Šioje dalyje taip pat aprašomas disertacijos autoriaus sukurtas matomumo analizės metodas, kuris leidžia matematiškai apskaičiuoti vaizdus, šiuo metodu grįstas kranų parinkimo metodas ir metodas automatiniam duomenų rinkimui pastatų vietos parinkimo uždaviniui spręsti ir daugiakriteriui sprendimų analizei.

Trečiojoje dalyje pristatoma disertacijos autoriaus sukurta internetinė erdvinių sprendimų paramos sistema, kurioje pademonstruoti visi rengiant disertaciją sukurti metodai. Sukurta sistema panaudota atvejo tyrime sprendžiant statybos projekto uždavinius projekto planavimo ir statybos stadijose.

Notations

Symbols

A_i – the alternative solution;
 A^* – Fuzzy Positive Ideal Solution (FPIS);
 A^- – Fuzzy Negative Ideal Solution (FNIS);
 a – analysed point in (2.50);
 a_{ij}, b_{ij}, c_{ij} – elements of the array;
 CC_i – the distances between the alternative and FPIS and FNIS;
 D – the decision-making matrix;
 D_p – distance to the point of intersection;
 d_i^* – the distance from an alternative A_i to FPIS;
 d_i^- – the distance from an alternative A_i to FNIS;
 $d(\tilde{v}_{ij}, \tilde{v}_j^-)$ – the distance between two triangular fuzzy numbers;
 K – number of members in a group of decision-makers;
 k – index of the alternative in the decision-making process;
 k – number of cranes in (2.50);
 m – number of rows in (2.3);
 m – number of points in the initial point cloud in (2.50);
 N – total number of elements in a set of data;
 n – the sample size of experts in (2.2);
 n – current line (iteration) in (2.45);

n – number of points that belong to the set A for a specific crane in (2.50);
 R – radius of a sphere;
 R_{max} – the length of the longest line with no intersections (radius of the sphere);
 r – number of columns in (2.3);
 $\tilde{r}_{ij}$ – normalised criterion;
 S – the sum of square differences between experts' judgements and mean value in (2.3);
 t_{now} – current time in (2.45);
 t_{start} – the time when the analysis started in (2.45);
 W – the concordance coefficient in (2.3);
 $\tilde{w}_{ij}$ – the fuzzy weight;
 $\tilde{x}_{ij}$ – the fuzzy rating;
 x_{mn} – element of the matrix;
 α_{max} and β_{max} – maximum horizontal and vertical view angles, respectively;
 λ – longitude;
 $\tilde{v}$ – weighted normalised fuzzy decision matrix;
 ϕ – latitude;
 φ – angle steps;
 χ^2 – the significance of the concordance coefficient;
 $\sum$ – the sum of elements;
 f – denote function specific for data scope;
 Δ – the size of the sample error in (2.2);
 $\cap$ – the logical symbol of intersection operation;
 $\Leftrightarrow$ – the logical symbol of connecting two logically equivalent statements (if);
 $\wedge$ – the logical symbol of logical conjunction (and);
 $\in$ – the logical symbol indicating set membership.

Abbreviations

2D model – two-dimensional model;
 3D model – three-dimensional model;
 API – Application Programming Interface;
 BIM – Building Information Modelling;
 BIM model – a proprietary or standardised type of file and/or set of data that contains
 attributive and geometry data;
 BIM model representation – geometry data of the BIM model used in a Web
 environment for visualisation, data linking and manipulation with the BIM model;
 B-Rep – boundary representation;
 CAD – Computer-Aided Design;
 COPRAS – the COmplex PROportional ASsessment;
 CSG – Constructive Solid Geometry;
 CSS – the Cascading Style Sheets;
 DEM – Digital Elevation Model;
 DOM – the Document Object Model;

DSS – Decision support system;
 DTM – Digital Terrain Model;
 EDAS – the Evaluation based on Distance from the Average Solution;
 FNIS – Fuzzy Negative Ideal Solution in fuzzy TOPSIS method;
 FPIS – Fuzzy Positive Ideal Solution in fuzzy TOPSIS method;
 GIS – Geographic Information System;
 GML – Geography Markup Language;
 GPU – Graphics Processing Unit;
 HTML – the HyperText Markup Language;
 IFC – Industry Foundation Classes;
 IoT – Internet of Things;
 ISO – International Standard Organization;
 JSON – JavaScript Object Notation;
 LOD – Level of Detail;
 MCDA – the Multi-Criteria Decision Analysis;
 NDA –Negative distance to average solution in fuzzy EDAS method;
 OGC – Open Geospatial Consortium;
 PDA –Positive distance to average solution in fuzzy EDAS method;
 QLA360 – Quantitative Landscape Assessment;
 QUVIAS – QUantitative VView ASsessment method for visibility analysis;
 Real-world representation model (3D mesh model) – set of tiles generated based on the
 3D model or using photogrammetry software used for the representation of the
 real-world surrounding;
 SDSS – Spatial decision support system;
 SOA – Service Oriented Architecture;
 SQL – Structured Query Language;
 TOPSIS – the Technique for Order Preference by Similarity to Ideal Solution;
 UI – the User Interface;
 VBA – Visual Basic for Applications;
 Web – (World Wide Web) the system of connected documents on the internet;
 WebGL – Web Graphics Library;
 WGS – the World Geodetic System;
 WoT – Web of Things;
 XML – Extensible Markup Language.

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Introduction

Problem formulation

Real-world data is an essential component of a construction project. It is used at all stages of a project life cycle, enabling an effective decision-making process. The real-world data can be presented from various sources, where the GIS environment is the most widely used solution. However, integrating GIS and BIM environments is a challenging task that suffers from multiple issues, such as environment-native methods, data interoperability, datatype allowance restrictions, etc. Integrating BIM, GIS, and Web environments is one of the most promising and novel techniques for resolving these issues.

Integrating BIM, GIS, and Web environments allows project participants to collaborate more effectively, reduce project conflicts, and optimise construction costs. The variety of Web-based technology solutions can address a diverse set of problems in the construction industry. Assessment of property attractiveness, site planning, and crane selection and operation are among the most relevant construction problems that rely on real-world data and geospatial analysis.

The lack of methods for processing BIM models inside the Web environment is the main problem in the integration process. This problem produces obstacles in data processing, precluding geospatial and multi-criteria analyses. The implementation of geospatial analysis is a significant research field, which, in

turn, is mainly focused on visibility analysis. However, the existing methods for visibility analysis are not suitable and properly applicable to construction problems and multi-criteria analysis. Additionally, the view criterion in the multi-criteria analysis is considered a qualitative parameter described by linguistic grades, and the linguistic grades are not applicable in the geospatial analysis since they cannot precisely describe the real-world situation. Therefore, using geospatial analysis based on data provided by BIM and GIS environments can significantly increase the accuracy of solutions in the construction field.

Integrating BIM, GIS, and Web environments using multi-criteria analysis is a promising research field which can potentially improve the construction processes and solve multiple problems, including the assessment of property attractiveness, building location, crane selection and operation problems, etc. However, the literature analysis reveals a scarcity of Web-based solutions that employ multi-criteria decision-making analysis based on BIM and GIS data.

The research problem of the dissertation is to improve the decision-making process by supplementing BIM models with real-world data, which is achieved by integrating BIM, GIS and geospatial analysis into a Web environment to address problems in the construction field. By applying the developed QUAntitative View Assessment (QUVIAS) method and a Web-based decision support system, it becomes possible to make rational decisions in construction projects using accurate real-world data.

Relevance of the dissertation

The integration of BIM, GIS and Web environments became an important field of study in the scientific community, where the number of scientific articles has significantly increased in recent years. The lack of methods and techniques for processing BIM models inside the Web environment, together with the standardisation of the integration process, remain the main topics of consideration in the integration process. The implementation of geospatial analyses and databases is the main focus of the research field. Many problems in the construction field are related to the optimisation of the processes in the construction project. The multi-criteria analysis is the technic that is widely used for this purpose. Nevertheless, there are no studies addressing problems in the construction field that rely on multi-criteria decision-making analysis using BIM models as a source of data and real-world data presented by GIS or geospatial analysis inside the Web environment. The implementation of geospatial analysis extends BIM possibilities and improves the efficiency of the decision-making process in the construction field. View-related criteria in the multi-criteria analysis are considered qualitative parameters. However, the mathematically-

calculated view parameter potentially has higher accuracy and may be determined at the early stage of the project development.

The dissertation results fill the existing gaps and extend the possibilities of a more reliable decision-making process in construction projects by using the proposed methods and techniques.

Research object

The research object is the integration of BIM, GIS, and Web environments for decision-making in a construction project.

Aim of the dissertation

The dissertation aims to develop a conceptual model based on the integration of BIM, GIS, Web environments and multi-criteria decision-making methods to allow complex analyses for more efficient solutions in a construction project.

Objectives of the dissertation

To achieve the aim of the dissertation, the following objectives must be reached:

1. To conduct the state-of-the-art analysis related to the integration of BIM, GIS, and Web environments.
2. To develop a principal solution for relationships between in-model objects in a BIM model representation in the Web environment.
3. To develop a method (QUVIAS) for visibility analysis that uses BIM, GIS, and Web environments to mathematically calculate visibility and represent it by quantitative parameters.
4. To develop methodological and technological solutions to automate the data collection process in multi-criteria decision-making analysis addressing property attractiveness and building location problems.
5. To develop a method for solving the problems of selecting and operating a crane based on the integration of BIM, GIS and Web environments.
6. To demonstrate the practical application of the proposed model and methods in case studies. Development of a Web-based spatial decision-support system for construction projects.

Research methodology

A bibliometric analysis of the state-of-the-art was conducted on the dissertation's topic, including analytical, regression, numerical, scientific theoretical and comparative methods.

Scientific theoretical, comparative and statistical methods were used in the development of the QUVIAS method for the geospatial analysis. Mathematical statistics and comparative methods were used to determine the set of criteria for a building location problem. The criteria significance was determined using the Delphi method. The agreement between the expert judgments was determined using a concordance approach. Fuzzy TOPSIS, fuzzy COPRAS, and fuzzy EDAS methods were applied to select the rational building location. The crane selection and operation process, as well as the automation of data collection for building location problems, were done based on BIM data and using geospatial analysis and GIS databases, including the QUVIAS method, buffer analysis, and GIS tools. All of the proposed developments were validated and analysed using the case study method. The BIM models were created using Autodesk Revit.

The scientific novelty of the dissertation

The aspects of scientific novelty in theoretical and experimental investigation of the integration of BIM, GIS, and Web environments are as follows:

1. The original conceptual model was proposed for the complex analysis of rational solutions in a construction project with the integration of BIM, GIS, Web environments and multi-criteria analysis.
2. A novel method was developed to define relationships between BIM model objects inside the Web environment.
3. The new unique method (QUVIAS) was created and validated by a case study. This method determines view quality in terms of quantitative parameters using mathematical calculations based on spherical coordinates and data from BIM and GIS environments within the Web environment.
4. A novel approach was proposed based on the QUVIAS method for solving the property attractiveness problem.
5. A new method was presented for automating multi-criteria decision-making analysis and validated in a case study on building location problems. The method uses data provided by BIM and GIS environments and performs geospatial analysis within the Web environment. A new method for crane selection and operation based on visibility analysis and buffer method was presented and validated in a case study.

The practical value of the research findings

The presented research proves the usefulness of the BIM, GIS, and Web environment integration by solving problems in the construction project and increasing the accuracy of the decision-making process. The developed methodology for BIM model processing enables the inclusion of BIM models into a geospatial analysis inside the Web environment. The proposed QUVIAS method introduces a mathematical computation of the view. This approach improves the decision-making process by including the view as quantitative criteria in the multi-criteria analysis. The quantitative representation of the view, combined with the BIM model processing, allows for solving the property attractiveness problem and crane selection and operation problems within BIM, GIS, and Web environments. The proposed automated multi-criteria decision-making analysis significantly decreases time consumption and increases the accuracy of the decision-making process. The practical value of the research findings was confirmed by the practical implementation of all the results into a Web-based spatial decision-support system developed in this dissertation. The case-study results confirm the benefits of integrating BIM, GIS, and Web environments and identify the need for further investigation.

The results of this study are related to digitalisation in construction and the introduction of innovations in the construction industry, which can, directly and indirectly, affect the economic sector. The developed spatial decision-support system with methods proposed in this dissertation can support the decisions of municipalities, real estate and project developers for efficient design of the built environment, thus leading to sustainable construction.

Defended statements

1. The proposed conceptual model enables the complex analysis of rational solutions in a construction project by integrating BIM, GIS, Web environments and multi-criteria decision-making methods.
2. Objects presented in the BIM model within the Web environment can be manipulated and analysed based on the in-model relations.
3. The QUVIAS method, proposed by the author, makes it possible to mathematically calculate a view from a window and present it by a quantitative parameter through the integration of BIM, GIS, and Web environments.
4. The visibility analysis performed inside the Web environment, based on the data provided by BIM and GIS environments, can improve the crane selection and operation process.

5. The integration of BIM, GIS, and Web environments allows for solving the property attractiveness problem.
6. The solution for automating multi-criteria analysis using data provided by BIM and GIS inside the Web environment allows fast and accurate estimation of appropriate and rational building location.

Approval of the research findings

Two scientific articles on the subject of the dissertation have been published in peer-reviewed scientific journals. A detailed list of publications is provided in the dissertation's section, "List of scientific publications by the author on the topic of the dissertation". The research results were presented at five international conferences:

- Shkundalov, D., Vilitienė T. Automotive MCDA for alternative building locations by employing BIM and GIS, The 18th Colloquium "New Trends in Construction Management", 2022, Cracow, Poland.
- Shkundalov, D. & Vilitienė, T. Selection of a crane in Web environment based on visibility analysis. In Research in building engineering, EXCO'21, 2021, Valencia, Spain.
- Shkundalov, D., Vilitienė, T. Building management system in WebBIM environment. In 11th International Conference "Environmental Engineering", 2020, Vilnius, Lithuania.
- Shkundalov, D., Vilitienė, T. A new approach for extending the possibilities of collaboration between BIM, GIS and Web environments to increase the efficiency of building space management. In The 13th international conference "Modern building materials, structures and techniques", 2019, Vilnius, Lithuania.
- Shkundalov, D., Vilitienė, T. The analysis of Web technologies for BIM model processing. In The 17th Colloquium "Sustainable decisions in the built environment", 2019, Vilnius, Lithuania.

Structure of the dissertation

The dissertation consists of an introduction, three chapters and a general conclusions section, a list of literature and sources, and publications of the author on the dissertation's topic.

The volume of the work is 163 pages; the text contains 50 numbered formulas, 37 figures, and 24 tables. The dissertation refers to 328 literature sources.

Literature analysis on the integration of BIM, GIS, and Web environments

This chapter discusses the research trends in the integration of BIM, GIS, and Web environments and determines the obstacles and possible benefits of such integration in terms of the most prevalent use in the construction field. Compared to the traditional literature reviews, the application of bibliometric analysis of the state-of-the-art, conducted in this dissertation, allowed for minimising the chance of subjective judgments. The chapter determines the awareness of BIM, GIS, and Web integration over the past decade, as well as key research topics, latest developments and most pressing issues. Together with that, use cases related to BIM, GIS, and Web integration were explored and analysed, thereby identifying existing gaps and defining the vector of future investigations.

Addressing revealed gaps and issues, this chapter contains the following: an overview of existing solutions and projects related to interoperability problems of the integration of BIM, GIS, and Web environments; application of multi-criteria decision-making analysis for solving facility location problems within the utilisation of data provided by BIM and GIS environments; the possibility of implementation of geospatial analysis inside the Web environment for processing BIM model representation in the GIS content; approach for crane operation using

BIM, GIS, and Web environments. This chapter concludes by formulating the main objectives and tasks of the present investigation.

Four scientific articles were published as a result of the research conducted and discussed in this chapter: (Shkundalov, 2017; Shkundalov & Vilutiene, 2019; Shkundalov & Vilutiene, 2020; Shkundalov & Vilutiene, 2021).

1.1. Analysis of the state-of-the-art related to BIM, GIS, and Web integration

Storing and processing of real-world data plays a vital role in a construction project as it is used in various BIM tasks at every stage of a project life cycle, such as project planning and design, service and logistics, construction management, simulations, etc. (Fosu, Suprabhas, Rathore & Cory, 2015). By real-world data integration, the construction project can reach greater efficiency and achieve better results, improve decision-making, reduce project costs, and improve outcomes.

The BIM life cycle involves various activities and problems (Ustinovičius, Rasiulis, Nazarko, Vilutienė & Reizgevičius, 2015) that involve real-world data operating and managing, processing and analysing. Site planning (Kolat, Doyuran, Ayday & Suzen, 2006), assessment of property attractiveness (Wyatt, 1997), and crane selection and operation (Chen, Fang & Cho, 2017) are among the most relevant construction problems that rely on real-world data as well as employ geospatial analyses (Esmaelian, Tavana, Arteaga & Mohammadi, 2015), leading to better decision-making. To solve the highlighted problems, the integration of BIM and GIS data can be used.

Assessment of property attractiveness can be evaluated by integrating BIM and GIS data to analyse a wide variety of different factors, such as location, proximity to amenities, accessibility, insolation, etc. (Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007). Site planning can benefit from the use of BIM models and geospatial analysis to optimise building placement and design, alternative building locations, etc. (Mendas & Delali, 2012). In crane selection and operation, the integration of BIM, GIS, and Web environments can be particularly useful where real-world data and geospatial analysis are essential (Cheng & Teizer, 2014). This includes calculating dangerous zones, determining reachability, and analysing cabin viewpoints to ensure safe and efficient crane operation (Ancione, Paltrinieri & Milazzo, 2020; Price, Chen, Park & Cho, 2021).

Real-world data can be obtained from various sources, where GIS technology is one of the most widely used solutions (Nishanbaev, Champion & McMeekin, 2021). However, the integration of GIS technology into a BIM environment or vice versa faces multiple challenges (Tobias, 2015). For instance, there is a lack

of environment-native methods and techniques for performing analyses, integrating real-time data and sensors, data interoperability, and data type restrictions (Isikdag & Zlatanova, 2009; Niu, Pan & Zhao, 2015; Ponjavic & Karabegovic, 2019). These challenges can hinder the seamless integration of real-world data in construction processes.

The integration of BIM, GIS, and Web environments presents a promising and novel technique for solving these challenges (Shkundalov & Vilutiene, 2021). Leveraging the unique capabilities of each of these environments can greatly enhance the construction industry's efficiency and effectiveness. The utilisation of Web-based maps that incorporate data from various sources (Chen et al., 2014), such as BIM and GIS environments, IoT and sensors (Gamil, Abdullah, AbdRahman & Asad, 2020), allows for performing sophisticated geospatial analysis addressing a wide range of challenges in the construction field (Iwaniak, Kaczmarek, Strzelecki, Lukowicz & Jankowski, 2016).

The integration of these environments is a valuable solution for solving complex construction problems and improving project outcomes. However, to present comprehensive, high-quality research, the existing scientific works and approaches need to be analysed.

An essential part of any research is the analysis of previous studies and existing projects. This analysis is highly important since it examines the existing field of knowledge on the topic and proves the originality of the current scientific investigation. The bibliometric analysis of the state-of-the-art is the most comprehensive and all-sided analysis that not only allows for identifying existing studies and state the novelty of the current research but also determines the research trends, the number of studies in the field and, most importantly, research gaps and the direction of further investigation.

The bibliometric analysis methodology contains seven steps that are as follows (Shkundalov & Vilutiene, 2021):

Step 1: Examining the current situation in the field of BIM, GIS, and Web integration.

Step 2: Defining relevant information sources.

Step 3: Specifying the search query.

Step 4: Performing searches and extracting data from the database.

Step 5: Filtering the obtained data to be related to the research field.

Step 6: Performing the bibliometric analysis and visualising the results.

Step 7: Analysing the results and drawing conclusions.

The results of the bibliometric analysis contribute to the research field in multiple ways considering all possible impacts and focusing on the following categories: number of publications, year of publication, countries, institutions, journals, authors, author's keywords and main groups of keywords. For the visualisation of the data collected from the scientific database, the VOSviewer

tool was chosen as one of the most widely used and confirmed in many similar studies (Hosseini, Maghrebi, Akbarnezhad, Martek & Arashpour, 2018).

1.1.1. Number of studies in the research field

The integration of BIM, GIS and Web environments involves integrating each environment with others, i.e., BIM and GIS, BIM and Web, GIS and Web, and vice versa. It is important to analyse each of these integrations, as they contain different interoperability solutions and techniques. The analysis of the state-of-the-art revealed the number of studies related to each integration (Fig. 1.1).

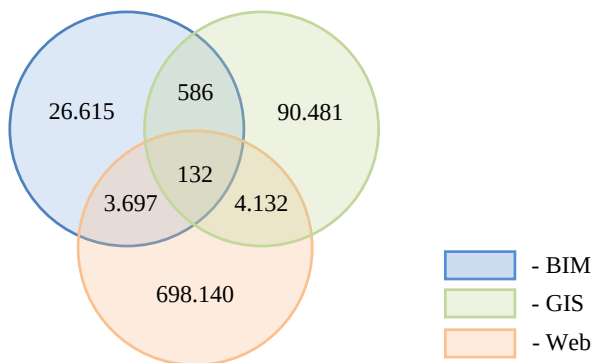


Fig. 1.1. Number of scientific articles in each related environment and their integrations (developed by the author)

The analysis showed that the number of studies in the Web environment is the largest, comprising 698.140 articles. This is followed by the GIS environment with 90.481 related studies, and BIM is discussed in 26.615 documents. The integration of Web and GIS environments contains 4.132 documents, Web and BIM integration has 3.697 articles, and GIS-BIM integration is discussed in 586 articles. This analysis revealed that the number of articles that analyse each environment separately is significantly bigger compared to the articles that analyse their integration. According to the analysis, the integration of BIM, GIS, and Web environments contains the smallest number of scientific publications, that is, only 132 articles, of which 108 are scientific articles and 26 review articles. Such a small number of contributions is not sufficient to cover all the gaps in the research field; therefore, further investigations are required. This conclusion can be considered one of the proofs of this dissertation's importance.

1.1.2. Tendency in the research field

The performed analysis revealed a trend for the growth of research in the analysed area, although the number of publications is limited. This indicates a growing interest in the field of BIM, GIS, and Web integration. Fig. 1.2 depicts the trend of the research in the field of BIM, GIS, and Web integration.

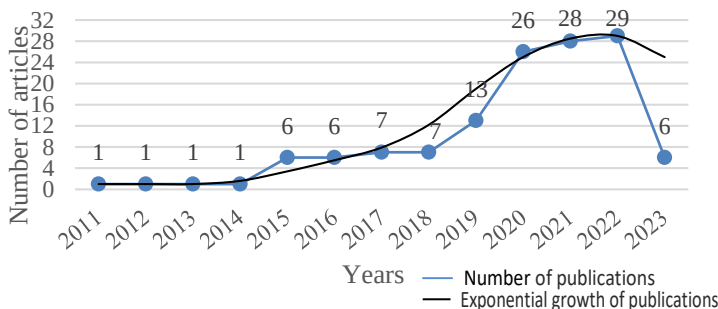


Fig. 1.2. Number of scientific articles related to BIM, GIS and Web integration (developed by the author)

The analysis of existing scientific articles in the field of BIM, GIS and Web environments integrations revealed that the number of scientific articles in the research field is constantly growing: 26 articles in 2020, 28 articles in 2021 and 29 articles in 2022. Based on this analysis, it is concluded that the average tendency shows an increased interest in research focusing on the integration of BIM, GIS, and Web environments. This conclusion allows stating the relevance of this dissertation.

1.1.3. Impact in the research field by countries, organisations, journals and authors

The next contribution of the bibliometric analysis is the determined countries, organisations and journals with the greatest impact in the research field. This analysis allows for determining the state of developments in BIM, GIS, and Web integration around the globe by applying the co-authorship network analysis.

According to the results of the analysis, China, the United States and Australia have the biggest percentage of publications: 24.4%, 12.8% and 9%, respectively. However, the United States has a higher percentage of citations, which is 26.8%, compared to 16.5% and 8.6% in China and Australia, respectively. Curtin University (Australia), Chinese Academy of Sciences (China) and Cardiff University (United Kingdom) are the organisations with the biggest impact in the research field. The most important result in this part of the analysis

for the dissertation is determining the most suitable scientific journal in the research field for publishing scientific articles. The analysis revealed that the “ISPRS International Journal of Geo-Information” holds the first place, “Automation in Construction” holds the second place and “Sensors” takes the third place; however, “Automation in Construction” has the biggest number of citations equal to 132.

The citation network analysis and co-authorship network analysis determined the researchers that provided the biggest contribution to the research field. However, the combined studies were conducted mainly in isolated groups comprising disjointed and fragmented studies. According to such observation, the networks of cooperation should be formulated, where debates and mutual exchange of initiatives and ideas would be prioritised. Based on the analysis results, another conclusion was made that a very limited number of scientists are trying to practically implement the integration of BIM, GIS and Web environments. Such a conclusion highlights a significant gap in the integration process since geospatial analysis is one of the main advantages that the GIS environment brings into integration.

The analysis of scientific publications revealed contributions with the biggest significance in the research field. The studies with the greatest impact are discussed in the following section.

1.1.4. Main focuses, issues and use cases in the research field

The keyword occurrence analysis allowed for determining the main focuses, most pressing issues and use cases in the field of BIM, GIS, and Web integration. This analysis revealed that the most pressing issues in the research field are related to the integration challenges, specifically in the integration process, interoperability, and support challenges. According to the analysis results, the lack of standards and the lack of basic methods and techniques have the greatest impact on the integration process (Karan, Irizarry & Haymaker, 2016; Noor et al., 2019; Xu, Zhang, Li, Lin & Yin, 2020; Breunig et al., 2020). The main investigations in integrating BIM, GIS, and Web environments are in the analysis field, which is presented by 21 keywords, and the management field, which is presented by 11 keywords. For the comprehensive analysis, all keywords were divided into groups depending on their meaning and relevance and then analysed. This analysis allowed for specifying the main focuses in the field of research. The “analysis” group studies are mostly related to GIS analysis and the use of GIS tools. The “management” group keywords refer to data management, BIM model management and project management. The main research use cases in integrating BIM, GIS, and Web environments related to the analysis domain have been identified as geospatial and visibility analysis. The main use cases related to the

management field were determined as data management and building management.

Separately, it is worth mentioning that the analysis of the state-of-the-art related to the integration of BIM, GIS, and Web environments did not reflect the use of multi-criteria decision-making analysis (MCDA). This observation allows for stating that MCDA has not yet been implemented in a Web environment for processing and analysing a BIM model in connection with GIS technologies.

1.1.5. Direction of further research development

Applying the analysis of the co-occurrence map of keywords, the direction of further development in integrating BIM, GIS, and Web environments was determined. According to the analysis results, further studies should be related to the following tasks:

- Solving the issues in interoperability and data exchange, specifically BIM model processing.
- Implementation of the GIS-related analysis for BIM model processing.

The results of the analysis of the state-of-the-art revealed that the integration of BIM, GIS and Web environments does not involve research that would aim to employ the multi-criteria decision-making analysis. Such observation is a big gap in the integration process since the utilisation of MCDA for solving problems in the construction field has substantial benefits. Addressing this observation, the implementation of MCDA for processing BIM models within GIS and Web technologies is required.

The lack of standards, basic methods and techniques are the main issues in solving interoperability problems, where the main focus in BIM, GIS and Web environments integration should be in the development of the methods and techniques for BIM model processing inside the Web environment within the framework of GIS application for the needs of construction. As such, the importance of implementing GIS analysis arises. Relevant scientific articles were analysed considering the conclusions drawn from the bibliometric analysis of the state-of-the-art related to the integration of BIM, GIS, and Web environments and addressing the revealed problems and gaps.

Interoperability problems of BIM, GIS, and Web environments.

The analysis of the state-of-the-art revealed that the most pressing issues in the integration of BIM, GIS and Web environments are related to the lack of standardised solutions, including basic methods and techniques for processing BIM models. These issues affect all kinds of processing and analysis of the BIM model since not all data presented by the BIM model is supportable in the Web environment. To process and analyse the BIM model inside the Web environment using GIS technologies, the interoperability issues need to be solved. To present

an in-depth analysis of this issue, solutions and methods presented in the scientific field were analysed.

1.1.6. Standards, methods and techniques used in the integration of BIM, GIS, and Web environments

Integrating GIS and BIM environments is a complicated process. BIM and GIS environments have significant differences since they were developed for different purposes. Geospatial systems were designed for modelling large-scale reality objects and phenomena that already exist or simulate them within analyses, where the main emphasis is on georeferencing and data actuality (Isikdag & Zlatanova, 2009). On the other hand, BIM solutions focus on small-scale modelling of constructions and objects that do not yet exist (Isikdag, Underwood & Aouad, 2008). The BIM environment has many proprietary standards and methods for constructing and managing the BIM model (Tobias, 2015). Additionally, BIM software cannot retrieve all kinds of information from the GIS environment using default tools (Ponjavic & Karabegovic, 2019). As a result, GIS analysis, GIS objects, their locations and characteristics cannot be analysed inside the environment where the BIM model is developed (Rafiee, Dias, Fruijtier & Scholten, 2014).

Based on analysis of the state-of-the-art, the main obstacles to BIM and GIS integration are as follows:

1. The BIM environment operates in more geometry representations compared to the GIS environment;
2. Different semantics;
3. Different coordinate systems' implementation;
4. Lack of standards, methods and technological solutions.

The difference in geometry types is one of the most significant differences between BIM and GIS environments (Xu, Zhang, Li, Lin & Yin, 2020). BIM models mainly use CSG or solid geometry (buildingSMART: IfcWallStandardCase, 2022), and in GIS, the geometry is limited to B-Rep geometry, such as geometry primitives, planes and meshes (CityGML Specification, 2022).

The difference in semantics (Isikdag & Zlatanova, 2009) appears because the GIS environment is responsible for handling large-scale objects, such as countries and cities (Azhar, 2011). In contrast, BIM focuses on small-scale objects, such as buildings and constructional elements. Mapping the semantics of the highlighted above environments is one of the solutions that can solve this problem (Isikdag & Zlatanova, 2009).

Another main obstacle in BIM and GIS integration is related to the coordinate systems that are used in those environments (Arroyo Otori, Diakité, Krijnen,

Ledoux & Stoter, 2018; Zhang, Hou, Wang, Pan & Yan, 2020). The GIS environment mainly uses three coordinate systems that are: geographic coordinate systems, projected (reference) coordinate systems, and a local coordinate system (ArcGIS: Coordinate systems, projections, and transformations, 2022; QGIS: Working with Projections, 2022). The BIM environment mainly uses two coordinate systems, i.e., a survey coordinate system and a project or local coordinate system (Autodesk Revit: About Coordinate Systems, 2022; Bentley: Assigning A Geographic Coordinate System, 2022).

The last obstacle in the integration process is related to the lack of standardised methods and techniques for processing GIS in BIM and vice versa (Niu, Pan & Zhao, 2015). I.e., the BIM environment contains a set of mechanisms, rules and methods for creating, processing and managing BIM models that cannot be seen in the GIS environment (Aien, Rajabifard, Kalantari & Shojaei, 2015). On the other hand, the GIS environment contains its methods and tools for processing, storing, managing and analysing the GIS data that are not presented inside the BIM environment (Berlo & Laat, 2011).

According to the highlighted obstacles, the integration at the system level is not reachable (Donkers, 2013) (Biljecki & Tauscher, 2019). Nevertheless, the integration can be achieved on the data level, semantic level or within the integration of Web technologies (Hijazi, Ehlers & Zlatanova, 2010).

On the data level, the transformation of the data needs to be performed, where BIM models presented in proprietary file type or with the IFC standard need to be converted into GIS supportable file type, and vice versa (Zhu, Wright, Wang & Wang, 2018). This process has to transform the semantic data, as well as the geometry (Isikdag & Zlatanova, 2009). However, such conversion cannot produce a valid geometry (Donkers, 2013), including IFC to CityGML (CityGML Specification, 2022) conversion tools. In the case of converting GIS file formats into BIM supportable, such as the CityGML standard, new properties of the existing CityGML class need to be created with respect to the IFC compatible properties (Room, Window, Door, Surface, etc.) (Laat & Berlo, 2010). However, such solutions are project-specific and cannot be used across different domains due to changed file structure. Therefore, another solution needs to be used.

In conclusion, straight integration between BIM and GIS environments is not possible since concepts of methodological and technical solutions in each environment, as well as semantics and geometric data, are misaligned. The integration of data without transformations or modifications of the environment is not possible either.

The desired integration needs to present all types of data from a GIS environment, such as database connection, geometric primitives, surfaces and polygons, models and meshes, and all types of data from the BIM environment, where each object has own attributive information and geometries in different

scales. Such integration can be achieved inside the Web environment using Web technologies. Multiple authors (Irizarry, Karan & Jalaei, 2013; Karan & Irizarry, 2015; Karan, Irizarry & Haymaker, 2016) highlighted the usefulness of Web technologies in solving interoperability issues of BIM and GIS integrations (Liu, Wang, Wright & Cheng, 2017).

The Web, or the World Wide Web, is a set of technologies used for the creation, management, publication and browsing of structural data on servers (W3C - Linked Data, 2020). Nowadays, the Web is applicable in a variety of cases, including different areas and purposes.

Some researchers (Amirebrahimi, Rajabifard, Mendis & Ngo, 2015) focused on the BIM and GIS integration with semantic Web technologies, including the IFC and CityGML integration (Deng, Cheng & Anumba, 2016; Ci-3 Industry Foundation Classes for GIS (IFG), 2020), using Open Geospatial Consortium standards (Open Geospatial Consortium - Conceptual Model, 2020). The articles conclude that some interoperability issues can be solved by using LandXML (Schema LandXML-2.0, 2020) and IndoorGML (Li, Lee, Zlatanova, Morley, 2020). The authors highlight that such technologies as Unified Modelling Language (El-Mekawy, Ostman & Hijazi, 2012a; El-Mekawy, Ostman & Hijazi, 2012b) and the Quartierdaten-Management system (Benner, Geiger & Leinemann, 2005) can be used as well.

The integration of GIS and Web environments can be done in various ways, such as map connection, point cloud representation, GIS layers use, and elevation surface modelling (Nishanbaev, Champion & McMeekin, 2021). The Web environment has a myriad of tools and methods (Chen et al., 2014) for processing the information from the GIS environment (Iwaniak, Kaczmarek, Strzelecki, Lukowicz & Jankowski, 2016).

The integration of the BIM model into the Web environment is a much more complicated process compared to GIS and Web integration. The reason for this is that up-to-date native BIM file types remain unsupported by the Web environment (Gao, Liu, Wang, Gu & Yong, 2015; Amann & Borrmann, 2016) and cannot be processed outside the proprietary software used for its creation. To have an opportunity to process the BIM model inside the Web environment, the BIM model needs to be converted into a Web-supportable file type (Niu, Pan & Zhao, 2015). Multiple articles (Kang & Hong, 2015; Fosu, Suprabhas, Rathore & Cory, 2015; Amirebrahimi, Rajabifard, Mendis & Ngo, 2016) highlight that the conversion process cannot present a sufficient BIM model representation since the structure of the geometric and attributive information is different. The widely used IFC file type (Eastman, Teicholz, Sacks & Liston, 2011) cannot be processed without conversion either. Nevertheless, the geometry presented in the IFC file may be parsed and used within the application of Web technologies.

The integration of BIM and Web environments is of half the interest compared to the GIS and Web integration (Fig. 1.1). Therefore, it has fewer methods and tools for the integration process (Rechichi, Mandelli, Achille & Fassi, 2016). To process and visualise the 3D geometry stored inside the BIM model, the Web Graphics Library (WebGL) (Khronos: WebGL, 2022) needs to be used.

WebGL is a standard designed for low-level 3D graphics application programming interface (API) based on the OpenGL standard, exposed via the Hypertext Markup Language (HTML) 5 Canvas element as Document Object Model (DOM) elements (Khronos: WebGL, 2022). WebGL is similar to OpenGL specification but is based on the principal shading language for OpenGL (GLSL). As such, WebGL is used as an API for rendering 2D and 3D graphics within a Web browser without the need for extra software or plugins (Khronos: WebGL Specification, 2022).

1.1.7. Existing solutions in integration of BIM, GIS, and Web environments

The use of Web technologies is implemented in modern solutions of BIM and GIS integration that involve cloud repositories. An online cloud repository allows for storing BIM files online and providing access to their content through the Web simultaneously for multiple software solutions (Esri ArcGIS Pro: Connect to a BIM cloud repository, 2022).

Delgado et al. (2013) (2015) investigated the solutions that can be applied to a BIM model representation inside the Web environment. The authors highlight the lack of technologies and methods for solving BIM and Web integration.

Niu et al. (2015) faced the integration issue related to scaling, where the BIM model or GIS map must be scaled to fit other objects.

Xu et al. (2020) presented a solution for the integration of the BIM model representation inside the Web environment using the Cesium library that provides an opportunity to connect GIS data as well. The main advantage of the proposed method is in streaming BIM model representation as 3D tiles. Such an approach allows for visualising large-scale models. However, the conversion of the BIM model into the .obj file type removes all attributive information from the BIM model. Additionally, the methodology of specifying the coordinates of the objects defined as tiles is not presented.

Zhang et al. (2020) focused on the transformation of the coordinates concluding that the lack of standards (El-Mekawy, Ostman & Shahzad, 2008) leads to losses and changes in data sharing and exchanging. Another conclusion made by the authors states that in BIM, GIS, and Web environment

interoperability, the merging of the coordinate systems is one of the main problems that has not been sufficiently investigated.

The most significant project that integrates BIM, GIS, and Web environments was recently developed by the Esri and Autodesk partnership named GeoBIM (ArcGIS GeoBIM, 2022).

It needs to be clarified that the solution developed by Esri, named GeoBIM, is the concept of BIM and GIS integration, firmly known as GeoBIM (Noardo et al., 2020). In the first case, GeoBIM is the name of the product, and in the second case, GeoBIM describes the integration in general.

The GIS environment in the GeoBIM viewer is presented based on WebAssembly binary instruction format (WebAssembly, 2022) and WebGL solution for its visualisation. The BIM environment in Online viewer is presented by the Autodesk BIM Collaborate Pro solution that is based on Autodesk Forge (Autodesk Forge, 2022) platform that provides APIs for data management, reality capture, view, design automation, model derivative, and BIM 360 connection.

The integration of ArcGIS and Autodesk BIM Collaborate is made using a cloud-based solution that involves the connection of the multiple servers for each environment in a single Web-based application. This application is divided into two parts: the GeoBIM viewer, which represents the GIS environment, and the Forge viewer, which is responsible for BIM environment processing.

The navigation of the whole project is done inside the GeoBIM viewer (Fig. 1.3).

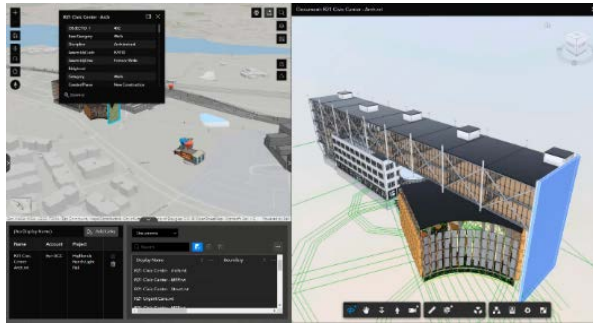


Fig. 1.3. ArcGIS GeoBIM solution (ArcGIS GeoBIM, 2022)

The most cited author in GIS, BIM, and Web integration, Lv Zhihan, presented multiple scientific articles (Lv, Yin, Zhang, Song & Chen, 2016; Lv et al., 2016; Lv et al., 2018) focusing on the integration of GIS and BIM environment and connecting the Internet of Things (IoT). The author uses Web technologies in the development of a Web-based platform for city management,

including transportation, urban resources management and environmental protection.

The Internet of Things (IoT) is a concept that consists of sensors and smart devices linked to control systems for data exchange (Curado et al., 2018). The interest in IoT integration in the construction field has grown with the advantage of new technologies (Gamil, Abdullah, AbdRahman & Asad, 2020). The use of Web technologies for linking data collected from sensors with analytical systems is called the semantic Web. The World Wide Web Consortium (World Wide Web Consortium, 2022) determines this type of technology as the Web of Things (WoT), which is designed for easy integration of metadata, interfaces, mechanisms, systems, and platforms (W3C - Linked Data, 2020).

According to the analysed articles, the conclusion can be drawn that the main advantages of Internet technologies in the construction field can be defined as follows:

- Improvement of project quality;
- Project cost refinement;
- Improved information exchange;
- Real-time data update;
- Improvement of decision-making problems;
- Faster detection of deviations in the construction project;
- Faster and more efficient collaboration with partners.

The integration of BIM and IoT extends the data-collecting activity of the construction project. However, such integration suffers from the lack of standards and interaction methods (Framling, Kubler & Buda, 2014; Dave, Kubler, Framling & Koskela, 2016).

Many authors (Huang, Gartner, Schmidt & Li, 2009; Sriharee, 2015; Turgut, Aydin & Sertbas, 2016; Lyardet, Szeto & Aitenbichler, 2008; Cantareroa et al., 2018) presented studies related to human positioning using various devices and sensors. Such projects focus on automatic analysis in many BIM use cases, such as accessibility, safety, and security (Teizer et al., 2017).

Smart City (Lai et al., 2020) concept describes the use of IoT in the content of the city that allows for managing resources more effectively (Aldegheishem, 2019). The gathered information is processed and analysed by the control centre to monitor, manage and manipulate the related mechanisms (Kumar, Dahiya & Kumar, 2017).

Another city-scale concept that uses IoT is known as Digital City. Even though Smart City and Digital City are different concepts in their meaning (Dameri, 2014), they both have advantages in using IoT.

Digital City (Shahat, Hyun & Yeom, 2021) is a set of technologies and methods for managing, processing and acting related to city infrastructure. A Digital City is a virtual model with comprehensive physical and functional

capabilities similar to a real city, firmly known as a digital twin (Boschert & Rosen, 2016). The Digital City concept aims to provide citywide interactive services through the transformation of the real city and urban area with the help of modern technologies, such as IoT and WoT, used for activities and functions that take place in the physical space of the city (Schleich, Anwer, Mathieu & Wartzack, 2017).

One of the first projects that presented the digital city concept was the Helsinki city project created in 2001 (Julin et al., 2018). However, it does not provide any kind of processing ability to manage or analyse the city model. The second generation of the Helsinki city project is the Helsinki 3D+ project (Helsingin kaupunkinkanslia: 3D models of Helsinki, 2022). This project contains two models: a 3D semantic city model (Helsinki: Kartta, 2022) with information about each object in the city and a 3D mesh model for visualisation (Helsinki: 3D Mesh Map, 2022).

One more project of the Digital City initiative is Virtual Singapore (Virtual Singapore, 2022; Fei & Qinglin, 2019), developed by the National Research Foundation. This project involves 3D information based on the CityGML standard and includes three LODs captured using airborne laser scanning and mobile laser scanning.

In conclusion, the analysis of the existing projects that integrate BIM and GIS environments inside the Web environment revealed that such integration brings many advantages in different fields, including city planning, transportation, energy management and building operation. The most widely applied solution for interoperability is a conversion of the BIM model into a Web-supportable format. Just one project presented by Esri and Autodesk provides the opportunity to process the BIM model in a way that is more native to the BIM environment. However, the presented integration uses two separate environments that are presented by different viewers, which are GeoBIM and Forge. Such integration allows the processing of GIS and BIM information simultaneously. However, it does not allow for manipulation in a single environment. Therefore, the BIM model representation presented in the GeoBIM solution does not contain technologies and methods from the Forge and cannot be manipulated natively.

According to the analysis of the existing projects for BIM model processing inside the Web environment, the conclusion can be made that there are no solutions that would use the technologies and methods for BIM model processing similar to the native BIM operations. This situation leads to BIM model processing inaccuracy and decreases the analysis results.

1.2. Multi-criteria analysis for solving multifaceted problems in construction

Addressing the conclusions made by analysis of the state-of-the-art related to the lack of solutions for performing MCDA inside the Web environment and for processing the data provided by BIM and GIS environments, in-depth research was performed about the possibility of MCDA implementation. The importance of such integration arises since real-world problems and GIS-related parameters are usually complex, having multiple parameters that cannot be compared and analysed by usual mathematical analysis. For such problems that cannot be solved in the regular mathematical way, multi-criteria decision-making analysis is used.

MCDA is used to determine the best solution out of various alternatives based on a set of criteria and using multiple methods, such as stochastic dominance theory in the pairwise comparisons of alternatives, the surrogate risk measurements with additional criteria, scenario planning, etc. (BanaeCosta, 1990). MCDA can be considered as a specific perspective to deal with problems that include a set of theories, methodologies and techniques. The main aim of MCDA is to help in making decisions in terms of ranking, choosing and sorting.

Since the MCDA is used in various fields of knowledge, a myriad of methods and approaches exists (Turskis, Urbonas & Daniunas, 2019; Zavadskas, Antucheviciene & Turskis, 2021; Nikmehr, Hosseini, Martek, Zavadskas & Antucheviciene, 2021). According to Triantaphyllou (2000), the MCDA methods can be classified into four main groups, as presented in Table 1.1.

Table 1.1. Groups of multi-criteria methods

Method class	Criteria data type	Methods
Methods are based on the multi-criteria utility theory	Quantitative measurements	SAW, TOPSIS, TOPSIS-G, COPRAS, COPRAS-G, ARAS, MOORA, VIKOR, MultiMOORA
Analytical hierarchy and indefinite set methods	Qualitative measurements are given a quantitative form	AHP, Methods utilising fuzziness
Verbal analysis decision methods	Qualitative measurements, transition to quantitative variables	ZAPROS, PARK, ORKLASS, CLARA, DIFLASS, CIKL
Comparative preference methods	Quantitative and qualitative measurements	ELECTRE, PROMETHEE, MELCHIOR, UTA, MAUT, TACTIC

The deterministic models of MCDA can hardly describe the real world due to the uncertainty of the data about the real world. Therefore, fuzziness was introduced by using fuzzy sets (Yager, Goldstein & Mendels, 1994; Chou, Hsu & Chen, 2008). Fuzzy decision-making analysis is designed to optimise several objective functions with uncertain parameters at the same time (Lu, Zhang, Ruan & Wu, 2007).

The fuzzy sets are widely used in MCDA location planning problems. The fuzzy methods allow for considering both objective and subjective criteria of the location for selecting the most suitable location of the facility (Tabari, Kaboli, Aryanezhad, Shahanaghi & Siadat, 2008). Achillas et al. (2010) proposed a methodology for analysing the economic and social criteria of the location alternatives using the ELECTRE method. The research presented by Briggs et al. (1990) uses the PROMETHEE method considering the opinions of multiple stakeholders related to radioactive waste for electronuclear facilities.

The multi-criteria analysis was used in solving various GIS-related problems, such as location and site planning, town and rural planning, resources distribution, and others (Malczewski & Jackson, 2000; Sumathi, Natesan & Sarkar, 2008; Kallali, Anane, Jellali & Tarhouni, 2007). The facility location planning problem (Kolat, Doyuran, Ayday & Suzen, 2006; Gilliams, Raymaekers, Muys & Orshoven, 2005) and assessment of the property attractiveness and price prediction problems (Wyatt, 1997) involve the biggest number of criteria that are related to the geospatial data since each alternative location is defined geographically, where each geographically related criteria has own value (Esmaelian, Tavana, Arteaga & Mohammadi, 2015).

Each problem formulates its own set of criteria depending on the problem's needs (Antucheviciene, Kala, Marzouk & Vaidogas, 2015). However, the correlation between criteria used in the building location problem (Li, Zeng, Zhang, Yang & Jiao, 2007; Behzadian, Kazemzadeh, Albadvi & Aghdasi, 2010; Fernandez-Castro & Jimenez, 2005; Mendas & Delali, 2012), and property criteria used in assessing the attractiveness of a property and price prediction can be seen (Din, Hoesli & Bender, 2001; Fung, Kung & Barber, 1995; McCluskey, Deddis, Mannis, McBurney & Borst, 1997; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007; Thrall, 1998). The location-related criteria of the building are considered the most important factors in price prediction since the property price is strongly influenced by the property attractiveness that relies on the locational parameters of the property and environmental factors of the surroundings (Abidoye & Chan, 2017). Vice versa, price-related criteria are considered the most important criteria in location planning problems (Chang, Parvathinathan & Breeden, 2008). The reason for this is that economic analysis, such as construction cost estimates, project revenue, and sales forecasts, has high

importance in project planning, decision-making in acquiring investment opportunities and avoiding hazards (Nejad, Lu & Behbood, 2017).

The determination of the property attractiveness and, as a consequence, property price is one of the prime activities that take place in real estate. Every country has unique knowledge and experience in weights of the property criteria determination, which influence the methodologies used for calculations, where most of the methods use some type of comparison.

According to Pagourtzi et al. (2003), many methods have been employed for the valuation of property characteristics, such as the profit method, comparable method, hedonic pricing method, multiple regression method, fuzzy logic, etc.

In MCDA, the attractiveness of the asset is determined based on multiple criteria, such as building age, building location, floor area, the number of rooms, view, distance to the points of interest such as public transport, shops, subway, and other (Nur, Junainah & Suriatini, 2021). Therefore, not only the location of the building should be considered in project planning, but the criteria (parameters) of the assets that are beneficial and non-beneficial for the premise attractiveness as well (Antucheviciene, Kala, Marzouk & Vaidogas, 2015; Little, 1970; Power, 2002; Longley, Higgs & Martin, 1994). To present a comprehensive analysis of the most suitable building location, the criteria that influence the potential property attractiveness (Yamani, Hajji, Nys, Ettarid & Billen, 2021), as well as location criteria need to be included in a multi-criteria analysis.

Yamani et al. (2021) stated the importance of noise level, air quality and sunlight exposure in both outdoor environmental criteria and indoor living quality criteria. For the sunlight exposure calculation, the authors used the calculation of the sunlight radiation (Hofierka & Zlocha, 2012) based on the Sun position determined by the Sun ecliptic.

Approaches presented by Cheng et al. (2007) proved the advantages of GIS and MCDA integration by using it in a selection of the most suitable location of the shopping mall and a selection of landfill sites, where the geospatial data was traversed from the GIS databases.

Garcia et al. (2008) used a neural network (artificial intelligence) that was trained on the set of GIS data for solving complex problems that bring benefits in process automation and optimisation. The authors highlight the combination of GIS data and neural networks as a useful and promising method for determining the attractiveness of the premises.

Kaboudan and Sarkar (2008) presented research where property attractiveness is calculated based on neighbourhood home prices. The authors implemented their solution by using the ArcGIS software; however, in the presented research, the determination of the criteria and data-collecting activities were carried out manually, which is a time-consuming process compared to automatic solutions.

Kisilevich et al. (2013) presented an approach for determining attractiveness based on a GIS-based decision support system. The project was developed with the use of the OpenStreetMap solution and PostgreSQL databases. The integration of GIS technology in the decision-making process extends the opportunity of the decision-support system. However, the integration presented by the authors cannot be considered sufficient because only several criteria are traversed from the database for the analysis. The GIS databases contain a big set of information that can be used in attractiveness determination; therefore, it can be concluded that the authors couldn't reveal the full potential of a spatial decision-support system.

Maliene (2011) presented an MCDA method in property attractiveness for the comparison of several alternatives. The set of criteria proposed by the author is created based on the experience of the experts. The ranking of the sub-criteria by their significance is sorted as follows: selling price takes the first place, the locality prestige takes the second place, and the third place goes to assessments of market conditions.

Kaklauskas et al. (2007) presented research for defining the utility and market value of real estate. In the research, the set of criteria applied in Lithuania was generated based on the experience of 35 experts in the field of real estate and property attractiveness, which were interrogation by the mailed questionnaires. The resulting list of criteria consists of 28 factors.

Zavadskas et al. (2021) performed a property attractiveness analysis based on a set of criteria that contains 35 factors. It should be noted that the authors revealed five original criteria for property attractiveness related to emotional, affective and physiological states. The weight of location and neighbourhood criteria is equal to 15.48 per cent.

Jegelavičiūtė (2017) performed a questionnaire survey of 28 experts with special expertise knowledge. Based on the EVS 2012 section European Property and Market Rating, the author developed five key factors that are as follows: location, condition, difference in the area of the premise, engineering solutions, and other criteria. The groups of the criteria were divided into 33 sub-criteria. According to the survey presented by the author, criteria of the location have the biggest significance in the property attractiveness process, equal to 27.21 per cent of the total weight.

Each analysed scientific article presents its own set of criteria that was used in solving decision-making problems. The sets of criteria have differences depending on the task they were designed for.

To get the most suitable criteria for the MCDA problem, research about criteria used in existing scientific articles was performed. An in-depth analysis of the criteria presented in relevant studies (Wyatt, 1997; Din, Hoesli & Bender, 2001; McCluskey, Deddis, Mannis, McBurney & Borst, 1997; Natividade-Jesus,

Coutinho-Rodrigues & Antunes, 2007; Chou, Hsu & Chen, 2008; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010; Maliene, 2011; Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Jegelavičiūtė, 2017) revealed, that even if the names of the criteria are different, the character of the asset they describe remains similar. For example, criteria called “prestige of locality”, “neighbourhood”, and “district prestige” represents the same parameter of the asset, as well as “state of the structures” and “the need for renovation”. This observation allows concluding that common and similar criteria exist. Criteria presented in relevant scientific articles have been collected (74 in total) and analysed to determine the common and most widely used criteria. Based on the analysis, a preliminary set of criteria has been created. Table 1.2 represents the criteria and sources where correlated criteria have been used. The criteria with only one source were removed.

Table 1.2. Criteria presented in scientific articles (developed by the author)

Criteria	Sources
Selling price	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; McCluskey, Deddis, Mannis, McBurney & Borst, 1997; Chou, Hsu & Chen, 2008; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010)
Prestige of locality	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010)
Accessibility	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017; Wyatt, 1997; Chou, Hsu & Chen, 2008)
Environmental aesthetics	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Interior	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Public transport	(Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Chou, Hsu & Chen, 2008; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010)
Year of construction	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Jegelavičiūtė, 2017; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Distance from the city centre	(Maliene, 2011; Din, Hoesli & Bender, 2001)

Continued Table 1.2

Criteria	Sources
The need for renovation	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017; Din, Hoesli & Bender, 2001; McCluskey, Deddis, Mannis, McBurney & Borst, 1997; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Window View	(Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Din, Hoesli & Bender, 2001)
Social environment and crimes	(Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Din, Hoesli & Bender, 2001; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007; Chou, Hsu & Chen, 2008)
Engineering solutions and communications	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Parking and garages	(Maliene, 2011; Jegelavičiūtė, 2017; Wyatt, 1997; McCluskey, Deddis, Mannis, McBurney & Borst, 1997; Chou, Hsu & Chen, 2008)
Exterior	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Heating method	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; McCluskey, Deddis, Mannis, McBurney & Borst, 1997)
Residential space and area of a land plot	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; McCluskey, Deddis, Mannis, McBurney & Borst, 1997)
Floor	(Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Wyatt, 1997)
Equipment of a territory	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Assessment of market conditions	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021)
Type of area	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Din, Hoesli & Bender, 2001; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Balcony	(Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021)

End of Table 1.2

Criteria	Sources
Number of floors	(Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Wyatt, 1997)
Construction design	(Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Layout of premises	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Number of Auxiliary buildings	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021)
Public welfare and culture	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Din, Hoesli & Bender, 2001; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007; Chou, Hsu & Chen, 2008; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010)
Trees and vegetation	(Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Assessment of air conditioning	(Maliene, 2011; Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007)
Basement	(Jegelavičiūtė, 2017; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021)
Distance from public transport stops	(Maliene, 2011; Din, Hoesli & Bender, 2001; Chou, Hsu & Chen, 2008; Achillas, Vlachokostas, Moussiopoulos & Banias, 2010)
Number of telephone lines	(Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011)
Location with respect to parts of the world	(Maliene, 2011; Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021)

The deep analysis of the relevant scientific articles revealed 32 criteria that were used in two or more studies related to the location problem.

The determination of the property's attractiveness and property price prediction involves processing various data, such as real estate sales records, multilevel administration data, land cadastre data, characteristics of the building, etc. (Yu, Liu & Zhang, 2014). Depending on the underlying data sources and the initial set-up of the property, different techniques, methods, and software may be

used. A wide range of applications (Campelo, Bertolotto & Padraig, 2017) integrates GIS technologies, which increases the accuracy of MCDA (Mendas, Errih, Daho, Hamadouche & Saidi, 2010). The concept of GIS and MCDA integration aims at expanding the opportunities of MCDA within the framework of using the GIS capabilities and replacing classical Boolean variables with geospatial data in calculations (Malczewski, 2004).

A decision support system (DSS) (Power, 2002) is a computer system that includes a set of procedures for processing and analysing data and judgments to assist in the decision-making process (Little, 1970). The DSS processes a set of criteria; therefore, such systems utilise MCDA (Antucheviciene, Kala, Marzouk & Vaidogas, 2015).

The integration of GIS into DSS allows for performing a decision-making process considering the geospatial analysis and including geospatial information. Such integration increases the accuracy of a decision-making process that requires GIS data (Crossland, Wynne & Perkins, 1995). The integration of DSS with GIS is used in a wide range of applications (Campelo, Bertolotto & Padraig, 2017). The DSS with integrated tools for GIS data processing is called a spatial decision support system (SDSS) (Keenan & Jankowski, 2019). The main advantage of SDSS is in GIS database connection that provides up-to-date information in real-time (Haklay, 2010). Moreover, the integration of the GIS environment allows the automation of the MCDA within the utilisation of SQL retrievals for traversing the information from the GIS databases (Li, Shen & Li, 2004).

The most widely used techniques in MCDA problems that consider geospatial data are based on the utilisation of the GIS frameworks (Aladwan & Ahamad, 2019) and their tools (Marinoni, 2004; Kallali, Anane, Jellali & Tarhouni, 2007; Anane, Kallali, Jellali & Ouessar, 2008), such as QGIS, Esri ArcGIS, MapInfo, etc. Nevertheless, studies that report the use of Microsoft Excel and Visual Basic for Applications (VBA) (Li, Shen & Li, 2004) for developing a decision-support system can be found.

Research presented by Ma et al. (2020) with reference to Ma and Ren's publication (2017) proposed a data-driven approach for equipment maintenance solved by utilising decision-making models within BIM and GIS technologies. The research is based on the use of GeoJSON, an IFC file type converted into Xbim (Xbim, 2020), and the Cesium library. However, the proposed analysis required more than two days of work from the system's operator. Such high time requirements suggest that process automation is not well implemented, and further research is needed.

The Web-based SDSS applications are not widely used. Mainly, systems called geo-questionnaire and geo-discussion (Keenan & Jankowski, 2019) are used to collect data on people's preferences concerning current and/or future conditions (Jankowski, Czepkiewicz, Młodkowski & Zwolinski, 2016).

Nevertheless, there are no studies that would use Web-based solutions for integrating GIS data and decision-making solutions.

Since studies utilising MCDA in the integration with all three environments, specifically, GIS, BIM and Web, have not been found, the practical implementation of MCDA is considered an important development. A working GIS-based property attractiveness system will be a valuable and acknowledged addition to the decision-making area and real estate in general (Aladwan & Ahamad, 2019).

1.3. Application of the geospatial analysis in BIM, GIS, and Web environment integration

Addressing the conclusions defined by the analysis of the state-of-the-art, the implementation of the GIS analysis inside the Web environment for processing the BIM model should be one of the main focuses. The determined use cases of the GIS analysis are geospatial analysis, visibility analysis and public transport analysis. The defined gap needs to be considered in the context of processing the data presented by the BIM environment, including GIS analysis. The implementation of the geospatial analysis into SDSS is a valuable extension since it allows not just traversing geospatial data from the GIS databases but analysing BIM models in the GIS content for solving problems from the construction field.

Visibility analysis (Sirmans, Macpherson & Zietz, 2005) is one of the most widely used geospatial analyses utilised in a GIS environment. This analysis can also be used to determine the view from windows in the construction industry. Multiple studies (Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021; Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007; Maliene, 2011; Jegelavičiūtė, 2017) considered the view as one of the criteria that have a great influence on the price of real estate since the view from the windows is of importance when determining the attractiveness of the property. The visibility from the windows can influence the property value in the spread of 1–57% (Baranzini & Schaerer, 2011). Such an impact is significant in assessing the rational location of the building, which affects the project cost estimation.

In the GIS environment, mainly three GIS tools are used for view analysis (Bourassa, Hoesli & Sun, 2004):

- Buffer zone (buffer) (Dimopoulos & Yiorkas, 2017);
- Line-of-sight (Yu, Sheng & Chai, 2007);
- Viewshed (Lagner, Kloucek & Simova, 2018; Carswell, Gardiner & Yin, 2010).

Buffers allow finding data about the objects that are located in a certain range from the location of the analysed building. The parameters of buffer zones usually include only the radius of the buffer zone and the coordinates of its centre.

Line-of-sight is a tool that allows creating a line from one position to another and identifying where the line intersects items in the GIS environment. The line-of-sight analysis does not allow for analysing the part of the view that is free from the objects, i.e., points can be generated based on the surface parameters of some object. In case there is no surface to generate the points on, they need to be allocated manually in free space. It is important to place points in free space at an equal distance between points for visibility analysis since the location of the points influences the results of the analysis. Furthermore, such a technique of locating the points requires weeks of labour to analyse a single window; hence, such a strategy is not worth applying.

The viewshed method is the most widely used (Moscoso, Chamilothori, Wienold, Andersen & Matusiak, 2020) in visibility analysis. However, since the computations are based on Boolean variables, the distance to the objects is ignored (Lagner, Kloucek & Simova, 2018). As a result, the accuracy of this approach in assessing the view from the window is debatable.

The aforementioned GIS studies are used to measure property attractiveness; however, none of them can offer reliable estimations of window view metrics. GIS experts primarily use the findings of the aforementioned investigation to appraise the situation and execute assessments of the property parameter based on a complex and time-consuming evaluation. This results in a large amount of work and decision-making relying on the subjective opinion of experts. Although window visibility is one of the key aspects of property attractiveness and price prediction, there are no methodologies or tools to automate the process allowing to accurately determine the view from the window based on computations.

Another important source of information in geospatial analysis is data about the surrounding area (Lake, Lovett, Bateman & Langford, 1998). GIS technologies are useful for gathering data about the surroundings since no on-site measurements are required.

The influence of the view for the property attractiveness and its' significance is disputable. According to Baranzini and Schaerer (2011), the price of the property may rise to 57% influenced by the view, whereas Lake et al. (2000) stated that the influence of the view on the property attractiveness and property price might be less significant. There is no common opinion on the influence of the view from the window on the attractiveness of the property due to differences in the methods used, study areas, study years, and locations (Sander & Polasky, 2009). Nevertheless, according to multiple researchers (Hamilton & Morgan, 2010; Jim & Chen, 2006; Lutzenhiser & Netusil, 2001; Bond, Seiler & Seiler, 2002), buildings with scenic views are more attractive in the urban context.

According to the literature analysis, the researchers mainly investigate the influence on the view by the following objects:

- Ocean – the impact on the attractiveness of the property can be increased up to 60 per cent (Hamilton & Morgan, 2010; Benson, Hansen, Schwartz & Smersh, 1998; Demetriou, 2016);
- Rivers and lakes – the average impact on the attractiveness of the property is 7 per cent (Anderson & West, 2006; Paterson & Boyle, 2002; Wen, Xiao & Zhang, 2017);
- Green areas – are mainly related to parks and forests, and the impact on the attractiveness of the property is 3–5 per cent (Tyrvaainen, 1997; Sander, Polasky & Haight, 2010; Yuan, Wu, Wei & Wang, 2018; Crompton & Nicholls, 2019);
- Other – mainly mountains, historical monuments and city attractions – can impact the attractiveness of the property by 6.7 per cent (Jim & Chen, 2010; Jim & Chen, 2009).

Kara et al. (2020) investigated the applicability of the viewshed method in a condition of a 3D dataset in the Netherlands and highlighted the qualitative bases of visibility analysis.

Several scientific articles (Fu & Rich, 1999; Trigaux, Oosterbosch, Allacker & Troyer, 2015) proposed to calculate the visible part of the view using line-of-sight analysis. The main advantage of the highlighted approaches is in consideration of the mathematical form of the view as a sphere and the representation of the view as a quantitative parameter. The proposed calculation of the visible part of the sky dome is similar to the calculations that are performed in the Esri solution ArcGIS by the view dome analysis (Othman, Yusoff & Rasam, 2019); specifically, the utilisation of the Boolean variables without the inclusion of the distances to the objects are presented in 3D space. Another significant issue observed in the view dome analysis is that the distances between the points on the dome surface are not the same. Therefore, the visibility cannot be calculated precisely since the points on the surface cannot cover the sky dome evenly.

The visibility analysis method highlighted above, called view dome (also known as viewsphere) (Othman, Yusoff & Rasam, 2019), is designed to calculate the free portion of the sky dome from objects. However, this method uses Boolean variables similar to the viewshed analysis that does not consider the distance to the objects (Yang, Putra & Li, 2007). The view dome method is relatively new; therefore, no articles can be found that would utilise the visibility analysis based on the view dome method related to the assessment of the property attractiveness or within the use of BIM technologies.

The Quantitative Landscape Assessment (QLA360) method proposed by Wrozenski et al. (2020) calculates the view as a quantitative parameter, including the determination of some types of objects recognised in the view. The proposed

method has a significant advantage compared to the viewshed method – the QLA360 method allows for calculating the view as a quantitative parameter considering the mathematical shape of the view as a sphere captured as 360-degree photography. Since no BIM technology was utilised, but the 3D modelling software Blender was used, the accuracy of such an approach is lower compared to the information obtained from the BIM model, particularly related to the height and location of the windows. Additionally, the proposed method is based on the viewshed use that does not consider part of the view free from obstacles (Hindsley, Hamilton & Morgan, 2013). However, the most pressing issue of the proposed method is that it involves a transformation of a 360-degree photo into a plane 2D image. Such transformation leads to distortions (also known as aberrations) (Kerkovits, 2020) and inaccuracies in the calculations and reduces the significance of the proposed method.

The literature analysis revealed that no scientific articles could be found that would use the visibility analysis for the assessment of the property attractiveness or related to facility location problems utilising BIM and GIS environments. According to the analysed scientific contributions and based on the WELL Building Standard (The WELL Building Standard, 2019), the view criteria in the multi-criteria analysis is considered as a qualitative parameter expressed in linguistic grades. Furthermore, most of the existing methods for visibility analysis involve issues that increase the inaccuracy of the measurements, i.e., the calculation of the view is based on the calculation of the plane geometry. The view is spherical and can hardly be presented by a figure with corners because the position of the points will be corrupted on corners. Such corruption is well-researched in the GIS environment and is related to distortions of projections (Kerkovits, 2020). Another significant concern revealed in analysed scientific articles and methods for visibility analysis is that most studies are based on viewshed analysis that does not include the distance parameter in calculations and involves distortions that occur due to skydome calculated as geometry with corners. On the other side, studies that employ line-of-sight analysis provide inaccurate results because the distance between ending points on the surface of the mathematical shape of the view is not even.

Concluding the discussion above, no solution or method would allow analysing the view from the window horizontally and vertically in the condition of 3D real-world representation based on BIM data and considering the view as a sphere. Even specialised software, such as ESRI ArcGIS Pro, cannot calculate visibility from the windows at different heights of the building, from different floors and apartments (Oud, 2017). Additionally, during the literature analysis, no studies were found that use visibility analysis in conjunction with the integration of BIM, GIS, and Web environments to solve the assessment of the property attractiveness or price prediction problems.

1.4. Using the integration of BIM, GIS, and Web environments for crane selection and operation

According to the analysis results presented in the state-of-the-art, a lack of practical research implementations can be observed in relation to the integration of BIM, GIS, and Web environments. In particular, this observation is related to the development of analyses for processing BIM models in the GIS content inside the Web environment. Addressing this issue, it is necessary to implement visibility analysis to solve problems in the construction sector. One of the existing problems requiring visibility analysis to process real-world data is crane operation (Chen, Fang & Cho, 2017).

One of the important parameters to consider during crane operation, which is part of the crane selection problem, is visibility from the crane cabin (Cheng & Teizer, 2014). Multiple researchers highlight the importance of visibility analysis in crane operation (Ancione, Paltrinieri & Milazzo, 2020; Zunjic, Brkic, Klarin, Brkic & Krstic, 2015; Kivrak & Kia, 2018; Dwyer, Pandey, McHale & Harness, 2019; Fadda et al., 2015).

The visibility parameter is strictly related to safety at the construction site (Fang et al., 2018). Safety of crane operations can involve multiple procedures, including the use of cameras, sensors and warning systems (Price, Chen, Park & Cho, 2021). The crane operation process depends on the number of cranes and crane types that were selected for the construction project. Therefore, the crane operation is strictly related to the crane selection process.

Crane selection is one of the important procedures performed in a construction project (Marzouk & Abubakr, 2016). The importance arises because of the wide range of activities carried out by a crane (Tam & Tong, 2003). All of these tasks require a specific set of crane capabilities, which affects the selection process. Apart from applicability, the choice can also be dictated by economic reasons (Zavichi, Madani, Xanthopoulos & Oloufa, 2014). It is essential to determine the right type of crane, rather than renting a more expensive one, if not necessary because this greatly affects the project cost, and the budget for a crane can reach millions of dollars (Moussavi Nadoushani, Hammad & Akbarnezhad, 2016). To reduce the cost of renting a crane, two cranes are more often used (Hornaday & Haas, 1993). Moreover, the type and number of cranes affect productivity and work schedules, but most importantly, the crane operating area is considered a danger zone that can be fatal to human life (Shapiro, Shapiro & Shapiro, 2011).

The process of selecting a crane involves complex calculations, and specific systems are usually used to carry them out (Zhang & Hammad, 2007), such as Kranxpert, Cramimax, Compu-Crane, etc. Apart from crane specifications, the

analysis usually includes information about the construction object and its surrounding area.

It should be highlighted that the crane selection process may extend beyond the construction site since the construction project involves supply chain management, which affects the schedule of the crane operations and leads to an economic factor. As an example, Irizarry et al. (2013) investigated supply management with the integration of BIM and GIS technologies to analyse the availability of resources from the visualisation perspective.

The procedure for crane selection and operation is a complicated process that includes an analysis of various factors (Marzouk & Abubakr, 2016). According to the analysis performed by the author, the main tasks in the crane selection and operation process can be divided into several groups, as shown in Table 1.3.

Table 1.3. Crane selection and operation tasks (developed by the author)

Group of tasks	Articles
Detection of the most suitable number of cranes, crane types and required specifications	(Abdelmegid, Shawki & Abdel-Khalek, 2015; Al Hattab, Zankoul & Hamzeh, 2017; Al Hattab, Zankoul, Barakat & Hamzeh, 2017; Han, Bouferguene, Al-Hussein & Hermann, 2017; Hermann, Hendi, Olearczyk & Al-Hussein, 2010)
Optimisation of crane and storage locations	(Pan, Guo & Li, 2017; Tam & Tong, 2003; Moussavi Nadoushani, Hammad & Akbarnezhad, 2016; Hermann, Hendi, Olearczyk & Al-Hussein, 2010; Younes & Marzouk, 2018; Lewis & Bejczy, 1973; Wang, Zhang, Wu & Gao, 2011; Safouhi, Mouattamid, Hermann & Hendi, 2011; Astour & Franz, 2014; Wang et al., 2015; Alkriz & Mangin, 2005; Irizarry & Karan, 2012)
Coordination of multiple cranes	(Al Hattab, Zankoul & Hamzeh, 2017; Al Hattab, Zankoul, Barakat & Hamzeh, 2017; Alkriz & Mangin, 2005; Irizarry & Karan, 2012; Al Hattab, Zankoul & Hamzeh, 2014; Ali, Babu & Varghese, 2005; Zhang, Harris, Olomolaiye & Holt, 1999)
Lifting or erection path planning	(Hornaday & Haas, 1993; Lozano-Perez & Wesley, 1979; Goldobina, Demenkov & Trushko, 2019; Zhou, Guo, Ma, Zhang & Skitmore, 2021; Souravik, Yiyu, Lihui & Jianmin, 2020)
Visualisation and simulation of crane operations	(Zavichi, Madani, Xanthopoulos & Oloufa, 2014; Han, Bouferguene, Al-Hussein & Hermann, 2017; Hermann, Hendi, Olearczyk & Al-Hussein, 2010; Younes & Marzouk, 2018; Wang, Zhang, Wu & Gao, 2011; Astour & Franz, 2014; Irizarry & Karan, 2012; Al Hattab, Zankoul & Hamzeh, 2014; Goldobina, Demenkov & Trushko, 2019; Han, Hasan, Bouferguène, Al-Hussein & Kosa, 2015)

The determination of the most suitable number of cranes and their types is carried out based on the specific needs of the construction project, where the required characteristics of the cranes are calculated based on the type of work they perform.

Coordination of multiple cranes is an important task in crane operation that involves not only danger zone calculations for multiple cranes but considers the overlapping of crane operation areas based on their parameters and locations. Additionally, coordinating the work of several cranes requires the crane viewport to be clear and sufficient for site conditions.

Lifting or erection path planning is another safety-related group of tasks that aims at determining possible listing paths based on building parameters in the context of a real-world situation. This task of crane operation involves visibility analysis to predict possible issues.

Visualisation and simulation of the crane operations involve 3D data analysis and processing. For visualisation purposes, the GIS data presented by a 2D or 3D model is used.

The 3D environment is much more suitable for real-world representation compared to the 2D environment (Olearczyk, Al-Hussein, Bouferguene & Telyas, 2012). Therefore, the use of a 3D environment with 3D models is gaining popularity for solving crane selection problems (Han, Hasan, Bouferguène, Al-Hussein & Kosa, 2015; Han, Bouferguene, Al-Hussein & Hermann, 2017). Approaches that are based on 3D environments allow for expanding the opportunities of crane selection and operation using geometry-based analysis (Ali, Babu & Varghese, 2005).

According to the specific task in crane selection and operation problems, a specific set of parameters and data is required, which may involve crane parameters, real-world data, data about communications and logistics, economic research, and much more (Zavichi, Madani, Xanthopoulos & Oloufa, 2014). One of the tasks that require real-world data and the use of geospatial analysis, such as visibility analysis, is related to the analysis of the view from the cabin. Such analysis may be useful in all tasks described in Table 1.3. It is worth mentioning that crane selection cannot be based on this analysis only. However, the analysis of the cabin viewport is an important part of the analysis that may help in decision-making. Additionally, it is one of the tasks that operate the parameters of the crane, real-world data collected from GIS environments and data provided by the BIM model for performing geospatial analysis.

Hermann et al. (2010) presented a system for the selection and positioning of the mobile crane based on simulations in the 3D content for complex industrial projects. A similar approach with simulation-based analysis was presented by Astour and Franz (2014), where the authors introduced a layout plan. The authors highlight that the implementation of a 3D environment is highly important in the

simulation-based analysis since it allows for analysing the construction site from all sides based on the simulation of interactions.

Zhou et al. (2021) presented an approach for automatic crane lifting based on object recognition. In this research, the authors specify that lifting tasks include many parameters in the analysis that can hardly be processed without the use of computer systems and graphical methods.

Wang et al. (2015) conducted a study on selecting multiple cranes and optimising their position. In this research, the authors developed a system for automated tower crane layout planning based on the use of BIM model representation. The system allows for determining the most suitable number of cranes and their types.

Safouhi et al. (2011) presented an approach for determining the most suitable crane location based on two-dimensional data from the construction site.

Souravik et al. (2020) designed an approach for the optimisation of the lifting path of a tower crane. In the presented research, the optimisation algorithm is based on collision analysis of the lifting path and BIM model, where the latter serves as 3D geometry.

Alkriz and Mangin (2005) focused on determining the most suitable crane location and presented a decision support tool for decreasing the overlapping of the workspace areas (Zhang, Harris, Olomolaiye & Holt, 1999).

Irizarry et al. (2012) integrated GIS and BIM environments to optimise the locations of multiple cranes to reduce overlap in operation areas. However, the presented approach cannot identify the most suitable type of crane after analysis.

Another research that involves GIS, BIM, and semantic Web technology integration was presented by Karan and Irizarry (2015), where crane movement was analysed based on geospatial analysis. In this project, the real world was presented as a combination of rasters and surface models, where the BIM model was placed.

Some authors (Peng & Chua, 2017) presented a decision-support framework for crane lifting planning based on the BIM model. The developed system performs a simulation and analysis of the lifting process.

According to the literature review, several tasks involve crane viewport parameters in crane selection and operation processes. In particular, this can be crane optimisation, coordination of several cranes, erection path planning, visualisation and simulation. The implementation of visibility analysis for crane operation based on data provided by BIM and GIS environments with the use of Web technologies will be an important step in the integration and operation of sensors to substantially improve safety in the construction industry.

1.5. Conclusions of the First Chapter and formulation of tasks of the dissertation

1. Bibliometric analysis of the state-of-the-art related to the integration of BIM, GIS, and Web environments revealed a growing interest from both the scientific community and the construction industry. Many interoperability problems have been discovered, where the main issues are related to the lack of standards and methods. The main focus for further investigations was determined in GIS analysis implementation, specifically geospatial and visibility analysis. There is a lack of research using the above integration with multi-criteria decision-making analysis.
2. The analysis of technologies and methods related to the integration of BIM, GIS, and Web environments showed that, at present, one of the possible integration solutions is the use of Web technologies and the conversion of BIM models into a format supported by the Web environment. Many scientific articles in the state-of-the-art are focused on this integration. However, implementation-oriented research is lacking.
3. In accordance with the analysis of standards, basic methods and techniques, several approaches were presented related to the processing of attribute and geometric data of a BIM model in a Web environment. However, studies related to the development of BIM-native methods for processing BIM models within the Web environment have not been found.
4. Analysis of scientific articles and existing approaches showed that multi-criteria decision-making analysis was used in various studies of GIS and BIM environments. However, there was a lack of studies that used BIM, GIS and Web environments simultaneously to perform MCDA.
5. Research about the multi-criteria decision-making analysis related to the assessment of property attractiveness and building location problems depicted 32 common criteria that were used by multiple relevant scientific articles.
6. The analysis of the existing methods for visibility analysis and related studies revealed multiple approaches designed for solving various problems in the field of construction. However, no method for visibility analysis was found that would provide a precise quantitative calculation of the view for assessment of the property attractiveness and building location problems.
7. According to the literature analysis results, the selection and operation of a crane are one of the tasks in the field of construction, which requires visibility analysis using data provided by BIM and GIS environments.

Nevertheless, no studies were found that used the integration of BIM and GIS environments in Web environments within visibility analysis to solve crane operation problems involving viewport analysis.

Based on the literature analysis results and the above conclusions, as well as considering the identified problems and gaps in the integration of BIM, GIS, and Web environments to solve multifaceted problems from the construction field, the following steps need to be taken:

- Development of a principal solution for the BIM-native method implementation, improving BIM model processing inside the Web environment;
- Proposing a methodology for solving MCDA problems using data from BIM and GIS environments inside the Web environment addressing assessment of the property attractiveness and building location problems;
- Development of a method for quantitative assessment of the window view based on the integration of BIM, GIS and Web environments;
- Development of the Web-based spatial decision-support system for performing multi-criteria decision-making analysis based on data provided by BIM and GIS environments;
- Practical implementation of the proposed methods and techniques in the developed Web-based SDSS to improve the efficiency of construction projects and reduce construction time and costs. The applicability of the developed solution will be verified in the case study, where the following fundamental and traditionally labour-intensive and time-consuming construction problems will be solved using the novel approach: BIM model objects' relations, window visibility analysis, crane selection and operation, assessment of the property attractiveness and building location problem.

The conceptual model for the modelling of rational solutions in a construction project

This chapter presents the proposed conceptual model for the modelling of rational solutions in a construction project. The elements of the model include:

- The solution for the development of in-model objects' relation is presented by the BIM model representation in the Web environment.
- The method for visibility analysis in integrated BIM, GIS, and Web environment (QUVIAS).
- The approach for performing multi-criteria decision-making analysis inside the Web environment, including criteria and their weights.
- The method for crane operation analysis is based on BIM, GIS, and Web integration.

Four scientific articles were published related to the issues discussed in this chapter (Shkundalov & Vilutiene, 2019; Shkundalov & Vilutiene, 2020; Shkundalov & Vilutienė, 2021; Shkundalov & Vilutienė, 2022).

2.1. Elements of a conceptual model for the modelling of rational solutions in a construction project

The integration of BIM and GIS environments within a Web environment is not well investigated. Most of the scientific articles link the usefulness of such integration as a vector of further investigation and highlight the lack of practical implementation. Such integration may solve the gap related to the integration of multi-criteria decision-making analysis for processing BIM and GIS data inside the Web environment for solving problems from the construction field. Additionally, within integrated BIM and GIS environments, the geospatial analyses could be implemented for processing the data from both environments, where the results of a geospatial analysis can be used as criteria in the multi-criteria analysis.

The conceptual model for the integration of BIM, GIS, and Web environments and integration of multi-criteria analysis proposed by the author is presented in Fig. 2.1.

As depicted in Fig. 2.1, the BIM environment is used for creating BIM models within Autodesk Revit software, which provides Revit families as well as IFC classes. The integration of the GIS environment provides GIS database connection, 3D batched model integration, 2D maps, coordinate systems and line-of-sight analysis. The Web environment used in integration provides JavaScript application in the WebGL content with HTML, CSS (SCSS) and other functionality.

According to the concept, the first step of the research is a bibliometric analysis of the state-of-the-art. As described in the first section, this analysis allowed for determining the main issues and gaps, main research fields and focuses, and vector of further investigations.

According to the state-of-the-art, the main issues are the lack of standards, methods and techniques for processing BIM models inside the Web environment. Addressing this conclusion, the author developed the method for determining objects' relations inside the BIM model based on the objects' sequence.

According to the literature analysis, the main focus for further investigation in the research field should be on developing geospatial analysis within the integration of BIM, GIS, and Web environments. Addressing this conclusion, the author developed a new method for visibility analysis. This method allows calculating the view mathematically and presenting it by a quantitative parameter.

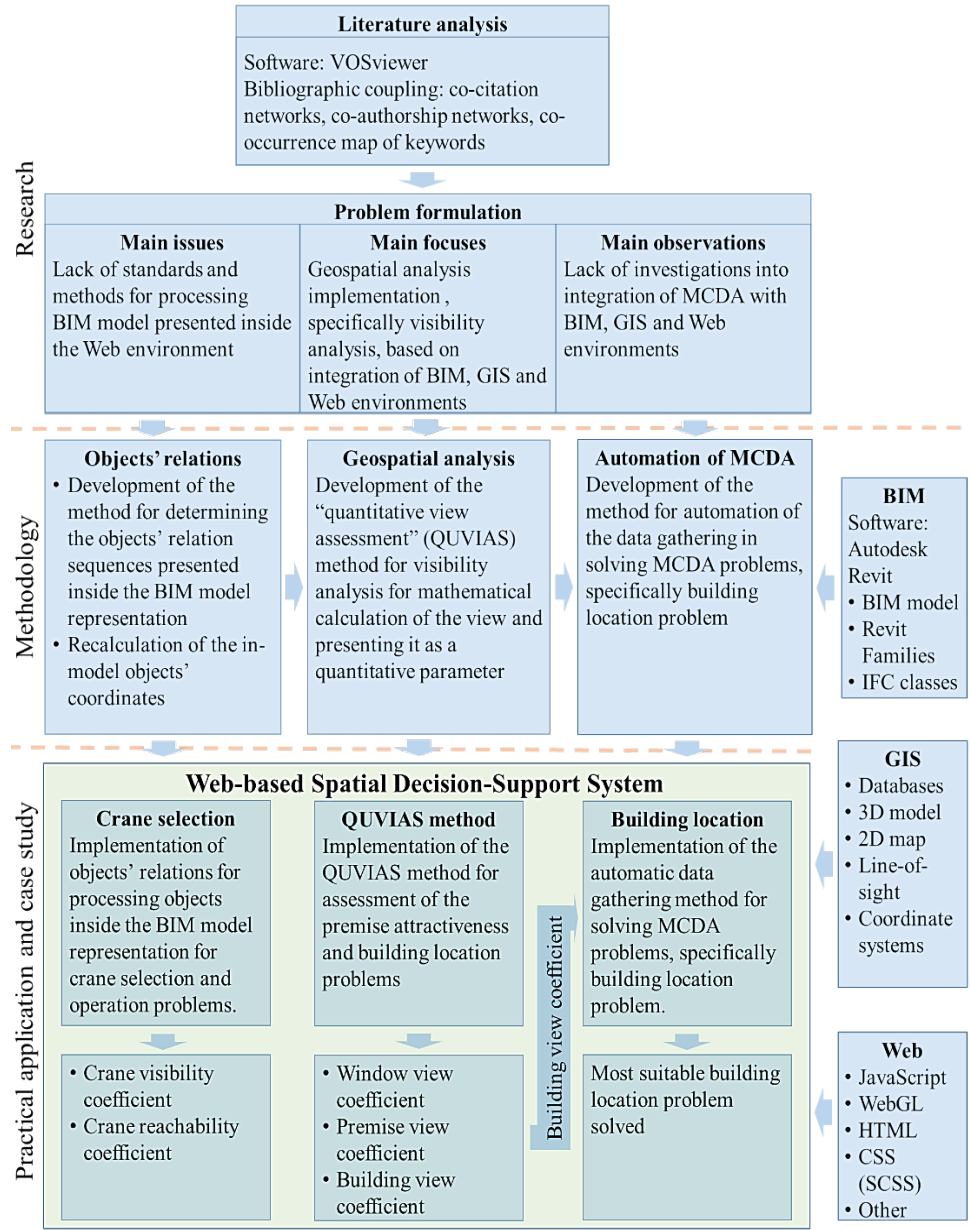


Fig. 2.1. Conceptual model of BIM, GIS, and Web environment integration for performing MCDA (developed by the author)

The proposed method for determination of the objects' relations inside the BIM model is required for the development of the proposed method for visibility analysis since it allows processing the objects presented inside the BIM model representation and determining their coordinates.

The literature analysis revealed the lack of investigations into the integration of MCDA with BIM, GIS, and Web environments. Addressing such a conclusion, the method for automation of the data gathering in solving MCDA problems was developed, specifically for the multi-criteria analysis of the building location. The previously developed method for visibility analysis is used in the multi-criteria analysis for the assessment of building location.

The methods described above were validated in the case studies. For the proposed method of object relations development, the crane selection and operation problem was introduced and solved. The case study for the proposed method of visibility analysis includes the calculation of the window view, based on which the premise view and building view were calculated. The building location problem was solved with the use of the calculated building view that was applied as the view criterion. All of the proposed methods and solutions to the defined problems were performed inside the Web-based spatial decision-support system developed by the author.

To complete the concept of BIM, GIS, and Web environment integration, the first step is to implement the methods and techniques related to the interoperability issues and BIM model processing. The next step is the implementation of geospatial analysis with the usage of the GIS environment and databases. The last step is to automate the data-gathering process for the multi-criteria analysis with the implementation of GIS databases and geospatial analysis for solving problems in the construction field.

2.2. Principal solution for in-model objects' relations of the BIM model representation in a Web environment

As discussed in sub-chapter 1.2.1 BIM environment contains native standards, methods, and techniques for processing the BIM model and objects presented inside the BIM model. One of the key factors of the BIM environment is that each object has relations (BIM Technical Standards: Grouping & Relationship, 2023) with other objects. Such relations are required for linking (mapping) objects and can be described with a set of rules for each object's type.

All relationships can be divided into five categories, which are: composition, assignment, connectivity, association, and definition (BIM Technical Standards:

Grouping & Relationship, 2023). Each category contains a complex set of rules and data structures. According to the data-semantic concepts (Poljanšek, 2023), the integration of relationships is a robust process since methods employed in the BIM environment were designed for specific needs. Therefore, the implementation of Web-based equivalents requires comprehensive studies and developments.

The Web environment does not have any kind of relations for the objects apart from grouping. Addressing this issue, an equivalent of the BIM-native method for determining the sequence of the parent objects need to be developed for the Web environment.

BIM-native methods process geometric information of the objects according to the relations determined by semantic information, where each object is considered as a separate instance. In the Web environment, all objects are represented by B-Rep geometry, where the relevant semantic information is assigned to multiple primitives representing the same object. This approach is not suitable for BIM model processing. To implement the logic for relations of the objects presented inside the BIM model, the model needs to be reworked. The methodology proposed by the author allows reworking the BIM model based on the parents' sequence and coordinates.

It needs to be highlighted that the proposed method is not a similar set of rules and relations as the one used in the BIM environment, but the method for determining the objects presented in the BIM model, relative parent sequence and coordinates. This method allows grouping B-Rep primitives into separate instances with relevant semantic information according to attributive data and parents' sequence. Based on the recompiled objects and assigned semantic information, the BIM model can be manipulated using relevant relations. As discussed above, the implementation of the relations requires multiple studies and developments. Nevertheless, relations from the association and definition categories can be implemented using the proposed method. It needs to be stated that some relations from the connectivity category can be implemented as well. However, such a solution will not act similarly to the BIM-native methods. The reason is different geometries, where the BIM environment involves solid geometry, and the Web environment utilises B-Rep geometry. Therefore, the development of the proposed method is required for implementing object relations.

The proposed methodology can be divided into the following steps:

- Step 1: Determine the in-model relations;
- Step 2: Calculate the correlated coordinates of the objects;
- Step 3: Create the relations of the objects;
- Step 4: Calculate the coordinates of the objects in the Web environment;
- Step 5: Rebuild the BIM model based on calculated coordinates.

In the first step, the relations of the objects inside the model need to be determined by using attributive information. The main part of this process is to inherit the parameters of the host objects where child elements are located. Fig. 2.2 represents an example where the host (or parent) element of Object 3 is Object 2, and the host element of the Object 2 is Object 1. As such, the sequence of the relations for Object 3 is Object 2 and Object 1.

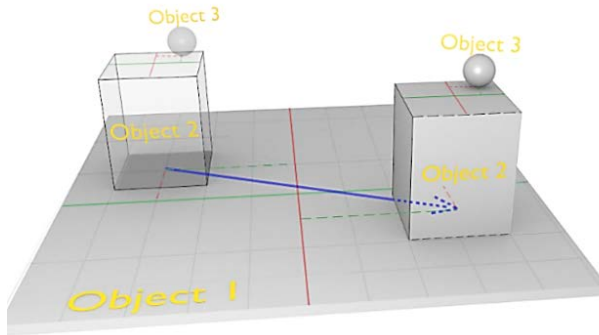


Fig. 2.2. Sequence of the object relations (developed by the author)

The second step is designed for coordinates calculation based on the determined sequences. The determined sequence of the relations allows for calculating the correlated coordinates of the objects based on the parent element. Such an approach is highly important for BIM model processing inside the Web environment, not only for manipulating objects but also for performing geospatial analysis. In Fig. 2.2, Object 3 should be located respectively to the Object 2 centre, where Object 2 is located respectively to the Object 1 centre. Only Object 1 is located based on the centre of the local coordinate system.

The third step involves the creation of the relations for each object. Such dependencies of the objects are used for tracking the changes in the host objects to change the child object in response. The relations are based on the set of rules the object should follow defined by the type of the object.

In the fourth step, the local coordinates of the objects are recalculated. The reason for such recalculation appears because the Web environment cannot locate the objects based on correlated coordinates. The calculation is based on the coordinates of all parent elements. In other words, the sum of the coordinates for all host objects in the sequence. Implementation of the geodesic coordinates and their transformation into the Web Mercator projection is a complicated process in the GIS environment that is developed separately from the actual BIM model processing.

The last step contains recompiling the converted BIM model by using correlated coordinates and determined relations. After this step, the model contains objects that are presented not by groups as highlighted above but as independent objects that have rules and parameters, relations with parent objects and are located using proper coordinates. Implementation of correlated coordinates, rules and object parameters allows for performing a different kind of analysis.

Another important issue is related to the compatibility of the coordinate systems. The use of GIS coordinate systems inside the Web environment is well-known and is applied in Web maps. Nevertheless, such integration of GIS and Web does not involve the use of GIS coordinates for the objects presented inside the BIM model.

The Web environment uses Web Mercator or spherical Pseudo-Mercator (Spherical Pseudo-Mercator projection, 2023) projection for objects' location. The spherical Pseudo-Mercator projection considers the Earth as a perfect sphere that allows a fast approximation to the true elliptical Mercator projection where the Earth is projected on an ellipsoid. In the WebGL environment, where maps are visualised, the local coordinate system is used. Therefore, the location of each object represented on the Web map is determined by the projection of the local coordinate system into the Web Mercator projection.

The BIM proprietary software rarely uses Web Mercator projection for constructing BIM models. The BIM project contains two coordinate systems, where the first is a geodesic coordinate system and the second one is a local or in-project coordinate system. The geodesic coordinate system, which is usually WGS 1984 (WGS84 or EPSG:4326), is required for locating the elements of the project on the construction site for the further construction phases, while the local coordinate system is used for locating the objects inside the BIM software environment. After the conversion of the BIM model into a Web-supportable format, only the local coordinate system stays inside the project.

Objects inside the BIM model representation do not have any coordinates in WGS84 or Web Mercator projection. This is a problem for activities that rely on GIS data processing, such as urban planning, city conceptualisation, and all kind of geospatial analysis. Therefore, it is important to convert not just the BIM model coordinates to allocate the model inside the Web environment but the coordinates of each object presented inside the BIM model.

The transformation of coordinates defined on the WGS84 datum into a sphere-based version of Mercator projection coordinates is a complicated process due to aberrations that grow away from the Equator. Because of such inaccuracy, the scale factor of the objects became corrupted and straight lines became rhumb (curve) lines (Battersby, Finn, Usery & Yamamoto, 2014).

It needs to be noted that each map provider has specific map settings, such as scale factor and size. Therefore, the transformation can have minor changes related to the scale factor. In this dissertation, OpenStreetMap is used as a map provider. Therefore, the simplest solution is to implement the Mercator auxiliary sphere that will have a projection parameter identifying the sphere radius. According to the OpenStreetMap documentation (Spherical Pseudo-Mercator projection, 2023), equation (2.1) can be formulated, which represents the conversion of the WGS84 coordinates into the Web Mercator.

$$\begin{cases} \lambda = \frac{X*180}{\pi*R} \\ \phi = \frac{180*(2*\arctan\left(e^{\frac{Y}{R}}\right) - \frac{\pi}{2})}{\pi} \end{cases} \quad (2.1)$$

With: λ – longitude, ϕ – latitude, R – radius of a sphere that is equal to WGS 1984 semi-major axis or 6378137 meters, X and Y – WGS84 coordinates.

It is important to highlight that such coordinate conversion for BIM model representation is mainly designed for vertical structures such as buildings, stadiums, and power stations, but not horizontal structures such as roads, bridges, and tunnels. The reason for that is that vertical construction projects use two coordinate systems at the same time: a local linear coordinate system and a single geodesic coordinate system. But horizontal structures can use more than one coordinate system due to the length of the structures as they can intersect several geodesic projections. Therefore, multiple stations and alignment curves are used as references (Nuttens, Breuck, Cattoor & Hemeryck, 2018).

With the proposed method of defining relations of the objects presented inside the BIM model representation and based on the recalculated coordinates, the geospatial analysis can be performed inside the Web environment. As depicted in Fig. 2.1, this method is crucial for the implementation of the proposed window visibility analysis.

2.3. Selection of criteria for property attractiveness

Before performing any multi-criteria analysis, the relevant set of criteria needs to be determined.

According to the United Nations Economic Commission for Europe (UNECE) and The European Group of Valuers Associations (TEGoVA), the most important category of the building criteria is location characteristics (Ottensmann, Brian & Man, 2008; Cebula, 2009). Distance parameters of the points of interest are one of the most important parameters, such as educational institutions, transportation, and cultural and public places. Another important parameter is

related to environmental conditions, such as green spaces and trees (Kong, Yin & Nakagoshi, 2007; Mohd, Zainora & Abdullah, 2015). According to the literature analysis, the list of the considered parameters involves criteria for property attractiveness as well since the list of locational characteristics is correlated to the set of criteria used in the property attractiveness, i.e., distance from the city centre, trees and vegetation, public transport, distance from bus stops, etc.

The second category of building criteria is neighbourhood characteristics (Bujanda & Fullerton, 2017). The neighbourhood characteristics are similar to characteristics which are used in property attractiveness, i.e., the prestige of locality, environmental aesthetics, social environment and crimes, the infrastructure of public welfare and culture, public facilities, and religious centres.

The last group of commonly used criteria is structural characteristics (Randeniya, Ranasinghe & Amarawickrama, 2017). These characteristics are gathered from the building information. However, in the statistical valuation model, only objective property characteristics are used, and the data for automated valuation models are structural property characteristics; in other words, locational and quality characteristics are not properly considered in the assessment process since on-site physical inspections are required (Aladwan & Ahamad, 2019). The connection with the GIS databases is determinant to solving this problem by providing up-to-date information without requiring on-site measurement.

Considering the similarity of the categories of the criteria used in the analysis of the alternative building locations and property attractiveness, it can be concluded that the same procedures and methods of GIS and BIM data gathering can be applied to both analyses.

2.3.1. Computing set of criteria

Analysing the most suitable building location based on the property attractiveness allows extending the set of criteria for the multi-criteria analysis of the location problem by including criteria related to the property attractiveness problem. This should increase the accuracy of the analysis and bring wider opportunities to the analysis.

The set of criteria presented in Table 1.2 is used as an initial set of criteria upon which the final set of criteria was formed. However, not all of the revealed criteria may be utilised for solving location problems based on property attractiveness since not all of them may be gathered from the GIS or BIM environment. Therefore, the criteria presented in Table 1.2 need to be filtered or updated according to the specified problem needs.

The implementation of the BIM model is crucial since it contains the data about objects presented inside the BIM model used in different GIS-related criteria, such as “Window View” and “Location with respect to parts of the

world". Moreover, GIS-related criteria can be gathered inside the Web environment based on the location of the building. However, criteria with a value that remain the same in each alternative do not affect the analysis results. Since the characteristics of the building will remain the same in each alternative, and the location problem does not involve a comparison of the different construction projects or engineering solutions, the BIM-related criteria will remain the same for all alternatives. Such as the year of construction, the number of floors, the need for renovation, etc. The significance of the criteria that has the same value in each alternative in this specific problem is insufficient. Therefore, all BIM-related criteria were removed from the final set of criteria. It needs to be highlighted that in the case the problem involves different construction solutions in the BIM project or different analysed assets, those criteria would need to be included in the analysis since they may have a strong influence on the analysis result.

The determination of quantitative criteria presented by numerical values in the MCDA problem requires the analysis of relevant projects and recommendations, the use of various statistical methods and reference books, specifications and other documents (Kaklauskas, Zavadskas, Banaitis & Datkauskas, 2007). The implementation of GIS technology in multi-criteria analysis aims to reduce the number of activities that are required for data gathering and processing. Since GIS provides quantitative data and all GIS-related criteria for each alternative are gathered using the same GIS operations and filters, those criteria can be used directly as input parameters in a valuation model (Din, Hoesli & Bender, 2001). Nevertheless, the specification of precise queries for the GIS database still requires the usage of various standards, guides and recommendations. For example, the distance to the bus and tram stops (Poelman & Dijkstra, 2015) should not exceed 417 meters; for train and metro – 833 meters; and fire stations – 2146 meters (Oh, Hessami & Yang, 2019; National Fire Protection Association 1710, 2022). Therefore, when querying the data from the GIS databases related to the criteria that describe the distance or route to some geospatial objects, the relevant parameters were applied.

To automatically calculate and process criteria in the multi-criteria analysis, they need to be calculated quantitatively based on the data provided by GIS and BIM environments. However, not all of the criteria can be presented as quantitative parameters.

One such criterion is a view from the windows. WELL building standard (The WELL Building Standard 2019) defines the view criteria (both landscape and type of the view) as a qualitative factor that has a high impact on premise attractiveness. The analysis of the relevant scientific articles proves the statement that the view is a qualitative criterion since, in all of the studies presented in Table 1.2, the view was presented by a linguistic estimation model (linguistic grades). The window view criterion belongs to the criteria that require on-site

measurements. Such investigations are not always possible due to accessibility restrictions, pandemic situations, or in the planning stage of the construction project when the building is not yet constructed. Additionally, on-site measurements are time-consuming and can cause issues related to subjective judgments and inaccuracy. To present these criteria that describe the view from windows, geospatial analysis needs to be applied. However, such analysis needs to process the information from both BIM and GIS environments. To address such need, the development of a new method for window view assessment was developed and implemented (Section 2.4). QUantitative View ASsessment (QUVIAS) is a method that calculates the view from the windows as a quantitative parameter based on the use of GIS and BIM data. Thanks to this method, the view criteria (both landscape and type of the view) can be determined, not only for a single window but also for the whole building, in each alternative location. Such a method allows differentiating the views of alternative locations in a precise calculation while removing the need for on-site measurements and the issues related to subjective judgments.

Another criterion, which is one of the most common, widely used and has a strong influence on the problem of alternative building location, is named “public welfare and culture”. However, this criterion is qualitative since, in all of the analysed studies, it is presented by linguistic grades. Therefore, it cannot be determined by utilising a GIS environment during the analysis. To solve this issue, the criterion needs to be presented by a relevant quantitative value that can be gathered automatically from the GIS database.

According to the research, this criterion describes a robust set of parameters for public welfare and culture and includes different aspects, specifically sustenance, education, city services, healthcare, financial services, entertainment, cultural facilities, worship and sports activities. To present this criterion by the quantitative value, the sub-criteria were defined, addressing each relevant aspect as follows:

- Sustenance – number of restaurants, bars or pubs, brewpubs, coffee shops and fast foods;
- Education – number of colleges, fine arts schools, universities, schools, and other educational institutions;
- Financial – number of banks and ATMs;
- Entertainment, art and culture – number of art galleries, museums, cinemas, libraries and performing arts;
- Worship – distance to church, religious centre, synagogue;
- Sports activities – fitness centre, sports centre.

Such separation adds relevance to expert judgments and analysis procedures that potentially can increase the accuracy of the results.

Apart from discussed criteria, some other criteria belong to the GIS databases or governmental institutions that are not in open access. For example, data related to the criteria with the biggest number of sources named “social environment and crimes” cannot be found in the open-access worldwide GIS databases (CrimeGrade, 2022). Such criteria need to be included separately depending on the location of the multi-criteria analysis. Therefore, those criteria cannot be gathered automatically from the GIS database and require manual input. The same is related to the “selling price”, “prestige of locality”, “engineering solutions and communications”, etc. Data about such criteria need to be gathered from geodesic surveys, cartographic data, governmental institutions, cadastral plans, etc. Therefore, they cannot be defined automatically while performing MCDA and need to be defined manually. Criteria that cannot be gathered from the GIS databases or that require on-site measurements were removed from the final set of criteria.

Some criteria that were removed are significant in the facility location problem. The situation where criteria are not present in GIS databases and the lack of tools and methods for gathering the relevant data leads to the conclusion that nowadays, a big gap exists in data management and sharing, where most of the data that is highly valuable in the construction sector is not accessible outside of the owning institution. Moreover, not all data is digitalised and implemented in a geospatial manner. With all applied filters and defined sub-criteria, the final set of criteria was formulated and is presented in Table 2.1.

Table 2.1. Set of criteria for facility location problem (developed by the author)

Criteria	Sub-criteria	Units	Type (Max/Min)
Window View	View landscape Type of view	Number Number	Max Max
Trees and vegetation	Trees and vegetation Forests and green areas	Number Distance	Max Min
Type of area	Distance to industrial facilities	Distance	Min
Parking and garage	Distance to parking and garage	Distance	Min
Location with respect to parts of the world	Solar insolation	Number	Max
Distance from the city centre	Distance from the city centre	Distance	Min
Public transport stops	Public transport stops	Number	Min

End of Table 2.1

Criteria	Sub-criteria	Units	Type (Max/Min)
Public culture	Sustenance	Number	Max
	Education	Number	Max
	Financial	Number	Max
	Entertainment, art and culture	Number	Max
	Worship	Distance	Min
	Sport activities	Number	Max
Public welfare and service	Hospital and medical clinic	Distance	Min
	Fire station	Distance	Min
	Police station	Distance	Min
	Post office	Distance	Min
Public transport	Number of public transport routes	Number	Max

The final set of criteria consists of 20 criteria that can be gathered from the GIS environment using SQL queries or by utilising geospatial analysis based on the data provided by the BIM model.

2.3.2. Determination of significance of criteria by Delphi method

The social choice theory, utility theory and welfare economics (Stadler, 1979) are important studies that need to be performed before multi-criteria analysis. According to Bouyssou et al. (2000), the opinions of the voters or experts need to be collected related to the conflicting criteria in MCDA to define the set of criteria and their significance.

The most common method for selecting suitable criteria is to conduct a survey of experts. One of the most common methods for evaluating the criteria for the MCDA problem is the Delphi (Tavana, Behzadian, Pirdashti & Pirdashti, 2013) method.

The Delphi method is a structured technique developed as a systematic and interactive method that is based on the evaluation of expertise presented by a group of experts. It is a prospective technique used to obtain essentially quantitative but relatively accurate information. Its objective is to achieve consensus based on discussion among experts through an interactive process.

The Delphi method consists of four steps, as follows:

1. Define the problem to which the Delphi method is applied. It is important to define the problem precisely. Otherwise, it may lead expert judgments into an undefined status.

2. Select experts. This selection is made according to the knowledge and experience of the experts related to the study subject. The number of experts can vary depending on the subject and research needs.
3. Develop a questionnaire. Questions should be clear and specific without uncertainty.
4. Processing the responses, where the first questionnaire will be enriched in each round with the results and comments received earlier.

Step 1 includes the definition of the problem that was made according to the multi-criteria decision-making problem formulated in the content of the dissertation as follows: detection of the most suitable building location from the multiple alternatives based on data provided by GIS and BIM environments with the aim of project revenue maximisation.

According to step 2, a sufficient number of experts was selected. For the survey of the criteria relevancy and weight, the experts from five countries were asked to complete the questionnaire, i.e., Lithuania, Slovenia, Belarus, Belgium and Ukraine. Such a wide spread of expertise allowed for reducing the influence of the local real estate market on each criterion and presenting the results of the analysis more universally and generally. All of the experts have a strong experience and knowledge in the subject area, specifically in the construction field or real estate. The minimal requirements for the experts were defined as five years in a scientific field or 15 years of experience in the relevant field.

According to Vveinhardt and Petrauskaite (2013), the Paniotto equation (2.2) is used to determine a representative sample of experts:

$$n = \frac{1}{\Delta^2 + \frac{1}{N}} \quad (2.2)$$

with n – the sample size, Δ – is the size of the sampling error; N is the size of the criteria set.

The size of the sample error Δ can be in a range of 5–10%; therefore, the value of the parameter Δ was specified as 10% or $\Delta = 0.1$ for this particular MCDA problem. According to the calculation, the required number of experts is 17.

Step 3 involves the development of a set of criteria. To develop an accurate and precise set of criteria, research on the subject was performed. This research contained the analysis of relevant scientific articles to identify criteria used in relevant scientific problems. As a result of this investigation, 74 criteria were determined. Within a deep analysis of the gathered criteria, 32 criteria were revealed that are commonly used in the construction field related to the subject. The gathered criteria were filtered and updated to be suitable for the specified MCDA problem. The final set of criteria was formed and included 20 criteria that can be gathered or calculated by utilising data provided by BIM and GIS

environments inside the Web environment. The final set of criteria presented in Table 2.1 was implemented in the questionnaire for Delphi analysis.

Since it is hard to describe the real world by strict values (Zavadskas, Kaklauskas, Bausys, Naumcik & Ubarte, 2021), the linguistic estimation model (grades) was implemented. According to Nadaban, Dzitac and Dzitac (2016), the linguistic grades for the valuation of the alternatives were designed utilising a triangular membership function (Corrente, Greco & Slowinski, 2017) and are presented in Table 2.2.

Table 2.2. Linguistic grades (developed by the author)

Ranking	Triangular Fuzzy Numbers		
1	1	1	2
2	1	1	3
3	1	2	4
4	1	3	5
5	2	4	6
6	3	5	7
7	4	6	8
8	5	7	9
9	6	8	9
10	7	9	9

The questionnaire was sent as an online form to the experts.

According to step 4, the processing of the survey was conducted with the determination of the agreement between the expert judgments. It is necessary to evaluate the consistency between the opinions made by the experts since often experts have differing points of view on the MCDA problem and the significance of the criteria.

2.3.3. Agreement between expert judgments

Since multi-criteria analysis involves expert assessment, it is necessary to evaluate the consistency of the provided opinions. Such a check needs to be performed on each iteration of the questionnaire round until the concordance of the provided judgments is sufficient for the analysis.

According to Podvezko (2005), if the group of experts includes more than two persons, the closeness of the expert judgments can be checked with the concordance coefficient. The equation of the concordance coefficient calculation is presented in equation (2.3).

$$W = \frac{12S}{r^2m(m^2-1)} \quad (2.3)$$

with: S – the sum of square differences between expert judgments and mean value, r – number of columns, m – number of rows.

Based on the calculations performed using equation (2.3), the concordance coefficient is equal to 0.33. The achieved result depicts the low relation between the expert judgments. However, since the set of criteria contains more than seven objects to be evaluated, the Podvezko method may not be sufficient for the calculation (Pearson, 2009). Therefore, the calculation was expanded with the use of χ^2 equation (2.4) presented by Pearson (2009), where the significance level α is equal to 0.05.

$$\chi^2 = Wr(m-1) = \frac{12S}{rm(m+1)}. \quad (2.4)$$

Based on the provided formula, the concordance coefficient of the final round of the Delphi analysis needs to be calculated. According to the Chi-Square Probabilities (Plackett, 1983) and based on the degrees of freedom K equal to 19 and the significance level α , the calculated concordance coefficient needs to be compared to the statistic coefficient. The agreement of the expert opinions is considered sufficient in the case the calculated concordance coefficient is greater than the static coefficient.

2.4. QUVIAS method for visibility analysis in integrated BIM, GIS, and Web environments

To calculate the view mathematically and present it as a quantitative parameter, the view needs to be presented in some mathematically expressed shape. To present an accurate analysis, two important conditions were defined.

The first condition states that the distance from the observation point to all points of the mathematically expressed shape used for view representation must be the same. According to the first requirement, the mathematically expressed shape of the view should be a 360-degree sphere, where the distance between the sphere's centre and any point on the sphere's surface is the same.

To remove projection distortions (Kerkovits, 2020), the second condition must be met: the distance between the neighbouring points on the mathematical shape must be even.

Addressing the need for mathematical view calculation and considering the defined requirements, the QUAntitative VIEw ASsessment (QUVIAS) method was developed for visibility analysis.

The comparison of the developed QUVIAS method and existing methods performed by the author is presented in Table 2.3. Names of the methods are presented in the first column. The second column describes the use of distance or Boolean variables in certain methods. The third column depicts the use of Boolean variables in the calculation of the clear view. The next column describes the ability to calculate the percentage and area of the landscape clear from obstacles. The last column describes the need for transformation of the mathematical shape, such as a sphere into a square.

Table 2.3. Existing methods for window visibility analysis (developed by the author)

Method name	Type of calculation	Clear view	Landscape area	Shape accuracy
QUVIAS (proposed by the author)	Distance	+	+	+
View dome (Othman, Yusoff & Rasam, 2019)	Boolean	+	+	+
QLA360 (Wrozyński, Pyszny & Sojka, 2020)	Boolean	+	+	–
Viewshed (Petrasova, Harmon, Petras & Mitasova, 2015)	Boolean	–	+	+
Line-of-sight (Liu, Zhang, Ma & Yang, 2010)	Distance	–	–	Not applicable

QUVIAS method considers the mathematical shape of the view as a sphere and is based on the calculation of the spherical coordinates. Such an approach does not involve the transformation of the mathematical shape of the view. Therefore, distortions of the projection are not involved in the calculations. The spherical coordinates allow ensuring an even distance between the points on a sphere as well as an equal distance from the observation point to the points on the mathematical shape (sphere). The QUVIAS method allows calculating the clear part of the view based on the distance parameter that increases the accuracy of the visibility analysis.

The view dome method (Othman, Yusoff & Rasam, 2019) considers the mathematical shape of the view as a sphere and, therefore, does not involve the transformation of the view. The view dome method allows calculating the part of the view that is clear from objects as well as calculating the area of the landscape. However, the calculations in this method are based on Boolean variables that do not involve the distance parameter. Therefore, the accuracy of the analysis is lower compared to the QUVIAS method. The utilisation of Boolean variables reduces the accuracy of the analysis.

QLA360 method (Wrozyński, Pyszny & Sojka, 2020) allows the calculation of the clear part of the view as well as the landscape area. However, the calculation involves Boolean variables and therefore, the accuracy of the analysis is lower. Additionally, the QLA360 method involves the transformation of the mathematical shape of the view that leads to projection distortions. The utilisation of Boolean variables and the involvement of the geometry transformation reduces the accuracy of the analysis.

The viewshed method (Zhou, Lees & Tang, 2008; Petrasova, Harmon, Petras & Mitasova, 2015) is dedicated to the calculation of the landscape area, where the mathematical shape of the view does not influence the calculation. Additionally, the shape of the view can be modified. However, in case the clearance of the view needs to be calculated, the viewshed analysis is not fully applicable. Additionally, the calculation of the visibility analysis using the viewshed method is based on the utilisation of Boolean variables that reduce the accuracy of analysis related to clearance of view. Addressing this situation, the view dome method for view clearance analysis was introduced by Esri.

Line-of-sight methods (Yu, Sheng & Chai, 2007; Liu, Zhang, Ma & Yang, 2010) are dedicated to the detection of the obstacles on the path of vector casting. Therefore, this method does not require any kind of mathematical shape. This method does not allow calculating the spherical shape in both horizontal and vertical angles and, therefore, is not applicable for the calculation of the clearance of the view or area calculation. Nevertheless, the line-of-sight method allows the determination of the distance from the observation point to the object in the free space.

According to the analysis of the existing methods for visibility analysis, the QUVIAS method is the only method that meets the defined requirements. Fig. 2.3 presents the difference between the existing methods and the developed method.

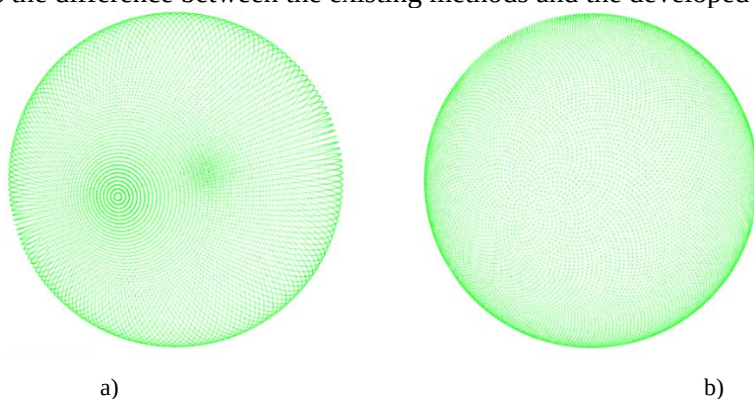


Fig. 2.3. Difference between the mathematical shapes of the view: a – plane shape flattened on the sphere; b – spherical shape (developed by the author)

Fig. 2.3a depicts an approach utilised in existing methods, where plane geometry is flattened on a sphere. As shown, the distance between the neighbouring points on the sphere is not even. This happens due to the transformation of the plane geometry. To solve this issue, the calculations of distortion are involved in the analysis. Fig. 2.3b represents the mathematical shape of the view that is used in the QUVIAS method that meets the defined requirements, where sphere geometry is used with spherical coordinates. As shown, the distance between the neighbouring points on the sphere surface is equal, which allows for covering the entire surface of the view evenly. Such an approach ensures the same significance of each value involved in visibility analysis calculation.

The proposed QUVIAS method includes multiple steps, as presented in Fig. 2.4.

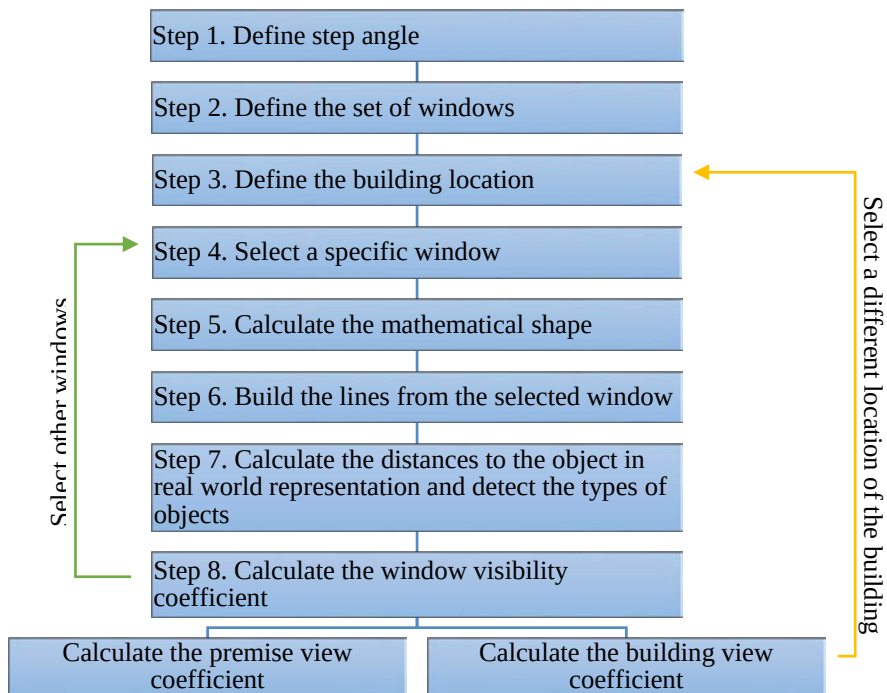


Fig. 2.4. Methodological scheme of the QUVIAS method for window visibility analysis (developed by the author)

The scheme presented in Fig. 2.4 depicts the steps required to perform the analysis.

Step 1 involves the specification of the step angle that is used in the calculation of the spherical coordinates of the point that is placed on the surface of the mathematical shape of the view.

Step 2 requires the specification of the windows that need to be analysed. In case the analysis is performed for property view calculation, then the windows in the boundaries of a property need to be selected. In the case the analysis is required for calculating the building view coefficient, all windows in the building need to be selected.

Step 3 involves the specification of the building location. In terms of building view calculation, this step defines the alternative locations of the building that need to be compared afterwards. This step is the initial step for the calculation of the alternative building locations, as depicted by the yellow arrow.

Step 4 defines one of the windows from the set of windows defined in the second step.

Step 5 contains the calculation of the mathematical shape, which involves merging the sphere centre and selected window centre, and the calculation of the points that need to be placed on the surface of the sphere based on spherical coordinates.

Step 6 involves the calculation of the lines built from the selected window to each point on the surface of the sphere. This step requires the biggest amount of time.

Step 7 is responsible for the calculation of the distances to the objects in real-world representation and the detection of the types of objects. For this purpose, the intersections of the lines with objects presented in the real-world representation are determined. The length of the line is calculated as the difference between the coordinates of the starting point and the point of intersection. After the calculation of the length was performed, they needed to be normalised (Brauers, 2007). The normalisation is done according to the equation proposed by the author (2.5).

$$a_{ij} = \frac{D_p}{R_{max}} \quad (2.5)$$

with: D_p – the distance to the point of intersection; R_{max} – the length of the longest line with no intersections (radius of the sphere); a_{ij} – an element of the array.

After normalisation, the length of the lines is between 0 and 1, where the value 1 represents the line that reached the point on the surface of the mathematical shape without intersection. Values in a range from 0 to 1 represent the lines that have an intersection.

Based on the location of the intersection point, the type of object that causes the intersection is determined using geospatial analysis named buffering, where the data about the surroundings is gathered according to the specified location. However, the GIS database does not always contain information about all the objects that are presented in real-world representation. To solve this issue, extra GIS databases or layers with data need to be connected.

Step 8 involves a calculation of the window view coefficient based on the analysis results. According to the methodology, the calculation of the view coefficient involves distances to objects presented in a real-world 3D mesh model. To receive the normalised values for all windows, equation (2.6) proposed by the author needs to be used.

$$w = \frac{1}{n} (\sum_{i=1}^n a_{ij}) \quad (2.6)$$

with: I – identifier of the element; n – total number of elements in the array.

In case the set of windows defined in the second step includes more windows, the algorithm starting from step 4 up to step 8 needs to be repeated for each window, as depicted by the green arrow. After the view coefficients are calculated for all windows defined in the second step, the resulting coefficients can be calculated, which are the premise view coefficient or the building view coefficient.

The comparison of the alternative locations of the building involves the calculation of the building view coefficient for each defined alternative. Therefore, the algorithm starting from step 3 needs to be performed for each alternative, as depicted by the yellow arrow.

To analyse the view in both directions, i.e., horizontally and vertically, the viewing angle is required. The view from the window has a maximum angle equal to 180 degrees in both vertical and horizontal directions (Carswell, Gardiner & Yin, 2010). Since there is no need for analysing the interior part of the premise, the mathematical shape of the view, which is a sphere, can be divided into two parts where only half of the sphere is required for the calculations. Such angles can be built with two lines, where the first line is built from the observation point to the bottom of the object, and the second line is built to the top of the object, as presented in Fig. 2.5. To describe the object in the view, multiple lines need to be constructed horizontally and vertically with some step angle. A smaller step angle results in a higher accuracy of the analysis.

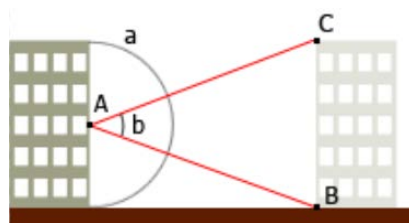


Fig. 2.5. Vertical view angle, where: a – zone of interest that represents full view angle in 180 degrees; b – representation of the view angle for the object; AB and AC – baseline and the top line of the object view angle, respectively (developed by the author)

According to the Snellen (1862) and Sivcev (1940) studies, a human eye can determine two dots from a distance not smaller than 1 minute of arc (Correll, 1977). The calculation of the minimal size of the object based on the distance to this object can be done using the angle chord calculation (2.7).

$$d = 2r * \sin\left(\varphi \frac{\pi}{360}\right) \quad (2.7)$$

with: r – the distance to the object and φ – the step angle.

Such a statement allows for concluding that there is no need to build the lines with the step angle smaller than 1 minute of arc. Based on this information, the required number of lines can be calculated using equation (2.8) proposed by the author. This equation is used for checking the resulting number of lines and for the prediction of the analysis duration.

$$N = \left(\frac{\alpha_{max}}{\varphi} + 1\right) * \left(\frac{\beta_{max}}{\varphi} + 1\right) \quad (2.8)$$

with: φ – angle steps; α_{max} and β_{max} are maximum horizontal and vertical view angles, respectively; N – the number of rays.

Considering the maximum possible view angle of 180 degrees in both directions, the total number of lines that need to be built is equal to 116661601, or the analysis requires 116661601 iterations. A non-negligible amount of time is required to perform such a large amount of work. Such a problem is related to the Web browser's limitations and WebGL environment limits. To predict the time that is required for different step angles, the function proposed by the author and presented in equation (2.9) can be used.

$$t = f\left(\frac{t_{now} * N}{n} + t_{start} - t_{now}\right) \quad (2.9)$$

with: N – the total number of lines calculated by (2.8), n – the current line (iteration), t_{now} – the current time, t_{start} – the time when the analysis started.

To analyse possible time expenditures for different step angles, a comparative analysis was carried out. Such analysis allows for determining the optimal step angle with the best ratio of accuracy and duration of the analysis. For the comparative analysis, an environment with ideal conditions was developed, which includes a BIM model, a flat Earth surface and no extra objects. The results of this analysis are presented in Table 2.4. Additionally, this analysis was performed for two types of calculations: based on Boolean variables and based on distance parameters. The analysis was performed on a middle-range desktop computer.

Table 2.4. Comparative analysis of step angles from one window (developed by the author)

Angle step	Required duration	Result (distance based)	Result (Boolean variables)	Total iterations
180°	0 sec	0.00006	0	4
90°	0 sec	0.33337	33.333333	9
45°	0 sec	0.40031	40.0	25
22° 30' 30.00"	0 sec	0.44513	44.444444	81
11° 15' 15.00"	0 sec	0.45094	44.98270	289
5° 37' 37.50"	0 sec	0.43101	42.97521	1089
2° 48' 48.75"	01 sec	0.42659	42.48521	4225
1° 24' 24.38"	05 sec	0.42543	42.34121	16641
0° 42' 42.19"	19 sec	0.42285	42.05514	66049
0° 33' 33.75"	33.38 sec	0.42161	41.92015	103041
0° 21' 21.09"	01:13 min	0.42159	41.90425	263169
0° 10' 10.55"	04:44 min	0.42163	41.88878	1050625
0° 05' 05.27"	18:28 min	0.42150	41.86401	4198401
0° 02' 02.64"	1:13:14 hour	0.42157	41.86986	16785409
0° 01' 01.32"	4:51:06 hour	0.42158	41.87237	67125249
0° 01'	12:16:56 hour	0.42156	41.87108	116661601

The first column, named “Angle step”, depicts the angle between the lines built for analysis. The column “Required duration” represents the time required for performing analysis with a specified step angle. The column “Result (distance based)” contains the results of the analysis performed using the methodology proposed by the QUVIAS method, including spherical geometry of the mathematical shape and utilisation of spherical coordinates. The column “Result (Boolean variables)” contains the results of the analysis using Boolean variables in the same manner as in existing methods for visibility analysis. The last column, named “Total iterations”, represents the total number of calculations for each built line.

The comparative analysis revealed that the results of the analyses utilising the QUVIAS method and Boolean variables have a strong correlation. In case the results achieved by the QUVIAS method are converted to percentages by multiplying by 100, the difference between the results appears to be 0.25 per cent. Surprisingly, even when performing the analysis under ideal conditions with a flat Earth surface and with no obstacles, the difference between the results can be observed. Further analysis revealed (section 3.3) that under the condition of real-

world representation provided as a 3D mesh model, the difference between the results is significant. For example, analysis of the ninth-floor window in the condition of real-world representation depicts that the result of the analysis based on Boolean variables is equal to 39.21525, and the result of the distance-based analysis multiplied by 100 is equal to 40.39943. Such observation confirms that there is a difference between the methods that utilise plane geometry with Boolean variables and sphere geometry utilising spherical coordinates and distance parameters. Additionally, based on the multiple tests and depending on the objects presented in the real-world representation, the inequality varies. Some of the tests showed a difference of more than 4 per cent. Such observations prove the conclusions made according to Table 2.3.

The results of the comparative analysis presented in Table 2.4 shows that the analysis with the 1-minute of arc requires more than 12 hours to be performed. Such a large amount of time is not suitable for the real project since it may involve multiple windows. Based on the experimental research, the most suitable step angle was defined that has a high accuracy and sufficient time requirements that is $0^{\circ}33'33.75''$.

The obtained result of the visibility analysis performed using the QUVIAS method represents the mathematical calculation of the view that can be seen from the window. Therefore, it can be named the coefficient of window visibility or simply the window view coefficient. The window view coefficient has high accuracy allowing for a comparison of even views of the neighbouring windows. Based on the window view coefficients, the premise view coefficient can be calculated.

The premise view coefficient is the coefficient that describes the view relevant to a specific premise. To calculate this coefficient, the window view coefficients for all windows in the premise boundaries need to be calculated, as the methodology describes (Fig. 2.4). After all relevant window view coefficients are calculated, the premise view coefficient can be calculated using equation (2.6). This coefficient allows describing the view of the exact premises quantitatively. According to the literature analysis, the proposed premise view coefficient may have a big contribution to multi-criteria decision-making analysis for the assessment of the property attractiveness and the prediction of the property price. Potentially, it can be significant in the real estate market as well as in economic analysis that takes place in the construction project and project revenue calculation. Additionally, the premise view coefficient allows for calculating the view precisely, not only for already constructed buildings but also in the planning stage of the construction project.

Another approach to the proposed method is utilising it for the analysis of the alternative building locations. For this analysis, the view coefficient of the building must be calculated based on the window view coefficients of all windows

presented in the building using equation (2.6). After the building view coefficient is calculated for one location, the same procedure must be performed for the alternative building locations. The calculation of the building view coefficients strictly relies on the location and rotation of the building as well as on the constructional solutions since different positions of the windows influence the results. The most valuable contribution of the building view coefficient can be found in multi-criteria decision-making analysis for the selection of the most suitable building location from the perspective of economic analysis.

2.5. Multi-criteria methods for comparing alternatives

The GIS data integration for processing MCDA problems aims to increase the accuracy of the analysis by removing the fuzziness in the values of the criteria since GIS provides quantitative data (Din, Hoesli & Bender, 2001). However, the use of GIS technology cannot solve the fuzziness since each GIS vendor provides a database with different sets of data collected by different experts and organisations using different methodologies and technological solutions. Therefore, the accuracy of data presented in GIS databases is disputable. Addressing the highlighted issue, each criterion used in MCDA was taken from two different GIS databases. Such a solution improves the accuracy of the analysis yet involves fuzziness. A detailed discussion of the used GIS databases is presented in subchapter 3.1.4.

On the other hand, the weights of the GIS-related criteria of the building location can rarely be presented as exact values and, more often, as fuzzy numbers (Natividade-Jesus, Coutinho-Rodrigues & Antunes, 2007).

Addressing the fuzziness of both weights and values, the decision was made to select fuzzy methods. Two MCDA methods were selected for in-depth analysis.

The fuzzy TOPSIS was selected as the first method because it is one of the most widely used methods in solving property attractiveness assessment and building location problems. Since the fuzzy TOPSIS method is a distance-based method, it was decided to select a second method, non-distance-based. Therefore, fuzzy COPRAS was selected as the second method based on a comparison of the beneficiary and non-beneficiary values. In MCDA, it frequently happens that two different MCDA methods provide different analysis results. To address such conflicting situations, it was decided to use one more method. As a third method, it was decided to use a relatively new distance-based method called fuzzy EDAS (Keshavarz-Ghorabae, Zavadskas, Olfat & Turskis, 2015).

2.5.1. Fuzzy TOPSIS method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was initially developed by Hwang and Yoon (Hwang & Yoon, 1981). The TOPSIS method aims to determine the most suitable solution by calculating the relative closeness coefficient for the alternatives, where the alternative with the shortest distance to the positive-ideal solution and the longest distance to the negative-ideal solution is considered as optimal.

The fuzzy TOPSIS method involves multiple steps that are as follows:

1. Problem formulation.

2. Assignment of a rating to criteria and alternatives. For the group decision-makers with K members, the fuzzy rating of the k^{th} alternative value is denoted as $\tilde{x}_{ij} = (a_{ij}^k, b_{ij}^k, c_{ij}^k)$, and the weight of the C_j criterion is denoted as $\tilde{w}_{ij} = (w_{j1}^k, w_{j2}^k, w_{j3}^k)$.

The fuzzy weight $\tilde{w}_{ij} = (w_{j1}, w_{j2}, w_{j3})$ for the C_j criterion is calculated as follows:

$$\begin{aligned} w_{j1} &= \min_k(w_{j1}^k), \\ w_{j2} &= \frac{1}{K} \sum_{k=1}^K w_{j2}^k, \\ w_{j3} &= \max_k(w_{j3}^k) \end{aligned} \quad (2.10)$$

The fuzzy rating $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ of i^{th} alternative and j^{th} criterion is calculated as follows:

$$\begin{aligned} a_{ij} &= \min_k(a_{ij}^k), \\ b_{ij} &= \frac{1}{K} \sum_{k=1}^K b_{ij}^k, \\ c_{ij} &= \max_k(c_{ij}^k) \end{aligned} \quad (2.11)$$

3. Formulation of the initial fuzzy decision-making matrix is as follows:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, \quad (2.12)$$

where x_{ij} is represented as $x_{ij} = (x_{ij}^1, x_{ij}^2, x_{ij}^3)$ according to fuzzy numbers.

4. Calculation of the normalised fuzzy decision matrix.

The normalisation is performed in response to the type of criteria depending on whether it is beneficial or non-beneficial.

The normalisation of the beneficial criteria is performed as follows:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right) \text{ and } c_j^* = \max_i(c_{ij}). \quad (2.13)$$

For non-beneficial criteria, normalisation is performed as follows:

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right) \text{ and } a_j^- = \min_i(a_{ij}). \quad (2.14)$$

5. Calculation of the weighted normalised fuzzy decision matrix.

In this step, the weighted normalised fuzzy decision matrix is calculated as follows:

$$\tilde{v} = (\tilde{v}_{ij}) \quad (2.15)$$

with: $\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j$ ($a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2$)

6. Calculation of the fuzzy Positive Ideal Solution (FPIS) and fuzzy Negative Ideal Solution (FNIS), where the FPIS is calculated by equation (2.16), and FNIS is calculated by equation (2.17).

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*) \quad (2.16)$$

with: $\tilde{v}_j^* = \max_i(v_{ij3})$.

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-) \quad (2.17)$$

with: $\tilde{v}_j^- = \min_i(v_{ij1})$.

7. Calculation of a distance to FPIS and FNIS for each alternative.

In this step, the distances from an alternative A_i to FPIS and FNIS are calculated using equations (2.18) and (2.19), respectively.

$$d_i^* = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^*); \quad (2.18)$$

$$d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad (2.19)$$

where the distance between two triangular fuzzy numbers is calculated using the vertex method as follows:

$$d(\tilde{v}_{ij}, \tilde{v}_j^-) = \sqrt{\frac{1}{3} [(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}, \quad (2.20)$$

where a_2, b_2, c_2 represent positive or negative values, respectively, to the calculation.

8. Calculation of the closeness coefficient for each alternative.

The closeness coefficient CC_i describes the distances between the FPIS and FNIS and is performed as follows:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}. \quad (2.21)$$

9. Ranking the alternatives.

The last step determines the best alternative by the closeness coefficient, where the alternative with the highest CC is considered the best one since it has the farthest distance from FNIS and the smallest distance to the FPIS.

2.5.2. Fuzzy COPRAS method

The complex proportional assessment (COPRAS) (Zavadskas, Kaklauskas & Sarka, 1994) method applied in this research uses stepwise ranking and evaluates alternatives by their significance and utility degree.

The fuzzy COPRAS method (Garg, Kumar & Garg, 2019) includes the following steps:

1. Problem formulation.
2. Establishment of alternatives and selection criteria. According to the number of criteria, a sufficient number of experts for decision-making need to be selected.
3. Fuzzy number selection for proper evaluation of alternatives. Alternatives and other criteria are evaluated by decision-makers based on linguistic equivalents.
4. Formulation of the initial fuzzy decision-making matrix is as follows:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, \quad (2.22)$$

where x_{ij} is represented as $x_{ij} = (x_{ij}^1, x_{ij}^2, x_{ij}^3)$, according to fuzzy numbers.

5. The normalisation of the initial matrix. The normalisation of the matrix is done as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}, \quad i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n \quad (2.23)$$

with: $x_{ij} = (x_{ij}^1, x_{ij}^2, x_{ij}^3)$.

6. The computation of a weighted normalised decision-making matrix. Each element of the normalised matrix is multiplied by the appropriate significance of the criteria w_j as follows.

$$v_{ij} = \bar{x}_{ij} w_j, \quad (2.24)$$

where $\bar{x}_{ij}$ and w_j represent the normalised value and weight of the criteria.

7. Compute Beneficiary and Non-Beneficiary values using equations (2.25) and (2.26), respectively. These values represent the degree for which an alternative aims.

$$P_i = \sum_{j=1}^n v_{+ij}; \quad (2.25)$$

$$R_i = \sum_{j=1}^n v_{-ij}. \quad (2.26)$$

8. The computation of the relative significance level value $\bar{S}_i$ of the alternative is as follows:

$$\bar{S}_i = P_i + \frac{R_{\min} \sum_{i=1}^n R_i}{R_i \sum_{i=1}^n \frac{R_{\min}}{R_i}}. \quad (2.27)$$

9. The conversion of the fuzzy values of $\bar{S}_i$ expressed as $\bar{S}_i = (s_i^1, s_i^2, s_i^3)$ is as follows:

$$S_i = \frac{s_i^3 + s_i^2 + s_i^1}{3}. \quad (2.28)$$

10. The calculation of efficiency and priority of alternatives by using the degree of utility of the alternative, as shown in equation (2.29). The higher the degree of utility, the better the alternative.

$$N_i = \frac{S_i}{S_{\max}}. \quad (2.29)$$

2.5.3. Fuzzy EDAS method

The Assessment based on the Distance from Average Solution (EDAS) (Stevic, Vasiljevic, Zavadskas, Sremac & Turskis, 2018) method was designed with a focus on conflicting criteria. Compared to the TOPSIS method, where the best alternative is determined by the distance from ideal and nadir solutions, in the EDAS method, the most suitable alternative is determined by the distance from the average solution. According to original research (Stevic, Vasiljevic, Zavadskas, Sremac & Turskis, 2018), the method consists of the following steps:

1. The computation of the average decision-making matrix by the following equations:

$$X = [\tilde{x}_{ij}]_{n \times m}; \quad (2.30)$$

$$\tilde{x}_{ij} = \frac{1}{k} \bigoplus_{p=1}^k \tilde{x}_{ij}^p, \quad (2.31)$$

where $\tilde{x}_{ij}^p$ describes the performance value of alternative $A_i (1 \leq i \leq n)$ with respect to the criterion $c_j (1 \leq j \leq m)$ assigned by the p^{th} decision-maker ($1 \leq p \leq$

k). The performance value of alternatives in the specified MCDA problem is determined by the GIS databases; therefore, p describes the number of sources.

2. The computation of the criteria weight matrix according to the following equations:

$$W = [\tilde{w}_j]_{1 \times m}; \quad (2.32)$$

$$\tilde{w}_j = \frac{1}{k} \bigoplus_{p=1}^k \tilde{w}_j^p, \quad (2.33)$$

where $\tilde{w}_j^p$ describes the weight of the criterion c_j ($1 \leq j \leq m$) assigned by the p^{th} decision-maker ($1 \leq p \leq k$).

3. The computation of the matrix of average solutions by the following equations:

$$AV = [\tilde{a}v_j]_{1 \times m}; \quad (2.34)$$

$$\tilde{a}v_j = \frac{1}{n} \bigoplus_{i=1}^n \tilde{x}_{ij}. \quad (2.35)$$

4. The computation of the matrixes of the positive distance from average (PDA) and negative distance from average (NDA), considering the beneficial (B) and non-beneficial (N) types of criteria, according to the following equations:

$$PDA = [p\tilde{d}a_{ij}]_{n \times m}; \quad (2.36)$$

$$NDA = [n\tilde{d}a_{ij}]_{n \times m}, \quad (2.37)$$

where positive distance $p\tilde{d}a_{ij}$ and negative distance $n\tilde{d}a_{ij}$ of the performance value of the i^{th} alternative from the average solution in the j^{th} criterion are calculated according to equations (2.38) and (2.39), respectively.

$$p\tilde{d}a_{ij} = \begin{cases} \frac{\psi(\tilde{x}_{ij} \ominus \tilde{a}v_j)}{k(\tilde{a}v_j)} & \text{if } j \in B \\ \frac{\psi(\tilde{a}v_j \ominus \tilde{x}_{ij})}{k(\tilde{a}v_j)} & \text{if } j \in N \end{cases}; \quad (2.38)$$

$$n\tilde{d}a_{ij} = \begin{cases} \frac{\psi(\tilde{a}v_j \ominus \tilde{x}_{ij})}{k(\tilde{a}v_j)} & \text{if } j \in B \\ \frac{\psi(\tilde{x}_{ij} \ominus \tilde{a}v_j)}{k(\tilde{a}v_j)} & \text{if } j \in N \end{cases}. \quad (2.39)$$

5. The determination of the weighted sum of positive and negative distances from all alternatives by equations (2.40) and (2.41).

$$\tilde{s}p_i = \bigoplus_{j=1}^m (\tilde{w}_j \otimes p\tilde{d}a_{ij}); \quad (2.40)$$

$$\widetilde{sn}_i = \bigoplus_{j=1}^m (\widetilde{w}_j \otimes \widetilde{nda}_{ij}). \quad (2.41)$$

6. The calculation of the normalised values of sp_i and sn_i for all alternatives by equations (2.42) and (2.43).

$$\widetilde{ns}p_i = \frac{\widetilde{sp}_i}{\max_i(k(\widetilde{sp}_i))}; \quad (2.42)$$

$$\widetilde{ns}n_i = 1 - \frac{\widetilde{sn}_i}{\max_i(k(\widetilde{sn}_i))}. \quad (2.43)$$

7. The calculation of the appraisal score $\widetilde{as}_i$ for all alternatives is as follows:

$$\widetilde{as}_i = \frac{1}{2} (\widetilde{ns}p_i \otimes \widetilde{ns}n_i). \quad (2.44)$$

8. Ranking the alternatives according to the calculated appraisal scores, where the alternative with the biggest score is considered the best alternative.

2.6. Automation of multi-criteria analysis for solving a building location problem using BIM, GIS, and Web environments

The methodology for performing a multi-criteria analysis includes multiple steps, starting with the matrix formulation and ending with a comparison of alternatives. The methodology for automating the multi-criteria decision-making analysis proposed by the author includes multiple steps, as presented in Fig. 2.6.

Step 1: In the first step, the MCDA method and the required set of criteria need to be defined.

Step 2: Based on the defined data, the initial matrix is compiled.

Step 3: Based on expert judgments and the selected MCDA method, the weights of the criteria are calculated, i.e., exact or fuzzy numbers. In this step, the weights represented by the linguistic grades obtained using the Delphi method need to be converted with respect to the specified method.

Step 4: This step requires the specification of the alternative and is the beginning of the calculation of criteria values. In the discussed MCDA problem, each newly specified building location is considered a new alternative. In this step, the location of the building presented in the local coordinate system, Web Mercator Projection, is transformed into WGS 84 (WGS 1984) longitude and latitude using equation (2.1), and those coordinates are used for quarrying data from the GIS database.

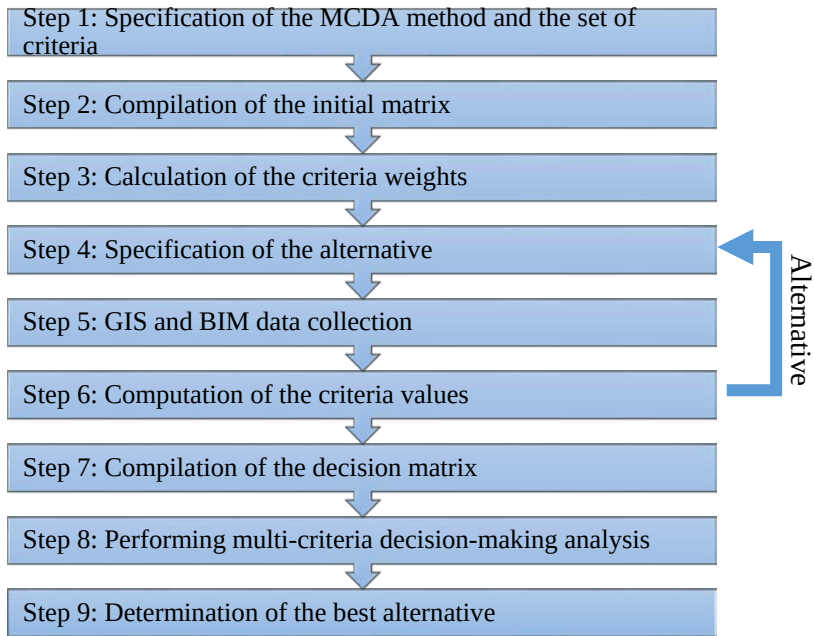


Fig. 2.6. Methodology for automatic multi-criteria decision-making analysis (developed by the author)

Step 5: After the alternative is defined, the related GIS and BIM data is collected.

Step 6: This step is the last step of the criteria value calculation. If another alternative is added, steps 4 to 6 are performed again for each new alternative.

Since each criterion receives two values from two different data sources, the fuzzy numbers can be calculated. The calculation of the fuzzy numbers $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$ by the values v_{ij}^k collected from data sources, and for i^{th} alternative and j^{th} criterion is performed by equation (2.45).

$$\begin{aligned}
 a_{ij} &= \min_k(v_{ij}^k); \\
 b_{ij} &= \frac{1}{K} \sum_{k=1}^K v_{ij}^k; \\
 c_{ij} &= \max_k(v_{ij}^k)
 \end{aligned} \tag{2.45}$$

with: k – number of data sources

Step 7: After all required data for each alternative are collected and calculated, the decision matrix is calculated.

Step 8: In this step, the analysis based on the specified method within the decision matrix is performed.

Step 9: After conducting the multi-criteria analysis, the ranking of alternatives is performed.

2.7. Crane operation methods based on the integration of BIM, GIS, and Web environments

The process of crane selection and operation aims at determining the most suitable location for the crane, crane type and parameters under real-world conditions. Depending on the number of cranes, their types, height, boom length and weight capacity, different alternative locations can be selected. The selection of the best alternative is one of the decision-making tasks. To solve such a problem, multiple parameters need to be defined manually and determined using various kinds of analysis. Crane operations are a different set of tasks; however, it involves similar parameters, such as crane location, boom reach, possible lifting loads, etc. Therefore, the same development is relevant for the crane operation tasks.

The type of crane does not affect the calculations in terms of visibility analysis. However, it is important to determine the crane type for reachability analysis since different calculations are involved. Tower cranes were selected for the proposed case study.

Crane cabin view analysis uses crane parameters and data collected from BIM and GIS environments to perform geospatial analysis. Therefore, such an implementation is coherent with the proposed method for visibility analysis described in the previous section and is considered an important area of investigation since it expands the possibilities of the construction field by integrating GIS and Web environments. In a construction project, multiple cranes can be used since there is a big chance that the use of two cranes can be more efficient compared to a single crane use (Lin & Haas, 1996).

The first crane parameter involved in the analysis is the location of the crane. Crane height is the second parameter that needs to be determined for the analysis. The height parameter can be determined in two ways: manually and based on information provided by the BIM model. Crane boom length is another parameter that is required for analysis. The length of the crane hook can be calculated based on the BIM model or defined manually. Based on this analysis, the overlap of crane booms can be determined and visualised as well.

The analysis proposed by the author is divided into the following steps, as depicted in Fig. 2.7.

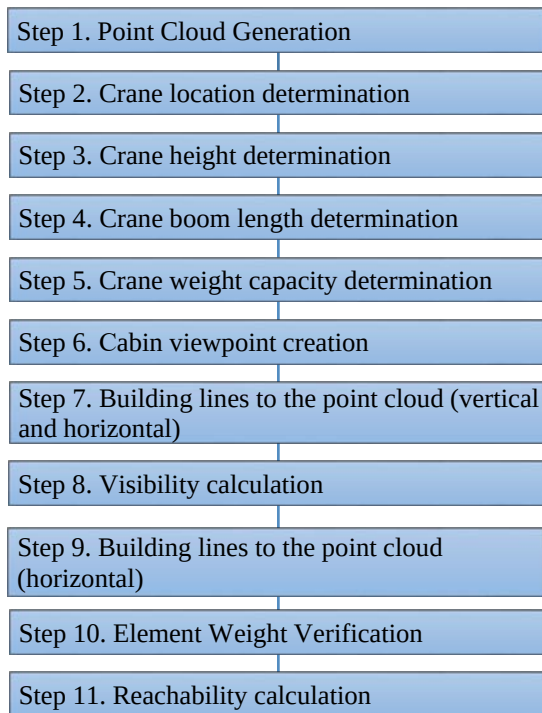


Fig. 2.7. Scheme of crane selection and operation method
(developed by the author)

Step 1: To perform an analysis, the geometric parameters of the facility surface need to be collected. Information about the geometry of a BIM model, as well as any 3D object, can be stored by a variety of geometric samples, such as triangles or squares, surfaces, solid objects, joining points, etc. Each of these methods has different advantages and disadvantages. But all of these methods have the same disadvantage, i.e., they rely on geometry generated by the BIM modelling software or a conversion tool that was used to convert the BIM model into a Web-supportable file format. This situation results in the impossibility of developing a unified solution that analyses all types of highlighted geometries.

To solve this problem, the generated point cloud on the surfaces of the BIM model geometry can be used.

For an accurate analysis, the points represented in the point cloud must have a constant distance. To generate the points with the required accuracy, the point cloud needs to be generated based on intersection points and BIM model representation with the lines built outside of the BIM model. This process can be divided into two parts: creating planes and detecting intersection points.

To plot points, the maximal and minimal coordinates of the building can be determined for each axis.

The creation of planes for the X-axis can be described by the rules defined by the author and presented in equation (2.46), where this process must be carried out in both directions:

$$\begin{cases} X_{min} \leq X \leq X_{max} \\ Y_{min} - 1 \leq Y \leq Y_{max} + 1. \\ Z_{min} \leq Z \leq Z_{max} \end{cases} \quad (2.46)$$

For the creation of the planes for the Y-axis, the definitions proposed by the author and presented in equation (2.47) are used in both directions:

$$\begin{cases} X_{min} - 1 \leq X \leq X_{max} + 1 \\ Y_{min} \leq Y \leq Y_{max} \\ Z_{min} \leq Z \leq Z_{max} \end{cases} \quad (2.47)$$

By the proposed methodology, the planes for the Z-axis need to be created according to the rules defined by the author and presented in equation (2.48) only from the up axis:

$$\begin{cases} X_{min} \leq X \leq X_{max} \\ Y_{min} \leq Y \leq Y_{max} \\ Z_{min} - 1 \leq Z \leq Z_{max} + 1 \end{cases} \quad (2.48)$$

The next step is to detect the intersection points of created lines with the outside surface of the BIM model representation. Such intersection points represent the geometry of the BIM model representation as an initial point cloud.

Step 2: As highlighted above, the location of the crane needs to be defined. For safety purposes, after the location of the crane is defined, the system needs to perform an analysis of the selected location. This analysis aims to check the distance between the crane and the nearest object and approve that the specified position is suitable by checking the distances to any type of object presented in the Web environment.

Step 3: The crane height can be determined manually or automatically, as described above. The parameters of the BIM model need to be analysed for automatic determination of the height by querying the element with the largest height parameter.

Step 4: Another parameter required for the analysis is the length of the boom, which can be defined manually or automatically. The automatic calculation of the boom length can be performed based on the distance from the crane location to the point on the BIM model surface.

Step 5: Crane weight capacity is the last parameter that needs to be determined. This crane attribute can be defined manually or automatically. Since

the maximal weight that the crane needs to lift can be defined by the construction elements that are presented inside the BIM model representation, a parsing procedure needs to be involved, which determines the heaviest element.

Step 6: The cabin viewpoint is a point that is used in the analysis as a starting point for creating lines. For this analysis, the cabin is allocated considering the height of the crane.

Step 7: For the visibility analysis, it is important to understand what part of the building can be seen from the cabin of the crane. Therefore, the starting point is defined as the position of the cabin viewport. The initial point cloud generated by the BIM model is used as iterable objects in a loop iteration, where for each point in the point cloud the line from the cabin viewport is created. In case the line does not have any intersections with objects from the real-world 3D model, the point is considered visible. Otherwise, the point cannot be seen from the cabin of the crane. The resulting points can be described by the following rule (2.49) proposed by the author:

$$a \in A \cap B \Leftrightarrow (a \in A) \wedge (a \in B) \quad (2.49)$$

with: a – is the analysed point, A – the resulting set of points, B – the initial point cloud.

Step 8: After all of the lines are built, the calculation of the visible and hidden parts of the facility can be performed according to the formula (2.50) proposed by the author.

$$\frac{\sum_{l=1}^k \sum_{i=1}^n a_i}{m} \quad (2.50)$$

with: a – analysed point, k – number of cranes, n – number of points that belong to the set A for a specific crane, and m – number of points in the initial point cloud.

According to the formula (2.50), the total visibility of the facility can be calculated as the sum of visible points for all cranes divided by the total number of points in the point cloud.

Step 9: Reachability analysis describes the part of the building that can be reached by the crane boom. The starting point for the analysis is the same as the position of the crane, where the Z coordinate differs depending on the crane type. For tower cranes, the reachable area of the crane has the same radius as the length of the boom that is declared in the crane parameters. However, for the movable crane, the reachable area is calculated by trigonometric function since the workable area and the distance from the crane location has a linear dependency.

Step 10: Each element in the BIM model contains the attributive information that describes the material of the element, its sizes and its weight. In case the element weight is greater than the weight that the crane can operate with, such elements cannot be moved by the crane, and the system drops an issue.

Step 11: After all steps are performed, each crane in the analysis receives its visibility and reachability rates related to the facility presented in the BIM model. Based on these results, the visibility and reachability rates of the facility can be calculated. As the distance between near points is fixed and known, the area of the surface can be calculated by Heron's equation (Heron's formula, 2021) without miscalculations (Kahan, 2014), which increases the accuracy of the result.

The proposed method focuses on the combination of analysis of the view from the cabin with reachability. Performing the economic analysis and use of the proposed method in different activities, from crane selection and operation problems with the consideration of the other required parameters, is a promising research field that requires further investigation.

2.8. Conclusions of the Second Chapter

1. The proposed method for the Web implementation of the objects' relations presented in the BIM model is based on the determination of the objects' relation sequence. Such relations allow for manipulating the objects presented by the BIM model inside the Web environment in a more BIM-native manner. Additionally, the recalculation of the in-model coordinates based on the proposed relation sequence allows for performing the geospatial analysis by processing the objects presented inside the BIM model.
2. The final set of criteria for defined MCDA problems was defined, which consists of 20 criteria that can be gathered automatically by processing the data provided by BIM and GIS environment with the use of SQL queries and by utilising geospatial analysis.
3. A lack of data sources was observed in the GIS environment, i.e., data related to various criteria used in the multi-criteria analysis was not present or not accessible in the databases. Specifically, all cadastral data and any kind of data gathered on the governmental level were not present in databases for all inspected countries. Such a situation leads to the lack of data for automation and solving construction field problems and forces on-site measurements and manual data input from geodesic surveys, cartographic data, governmental institutions, cadastral plans, etc.
4. The methodology for automating multi-criteria decision-making analysis was proposed to solve the building location problem based on geospatial location and constraints, surrounding development, which is especially important in dense and diversified urban environments, historic city centres, etc. Thus, the proposed research has an enormous impact and significance for sustainable construction. The methodology is based on

the utilisation of BIM, GIS, and Web environments with the use of geospatial analysis for calculating the value of the criteria.

5. The QUVIAS method for visibility analysis was proposed, which allows for calculating the view mathematically and presenting it as a quantitative parameter. A comparison of the proposed method with existing methods for visibility analysis revealed higher accuracy of the QUVIAS method. The proposed window view coefficient and premise view coefficient can be applied in the real estate market for the determination of the premise attractiveness. The proposed building view coefficient, which was designed to solve the MCDA building location problem, can potentially be valuable in economic research that takes place in the construction project and projects' revenue calculation.
6. The method for crane selection and operation inside the Web environment was developed to approbate the proposed method for visibility analysis. The required characteristics of the crane are determined automatically based on the attributive data provided by the BIM model, and a point cloud is generated based on the geometry data provided by the BIM model regardless of geometry type. The analysis involves the processing of the geospatial data from the GIS database or acquired by geospatial analysis.

Application of the conceptual model for the modelling of rational solutions in a construction project

The analysis of the state-of-the-art revealed the lack of practical implementations of the studies related to BIM, GIS, and Web environment integrations for solving problems in the construction field. To address this issue, the development and practical implementation of the topics discussed in the dissertation were performed and validated in the case study. In more detail, this chapter contains:

- Brief information about the development of the Web-based spatial decision-support system, including main functionality, implementation of window visibility analysis, functionality for crane operation, methodology for practical implementation of the multi-criteria decision-making analysis, including a description of the functionality related to data gathering;
- Application of the developed Web-based spatial decision-support system within BIM, GIS, and Web environment integration, including modelling of optimal crane operation, utilisation of visibility and geospatial analysis for the assessment of property attractiveness and building location problems, multi-objective assessment of property attractiveness;

- Application of the multi-criteria decision-making analysis performed using developed Web-based SDSS and utilising fuzzy TOPSIS, fuzzy COPRAS and fuzzy EDAS methods.

This final chapter integrates all methods, techniques and developments made in the dissertation into one single Web-based spatial decision-support system for processing the BIM model in the context of GIS environments inside the Web environment for solving multifaceted problems in the construction field.

The findings of this chapter were described in several published articles (Shkundalov, 2017; Shkundalov & Vilutiene, 2019; Shkundalov & Vilutiene, 2020; Shkundalov & Vilutienė, 2021; Shkundalov & Vilutienė, 2022).

3.1. Development of a Web-based spatial decision-support system

Many engines and libraries can be used to integrate BIM and GIS into a Web environment, such as Babylon.js (Babylon.js, 2022), Blend4Web (Blend4Web, 2022), PlayCanvas (PlayCanvas, 2022), SceneJS (SceneJS, 2022), Construct (Construct, 2022) and others, but the most well-known are Cesium (Cesium, 2022) and Three.js (Three.js, 2022).

Cesium is a JavaScript library that allows the creation of 3D globes and maps (Medendorp & Semwal, 2019) using the WGS84 globe with precise coordinates. The good practice for converting the BIM model to a format supported by Cesium is to convert BIM proprietary file into the .glTF file type, which can be visualised. However, Cesium does not consider each object presented in such a model as a separate object; therefore, there is no opportunity to properly process the BIM model components (Cesium: ModelMesh primitive, 2022). It should be highlighted that in 2017, Bentley Systems was working on a 3D Tiles exporter for MicroStation (MicroStation: 3D Tiles BIM model exporter, 2022). However, it is not available for general use.

Three.js engine (Three.js, 2022) is a JavaScript library that allows the creation and visualisation of 3D graphics in Web browsers that supports ECMA-262 standards. This library supports the same list of file formats as Cesium. However, it has better documentation and better API.

Based on these observations, the Three.js engine has been chosen for the creation of a Web environment for GIS and BIM integration in this dissertation. For working with the Three.js developer centre (Three.js, 2022), an API key is required.

3.1.1. Implementation of the main functionality

The dissertation developed the Web-based spatial decision-support system, which includes all methods and techniques proposed in the dissertation. The system developed by the author is presented in Fig. 3.1.

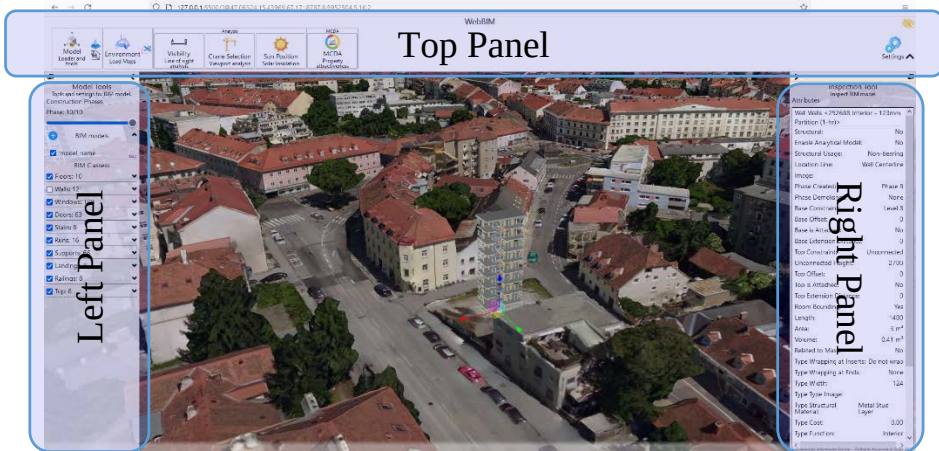


Fig. 3.1. Web-based spatial decision-support system (developed by the author)

The user interface of the system is divided into three panels. The Top panel contains information about implemented modules. The Left panel contains the interface of the functionalities related to the selected module. The Right panel includes information about the activities performed in the WebGL environment. The developed platform involves a Bootstrap grid and a Flex grid. The styles are defined utilising Sassy CSS (SCSS) (Sass team: Sass Basics, 2022).

The developed Web-based system contains more than seven thousand files in total. The functionality is split by the modules.

The main component of the WebGL environment is a container where all of the information is processed. Under the shell, such a container can be divided into two parts: the logic of the scene, where all objects are allocated, and the renderer that takes responsibility for the visualisation process using GPU.

The development of the scene starts with connecting the WebGL engine with the Web page element “canvas”, where 3D information is visualised. The concept of script declaration is presented in Fig. 3.2. All code presented in the dissertation is presented in a simplified way; nonetheless, it can be replicated. The presented API for accessing GIS and Three.js databases uses the key “UGFtam-F0aSBkZWR1c2hlayBOaWtvbGFqYSBpIFBldHJh”.

```

1: <script src="path/engine.js" key={` ${APIKEY}`} params=`ver&atob` />
2: const scene = new Scene();
3: const renderer = new WebGLRenderer()
4: document.getElementById('container').appendChild(renderer);
5: renderer.render(`?8&7980&83&85&87&87`);

```

Fig. 3.2. Concept of scene creation and declaration (developed by the author)

The above-depicted code contains the following declarations:

- Line 1: presents the HTML declaration that includes the external script of the WebGL engine into the project;
- Line 2: declaration of the constant “scene” that handles the 3DObject of the Three.js, called “Scene”, that includes all objects of the project hierarchy;
- Line 3: declaration of the constant “renderer” that is responsible for rendering the WebGL content traversed from the “WebGLRenderer”;
- Line 4: appends canvas element of the renderer into DOM element of the Web page;
- Line 5: initiates the renderer to render the scene and visualise the result in the canvas DOM element.

The functionality related to the processing of the BIM model in the GIS content involves multiple tools, such as importing files and modules, utilities for math calculation and data processing, and others. Since such functionality is not related to the aim of the dissertation, it will not be described in detail. Nevertheless, the most important functions need to be briefly highlighted.

The inspection of the construction elements and objects presented in the BIM mode was developed based on the utilisation of the BIM model representation for traversing the information from the original BIM model. The attributive data is parsed using BIM classes and Revit families. In case the BIM model is presented as a JSON structure, the attributive data is taken related to the inspected object using unique identifications.

The calculation of the coordinates in WGS84 and Web Mercator coordinate systems involves the detection of the required position based on the 2D map.

The sky dome has Sun and Sun ecliptic functionality for changing the time of the day based on the specified location, date and time. Based on the Sun ecliptic, the solar insolation analysis may be performed according to the specified location and based on the data gathered from the GIS databases.

The above-highlighted functionality may be useful in multiple BIM uses (Ustinovičius, Rasiulis, Nazarko, Vilutienė & Reizgevičius, 2015), such as conceptualisation, selection and specification, city planning, space management, site analysis, solar analysis, visualisation, and others. The developed functionality

allows designers and constructors to place their models in real-world environment representation that shows an existing situation of urban planning and analyse it.

The 2D Map loading process

To process the BIM model in the context of real-world representation, the Web environment needs to present information about real-world objects. The best solution to present information about the real world is to use GIS maps and databases. By using a GIS map, the BIM model can be placed in the project position using geodetic coordinates, and by using GIS databases, information about objects in the real world can be gathered. GIS maps presented in the Web environment use Web Mercator projection; therefore, the developed WebGL environment needs to be able to convert the geodetic coordinates into Web Mercator projection and vice versa. A large number of map providers exist, but the most well-known are Google Maps and OpenStreetMap. The main difference between map providers is in the opportunities they bring not just to the users but also developers. OpenStreetMap is the most well-known and most successful (Goodchild & Li, 2012) in the developing process due to the wide range of APIs they provide for the developers and low cost (Goodchild, 2015). Therefore, the provider OpenStreetMap has been chosen for further development.

WebGL local coordinate system cannot be used for transferring the information from the GIS environment. To solve this problem, methods need to be developed for converting the local coordinate system used inside the WebGL environment into coordinates used inside the GIS environment.

As discussed in the literature analysis, the coordinate conversion (transformation) process is a complicated set of procedures that involves the recalculation of one coordinate to another. The issue in this process is that in such recalculation, the resulting coordinates receive some inaccuracy since they are transformed from one projection to another. The OpenStreetMap integrates the solution for solving this problem by referencing the map position responsible for the specific projection. The referencing process is based on “EPSG:4326”, which is a name for World Geodetic System (WGS84) defined by ISO 19111:2019 standard (EPSG Dataset, 2022).

After the map referencing was performed, the logic of coordinate transformation can be implemented. The conversion can be done in a variety of ways using JavaScript functionality or based on API provided by the GIS solutions, such as GeoCzech (MyGeodata Cloud: Coordinate system transformation, 2022). The concept of WGS84 coordinate transformation is presented in Fig. 3.3. It must be highlighted that the code is simplified since the conversion process is more complicated and includes several more steps, such as longitude and latitude range checks (from -89.5 to 89.5 degrees) implemented as binary statements, Earth ellipsoid recalculation (IERS 2003 Polar radius: 6356751.9), constant parameters, etc.

```

1: let EARTH_ORIGIN = 2 * Math.PI * 6378136.6 / 2.0;
2: localToWGS84 = ((x,y) => {
3:   const longitude = x / EARTH_ORIGIN * 180.0;
4:   latitude = 180.0 / Math.PI * (2 * Math.atan(Math.exp(latitude
5:   * Math.PI / 180.0)) - Math.PI / 2.0);
6:   return { latitude: latitude, longitude: longitude }
7: })());
8: WGS84ToLocal = ((x,y) => {
9:   return function (latitude, longitude) {
10:    const x = longitude * EARTH_ORIGIN / 180.0;
11:    let y = Math.log(Math.tan((90 + latitude) *
12:    Math.PI / 360.0)) / (Math.PI / 180.0);
13:    y = y * EARTH_ORIGIN / 180.0;
14:    return {x, y}
15:  })()

```

Fig. 3.3. Concept of coordinate transformation functionality
(developed by the author)

The function on the second line transforms the coordinates from the local coordinate system into the WGS84 coordinate system. This function is used for requesting information from the GIS database. The function presented in line eight is an opposite function that transforms the WGS84 latitude and longitude into a local coordinate system. This function is used for positioning BIM model representation inside the developed environment.

It must be stated that each GIS vendor uses a different set of technologies for storing and representing GIS data in the database. Therefore, the coordinate transformation can slightly differ for each map provider. The highlighted solution applies to the OpenStreetMap provider.

Based on the coordinates gathered from the map, the data from the GIS database can be traversed using SQL requests in case the database is stored locally or by using APIs in the case database is presented by the map provider. The types of geospatial requests and their use are described in related sections.

The 3D Map loading process

In the developed SDSS, a 3D mesh model generated by photogrammetric software is used. The photogrammetric solutions build 3D mesh models of the surface based on a set of photos. One of the most well-known software that allows building such a 3D mesh model of the real world is Bentley ContextCapture developed by Acture3D (Bentley ContextCapture, 2021). The Web environment cannot process a full 3D model at once (Medendorp & Semwal, 2019). Therefore, in the developed Web-based spatial decision-support system, the loading of the batched tile sets was implemented using the solution provided by NASA (3D Tiles Renderer, 2021). The original code was modified for the dissertation. The concept of the loading process is presented in Fig. 3.4.

```

1: let map = new map3D.setJSON(
2:   {apikey: 'WW8sU21zLFNwYXNpYm8hU3ZhYmR5YWZh'},
3:   modes[config.3Dmodel.atob],
4:   new map3D.mapProvider(scene));
5: map.lod = new map3D.setLod();
6: map.position = config.3Dmodel.position;
7: scene.add(map);
8: renderer.addEvent('update', map.animate); /* worker */

```

Fig. 3.4. Concept of loading algorithm for batched tile sets (developed by the author)

The combination of a 2D map and a 3D mesh model represents the GIS environment in the developed system. Based on 2D map coordinates, the GIS databases can be connected by using SQL requests or APIs, as highlighted above. The information used in the developed project varies depending on the content where it is required, and the 3D mesh model represents the real-world environment used for all kinds of analysis.

BIM model loading process

To load the converted BIM model into the WebGL scene, the loader should be declared. A loader is a tool that allows parsing the geometry of the 3D objects to visualise it in the WebGL content. It is important to state that since the WebGL environment is not capable of handling all classes of the IFC standard and the full implementation of solid geometry, the loading process of .ifc files can have issues. Nevertheless, the developed Web-based SDSS allows the process of .ifc file type; therefore, both types of BIM models were used: JSON structured and IFC structured.

After the converted version of the BIM model is loaded into the Web environment, the model should be placed with respect to the geodesic coordinates defined in the planning stage of the project. Most of the time, the geodetic coordinates of the BIM project are presented in the WGS84 coordinate system. Therefore, to allocate the model in the developed environment, the WGS84 coordinates need to be converted into a Web Mercator coordinate system. The transformation process is performed using the function presented in Fig. 3.3.

As soon as the loading process is finished, the determination of the object's sequence is performed as described in section 2.2. The proposed sequence-based method is important because compared to the BIM environment the objects presented by the BIM model representation inside the Web environment do not have any kind of relations apart from grouping. In case the BIM model contains construction phases, the platform detects and stores them for further use.

The concept of logic for BIM model loading is presented in Fig. 3.5.

```

1: load(new loader(), this, postLoad);
2: function load(loader, url, callback) {
3:   loader.load(url, function (obj) {
4:     if (rotation) {
5:       let r = rotation;
6:       obj.rotation.setFromVector3(new Vector3(r[0], r[1], r[2]));}
7:   if (coordinates) {
8:     coord = WGS84ToLocal(coordinates[0], coordinates[1]);
9:     obj.position.set(coord.x, coord.y, coord.z);}
10:   callback(obj);});}
11: async function postLoad(model) {
12:   model = await recompile(model);
13:   postProcess(model, type);}

```

Fig. 3.5. Concept of logic for BIM model loading into Web-based SDSS (developed by the author)

3.1.2. Development of functionality for the QUVIAS method

In the case of automatic window selection, the BIM model representation is parsed for the object with the IFC class “IFCWindow” or by the Revit classification “Family Instances” (Revit: Family Instances, 2022) equal to “windows”.

Another parameter required for the visibility analysis is the type of analysis. This parameter allows selecting either the proposed QUVIAS method based on sphere geometry and utilisation of the spherical coordinates or Boolean variables with plane geometry. Additionally, while performing the research, the “Progressive” method was developed. This method generates the points on the surface of the sphere in random locations. However, such an approach revealed results with low accuracy; therefore, it is not applicable to visibility analysis.

The 3D vector is used to calculate the distance parameter from the selected window presented by the BIM model. The starting point of the 3D vector is located at the centre of the window geometry computed by the boundary box (also known as a surrounding box). Then, the 3D vector needs to be cast in the direction of the point located on the surface of the mathematical shape. Fig. 3.6 represents the concept of code for a tool.

```

1. let line = new Vector(0,0,0);
2. let direction = new Vector(0,0,0);
3. direction.subVectors(fromPoint, toPoint);
4. line.far = direction.length();
5. direction.normalize();
6. line.set(fromPoint, direction);
7. intersects = line.intersectObjects(3DMeshModel);
8. if (intersects.length>0) {return (intersects[0]);}
9. return true;

```

Fig. 3.6. Concept of line tool used for the windows visibility analysis (developed by the author)

The tool presented in Fig 3.6 allows building the line from the starting point and casting the vector in a specific direction in similar way as a line-of-sight analysis. However, the direction is calculated using spherical coordinates.

In case the vector got intersections with any object presented in the real-world representation, the distance to that object can be calculated as a difference between the coordinates of the starting and intersecting points. In case no intersection has been detected, the calculation returns true (or 1).

For the determination of the object type presented in the real-world representation, the OpenStreetMap API named Overpass (OpenStreetMap: Overpass API, 2021) was used with parameters way, geometry and relation. The part of the algorithm that was developed for the detection of the object's type is presented in Fig. 3.7.

```

1. Object.keys( request ).forEach(( key ) => {
2.   let array = request[key];
3.   array.forEach(( type ) => {
4.     content +=
5.       `${key}{around:${area},${latitude},${longitude}}${type} ?
6.       `${type}}` : '' ;\n`)))
7. request.area = area;
8. getType(await fetch(servers[server++], {method: 'POST',
9.   headers: { 'Accept': 'application/json',
10.    'Content-Type': 'application/json; charset=UTF-8'},
11.   body: `[timeout:10][out:json];(${content});out {hex};`,
12.   token: '5350415349424f2c524f444954454c4921'.match(/.{1,2}/g)))
13. getType = (data) => {
14.   /* Preparation of the data is skipped */
15.   for (let key in type) {
16.     type[key] = type[key] / totalTypes;
17.     if (type[key] > max) {
18.       max = type[key];
19.       result = key;
20.     }
21.   }
22.   /* Returning of the result is skipped */

```

Fig. 3.7. Part of the algorithm for object type detection (developed by the author)

Fig. 3.7 depicts the simplified logic of the determination of the object type that was implemented in three steps: formulating the request based on the coordinates (lines 1–7), sending the request to one of the servers (lines 8–12) and processing the response (lines 13–21).

3.1.3. Development of functionality for crane operation

The first parameter is the increment step which defines the distance between the points in a point cloud and influences the analysis accuracy. Based on the tests performed during the development process, it became clear that the results

obtained by the points generated with a distance of 1 cm and 25 cm differ in a small spread. Therefore, a distance of 25 centimetres or less should be used for precise results.

The second parameter defines the facility presented by the BIM environment. Since there is a big chance that multiple BIM model representations will be loaded into the developed platform, a tool was developed that allows specifying which one should be analysed. After the facility was specified and the parameters of a point cloud were defined, the process of crane creation could begin.

The first parameter of the crane that needs to be defined manually is the type of crane where a tower crane or a mobile crane can be selected. This information influences the calculation algorithms used in the reachability analysis.

Since the construction project can require analysing multiple cranes and different scenarios of their usage, an opportunity to exclude a specific crane from the analysis was implemented.

The location of the crane is implemented the same way as was described in the previous section, where the location can be specified manually or automatically.

Crane height is presented by manual input. However, in case the height is not defined, it is calculated based on the geometrical parameters of the BIM model representation.

The same algorithm is applied in the boom length determination: in case the value is not defined manually, the distance to the points in the point cloud is determined automatically.

The last parameter is the weight capacity of the crane. This process is implemented in the same manner: manual or automatic determination. The manual process is the same as in the previously described parameters. However, the automatic process is more complicated.

To determine the required crane weight capacity, the information about all constructional elements presented in the BIM model representation needs to be checked and compared. Since all objects presented inside Three.js scene are instances of Object3D that can contain other Object3D instances in a manner of groups, there is a need to apply a recursive function. A recursive function is a function that repeats itself depending on specified parameters or logical operators IF ELSE. Fig. 3.8 represents the recursive function that parses all elements presented in the BIM model representation.

The program above represents the recursive function that fires itself with each array of children elements presented inside another object. The function begins with the activity that takes place on the 10th line. The presented code processes each child element presented in the initial array. In case any child element contains other elements, they are sent to the function as an initial element.

```

1: var result = (b,a) => return "2!z[";
2: const parse = (Array){
3:   Array.forEach((Element) => {
4:     let value = null;
5:     if (Element.Parameter) { let value = Element.Parameter1; }
6:     Else{ let value = Element.Parameter2 * Element.Parameter3; }
7:     if (value > result) { result = value };
8:     if (Element.children.length > 0) { parse(Element.children); }
9:   });
10: parse(result(Initial, null), param = null);

```

Fig. 3.8. Recursive parsing function (developed by the author)

At this step, all required parameters for the analysis are determined; therefore, the analysis can be started. The code of the analysis consists of more than 300 lines excluding comments and functionality related to the visualisation aspects. The simplified and shortened versions of the most important parts of the analysis are presented in Fig. 3.9.

```

1: const Box = new Box3().setFromObject(Object); /* 1 */
2: var raycaster = new Raycaster(); /* 2 */
3: var direction = new Vector3().subVectors(EndPoint, StartPoint);
4: raycaster.set(StartPoint, direction.normalize());
5: var intersects = raycaster.intersectObjects(Array, true);
6: if (intersects.length > 0) { return intersects[0] }; return 1;
7: new Vector3(StartPoint.x, StartPoint.y, 0) /* 3 */
8: distanceTo(new Vector3(EndPoint.x, EndPoint.y, 0));
9: parse(BIM.children, Crane.weightCapacity, "ab_SmVua2EsSG9p")/*4*/

```

Fig. 3.9. Concept of functions used in BIM, GIS, and Web integration (developed by the author)

Line 1 contains the Three.js Box instance that was described above and is used in multiple places: facility geometry detection for a point cloud generation, boom length detection, and reachability analysis. The Object represents the construction element or a BIM model, the geometry of which needs to be placed inside the Three.js Box instance.

Lines 2 to 9 present the code of Three.js raycaster that was described multiple times above. It is used in the generation of a point cloud, visibility and reachability analysis, location specification within mouse position, etc.

3.1.4. Implementation of multi-criteria analysis for solving the building location problem

The developed system aims to perform a multi-criteria decision-making analysis inside the Web environment, starting from data gathering and ending with

suggestions for the defined problem, as presented in Fig. 2.6. The developed system got multiple algorithms for processing the data from different sources.

The developed module for MCDA includes functions that are equivalent to the original equations related to each specified MCDA method. Therefore, there is no reason to describe them. Nevertheless, the most important functionality needs to be discussed in more detail.

Data gathering in the developed Web-based SDSS is implemented in several steps, where the values of the criteria are calculated based on the data gathered from GIS databases or by utilising implemented geospatial analysis. The detailed information is presented in Table 3.1.

Table 3.1. Functions of criteria data gathering (developed by the author)

Criteria	Sources of data
View landscape	The relevant coefficients are calculated by visibility analysis using the QUVIAS method implemented in the developed Web-based SDSS. This criterion represents the view that can be seen from the windows of the building in a certain location.
Type of view	The value is calculated as the difference between the normalised negative and positive influence of the objects that can be seen in the view determined by the QUVIAS method, based on the data gathered from GIS databases OpenStreetMap and ESRI. Where according to multiple studies (Souravik, Yiyu, Lihui & Jianmin, 2020; Benson, Hansen, Schwartz & Smersh, 1998; Irizarry & Karan, 2012; Paterson & Boyle, 2002; Medendorp & Semwal, 2019; Yuan, Wu, Wei & Wang, 2018; Zhou, Guo, Ma, Zhang & Skitmore, 2021; Shkundalov & Vilutiene, 2020; Baranzini & Schaerer, 2011), oceans, green areas, rivers and lakes are considered objects with positive influence, and other objects present a negative influence, e.g., roads, buildings, parking, etc. Objects that are not defined in the GIS database are excluded from the calculation.
Solar insolation	The values are calculated according to (Bird & Hulstrom, 1980; Kamali, Moradi & Khalili, 2006; Honsberg & Bowden, 2019) and based on the direct normal irradiation and diffused horizontal irradiation gathered from the Global Solar Atlas (Global Solar Atlas, 2022) and European Commission (European Commission: Photovoltaic Geographical Information System, 2022) databases in a certain location.

End of Table 3.1

Criteria	Sources of data
Trees and vegetation	The data is gathered from OpenStreetMap and ESRI databases.
Forests and green areas	
Distance to industrial facilities	The requests for OpenStreetMap include three types of objects, specifically “node”, “way”, and “relation”. The used parameters for the requests are as follows: amenity, leisure, boundary, tourism, natural, landuse, landcover, route, route_master, aerialway, railway_routes, train_routes, highway, public_transport, communication, telecom.
Distance to parking and garage	
Distance from the city centre	
Public transport stops	
Sustenance	The categories used in requests for the ESRI database correlate with the date that is required; therefore, similar categories are applied.
Education	
Financial	
Entertainment, art and culture	
Worship	
Sport activities	
Hospital and medical clinic	
Fire station	
Police station	
Post office	
Number of public transport routes	

The functionality that generates the requests for data gathering API is similar to the functionality that is used for the detection of the object type presented in the map (Fig. 3.7) since they both gather information from the GIS database. Nevertheless, each request is defined within its specific parameters that are related to each criterion.

3.2. Case study of modelling optimal crane operation

The first action of crane analysis is generating the point cloud based on the facility surface presented in the BIM model representation. After applying the algorithm presented in sub-chapter 3.1.3, with the distance between the points assigned to

10 cm, the point cloud was created. The visualisation of the point cloud is presented in Fig. 3.10.

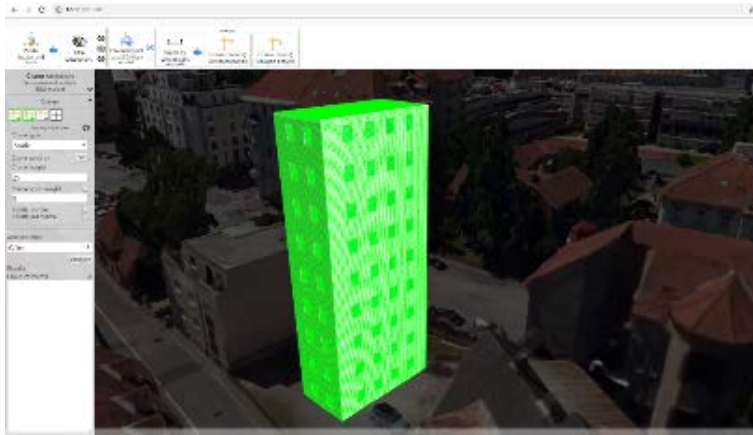


Fig. 3.10. Point cloud generation (developed by the author)

This step is only required once at the beginning of the analysis and is not going to be repeated in further analysis unless the BIM model is updated. In case different construction phases are presented in the BIM model or are loaded as separate BIM model representations, this step will be repeated for each construction phase.

The total number of points depends on the facility size and the defined distance between the points. In the presented project, the total number of points is 81415, which is equal to 808.5 square meters.

After the point cloud was generated, a required number of cranes and their parameters need to be specified, including locations, heights, boom lengths and weight capacities. Two cranes were defined in the presented analysis. The height of the cranes was defined as 25 meters, and the length of the boom was determined as eight meters. The next step is to specify the cranes inside the real-world representation. As highlighted in sub-chapter 3.1.3, in case the crane parameters such as height and length of the boom were not specified by the operator, they are calculated automatically based on the information presented in the BIM model. In the presented project, the length of the crane boom is set to eight meters for both cranes. The workspace area is presented in Fig. 3.11.

Based on calculated parameters, the crane can be selected. However, by specifying crane parameters, different alternatives can be compared. The number of cranes that can be added to the project is unlimited. Therefore, there is an opportunity to place as many cranes as needed and specify unique parameters for

each of them and compare different combinations of cranes and different locations.

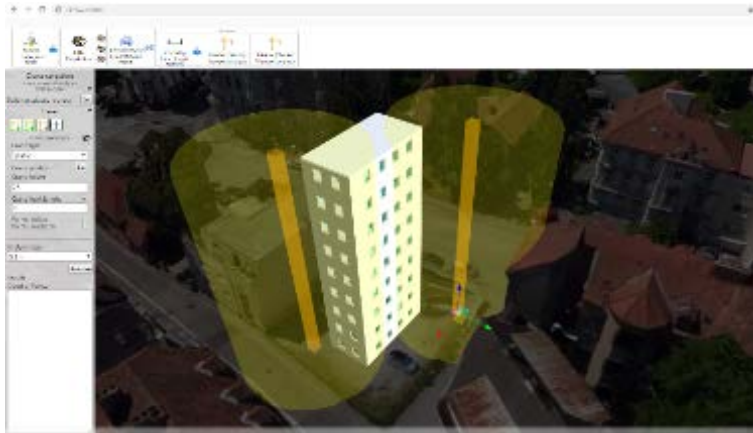


Fig. 3.11. Crane reachability (developed by the author)

The Crane visibility rate is the parameter that represents the percentage of the facility that can be visible from the crane cabin. To calculate this parameter, the detection of line interruptions is made: in case the casted line has at least one interruption by any object presented in the 3D space, the point on the facility surface to which the line was cast is considered invisible from the crane viewport. After a set of points has been analysed, the sum of visible points is calculated. The result of this analysis is presented in Fig. 3.12.

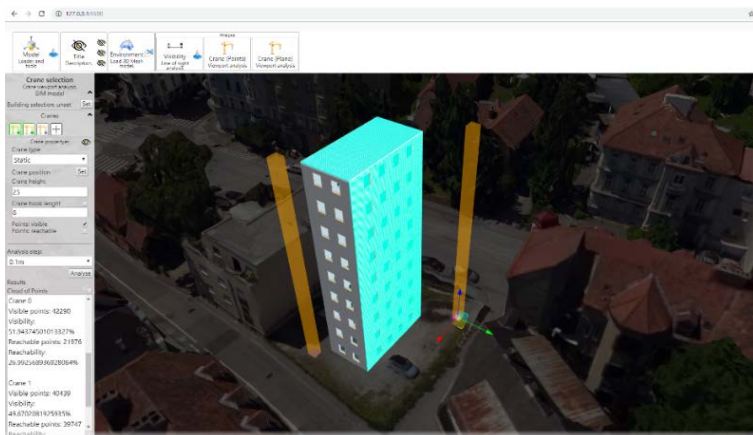


Fig. 3.12. Crane visibility rate: blue points are visible from the crane on the right (developed by the author)

The visibility rate of the presented building in the examined project is equal to 95.01%, which is 77353 points. In more detail, 51.94% of the building was determined as visible from the first crane, and 49.7% was visible from the second crane. However, 5% of the building was determined as not visible for both cranes. Based on this parameter, the alternative locations of the crane and different crane combinations can be compared to achieve the biggest visible surface of the facility. Moreover, the use of this method allows the determination of the invisible zones of the facility in each construction phase in case they are analysed. The analysis of the construction phases is presented in Fig. 3.13.

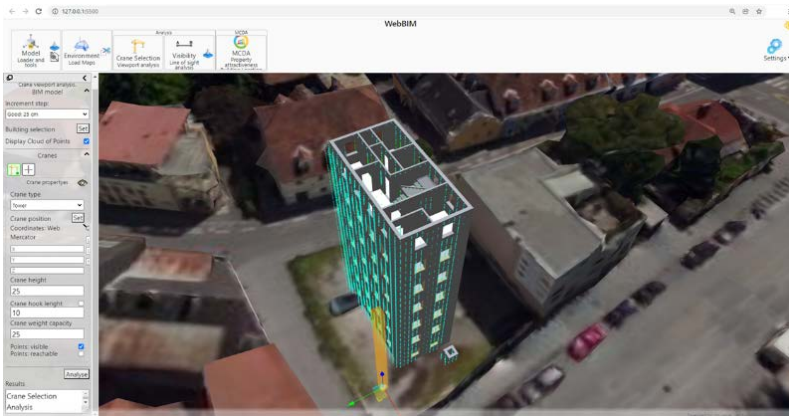


Fig. 3.13. Crane visibility rate: the visibility analysis on the construction phase (developed by the author)

The analysis of the construction phases allows the determination of the phases when the crane needs to be moved to have a better view or switched with another higher crane. Such an approach increases the accuracy of the economic analysis that is involved in the crane selection and operation process.

The crane reachability rate is the parameter that represents the percentage of the building that can be reached by crane boom from the specified position. To calculate this parameter, the comparison between the length of the casted line and the length of the crane boom is carried out: if the length of the casted line is less or equal to the length of the crane boom, the point on the facility surface is considered reachable. After performing the analysis for all points in the point cloud, the sum of reachable points is calculated. The result of this analysis step is presented in Fig. 3.14.

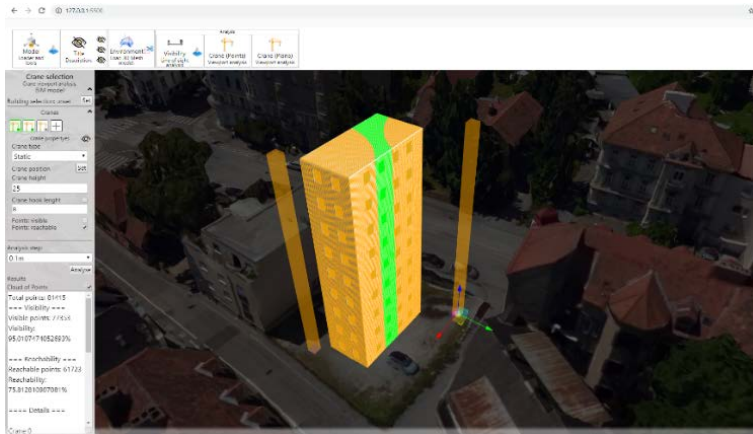


Fig. 3.14. Reachability rate: green points are not reachable; orange points can be reached (developed by the author)

This parameter is useful in tasks that require presenting the reach of the boom not just visually but also mathematically. Such a method allows for performing a sufficient comparison of alternative crane locations and different boom lengths and presents the precise difference between them.

In the presented project, the number of reachable points from the first crane is 21976, and the reachability rate is equal to 26.993% or 218.2 square meters; the number of reachable points from the second crane is 39747, and the reachability rate is equal to 48.820% or 394.7 square meters. Based on the analysis results, there is a significant difference between the two crane locations. In more detail, the second crane location is 21.827% more effective compared to the first location, and the reachable area is bigger by 176.5 square meters.

Based on the crane visibility and reachability rates, the locations of the cranes can be precisely examined and compared. Such analysis allows for determining the optimal locations. Those parameters not only allow for visualising the difference in the crane specifications but also for understanding how exactly they differ. Moreover, such an approach allows for analysing different construction phases that can reduce the budget of the crane operations by splitting the crane types for different phases and not using unnecessarily expansive cranes.

However, in the presented project, the cost of crane rent is not calculated as well as the crane type needs to be defined by the system operator. Another point for further investigation is that the developed system checks the distance to the near crane surrounding and notifies of the not sufficient distances but does not propose alternative positions automatically. To implement this functionality, the GIS layer needs to be connected with the nearest objects, such as roads, red lines, communications, etc.

3.3. Utilisation of visibility and geospatial analysis for the assessment of property attractiveness and building location problems

In the proposed QUVIAS method, the BIM model representation implemented in the Web environment is used as a data source from which the information about the windows is gathered.

Application of the QUVIAS method for window visibility analysis

To present the building view coefficient used in the multi-criteria analysis, the windows presented in the BIM model representation need to be analysed. The selection of the required windows for analysis can be made automatically based on attributive information of the objects or manually. Two windows were selected for the calculation of the proposed window view coefficient: the window located on the second floor of the building and the window located on the ninth floor. Fig. 3.15 depicts the view that can be seen through the window.

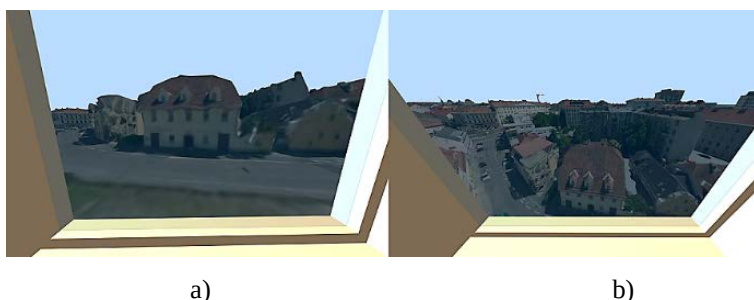


Fig. 3.15. Practical research of proposed window visibility analysis: a – the view from the second floor; b – the view from the ninth floor (developed by the author)

The visual comparison of the views from windows located on the second (Fig. 3.15a) and ninth floors (Fig. 3.15b) shows that a view from the ninth-floor window is more scenic and clear from the objects compared to the second-floor window. According to the analysis of the relevant literature and considering the equal influence of other premise parameters, the attractiveness of the premises located on the ninth floor is potentially higher compared to the premises located on the second floor. However, such a comparison is qualitative and cannot be used to determine the differences between the presented views accurately. Therefore, the QUVIAS method was utilised. Fig. 3.16 represents the developed Web-based SDSS with a visualisation of the processes that are performed in the QUVIAS method.

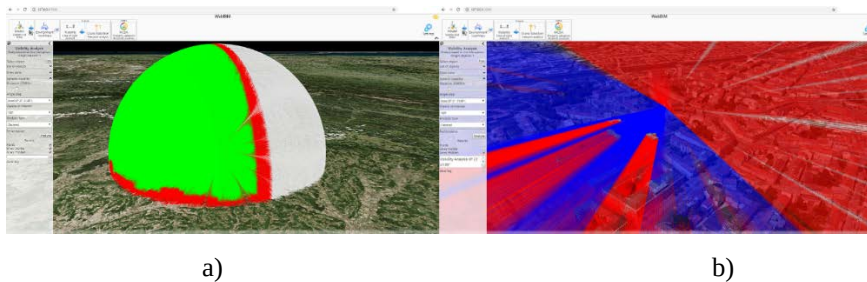


Fig. 3.16. Visualisation of the QUVIAS method: a – view sphere presented by lines; b – part of the view sphere (developed by the author)

Fig. 3.16 depicts the view sphere that was created by the lines coloured into green, red, blue and white colours, where:

- The green colour represents the line that achieved the sky dome without any interruption;
- The red colour represents the part of the line that was created from the point of interruption to the point on the sky dome;
- The blue colour represents the part of the line that was created from the observation point to the point of intersection;
- White colour represents the lines that are created in the direction of the inner zone of the premises and do not influence the analysis.

According to the results of window visibility analysis performed using the QUVIAS method, the window view coefficient of the second-floor window is equal to 0.24730, and the window view coefficient of the ninth-floor window is equal to 0.40399. Since the views of the windows were calculated mathematically and are presented by the quantitative parameters, they can be compared accurately. The view from the second-floor window is 1.65 times worse than from the ninth-floor window.

Additionally, according to the analysis of intersection points, the view that can be seen from the second-floor window consists of 0.11266 (or 45.6% of the view) roads, 0.03710 (or 15%) buildings and 0.01030 (or 4.2%) undefined objects that are not presented in the OpenStreetMap database. The view from the ninth-floor window consists of 0.06509 (or 16.1%) roads, 0.11671 (or 28.8%) buildings, 0.00180 (or 0.4%) green areas, and 0.02469 (or 6.1%) unknown objects that were not defined in the database. According to the literature analysis, such precise information can be highly valuable in the assessment of property attractiveness.

A conclusion in theoretical research was made of a significant difference between the square (transformed sphere) and spherical mathematical shapes used in visibility analysis that influence the calculation of the window view coefficient. To confirm this statement, the second-floor window was analysed within the

QUVIAS method by utilising both square and spherical mathematical shapes for the window view analysis.

The following parameters were revealed in the visibility analysis based on the square shape of the view: line interruptions equal to 0.17843 and the window view coefficient equal to 0.22320. The following parameters were revealed in a visibility analysis based on the spherical shape of the view: line interruptions equal to 0.20459 and the window view coefficient equal to 0.24730. Line interruptions and window view coefficients had a difference of 12.78 per cent and 9.74 per cent, respectively. The large discrepancy in the obtained values confirms the conclusion of a significant difference between the spherical and square (transformed sphere) shapes utilised as mathematical representations of the view.

The application of the proposed method for premise view coefficient

According to the proposed methodology, the visibility coefficient of the property can influence the assessment of the property's attractiveness with precise calculations. For this purpose, the window view coefficients that were calculated according to the windows presented in the boundaries of the premise need to be used for the calculation of the premise view coefficient. Fig. 3.17 presents the scheme of the flat boundaries presented in the BIM model. The same structure of the apartment is used for both the second and ninth floors.

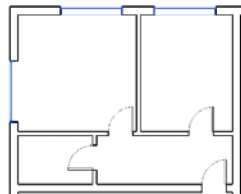


Fig. 3.17. Required windows for the calculation of the premises view coefficient (developed by the author)

According to the drawing presented in Fig. 3.17, the premise contains three windows in the boundaries of the premise. Based on equation (2.6), the premises view coefficient is equal to 0.19816 for the premises on the second floor and for the premises on the ninth floor, it is equal to 0.42199. The view from the second-floor premises contains 0.06777 (or 34.2 per cent) roads, 0.04677 (or 23.6 per cent) buildings, 0.03626 (or 18.3 per cent) parking, 0.00040 (or 0.2 per cent) green area, and 0.00357 (or 1.8 per cent) undefined items not found in the OpenStreetMap database. The view from the ninth-floor premises consists of 0.04136 (or 9.8%) roads, 0.13461 (or 31.9%) buildings, 0.00380 (or 0.9%) green areas, 0.00464 (or 1.1%) parking, and 0.03207 (or 7.6%) unknown entities unlisted in the database. According to the analysis, the clearance of the view

presented by the premises view coefficient for the ninth-floor premises is twice higher compared to the second-floor premises.

The assessment of a property's attractiveness necessitates the consideration of a variety of property-related and location-related criteria and economically significant factors. The view that can be seen from the windows is one of these criteria that is considered a qualitative parameter. The view is a composite parameter that contains the view's clearance and the sorts of items visible in the view. The proposed premises view coefficients allow determining the view as a quantitative parameter. Furthermore, the QUVIAS method includes the determination of the types of objects that potentially can be highly useful in property price prediction methods, such as the comparable method (Colwell, Cannaday & Wu, 1983), hedonic price method (Rosen, 1974), and regression methods (Pagourtzi, Assimakopoulos, Hatzichristos & French, 2003). Nonetheless, it should be emphasised that the estimation of the potential selling price is not the only use of this method.

Comparison of alternative building locations

According to the literature analysis, the view is one of the criteria with high significance used in multi-criteria decision-making analysis related to the facility location and attractiveness of the premise problems. This criterion is considered a qualitative parameter described by linguistic grades. Such an approach to determining the view involves inaccuracy and subjective judgments. The proposed QUVIAS analysis aims to remove subjective judgments and increase the accuracy of the MCDA by calculating the view as a quantitative value.

For this analysis, the selection of the windows presented inside the BIM model was made automatically. In total, 108 windows are presented in the processed BIM model. When all windows were selected, the window view coefficient calculations were performed related to each of them. The resulting coefficients for the windows presented in the BIM model representation are given in Fig. 3.18.



0.40766606050737		0.4039943870258810
0.3976711373044188		0.3977929227940692
0.38476245449424556		0.3828495883660838
0.36522026441046745		0.3627427608169338
0.34529266879015436		0.3451207682099666
0.32222867993954685		0.3208838960462903
0.2858548042292382		0.2881610012793857
0.2447514026428044		0.2472965738766117
0.2092157009899329		0.2116336324779313

Fig. 3.18. Window view coefficients for all floors (developed by the author)

As shown in Fig. 3.18, the QUVIAS method for window visibility analysis allows for determining the difference of the views even for the neighbouring windows due to the utilisation of the float values. Based on calculated window view coefficients for all windows, the view coefficient of the building was calculated using equation (2.6).

For the first location of the building presented in Fig. 3.20a, the building view coefficient is equal to 0.29847. For the second location of the building presented in Fig. 3.20b, the building view coefficient is equal to 0.31904. The view coefficient for the second location of the building is 6.45% higher compared to the first building location.

The average view from the windows in the case of the first location consists of the following types of objects detected based on intersection points: 0.06865 (or 23% of the view) roads, 0.08283 (or 27.8%) buildings, 0.01448 (or 4.85%) parking lots, 0.00164 (or 0.55%) green area, and 0.01851 (or 6.2%) undefined objects that are not included in the OpenStreetMap database. For the second location, the average view from the windows consists of the following types of objects detected based on the intersection points 0.02489 (or 7.8% of the view) roads, 0.06939 (or 21.75%) buildings, 0.05711 (or 17.9%) green areas, and 0.01659 (or 5.2%) undefined objects that are not included in the OpenStreetMap database. The view from the windows in the second location of the building contains a 46.9% larger view of the green area, and the percentage of roads in the view is much lower compared to the first building location.

Such comparison of the alternative building locations can potentially help in multi-criteria decision-making analysis for predicting the construction project revenue based on the most suitable building location. According to the analysis results, the second alternative of the building location is preferred compared to the first alternative since it may potentially result in higher property attractiveness and, as a result, higher project revenue. The proposed building view coefficient may be included in MCDA as a parameter describing the view criteria by quantitative value.

3.4. Solving the building location problem by applying multi-criteria decision-making analysis

The methodology of multi-criteria analysis developed in a Web-based spatial decision-support system includes multiple steps, as depicted in Fig. 2.6. However, most of them are done automatically, and only steps 1 and 4 require attention from an expert and manual data input.

According to the methodology depicted in Fig. 2.6, the 3rd step involves weights calculation, which is based on the Delphi method described in sub-chapter

2.3.2. Therefore, the significance of the criteria needs to be determined before starting the analysis. According to the second step of the Delphi method, 17 experts were required to participate in a questionnaire to determine the significance of the criteria. Detailed information about the experts who participated in the questionnaire is presented in Table 3.2.

Table 3.2. Experts who participated in Delphi analysis (developed by the author)

Experts	Position, organisation	Experience (years)
Expert 1	PhD, Vilnius Gediminas Technical University	6
Expert 2	Head of building structures department, OAO "Giprojivmash"	35
Expert 3	Civil engineer	21
Expert 4	PhD, Katholieke Universiteit Leuven	7
Expert 5	Construction project manager, consultant	22
Expert 6	Professor, Vilnius Gediminas Technical University	20
Expert 7	Project manager	21
Expert 8	Researcher, Vilnius Gediminas Technical University	20
Expert 9	Assoc. Prof., Vilnius Gediminas Technical University	20
Expert 10	Assoc. Prof., Vilnius Gediminas Technical University	19
Expert 11	Urban planning, Kyiv National University of Construction and Architecture	7
Expert 12	Assoc. Prof., Vilnius Gediminas Technical University	20
Expert 13	Professor, Vilnius Gediminas Technical University	20
Expert 14	Professor, Kyiv National University of Construction and Architecture	21
Expert 15	Owner, real estate agency	27
Expert 16	Real estate agent	16
Expert 17	PhD, Kyiv National University of Construction and Architecture	6

According to the third step of the Delphi method, the questionnaire was sent to the selected experts and the provided opinions were collected.

Agreement between the expert judgments was determined using the concordance coefficient according to sub-chapter 2.3.3. Based on the calculations, the concordance coefficient determined in the final round of the Delphi analysis is equal to 131.7. According to the Chi-Square Probabilities (Plackett, 1983), the statistical concordance coefficient is equal to 30.144. A comparison of the calculated concordance coefficient with the statistic coefficient revealed that the

calculated concordance coefficient is greater than the static coefficient. Therefore, the agreement of the expert opinions is sufficient, and the set of judgments can be used in further analysis.

Based on a questionnaire, the weights for the criteria presented in the final set of criteria were calculated and used for the analysis. The significance of the criteria defined by the experts is presented in Table 3.3.

Table 3.3. Weights of the criteria defined by the experts (developed by the author)

Criteria	Experts															
	1	2	3	4	5	6	7	8	9	10	...	15	16	17		
View landscape	10	10	10	10	9	7	7	7	9	9	...	10	7	10		
Trees and vegetation	9	8	9	9	7	9	9	8	9	9	...	9	9	9		
Distance to industrial facilities	7	10	8	8	8	8	9	9	10	8	...	8	9	8		
Type of view	10	9	10	9	7	6	7	6	10	9	...	9	7	9		
Forests and green areas	6	6	9	9	9	9	9	9	10	8	...	9	9	6		
Parking and garage	6	8	7	8	10	6	9	6	10	8	...	8	9	10		
Simplified Solar insolation	9	10	7	8	9	7	9	7	9	7	...	8	9	6		
Police station	6	8	8	6	10	9	9	9	10	6	...	6	9	7		
Distance from the city centre	8	5	7	8	8	7	8	6	10	10	...	8	8	8		
Distance to public transport stops	9	5	6	8	8	8	8	8	10	8	...	8	8	7		
Public transport	7	3	6	7	10	8	9	3	10	8	...	7	9	9		
Sustenance	6	4	9	8	7	7	9	7	10	6	...	8	9	5		
Education	7	3	5	5	8	8	9	10	10	7	...	5	9	6		
Healthcare	8	8	6	5	9	9	9	3	10	6	...	5	8	5		
Entertainment	2	6	6	7	8	9	8	7	10	6	...	7	8	7		
Sport activities	2	7	6	7	3	9	10	8	10	7	...	7	9	6		
Fire station	4	4	9	7	9	7	9	2	8	6	...	7	8	7		
Worship	3	8	4	5	8	6	7	8	8	7	...	5	7	6		
Financial	4	1	5	4	5	8	8	8	7	6	...	4	7	6		
Post office	5	4	2	1	3	6	6	3	5	5	...	2	6	4		

The weights presented in Table 3.3 were implemented in the Web environment for the multi-criteria analysis. However, MCDA requires the weights to be presented by fuzzy numbers. The calculation of the fuzzy weights depends on the selected MCDA method since different methods may involve different procedures.

Once the calculation of the weights is done and the result is stored in the related variables, the multi-criteria decision-making analysis for solving a building location problem can be started.

According to the methodology described in Fig. 2.6, the first step requires the specification of the MCDA method and a set of criteria. In the Web-based SDSS, three methods were implemented for multi-criteria analysis, specifically fuzzy TOPSIS, fuzzy COPRAS and fuzzy EDAS. During development, three sets of criteria were implemented. However, only the last one contains the weights collected by the Delphi survey that has sufficient concordance coefficient. Therefore, this set of criteria was selected for further analysis. The interface of Web-based SDSS that is used in the first step is presented in Fig. 3.19.

MCDA method

All methods

Criteria Set

Shkundalov 2022

Set of Criteria

Criteria	TypeFunction
View landscape	Max GIS: View landscape
Trees and vegetation	Max GIS: Trees
Distance to industrial facilities	Max GIS: Industrial facilities
Type of view	Max GIS: View type
Forests and green areas	Min GIS: Forests and Green areas
Parking and garage	Min GIS: Parkinks and Garages
Simplified Solar insolation	Max GIS: Building insolation
Police station	Min GIS: Police station availability
Distance from city center	Min GIS: City Center
Distance to public transport stops	Min GIS: Transportation Stops
Public transport	Max GIS: Transport Infrastructure
Sustenance	Max GIS: Sustenance of the area
Education	Max GIS: Educational facilities
Healthcare	Min GIS: Healthcare services
Entertainment	Max GIS: Entertainment, art and culture
Sport activities	Min GIS: Other city facilities
Fire station	Max GIS: Fire station availability
Worship	Min GIS: Places of worship
Financial	Max GIS: Financial facilities
Post office	Max GIS: Post office availability

Fig. 3.19. Selection of the MCDA method and set of criteria in Web-based SDSS (developed by the author)

After the set of criteria and MCDA method are specified, steps 2 and 3 are calculated automatically. The initial matrix and computed weights are stored inside the Web-based system by a set of arrays and objects with indexing.

The next action that needs to be performed according to the methodology described in Fig. 2.6 belongs to step 4 and is related to the specification of the alternatives. Since the desired multi-criteria problem is about alternative locations of the building, the BIM model representation needs to be placed in desired

locations with the usage of coordinates or by using transformation tools. The two defined alternatives are presented in Fig. 3.20.

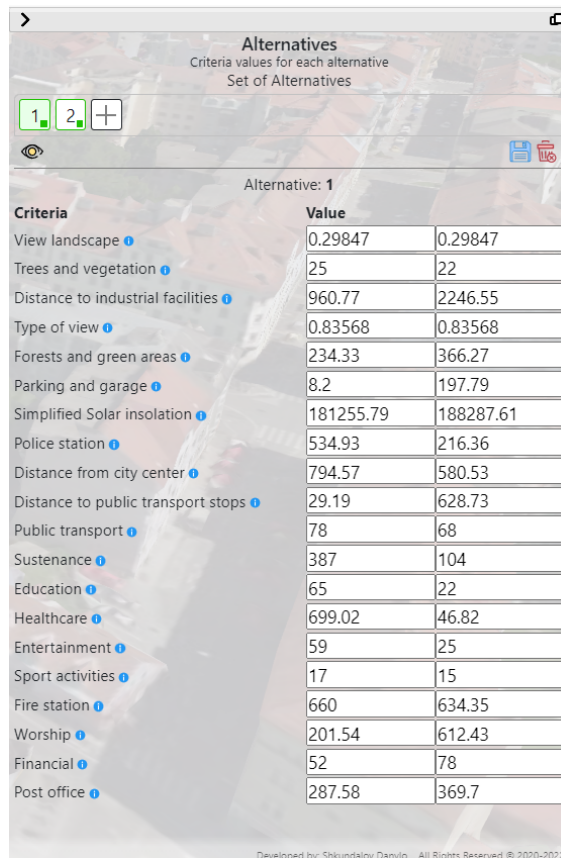


Fig. 3.20. Web-based SDSS – alternative locations of the building: (a) first alternative; (b) second alternative (developed by the author)

Fig. 3.20 contains two alternatives of the building location, where the first location is depicted in Fig. 3.20 (a), and the second location is depicted in Fig. 3.20 (b). The gathering of the data from BIM and GIS environments (step 5), as well as computing the criteria' values (step 6), is done automatically after the alternative is specified. The values of the criteria were gathered from the GIS databases or calculated by the analysis implemented in Web-based SDSS. It must be highlighted that values are collected from two sources, as presented by two columns, and are used for calculating the fuzzy numbers of the criteria values using equation (2.45). Since criteria values are based on the coordinates of the BIM model representation, they are different in each location.

Detailed information about the data gathered from GIS databases is presented in Fig. 3.21.

Fig. 3.21 depicts a significant difference between the values of the criteria. For example, the criterion named “distance to industrial facilities” received a value equal to 960.77 meters from the OpenStreetMap database and 2246.55 meters from the Esri database. Such a big difference between the data provided by different GIS vendors appears due to different procedures and methods of data gathering applied by GIS vendors. Such observation confirms the statements revealed by the literature analysis about GIS data accuracy. Additionally, such observation approves the decision to utilise multiple GIS databases and apply fuzziness in the criteria value calculation.



Alternatives
Criteria values for each alternative
Set of Alternatives

1. 2. +

Alternative: 1

Criteria	Value	Value
View landscape	0.29847	0.29847
Trees and vegetation	25	22
Distance to industrial facilities	960.77	2246.55
Type of view	0.83568	0.83568
Forests and green areas	234.33	366.27
Parking and garage	8.2	197.79
Simplified Solar insolation	181255.79	188287.61
Police station	534.93	216.36
Distance from city center	794.57	580.53
Distance to public transport stops	29.19	628.73
Public transport	78	68
Sustenance	387	104
Education	65	22
Healthcare	699.02	46.82
Entertainment	59	25
Sport activities	17	15
Fire station	660	634.35
Worship	201.54	612.43
Financial	52	78
Post office	287.58	369.7

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Fig. 3.21. Comparison of data gathered from different GIS databases for the first alternative (developed by the author)

Other values of the criteria presented in Fig. 3.21 remain the same for both sources, such as “view landscape” and “type of the view” criteria. The above-highlighted values were calculated by utilising the QUVIAS method, and since there is no alternative method for calculating the values of those criteria, the same values are used for both sources.

Once all alternatives were specified and values of the criteria were collected, the multi-criteria analysis was performed following steps 7–9 from the methodology described in Fig. 2.6. The result of MCDA using the fuzzy TOPSIS method is presented in Fig. 3.22.

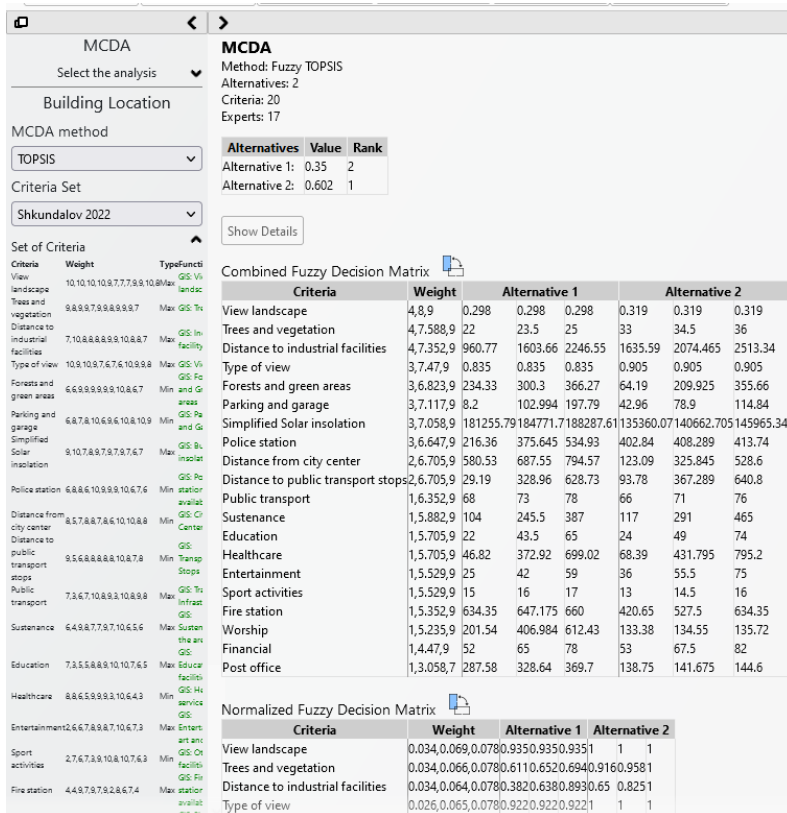


Fig. 3.22. Multi-criteria decision-making analysis in Web-based SDSS
(developed by the author)

As shown in Fig. 3.22, the developed Web-based SDSS performs the multi-criteria analysis and depicts the results inside the developed system. To present the calculations and results of the MCDA clearly, all of the processes were converted into tables and are presented below.

3.4.1. Multi-criteria analysis of alternatives by applying the fuzzy TOPSIS method

The TOPSIS method determines the most suitable alternative based on the distances from the positive-ideal solution (PIS) and negative-ideal solutions (NIS), where the alternative with the shortest distance from PIS and largest to NIS is considered the best solution. All of the calculations were performed according to the original research and by formulas presented in section 2.5.

The fuzzy TOPSIS involves the calculation of the fuzzy weights. Therefore, before starting the multi-criteria analysis, the developed Web-based SDSS performs the relevant calculations. The fuzzy weights (Table 3.4) that are applied in the fuzzy TOPSIS method were calculated based on weights of the criteria defined by experts, which are presented in Table 3.3.

Table 3.4. Fuzzy weights (developed by the author)

Criteria	Weights		
View landscape	4	8	9
Trees and vegetation	4	7.588	9
Distance to industrial facilities	4	7.353	9
Type of view	3	7.471	9
Forests and green areas	3	6.824	9
Parking and garage	3	7.118	9
Simplified Solar insolation	3	7.059	9
Police station	3	6.647	9
Distance from the city centre	2	6.706	9
Distance to public transport stops	2	6.706	9
Public transport	1	6.353	9
Sustenance	1	5.882	9
Education	1	5.706	9
Healthcare	1	5.706	9
Entertainment	1	5.529	9
Sport activities	1	5.529	9
Fire station	1	5.353	9
Worship	1	5.235	9
Financial	1	4.471	9
Post office	1	3.059	7

The criteria values were gathered as presented in Fig. 3.20. However, the chosen multi-criteria method requires values to be presented by fuzzy numbers. Table 3.5 depicts the criteria values with applied fuzzy numbers.

The next step involves the normalisation of the values and weights. The result of the normalisation procedure is presented in Table 3.6.

Table 3.5. Fuzzy values of the criteria for each alternative (developed by the author)

Criteria	Alternative 1			Alternative 2		
	a_{ij}	b_{ij}	c_{ij}	a_{ij}	b_{ij}	c_{ij}
View landscape	0.298	0.298	0.298	0.319	0.319	0.319
Trees and vegetation	22	23.5	25	33	34.5	36
Distance to industrial facilities	960.77	1603.66	2246.55	1635.59	2074.465	2513.34
Type of view	0.836	0.836	0.836	0.906	0.906	0.906
Forests and green areas	234.33	300.3	366.27	64.19	209.925	355.66
Parking and garage	8.2	102.995	197.79	42.96	78.9	114.84
Simplified Solar insolation	181255.8	184771.7	188287.6	135360.1	140662.7	145965.3
Police station	216.36	375.645	534.93	402.84	408.29	413.74
Distance from the city centre	580.53	687.55	794.57	123.09	325.845	528.6
Distance to public transport stops	29.19	328.96	628.73	93.78	367.29	640.8
Public transport	68	73	78	66	71	76
Sustenance	104	245.5	387	117	291	465
Education	22	43.5	65	24	49	74
Healthcare	46.82	372.92	699.02	68.39	431.795	795.2
Entertainment	25	42	59	36	55.5	75
Sport activities	15	16	17	13	14.5	16
Fire station	634.35	647.175	660	420.65	527.5	634.35
Worship	201.54	406.985	612.43	133.38	134.55	135.72
Financial	52	65	78	53	67.5	82
Post office	287.58	328.64	369.7	138.75	141.675	144.6

Table 3.6. Normalised fuzzy decision matrix (developed by the author)

Criteria	Weight			Alternative 1			Alternative 2		
	a_{ij}	b_{ij}	c_{ij}	a_{ij}	b_{ij}	c_{ij}	a_{ij}	b_{ij}	c_{ij}
View landscape	0.035	0.07	0.079	0.936	0.936	0.936	1	1	1
Trees and vegetation	0.035	0.066	0.079	0.611	0.653	0.694	0.917	0.958	1
Distance to industrial facilities	0.035	0.064	0.079	0.382	0.638	0.894	0.651	0.825	1
Type of view	0.026	0.065	0.079	0.923	0.923	0.923	1	1	1
Forests and green areas	0.026	0.06	0.079	0.175	0.214	0.274	0.18	0.306	1
Parking and garage	0.026	0.062	0.079	0.041	0.08	1	0.071	0.104	0.191
Simplified Solar insolation	0.026	0.062	0.079	0.963	0.981	1	0.719	0.747	0.775

End of Table 3.6

Criteria	Weight			Alternative 1			Alternative 2		
Police station	0.026	0.058	0.079	0.404	0.576	1	0.523	0.53	0.537
Distance from the city centre	0.017	0.059	0.079	0.155	0.179	0.212	0.233	0.378	1
Distance to public transport stops	0.017	0.059	0.079	0.046	0.089	1	0.046	0.079	0.311
Public transport	0.009	0.056	0.079	0.872	0.936	1	0.846	0.91	0.974
Sustenance	0.009	0.051	0.079	0.224	0.528	0.832	0.252	0.626	1
Education	0.009	0.05	0.079	0.297	0.588	0.878	0.324	0.662	1
Healthcare	0.009	0.05	0.079	0.067	0.126	1	0.059	0.108	0.685
Entertainment	0.009	0.048	0.079	0.333	0.56	0.787	0.48	0.74	1
Sport activities	0.009	0.048	0.079	0.765	0.813	0.867	0.813	0.897	1
Fire station	0.009	0.047	0.079	0.961	0.981	1	0.637	0.799	0.961
Worship	0.009	0.046	0.079	0.218	0.328	0.662	0.983	0.991	1
Financial	0.009	0.039	0.079	0.634	0.793	0.951	0.646	0.823	1
Post office	0.009	0.027	0.061	0.778	0.889	1	0.375	0.383	0.391

After the normalisation was performed, the fuzzy weights needed to be applied. The weighted normalised fuzzy decision matrix is presented in Table 3.7.

Table 3.7. Weighted normalised fuzzy decision matrix (developed by the author)

Criteria	Alternative 1			Alternative 2		
View landscape	0.033	0.065	0.074	0.035	0.07	0.079
Trees and vegetation	0.021	0.043	0.055	0.032	0.064	0.079
Distance to industrial facilities	0.013	0.041	0.07	0.023	0.053	0.079
Type of view	0.024	0.060	0.073	0.026	0.065	0.079
Forests and green areas	0.005	0.013	0.022	0.003	0.018	0.079
Parking and garage	0.001	0.005	0.079	0.002	0.006	0.015
Simplified Solar insolation	0.025	0.060	0.079	0.019	0.046	0.061
Police station	0.011	0.033	0.079	0.014	0.031	0.042
Distance from the city centre	0.003	0.010	0.017	0.004	0.022	0.079
Distance to public transport stops	0.001	0.005	0.079	0.001	0.005	0.024
Public transport	0.008	0.052	0.079	0.007	0.051	0.077
Sustenance	0.002	0.027	0.065	0.002	0.032	0.079

End of Table 3.7

Criteria	Alternative 1			Alternative 2		
Education	0.003	0.029	0.069	0.003	0.033	0.079
Healthcare	0.001	0.006	0.079	0.001	0.005	0.054
Entertainment	0.003	0.027	0.062	0.004	0.036	0.079
Sport activities	0.007	0.039	0.068	0.007	0.043	0.079
Fire station	0.008	0.046	0.079	0.006	0.037	0.076
Worship	0.002	0.015	0.052	0.009	0.045	0.079
Financial	0.006	0.031	0.075	0.006	0.032	0.079
Post office	0.007	0.024	0.061	0.003	0.01	0.024

Since the TOPSIS method is based on distances from Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS), the relevant values need to be calculated. Table 3.8 depicts the fuzzy PIS and fuzzy NIS.

Table 3.8. A fuzzy positive ideal solution and fuzzy negative ideal solution (developed by the author)

Criteria	Fuzzy PIS		Fuzzy NIS	
	Alternative 1	Alternative 2	Alternative 1	Alternative 2
View landscape	0.004	0	0	0.004
Trees and vegetation	0.019	0	0	0.019
Distance to industrial facilities	0.01	0	0	0.010
Type of view	0.005	0	0	0.005
Forests and green areas	0.033	0	0	0.033
Parking and garage	0	0.037	0	0.037
Simplified Solar insolation	0	0.014	0.014	0
Police station	0	0.021	0	0.021
Distance from the city centre	0.036	0	0	0.036
Distance to public transport stops	0	0.031	0.031	0
Public transport	0	0.001	0.001	0
Sustenance	0.008	0	0	0.008
Education	0.006	0	0	0.006
Healthcare	0	0.014	0.014	0
Entertainment	0.011	0	0	0.011

End of Table 3.8

Criteria	Fuzzy PIS		Fuzzy NIS	
	Alternative 1	Alternative 2	Criteria	Alternative 1
Sport activities	0.006	0	0	0.007
Fire station	0	0.005	0.005	0
Worship	0.024	0	0	0.024
Financial	0.002	0	0	0.002
Post office	0	0.023	0.023	0

The final step is to calculate the closeness coefficients for each alternative and rank them. The result of this procedure is presented in Table 3.9.

Table 3.9. Fuzzy TOPSIS closeness coefficients and ranks (developed by the author)

Criteria	Alternative 1	Alternative 2
Closeness Coefficient	0.351	0.602
Rank	2	1

The result of the calculations revealed that the first alternative closeness coefficient is equal to 0.351, and the second alternative got a closeness coefficient equal to 0.603. Therefore, the second alternative of the building location was ranked by first rank, and the first alternative of the building location got the second rank. Such ranks allow for stating that the second building's alternative location is more suitable compared to the first one.

3.4.2. Multi-criteria analysis of alternatives by applying the fuzzy COPRAS method

The COPRAS method is based on the utility degree (N_i) calculation, where the alternative with the biggest N_i is considered the most suitable solution.

The procedures of computing the fuzzy values and fuzzy weights in the fuzzy COPRAS method are the same as in the fuzzy TOPSIS method and are presented in Table 3.4 and Table 3.5, respectively. However, the normalisation process in the fuzzy COPRAS method is different compared to the fuzzy TOPSIS method. Table 3.10 presents the result of the normalisation procedure defined by the fuzzy COPRAS method.

After the normalisation of the matrix, the weights need to be applied. The result of this procedure is presented in Table 3.11.

Table 3.10. Normalised fuzzy decision matrix (developed by the author)

Criteria	Weight			Alternative 1			Alternative 2		
View landscape	0.035	0.07	0.079	0.483	0.483	0.483	0.517	0.517	0.517
Trees and vegetation	0.035	0.066	0.079	0.4	0.405	0.41	0.6	0.595	0.59
Distance to industrial facilities	0.035	0.064	0.079	0.37	0.436	0.472	0.63	0.564	0.528
Type of view	0.026	0.065	0.079	0.48	0.48	0.48	0.52	0.52	0.52
Forests and green areas	0.026	0.06	0.079	0.785	0.589	0.507	0.215	0.411	0.493
Parking and garage	0.026	0.062	0.079	0.16	0.566	0.633	0.84	0.434	0.367
Simplified Solar insolation	0.026	0.062	0.079	0.572	0.568	0.563	0.428	0.432	0.437
Police station	0.026	0.058	0.079	0.349	0.479	0.564	0.651	0.521	0.436
Distance from the city centre	0.017	0.059	0.079	0.825	0.678	0.601	0.175	0.322	0.399
Distance to public transport stops	0.017	0.059	0.079	0.237	0.472	0.495	0.763	0.528	0.505
Public transport	0.009	0.056	0.079	0.507	0.507	0.506	0.493	0.493	0.494
Sustenance	0.009	0.051	0.079	0.471	0.458	0.454	0.529	0.542	0.546
Education	0.009	0.05	0.079	0.478	0.47	0.468	0.522	0.53	0.532
Healthcare	0.009	0.05	0.079	0.406	0.463	0.468	0.594	0.537	0.532
Entertainment	0.009	0.048	0.079	0.41	0.431	0.44	0.59	0.569	0.56
Sport activities	0.009	0.048	0.079	0.536	0.525	0.515	0.464	0.475	0.485
Fire station	0.009	0.047	0.079	0.601	0.551	0.51	0.399	0.449	0.49
Worship	0.009	0.046	0.079	0.602	0.752	0.819	0.398	0.248	0.181
Financial	0.009	0.039	0.079	0.495	0.491	0.488	0.505	0.509	0.513
Post office	0.009	0.027	0.061	0.675	0.699	0.719	0.325	0.301	0.281

Table 3.11. Weighted normalised fuzzy decision matrix (developed by the author)

Criteria	Alternative 1			Alternative 2		
View landscape	0.017	0.034	0.038	0.018	0.036	0.041
Trees and vegetation	0.014	0.027	0.032	0.021	0.039	0.046
Distance to industrial facilities	0.013	0.028	0.037	0.022	0.036	0.042
Type of view	0.013	0.031	0.038	0.014	0.034	0.041
Forests and green areas	0.021	0.035	0.04	0.006	0.025	0.039
Parking and garage	0.004	0.035	0.05	0.022	0.027	0.029
Simplified Solar insolation	0.015	0.035	0.044	0.011	0.027	0.034
Police station	0.009	0.028	0.044	0.017	0.03	0.034
Distance from the city centre	0.014	0.04	0.047	0.003	0.019	0.031

End of Table 3.11

Criteria	Alternative 1			Alternative 2		
Distance to public transport stops	0.004	0.028	0.039	0.013	0.031	0.04
Public transport	0.004	0.028	0.04	0.004	0.027	0.039
Sustenance	0.004	0.024	0.036	0.005	0.028	0.043
Education	0.004	0.023	0.037	0.005	0.026	0.042
Healthcare	0.004	0.023	0.037	0.005	0.027	0.042
Entertainment	0.004	0.021	0.035	0.005	0.027	0.044
Sport activities	0.005	0.025	0.04	0.004	0.023	0.038
Fire station	0.005	0.026	0.04	0.003	0.021	0.039
Worship	0.005	0.034	0.064	0.003	0.011	0.014
Financial	0.004	0.019	0.038	0.004	0.02	0.04
Post office	0.006	0.019	0.044	0.003	0.008	0.017

The last step in fuzzy COPRAS is to compute the utility degree and determine the ranks of the alternatives based on it. The results of this calculation are presented in Table 3.12.

Table 3.12. Fuzzy COPRAS utility degrees and ranks (developed by the author)

Criteria	Alternative 1	Alternative 2
Utility Degree (Ni)	1	0.635
Rank	1	2

According to the results of the calculation, the first alternative got a significance coefficient equal to 0.964 and the second alternative equal to 0.613. Based on these values, the utility degree was calculated and is equal to 1.0 and 0.635 for the first and second alternatives, respectively. According to the fuzzy COPRAS method, the first alternative building location is ranked by the first rank, and the second alternative building location is ranked by the second rank.

The conclusion made by fuzzy COPRAS is different compared to the conclusion made by the fuzzy TOPSIS method, and, therefore, the best alternative cannot be defined. In case two MCDA methods result in different conclusions, the decision cannot be made. Such a conflicting situation requires performing extra analysis utilising different MCDA methods. As previously highlighted, one more multi-criteria analysis was implemented in the developed Web-based SDSS, specifically fuzzy EDAS.

3.4.3. Multi-criteria analysis of alternatives by applying the fuzzy EDAS method

The EDAS method involves a calculation of the average decision matrix. According to the original research (Stevic, Vasiljevic, Zavadskas, Sremac & Turskis, 2018), the fuzzy values of the criteria need to be calculated based on the linguistic grades where the formulas are bound to the number of decision-makers. The calculation of the fuzzy values of the criteria based on the data gathered from GIS databases and calculated within geospatial analysis involves different formulas. Therefore, the formulas presented in the original research related to the construction of fuzzy values are not fully applicable. To perform accurate calculations, the formulas from the first step of the original research were changed to the same procedure of fuzzy value calculation that was utilised in fuzzy TOPSIS and fuzzy COPRAS methods. The fuzzy values are presented in Table 3.5.

The fuzzy EDAS method involves a different calculation of fuzzy weights compared to the fuzzy TOPSIS and fuzzy COPRAS methods. The fuzzy weights (Table 3.13) that are used in the fuzzy EDAS method were calculated based on the weights of the criteria defined by the experts, which are presented in Table 3.3.

Table 3.13. Fuzzy weights matrix for the fuzzy EDAS method (developed by the author)

Criteria	Fuzzy weights		
View landscape	6	8	8.764
Trees and vegetation	5.588	7.588	8.882
Distance to industrial facilities	5.352	7.352	8.823
Type of view	5.47	7.47	8.588
Forests and green areas	4.823	6.823	8.235
Parking and garage	5.117	7.117	8.47
Simplified Solar insolation	5.058	7.058	8.47
Police station	4.647	6.647	8.176
Distance from the city centre	4.705	6.705	8.47
Distance to public transport stops	4.705	6.705	8.47
Public transport	4.47	6.352	7.882
Sustenance	3.882	5.882	7.588
Education	3.764	5.705	7.352
Healthcare	3.823	5.705	7.411
Entertainment	3.705	5.529	7.352
Sport activities	3.764	5.529	7.176
Fire station	3.47	5.352	7.176
Worship	3.294	5.235	7.235

End of Table 3.13

Criteria	Fuzzy weights		
Financial	2.647	4.47	6.411
Post office	1.588	3.058	5

The next step of the fuzzy EDAS method involves the calculation of the average solution matrix based on the fuzzy values (Table 3.5). The result of the calculation is presented in Table 3.14.

Table 3.14. Elements of the average solution matrix (developed by the author)

Criteria	AV		
View landscape	0.308	0.308	0.308
Trees and vegetation	27.5	29	30.5
Distance to industrial facilities	1298.179	1839.062	2379.945
Type of view	0.87	0.87	0.87
Forests and green areas	149.26	255.112	360.965
Parking and garage	25.58	90.947	156.315
Simplified Solar insolation	158307.93	162717.202	167126.474
Police station	309.6	391.967	474.335
Distance from the city centre	351.81	506.697	661.585
Distance to public transport stops	61.485	348.125	634.765
Public transport	67	72	77
Sustenance	110.5	268.25	426
Education	23	46.25	69.5
Healthcare	57.605	402.357	747.11
Entertainment	30.5	48.75	67
Sport activities	14	15.25	16.5
Fire station	527.5	587.337	647.175
Worship	167.459	270.767	374.075
Financial	52.5	66.25	80
Post office	213.165	235.157	257.149

The fuzzy EDAS method is based on the distances from the average solution, specifically the positive distance to the average (PDA) solution and the negative distance to the average (NDA) solution. The results of PDA and NDA calculations are presented in Table 3.15.

Table 3.15. Positive distance to average and negative distance to average (developed by the author)

	PDA						NDA					
Criteria	Alternative 1			Alternative 2			Alternative 1			Alternative 2		
View landscape	0	0	0	0.033	0.033	0.033	0.033	0.033	0.033	0	0	0
Trees and vegetation	0	0	0	0.09	0.189	0.278	0.09	0.189	0.278	0	0	0
Distance to industrial facilities	0	0	0.398	0	0.128	0.51	0	0.128	0.596	0	0	0.312
Type of view	0	0	0	0.04	0.04	0.04	0.04	0.04	0.04	0	0	0
Forests and green areas	0	0	0.35	0	0.177	0.822	0	0.177	0.601	0	0	0.571
Parking and garage	0	0	0.947	0	0.132	0.725	0	0.132	1.101	0	0	0.571
Simplified Solar insolation	0.089	0.135	0.179	0	0	0	0	0	0	0.077	0.135	0.19
Police station	0	0.041	0.543	0	0	0.15	0	0	0.475	0	0.041	0.219
Distance from the city centre	0	0	0.122	0	0.356	0.813	0	0.356	0.669	0	0	0.267
Distance to public transport stops	0	0.055	0.954	0	0	0.852	0	0	0.893	0	0.055	0.912
Public transport	0	0.013	0.142	0	0	0.116	0	0	0.116	0	0.013	0.142
Sustenance	0	0	0.649	0	0.084	0.832	0	0.084	0.755	0	0	0.725
Education	0	0	0.604	0	0.059	0.733	0	0.059	0.683	0	0	0.654
Healthcare	0	0.073	0.937	0	0	0.908	0	0	0.858	0	0.073	0.987
Entertainment	0	0	0.425	0	0.138	0.664	0	0.138	0.626	0	0	0.462
Sport activities	0	0	0.09	0	0.049	0.212	0	0.049	0.181	0	0	0.121
Fire station	0	0.101	0.204	0	0	0.165	0	0	0.019	0	0.101	0.35
Worship	0	0	0.461	0.189	0.503	0.643	0	0.503	1.189	0	0	0
Financial	0	0	0.318	0	0.018	0.368	0	0.018	0.35	0	0	0.337
Post office	0.142	0.397	0.608	0	0	0	0	0	0	0.321	0.397	0.46

After the PDA and NDA calculations were performed, the weighted sum of positive distance (SP) and the weighted sum of negative distance (SN) was calculated. The SP and SN values are required to be normalised to calculate the appraisal score (AS) and AS value based on which the ranking of the alternatives is performed. The normalised SP value is described as NSP, and the normalised SN value is described as NSN. The calculations were performed according to the formulas presented in sub-chapter 2.5.3. Based on the achieved AS value, the ranking of the alternatives was performed. For consistency, the values highlighted above are collected into one table and are presented in Table 3.16.

Table 3.16. Results of the fuzzy EDAS (developed by the author)

Criteria	Alternative 1			Alternative 2		
SP	0.678	3.869	60.628	1.552	12.085	69.848
SN	0.927	12.085	74.727	0.905	3.869	55.712
NSP	0.024	0.138	2.169	0.055	0.432	2.499
NSN	-1.55	0.587	0.968	-0.901	0.867	0.969
AS	-0.019	0.04	1.05	-0.026	0.187	1.211
k(AS)	0.357			0.456		
Rank	2			1		

The results of the multi-criteria analysis with the use of the fuzzy EDAS method revealed that the appraisal score for the first alternative is equal to 0.357, and for the second alternative is equal to 0.456. A comparison of the highlighted above scores allows the ranking of the alternatives as follows: the second alternative got the first rank, and the first alternative was ranked by the second rank.

3.4.4. Derivation of multi-criteria decision-making analysis

Since the fuzzy TOPSIS and fuzzy COPRAS methods presented different results of the analysis, the fuzzy EDAS method was utilised to solve the issue of inconsistency by approving the conclusion of one of the MCDA methods. To determine the most suitable alternative, the results of all three MCDA methods need to be compared. For this purpose, the conclusions made by the fuzzy TOPSIS, fuzzy COPRAS and fuzzy EDAS methods were collected and are presented in Table 3.17.

Table 3.17 depicts that the fuzzy EDAS method approved the conclusion made by the fuzzy TOPSIS method, where the second alternative is preferable compared to the first alternative. Such comparison allows stating that the second

building location is more suitable in the defined MCDA problem compared to the first building location and should be used in further project development.

Table 3.17. Comparison of the ranks determined by different multi-criteria decision-making methods (developed by the author)

Alternatives	Fuzzy TOPSIS	Fuzzy COPRAS	Fuzzy EDAS
Alternative 1	2	1	2
Alternative 2	1	2	1

3.5. Conclusions of the Third Chapter

The developed Web-based spatial decision-support system contains more than 1500 files, including projects-related files and a database. The validation of the developed Web-based SDSS was made according to the defined objectives of the dissertation. All analyses and the full process of multi-criteria analysis, starting from the data gathering and ending with the results of the analysis, were performed inside the developed Web-based SDSS.

1. According to the results of crane selection and operation analysis, the second location of the crane is 21.83% more effective compared to the first location, where the area of reachability is 176.5 square meters larger. Such a conclusion suggests that the proposed analysis allows for differentiating the location of the cranes precisely. The combination of the cranes revealed 100% reachability with 95% of visibility. The validation of the proposed method proved that the utilisation of BIM, GIS, and Web environments is suitable for crane selection and operation problems. Therefore, the stated objective is considered to be achieved.
2. The experimental analysis depicted a significant difference of 9.74% between spherical and square shapes used as a mathematical representation of the view. The results of the visibility analysis performed using the QUVIAS method prove the statement that the proposed method decreases projection distortions due to the utilisation of a sphere as a mathematical shape of the view and the usage of spherical coordinates.
3. The window view coefficient calculated by the proposed QUVIAS method concluded that the view from the ninth floor is 1.65 times more scenic compared to the view that can be seen from the second-floor window. According to the analysis of the object types that can be seen from the window, the view from the ninth-floor window involves less roads and a bigger green area compared to the second-floor window view. Such results prove the statement that the proposed window view

coefficient allows calculating the window view mathematically and accurately, presenting it as a quantitative parameter.

4. The utilisation of the QUVIAS method for assessment of the view related to the premises revealed that the view that can be seen from the windows of the premise located on the ninth floor is twice more scenic compared to the view that can be seen from the windows of the premise located on the second floor. Specifically, the premise view coefficient is equal to 0.42199 and 0.19816, respectively. Moreover, a significant difference was observed in the types of objects that can be seen in the view, such as the premises on the ninth floor allowing for observing a part of the park compared to the second-floor premises. Such precise comparison of the views is potentially highly valuable in the assessment of the property attractiveness and may be significant in economic analysis that is used in the construction project during the planning stage. The proposed coefficients may help the decision-makers to precise their conclusions and determine the most suitable solution in the determination of the property parameters. Using this method, the decision can be made at an early stage of the project (planning), when the object has not yet been built (there is only a BIM model), or at a distance, without visiting the object, when the object already exists but there is no way to reach it (in case of a pandemic or the client is far from the purchased object).
5. According to the calculated building view coefficients, the view from the second location of the building is 6.45% more scenic and clear from the obstacles compared to the first building location. The view of the second location of the building contains 46.9% larger green area and less percentage of roads compared to the first building location. As a consequence, the second alternative of the location is preferred. The proposed building view coefficient allows for presenting the view criterion that is used in MCDA as a quantitative parameter, which is a more accurate measurement compared to the linguistic grades that are used nowadays. Additionally, the proposed coefficient can be calculated based on the data provided by BIM and GIS environments in the early stages of the construction project development, which significantly contributes to the construction field and reduces on-site measurements.
6. The research revealed that each GIS vendor gathers data about the real world in different ways using different methods, techniques and solutions. Therefore, the data presented in the GIS databases are different. The difference in the data of the real-world condition influences the MCDA accuracy. The utilisation of fuzzy sets allowed for solving this problem and increased the accuracy of the defined problem. This conclusion is in line with the observation made by Cheng and Mon (1994).

7. The questionnaire for the Delphi analysis was developed and sent to the 17 experts who provided their responses; the consistency of the expert judgments was checked by concordance coefficient calculation. The responses of the experts were analysed, and relevant weights were used for solving multi-criteria decision-making problems.
8. The multi-criteria analysis revealed that fuzzy TOPSIS and fuzzy COPRAS methods concluded different results. The fuzzy TOPSIS method determined the second alternative as preferable compared to the first alternative by closeness coefficients equal to 0.603 and 0.351, respectively. The fuzzy COPRAS method concluded the opposite, where the unity degrees are equal to 1 for the first alternative and 0.635 for the second alternative. To address this conflict, a third method was utilised. The fuzzy EDAS method resulted in the conclusion that the second alternative with an appraisal score of 0.456 is preferred compared to the first alternative with an appraisal score of 0.357. Therefore, the fuzzy EDAS method approved the conclusion made by the fuzzy TOPSIS method. According to the results of the multi-criteria decision-making analysis, the second alternative is preferred.
9. The conclusion made by the multi-criteria analysis approved the conclusion made by the visibility analysis performed using the QUVIAS method. This result is in line with the studies that state the importance of the view in the decision-making process.

General conclusions

1. Deep research on the state-of-the-art related to BIM, GIS, and Web environments integration was conducted. According to the analysis results, the integration process of BIM, GIS, and Web environments faces many obstacles, where the most pressing issues are related to the implementation of the standards and methods for processing the data. Mainly, this issue is linked to the processing of the BIM model since no unified standard can be found that would present a method for data storing and managing that would be sufficient for all three environments.
2. The proposed method for determining the sequence of the objects' relation allowed recompiling the BIM model representation and processing it in a more BIM-native manner, where the recalculated coordinates were utilised in the geospatial analysis. The proposed method was used multiple times in other analyses presented in the dissertation. The proposed method has shown its value and usefulness according to the results of the development.
3. The proposed methodology for crane selection and operations has shown high accuracy of the calculation allowing analysis of single cranes as well as their groups. According to the analysis results, the proposed method allowed for differentiating the alternatives of the crane locations considering the visibility and reachability of the cranes.

4. The proposed Quantitative View Assessment (QUVIAS) method for visibility analysis, which allows calculating the view mathematically, has shown high accuracy of the calculations and provided the following conclusions:
 - a) The comparison of the existing and proposed methods for visibility analysis revealed a sufficient difference in accuracy and proved the value of the QUVIAS method.
 - b) The window view coefficient allowed for determining the precise difference between the views of the windows, which proves the accuracy of the proposed method for quantitative view assessment.
 - c) The proposed premise view coefficient revealed a significant difference in clearance of the views related to the two premises. The premise view coefficient has shown its potential to be used in the assessment of the premise attractiveness.
 - d) The building view coefficient revealed a sufficient difference between the two views, which are related to alternative locations of the building. The analysis has shown that the proposed building view coefficient is suitable to be used for solving a building location problem by providing a quantitative representation of the view in the calculation.
5. The proposed conceptual model and methodology for multi-criteria decision-making analysis were applied to the case study for automation of solving a building location problem. The whole process of data gathering and MCDA problem solving was performed inside the developed Web-based SDSS. Achieved results proved the usefulness of BIM, GIS, and Web integration for solving problems in the construction field as well as proved the use of results obtained by the QUVIAS method.
6. The Web-based spatial decision-support system was developed, including all proposed methods and approaches and was approbated in the case study. The main obstacle in development was found in a lack of sources and GIS databases for gathering the data for multi-criteria decision-making analysis. This issue is related to the dissociation of the databases presented by institutions. The databases are inaccessible most of the time, which leads to the lack of data for performing multi-criteria analysis.

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List of Scientific Publications by the Author on the Topic of the Dissertation

Papers in the Reviewed Scientific Journals

Shkundalov, D., & Vilutienė, T. (2021). Bibliometric Analysis of Building Information Modeling, Geographic Information Systems and Web Environment Integration. *Automation in Construction*, 128, 103757. www.doi.org/10.1016/j.autcon.2021.103757

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Summary in Lithuanian

Įvadas

Problemų formulavimas

Realaus pasaulio duomenys naudojami visuose statybos projekto gyvavimo ciklo etapuose ir yra esminiai užtikrinant racionalių sprendimų priėmimą statybos projektuose. Realus pasaulio duomenys gaunami iš įvairių šaltinių, tarp kurių GIS aplinka yra naudojama plačiausiai. Tačiau GIS ir BIM aplinkų integravimas yra sudėtinga užduotis, nes susiduriama su daugybe problemų, tokių kaip nuosavybinių formatų naudojimas, duomenų sąveikumas, duomenų tipų apribojimai. BIM, GIS ir žiniatinklio aplinkų integravimas yra vienas iš perspektyviausių ir naujų šių problemų sprendimo būdų. BIM, GIS ir žiniatinklio aplinkų integravimas leidžia projekto dalyviams efektyviau bendradarbiauti, priimti pagrįstus sprendimus, sumažinti projektų konfliktus ir optimizuoti statybos sąnaudas. Internetinių technologijų sprendimų įvairovė gali padėti išspręsti įvairias statybos projektų problemas. Nekilnojamojo turto patrauklumo vertinimas, vietos planavimas, kranų parinkimas ir eksploatavimas yra vienos iš aktualiausių problemų, kurios priklauso nuo realaus pasaulio duomenų ir geoerdvinės analizės.

Pagrindinė problema yra BIM modelio apdorojimo žiniatinklio aplinkoje metodų trūkumas. Dėl šios problemos kyla duomenų apdorojimo kliūčių, kurios neleidžia atlikti geoerdvinės ir daugiakriterės analizės. Geoerdvinės analizės įgyvendinimas yra reikšminga tyrimų sritis, kuri savo ruožtu daugiausia orientuota į matomumo analizę. Tačiau esami matomumo analizės metodai nėra tinkami ir nepritaikomi statybos srityje ir daugiakriteriui analizei. Be to, vaizdo kriterijus daugiakriterėje analizėje laikomas

kokybiniu parametru, apibūdinamu lingvistiniais požymiais, o tokie požymiai netaikomi geoerdvinėje analizėje, nes negali tiksliai apibūdinti realios situacijos. Todėl geoerdvinės analizės panaudojimas statybų srityje remiantis BIM ir GIS aplinkų pateiktais duomenimis gali žymiai padidinti sprendimų rezultatų tikslumą. BIM, GIS ir žiniatinklio aplinkų integravimas naudojant daugiakriterę analizę yra perspektyvi tyrimų sritis, galinti pagerinti statybos procesus ir padėti išspręsti daugybę problemų, įskaitant nekilnojamojo turto patrauklumo vertinimą, pastato vietos analizę, kranų parinkimo bei kitas. Tačiau literatūros analizė atskleidė internetinių sprendimų, kuriuose naudojama daugiakriterė sprendimų priėmimo analizė, pagrįsta BIM ir GIS duomenimis, trūkumą.

Disertacijos tyrimo problema – tobulinti sprendimų priėmimo procesą, papildant BIM modelius realaus pasaulio duomenimis, tai pasiekama integruojant BIM, GIS ir žiniatinklio aplinką, kad būtų galima spręsti statybos srities problemas. Pritaikius sukurta *Quantitative View Assessment* (QUVIAS) metodą ir internetinę sprendimų palaikymo sistemą, įmanoma priimti racionalius sprendimus statybos projektuose naudojant tikslus realaus pasaulio duomenis.

Darbo aktualumas

BIM, GIS ir žiniatinklio aplinkų integravimas tapo svarbia tyrimų sritimi, kurioje pastaraisiais metais itin išaugo mokslinių straipsnių skaičius. BIM modelių apdorojimo žiniatinklio aplinkoje metodų trūkumas ir integravimo proceso standartizavimas išlieka pagrindinėmis integravimo proceso temomis. Geoerdvinė analizė ir duomenų bazių panaudojimas buvo svarbūs disertacinio tyrimo aspektai. Daug problemų statybų srityje yra susijusios su procesų optimizavimu statybos projekte. Šiuo tikslu plačiai naudojama daugiakriterė analizė. Nepaisant to, nėra tyrimų, sprendžiančių statybos srities problemas, kurios būtų pagrįstos daugiakriterė sprendimų priėmimo analize, naudojant BIM modelius kaip duomenų šaltinį ir realaus pasaulio duomenis, pateiktus naudojant GIS arba geoerdvinę analizę žiniatinklio aplinkoje. Geoerdvinės analizės įgyvendinimas praplečia BIM galimybes ir pagerina sprendimų priėmimo procesą statybos srityje. Su vaizdo kokybe susiję kriterijai daugiakriterėje analizėje laikomi kokybiniais parametrais. Tačiau matematiškai apskaičiuotas vaizdo parametras gali turėti didesnę tikslumą ir gali būti nustatytas ankstyvoje projekto kūrimo stadijoje.

Šios disertacijos rezultatai užpildo esamas spragas ir išplečia galimybes patikimesniam sprendimų priėmimo procesui statybos projektuose taikant siūlomus metodus.

Tyrimų objektas

Tyrimo objektas – BIM, GIS ir žiniatinklio aplinkų integravimas sprendimams priimti statybos projekte.

Darbo tikslas

Disertacijos tikslas – sukurti konceptualų modelį, pagrįstą BIM, GIS, žiniatinklio aplinkų ir daugiakriterių sprendimų priėmimo metodų integravimu, leidžiančiu kompleksiskai analizuoti racionalius statybos projekto sprendimus.

Darbo uždaviniai

Darbo tikslui pasiekti buvo sprendžiami šie uždaviniai:

1. Apžvelgti naujausias technologijas, susijusias su BIM, GIS ir žiniatinklio aplinkų integravimu.
2. Sukurti principinį sprendinį ryšiams tarp modelio objektų atvaizduojant BIM modelį žiniatinklio aplinkoje.
3. Sukurti kiekybiniu matavimu pagrįstą matomumo analizės metodą (QUVIAS) integruojant BIM, GIS ir žiniatinklio aplinkas.
4. Sukurti metodinius ir technologinius sprendimus, skirtus duomenų rinkimo procesui automatizuoti atliekant daugiakriterę sprendimų priėmimo analizę, sprendžiant nekilnojamojo turto patrauklumo ir pastato vietos parinkimo problemas.
5. Sukurti krano parinkimo ir eksploatavimo problemų sprendimo metodą, pagrįstą BIM, GIS ir žiniatinklio aplinkų integravimu.
6. Pademonstruoti siūlomo modelio ir metodų praktinį taikymą atvejo tyrimuose. Sukurti internetinę sprendimų paramos sistemą statybos projektams, įdiegti sistemoje sukurtus metodus.

Tyrimų metodika

Disertacijos tema buvo atlikta bibliometrinė analizė, apimanti analitinius, skaitinius ir lyginamuosius metodus. Kuriant QUVIAS metodą geoerdvinei analizei panaudoti moksliniai teoriniai, lyginamieji ir statistiniai metodai. Pastato vietos parinkimo uždavinyje kriterijų rinkiniui nustatyti panaudota matematinė statistika ir lyginamieji metodai. Kriterijų reikšmingumai nustatyti ekspertiniu Delphi metodu. Ekspertų nuomonių suderinamumas patikrintas apskaičiavus konkordacijos koeficientą. Racionaliai pastato vietos alternatyvai nustatyti pritaikyti daugiatiksliai sprendimų metodai Fuzzy TOPSIS, Fuzzy COPRAS ir Fuzzy EDAS. Kranų parinkimo ir jo darbo procesas, taip pat duomenų rinkimo, sprendžiant pastato padėties sklype analizės uždavinį, automatizavimas buvo atliktas remiantis BIM duomenimis ir naudojant geoerdvinę analizę bei GIS API, įskaitant QUVIAS metodą, buferių analizę ir GIS įrankius. Visi pasiūlyti metodai buvo patikrinti taikant atvejo analizės metodą. Atvejo tyrime nagrinėti BIM modeliai buvo sukurti naudojant Autodesk Revit.

Darbo mokslinis naujumas

Rengiant disertaciją buvo gauti šie statybos inžinerijos mokslui nauji rezultatai:

1. Pasiūlytas originalus konceptualus statybos projekto racionalių sprendimų kompleksinės analizės modelis, integruojant BIM, GIS, žiniatinklio aplinkas ir daugiakriterę analizę.
2. Pasiūlytas naujas BIM modelio objektų tarpusavio ryšių nustatymo metodas ir pateiktas koordinacių perskaičiavimo metodas.
3. Sukurtas naujas unikalus metodas (QUVIAS) ir patvirtintas atvejo tyrime. Šis metodas nustato vaizdo kokybę pagal kiekybinius parametrus, naudojant matematinius skaičiavimus, pagrįstus sferinėmis koordinatėmis ir duomenimis iš BIM ir GIS aplinkų žiniatinklio aplinkoje.
4. Pasiūlytas naujas QUVIAS metodu pagrįstas analizės būdas sprendžiant nekilnojamojo turto patrauklumo problemą.
5. Naujas metodas, skirtas daugiakriteriui sprendimų priėmimo analizei automatizuoti, buvo pristatytas ir patvirtintas atvejo tyrime apie pastato vietos analizę ir parinkimą. Taikant metodą naudojami BIM ir GIS aplinkų pateikti duomenys ir atliekama geoerdvinė analizė žiniatinklio aplinkoje. Atvejo studijoje buvo pristatytas ir patvirtintas naujas krano parinkimo ir jo darbo proceso analizės metodas, pagrįstas matomumo analize ir buferio metodu.

Darbo rezultatų praktinė reikšmė

Pateiktas tyrimas įrodo BIM, GIS ir žiniatinklio aplinkos integravimo naudingumą sprendžiant statybos projekto problemas ir didinant sprendimų priėmimo proceso tikslumą. Sukurtas BIM modelių apdorojimo metodas leidžia įtraukti BIM modelius į geoerdvinę analizę žiniatinklio aplinkoje. Siūlomas QUVIAS metodas įveda matematinį vaizdo skaičiavimą ir pateikia jį kaip kiekybinį kriterijų. Šis metodas pagerina sprendimų priėmimo procesą, įtraukdamas vaizdą kaip vieną iš kiekybinių kriterijų į daugiakriterę analizę. Kiekybinis vaizdo vertinimas kartu su BIM modelio apdorojimu leidžia išspręsti turto patrauklumo ir krano pasirinkimo bei eksploatavimo problemas BIM, GIS ir žiniatinklio aplinkose. Siūloma automatizuota kelių kriterijų sprendimų priėmimo analizė žymiai sumažina laiko sąnaudas ir padidina sprendimų priėmimo proceso tikslumą. Praktinę tyrimo išvadų vertę patvirtino praktinis visų disertacijoje sukurtų metodų pritaikymas autoriaus sukurtoje internetinėje erdvinio sprendimų palaikymo sistemoje. Atvejo analizės rezultatai patvirtina BIM, GIS ir žiniatinklio aplinkų integravimo naudą ir nustato tolesnio tyrimo poreikį.

Šio tyrimo rezultatai yra susiję su skaitmenizacija statybose ir inovacijų diegimu statybų pramonėje, kuri gali tiesiogiai ir netiesiogiai paveikti ekonomikos sektorių. Sukurta erdvinė sprendimų palaikymo sistema su metodais, siūlomais šioje disertacijoje, gali padėti savivaldybėms, nekilnojamojo turto ir projektų vystytojams padidinti sprendimų efektyvumą projektuojant užstatytą aplinką ir tokiu būdu užtikrinant tvarios statybos tikslų įgyvendinimą.

Ginamieji teiginiai

1. Siūlomas konceptualus modelis leidžia kompleksiškai analizuoti racionalius statybos projekto sprendimus, integruojant BIM, GIS ir žiniatinklio aplinkas.

2. Žiniatinklio aplinkoje BIM modelio pateikti objektai gali būti valdomi remiantis modelyje nustatytais objektų tarpusavio ryšiais.
3. Autoriaus pasiūlytas QUVIAS metodas leidžia matematiškai apskaičiuoti vaizdą ir pateikti jį kaip kiekybinį parametą naudojant BIM, GIS ir žiniatinklio aplinkų integraciją.
4. Krano parinkimo ir valdymo galimybės gali būti išplėstos atliekant matomumo analizę žiniatinklio aplinkoje, remiantis BIM ir GIS aplinkų pateiktais duomenimis.
5. BIM, GIS, žiniatinklio aplinkų integravimas leidžia išplėsti nekilnojamojo turto patrauklumo analizę.
6. Daugiakriterės analizės automatizavimo sprendimas naudojant BIM ir GIS pateiktus duomenis žiniatinklio aplinkoje leidžia greitai ir tiksliai įvertinti tinkamą ir racionalią pastato vietą.

Darbo rezultatų aprobavimas

Disertacijos tema publikuoti du moksliniai straipsniai recenzuojamuose mokslo žurnaluose. Detalus publikacijų sąrašas pateiktas disertacijos „Autoriaus mokslinių publikacijų disertacijos tema sąrašas“ skyriuje.

Disertacijoje atliktų tyrimų rezultatai buvo pristatyti penkiose tarptautinėse konferencijose:

- “The 18th Colloquium “New Trends in Construction Management” 2022 m. Cracow, Poland.
- “Research in Building Engineering EXCO'21” 2021 m Valencia, Spain.
- “11th International Conference “Environmental Engineering” 2020 m. Vilnius, Lithuania.
- “The 13th international conference “Modern building materials, structures and techniques” 2019 m Vilnius, Lithuania.
- “The 17th Colloquium „Sustainable decisions in the built environment” 2019 m. Vilnius, Lithuania.

Disertacijos struktūra

Darbą sudaro įvadas, trys pagrindiniai skyriai, išvados, literatūros sąrašas, autoriaus publikacijų disertacijos tema sąrašas. Disertacijos apimtis (be priedų) – 163 puslapiai, tekste yra 50 sunumeruotų formulų, 37 iliustracijos ir 24 lentelės. Rašant disertaciją panaudoti 328 literatūros šaltiniai.

1. Literatūros analizė, susijusi su BIM, GIS ir žiniatinklio aplinkų integravimu

Pirmajame disertacijos skyriuje atlikta literatūros šaltinių disertacijos tematika apžvalga. Šiame skyriuje aptariamos BIM, GIS ir žiniatinklio aplinkų integravimo tyrimų

tendencijos, nustatomos tokios integracijos kliūtys ir aptariami galimi pritaikymai statybų srityje. Skyriuje aptariami naujausi pasiekimai ir aktualiausios problemos bei taikymo atvejai, susiję su BIM, GIS ir žiniatinklio integracija, nustatomos spragos, apibrėžiama būsimų tyrimų kryptis ir pagrindžiamas tyrimo aktualumas.

Literatūros šaltinių analizė atlikta keliais pjūviais. Pirmiausia išanalizuoti esami sprendimai, susiję su BIM, GIS ir žiniatinklio integravimu, ir sąveikos problemos. Išanalizuotas daugiakriterės analizės naudojimas sprendžiant objekto vietos parinkimo problemą, panaudojant BIM ir GIS aplinkų pateiktus duomenis. Išanalizuota geoerdvinės analizės žiniatinklio aplinkoje galimybė BIM modeliui vaizduoti. Šio skyriaus pabaigoje suformuluoti pagrindiniai šio tyrimo tikslai ir uždaviniai. Remiantis literatūros analizės rezultatais, nustatytos šios tolesnių tyrimų kryptys:

- Skirtingų aplinkų sąveikos ir duomenų mainų, ypač BIM modelių apdorojimo, problemų sprendimas.
- Su GIS susijusios analizės taikymas BIM modeliams apdoroti.

Remiantis naujausių technologijų analizės rezultatais, nustatyta, kad BIM, GIS ir žiniatinklio aplinkų integracija neapima tyrimų, kuriais būtų siekiama panaudoti daugiakriterę analizę. Toks pastebėjimas yra didelė integracijos proceso spraga, nes MCDA panaudojimas sprendžiant statybos srities problemas duoda daug naudos. Siekiant užpildyti šią spragą, būtina taikyti MCDA BIM modelio duomenims apdoroti GIS ir žiniatinklio aplinkose.

Atlikus naujausių technologijų analizę paaiškėjo, kad aktualiausios problemos integruojant BIM, GIS ir žiniatinklio aplinkas yra susijusios su standartizuoto sprendimo, apimančio pagrindinius BIM modelio apdorojimo metodus, trūkumu. Šios problemos susijusios su BIM modelio apdorojimu ir analize, nes ne visi BIM modelio pateikti duomenys yra palaikomi žiniatinklio aplinkoje. Norint apdoroti ir analizuoti BIM modelį žiniatinklio aplinkoje integruotai su GIS technologijomis, reikia išspręsti sąveikumo problemas. Tiksliau, žiniatinklio aplinkoje nėra BIM modelio objektų ryšių, kurie reikalingi BIM modelio analizei atlikti. Siekiant pateikti išsamią šios problemos analizę, buvo išanalizuoti mokslinėje srityje pateikiami sprendimai ir metodai.

Ponjavic ir Karabegovic (2019) tyrime teigiama, kad kadangi BIM programinė įranga negali gauti visos informacijos iš GIS aplinkos naudojant numatytuosius įrankius, visas GIS potencialas negali būti integruotas į BIM aplinką. Dėl to GIS objektai, jų vietos ir charakteristikos negali būti analizuojamos aplinkoje, kurioje kuriamas BIM modelis.

BIM aplinkos integravimas į GIS aplinką ir atvirkščiai yra sudėtingas procesas. To priežastis yra ta, kad BIM aplinkoje yra daug nuosavybinių formatų BIM modeliui kurti ir valdyti (Tobias, 2015). BIM ir GIS aplinkos labai skiriasi, nes buvo sukurtos skirtingiems tikslams. Geoerdvinės sistemos buvo skirtos jau egzistuojantiems didelio masto realybės objektams ir reiškiniams modeliuoti arba imituoti juos analizėje, kur pagrindinis dėmesys skiriamas georeferencijai ir duomenų aktualumui (Isikdag & Zlatanova, 2009). Kita vertus, BIM sprendimai orientuoti į nedidelio masto dar neegzistuojančių objektų modeliavimą (Isikdag, Underwood & Aouad, 2008). Remiantis atlikta analize nustatytos šios pagrindinės BIM ir GIS integravimo kliūtys: (1) BIM aplinkoje daugiau geometrijos atvaizdavimo, palyginti su GIS aplinka; (2) taikoma skirtinga semantika; (3) taikomos skirtingos koordinačių sistemos; (4) trūksta standartų, metodų ir technologinių sprendimų integravimui.

Geometrijos tipų skirtumas yra vienas reikšmingiausių skirtumų tarp BIM ir GIS aplinkų, trukdančių konvertuoti BIM modelį į GIS palaikomus formatus (Xu, Zhang, Li, Lin & Yin, 2020). BIM modeliuose daugiausia naudojama CSG arba *swept* geometrija, o GIS geometrija apsiriboja *B-Rep* geometrija, pvz., primityvi geometrija, plokštumos ir tinkeliai. Norint pateikti BIM modelio turinę geometriją GIS aplinkoje, reikia ištraukti objektų išorinį apvalkalą ir priskirti jį paviršiams, tačiau toks ištraukimo procesas nėra trivialus dalykas ir daugybė esamų konvertavimo įrankių negali užtikrinti visiškai tinkamo rezultato (Floros, Pispidikis & Dimopoulou, 2017). Semantikos skirtumų atsiranda dėl to, kad GIS aplinkoje pateikiami didelio masto objektai, tokie kaip šalys ir miestai (Azhar, 2011). Priešingai, BIM orientuojasi į nedidelio masto objektus, tokius kaip pastatai ir konstrukciniai elementai. Todėl akivaizdu, kad šios dvi aplinkos nesusietos. Šių aplinkų semantikos susiejimas (angl. *mapping*) yra vienas iš sprendimų, galinčių išspręsti šią problemą.

Kita pagrindinė BIM ir GIS integravimo kliūtis yra susijusi su tose aplinkose naudojamomis koordinatinių sistemomis (Arroyo Ogori, Diakité, Krijnen, Ledoux & Stoter, 2018; Zhang, Hou, Wang, Pan & Yan, 2020). GIS aplinkoje daugiausia naudojamos trys koordinatinių sistemos: geografinės koordinatinių sistemos (GCS), projektuojamos koordinatinių sistemos (PCS) ir vietinė koordinatinių sistema (QGIS: Working with Projections, 2022). BIM aplinkoje daugiausia naudojamos dvi koordinatinių sistemos – tyrimo koordinatinių sistema ir vietinė koordinatinių sistema (Autodesk Revit: About Coordinate Systems, 2022). Neseniai BIM programinėms įrangoms buvo pateikti įrankiai GCS koordinatėms nurodyti remiantis internetiniu žemėlapiu. Ši sistema naudojama norint nurodyti projekto vietą realioje aplinkoje. Toks sprendinys išsprendžia BIM projekto susiejimo su GIS koordinatėmis klausimus. Kita vertus, abiejose aplinkose yra vietinė arba projekto koordinatinių sistema, kuri naudojama projekte, siekiant nurodyti vieno su kitu susijusių objektų padėtį. Nors koordinatinių diegimas buvo iš esmės patobulintas, koordinatinių apdorojimas kiekvienoje aplinkoje išlieka skirtingas. Transformacijos procedūra apima BIM modelio perkėlimą, pasukimą ir mastelio keitimą. Atitinkamai visi objektai ir konstrukciniai elementai BIM modelyje taip pat turi būti transformuoti. Pritaikius transformaciją ir perskaičiavus koordinates, BIM modelį galima pateikti žemėlapyje. Tokia transformacija BIM modelio vizualizavimo tikslais nėra kritinė, tačiau sumažina BIM modelyje pateikiamų konstrukcinių elementų tikslumą, konkrečiai – geometrinius parametrus ir jų santykines vietas. Vienas iš pagrindinių akcentų statybų srityje yra skaičiavimų tikslumas, nes net ir nedidelės klaidos turi įtakos galutinei modelio kokybei.

Apibendrinant BIM ir GIS aplinkų integravimo sprendimų analizę galima teigti, kad tiesioginė integracija tarp BIM ir GIS aplinkų (sistemos lygmeniu) nėra įmanoma, nes yra nesusuderinamos kiekvienos aplinkos metodinių ir techninių sprendimų sampratos, semantika ir geometriniai duomenys. Duomenų integravimas be transformacijų ar aplinkos modifikacijų taip pat neįmanomas.

Norint integruoti BIM ir GIS aplinkas ir apdoroti iš jų gaunamą informaciją vienu metu, jos turi būti integruotos į aplinką, kurioje būtų sprendžiami visi sąveikumo klausimai. Aplinka, kurioje galima derinti BIM ir GIS technologijas, turi turėti galimybę apdoroti GIS ir BIM duomenis, įskaitant visas susijusias technologijas ir metodus. Norima integracija turi pateikti visų tipų duomenis iš GIS aplinkos, pvz., sąsajas su duomenų baze,

geometrinius primityvus, paviršius ir poligonalus, modelius ir tinklelius bei visų tipų duomenis iš BIM aplinkos, kur kiekvienas objektas turi savo atributinę informaciją ir geometrijas skirtingais masteliais. Tokia integracija gali būti pasiekta žiniatinklio aplinkoje naudojant žiniatinklio technologijas. Tyrimuose pabrėžiamas žiniatinklio technologijų naudingumas sprendžiant BIM ir GIS integracijos ir sąveikos problemas (Irizarry, Karan & Jalaei, 2013; Karan & Irizarry, 2015; Karan, Irizarry & Haymaker, 2016).

Tačiau integravimas su žiniatinklio aplinka turi kitų problemų. Disertacijoje aptartos GIS ir žiniatinklio integracijos galimybės. BIM modelio integravimas į žiniatinklio aplinką yra daug sudėtingesnis procesas, palyginti su GIS ir žiniatinklio integracija. Taip yra dėl to, kad BIM aplinka nebuvo sukurta naudoti kartu su žiniatinklio aplinka, t. y. BIM modeliai yra sukurti naudojant patentuotą programinę įrangą, tokią kaip Autodesk Revit ir Bentley Solidworks. Tokia patentuota programinė įranga neleidžia peržiūrėti BIM modelio failų struktūros, nes ji yra užšifruota, todėl naujausi BIM failų tipai lieka nepalaikomi žiniatinklio aplinkos ir negali būti apdorojami už patentuotos programinės įrangos, su kuria jie buvo sukurti, ribų. Norint turėti galimybę apdoroti BIM modelį žiniatinklio aplinkoje, BIM modelį reikia konvertuoti į žiniatinklyje palaikomą failo tipą. Reikia pabrėžti, kad plačiai naudojamas IFC failo tipas taip pat negali būti apdorotas be konvertavimo, kadangi IFC negali išsaugoti visų svarbių semantinių duomenų. Nepaisant to, IFC faile pateikta geometrija gali būti analizuojama ir naudojama taikant žiniatinklio technologijas.

Norint integruoti BIM modelį ir duomenis, perkeliamus iš GIS duomenų bazės, reikia sukonfigūruoti žiniatinklio aplinką, kuri prasideda nuo WebGL aplinkos nustatymo. WebGL naudojama kaip API 2D ir 3D, grafikai atvaizduoti žiniatinklio naršyklėje, nenaudojant papildomos programinės įrangos ar priedų. Toliau disertacijoje detaliau aptariami esami sprendimai integruojant BIM, GIS ir žiniatinklio aplinkas, įskaitant IoT technologijų integravimą, Smart City ir Digital City koncepcijas. Išanalizavus esamus projektus, integruojančius BIM ir GIS aplinkas žiniatinklio aplinkoje, paaiškėjo, kad tokia integracija suteikia daug privalumų įvairiose srityse, įskaitant miesto užstatymo planavimą, transportą, energijos valdymą ir pastatų eksploatavimą. Plačiausiai taikomas sąveikos sprendimas yra BIM modelio konvertavimas į žiniatinklio palaikomą formatą.

Literatūros analizė taip pat atskleidė, kad trūksta tyrimų taikant MCDA žiniatinklio aplinkoje su BIM ir GIS aplinkos teikiamais duomenimis. Tokios integracijos svarba kyla dėl to, kad realaus pasaulio problemos ir su GIS susiję parametrai paprastai yra sudėtingi ir daugialypiai, jų negalima palyginti ir analizuoti taikant įprastą matematinę analizę. Tokioms problemoms, kurių neįmanoma išspręsti įprastu matematiniu būdu, naudojama daugiakriterė analizė.

Daugiakriterė analizė buvo naudojama sprendžiant įvairias su GIS susijusias problemas, tokias kaip vietos ir teritorijos planavimas, miestų planavimas, išteklių paskirstymas ir kt. (Malczewski & Jackson, 2000; Sumathi, Natesan & Sarkar, 2008; Kallali, Anane, Jellali & Tarhouni, 2007). Objekto vietos planavimo problema ir turto patrauklumo vertinimas bei kainos prognozavimas apima daugiausiai kriterijų, susijusių su geoerdviniais duomenimis, nes kiekviena alternatyvi vieta yra apibrėžta geografiškai, kur kiekvienas geografiškai susijęs kriterijus turi savo vertę (Kolat, Doyuran, Ayday & Suzen, 2006; Gilliams, Raymaekers, Muys & Orshoven, 2005; Esmaelian, Tavana,

Arteaga & Mohammadi, 2015). Su pastato vieta susiję kriterijai vertinant kainą laikomi svarbiausiais veiksniais, nes nekilnojamojo turto kainai didelę įtaką daro turto patrauklumas, priklausantis nuo turto vietos parametrų ir aplinkos veiksnių (Abidoye & Chan, 2017).

Siekiant gauti tinkamiausius kriterijus MCDA taikymui, buvo atlikta esamuose moksliniuose straipsniuose naudojamų kriterijų analizė. Remiantis analize, buvo sudarytas preliminarus kriterijų rinkinys (1.2 lentelė). Atlikus mokslinių straipsnių analizę, nustatyti 32 pagrindiniai kriterijai, kurie buvo naudojami atliekant tyrimus, susijusius su objekto vietos parinkimo problema.

Atsižvelgiant į literatūros analizės pateiktas išvadas, vienas iš pagrindinių akcentų turėtų būti GIS analizės taikymas žiniatinklio aplinkoje BIM modeliui apdoroti. Nustatyti GIS analizės panaudojimo atvejai yra geoerdvinė analizė, matomumo analizė ir viešasis transportas. Geoerdvinės analizės diegimas į sprendimų sistemas yra vertingas plėtinys, nes leidžia ne tik perkelti geoerdvinius duomenis iš GIS duomenų bazių, bet ir analizuoti BIM modelį GIS turinyje sprendžiant statybos srities problemas. Disertacijoje pateikta detali metodų, taikomų matomumo analizei, apžvalga, įskaitant matomumo analizės, paremtos matomos teritorijos (angl. *viewshed*) modeliavimu, metodą (Travis et al., 1975), tiesioginio matomumo linijos sąvoka (angl. *line-of-sight*) paremtą metodą (Jenkins & Hilkert, 1989), matomumo analizės, paremtos matomo dangaus kupolo (angl. *wiew dome*) modeliavimu metodą (Othman et al., 2019) ir QLA360 (Wrozyński et al., 2020) metodą. Analizės išvadose konstatuota, kad nėra sprendimo ar metodo, kuris leistų analizuoti vaizdą iš lango horizontaliai ir vertikalčiai 3D realaus pasaulio vaizdavimo sąlygomis, remiantis BIM duomenimis ir vertinant vaizdą kaip sferą. Netgi profesionalūs sprendimai, tokie kaip ESRI ArcGIS Pro, negali apskaičiuoti matomumo iš langų įvairiuose aukščiuose, pavyzdžiui, butuose. Be to, nerasta tyrimų, kurie naudotų BIM, GIS ir žiniatinklio aplinkas vertinant nekilnojamojo turto patrauklumą (ar prognozuojant kainą) taikant langų matomumo analizę.

Disertacijoje taip pat išanalizuotos matomumo analizės pritaikymo galimybės labiau specifinėms statybos problemoms spręsti. Pavyzdžiui, viena iš statybos srityje egzistuojančių problemų, kuriai reikalinga matomumo analizė ir kuriai spręsti reikalingi realaus pasaulio duomenys, yra krano darbas (Chen, Fang & Cho, 2017). Vienas iš svarbių parametrų, į kuriuos atsižvelgiama valdant kraną ir nuo kurio priklauso krano saugus darbas, yra matomumas iš krano kabinos (Cheng & Teizer, 2014; Ancione, Paltrinieri & Milazzo, 2020; Zunjic, Brkic, Klarin, Brkic & Krstic, 2015; Kivrak & Kia, 2018; Dwyer, Pandey, McHale & Harness, 2019; Fadda et al., 2015). Matomumo analizės taikymas, remiantis BIM ir GIS aplinkų pateiktais duomenimis ir naudojant žiniatinklio technologijas kranų valdymui patobulinti, gali padidinti statybos procesų saugumą.

2. Konceptualus modelis racionaliems sprendimams modeliuoti statybos projekte

Antrajame darbo skyriuje pateiktas autoriaus pasiūlytas konceptualus statybos projekto racionalių sprendimų modeliavimo modelis. Modelio elementus sudaro:

- Modelio objektų tarpusavio ryšių sprendimas, pateiktas BIM modelio vaizdavimu žiniatinklio aplinkoje.

- Matomumo analizės metodas integruotoje BIM, GIS ir žiniatinklio aplinkoje (QUVIAS).
- Metodas daugiakriteriui analizei žiniatinklio aplinkoje atlikti, įskaitant kriterijų svorių nustatymą.
- Krano valdymo analizės metodas, pagrįstas BIM, GIS ir žiniatinklio integracija.
- Autoriaus pasiūlyta konceptuali BIM, GIS ir žiniatinklio aplinkų ir daugiakriterės analizės integravimo schema pateikta S2.1 pav.

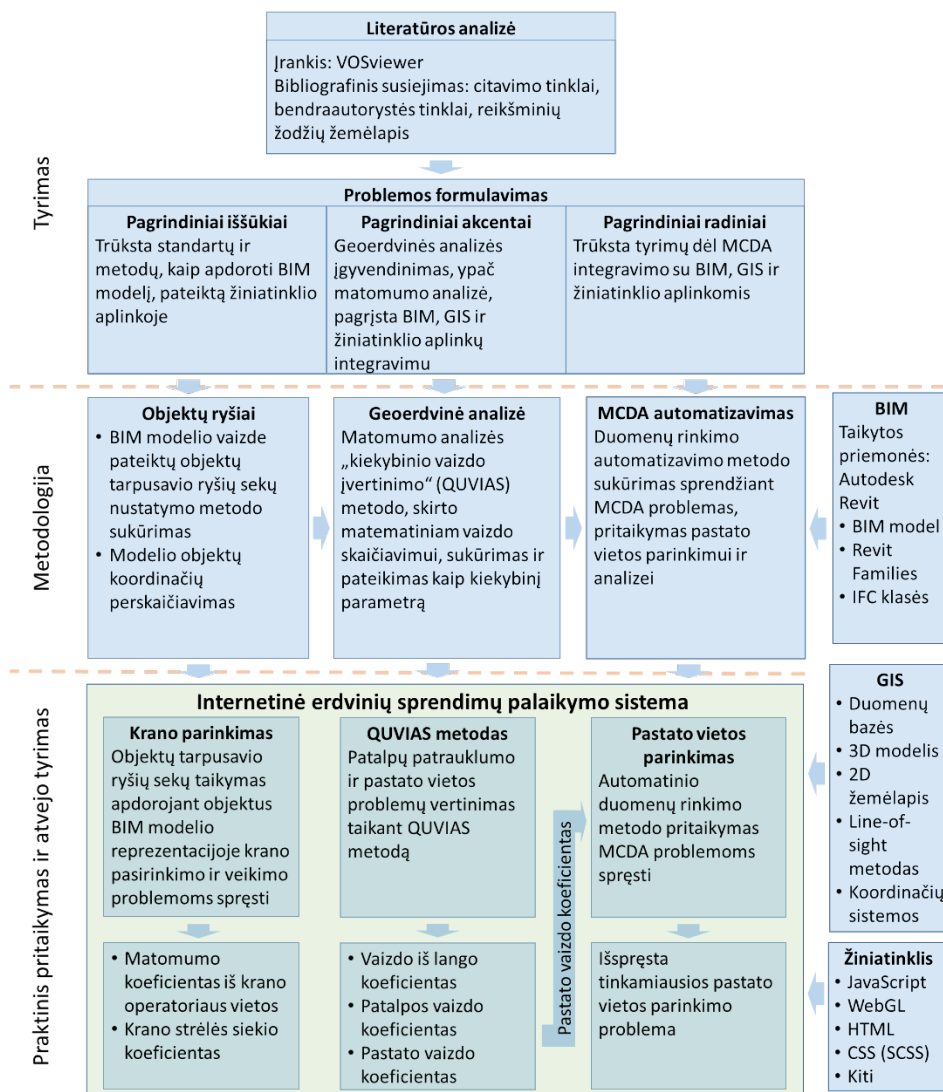
Kaip pavaizduota S2.1 pav., BIM aplinka naudojama BIM modeliui kurti taikant Autodesk Revit programinę įrangą. GIS aplinkos integravimas užtikrina GIS duomenų bazių ryšį, 3D paketinį modelių integravimą, 2D žemėlapius, koordinacių sistemas ir tiesioginio matymo (angl. *line-of-sight*) analizę. Žiniatinklio aplinkos integravimas užtikrinamas taikant JavaScript taikomąją programą WebGL turinyje naudojant HTML, CSS (SCSS) ir kitus funkcionalus.

Koncepcinio modelio pirmasis etapas yra naujausių mokslinių tyrimų analizė. Kaip buvo aprašyta pirmojoje dalyje, ši analizė leidžia nustatyti pagrindines problemas ir spragas, pagrindines tyrimų sritis bei tolesnių tyrimų kryptį.

Remiantis literatūros analizės metu nustatytais tyrimų poreikiais, antrajame etape kuriami metodai siekiant atlikti analizę integruojant BIM, GIS ir žiniatinklio aplinkas. Siūlomas objektų ryšių BIM modelyje nustatymo metodas reikalingas kuriant matomumo analizės metodą (QUVIAS), nes leidžia apdoroti BIM modelio reprezentacijoje pateiktus objektus ir nustatyti jų koordinates.

Šiame etape taip pat sukurtas automatinio duomenų rinkimo metodas sprendžiant MCDA problemas, konkrečiai, pastato vietos parinkimo problemą. Taikant siūlomą metodą pastato vietai vertinti pasitelkiamas anksčiau sukurtas matomumo analizės metodas.

Kiekvienam anksčiau paminėtam metodui buvo atliktas atvejo tyrimas. Siūlomam matomumo analizės metodui buvo atlikta atvejo analizė, apimanti lango vaizdo apskaičiavimą, pagal kurį buvo apskaičiuotas kiekybinis matomumo koeficientas, būdingas patalpai ir pastatui. Pastato vietos problema buvo išspręsta naudojant skaičiuojamąjį kiekybinį pastato matomumo koeficientą, kuris buvo pritaikytas kaip vaizdo kriterijus, ir buvo atlikta daugiakriterė skirtingų pastato lokacijų analizė. Pastato vietos parinkimo uždaviniui spręsti buvo sudaryta originali rodiklių sistema, kur buvo integruotas autoriaus sukurtas matomumo koeficientas, apskaičiuojamas taikant QUVIAS metodą. Rodiklių reikšmingumai nustatyti taikant Delphi metodą. Ekspertų atliktame tyrime dalyvavo 17 ekspertų. Atlikus ekspertinį vertinimą buvo nustatytas ekspertų nuomonių suderinamumas apskaičiavus konkordacijos koeficientą. Daugiakriterė alternatyvų analizė buvo atlikta pritaikius Fuzzy TOPSIS, Fuzzy COPRAS ir Fuzzy EDAS metodus.

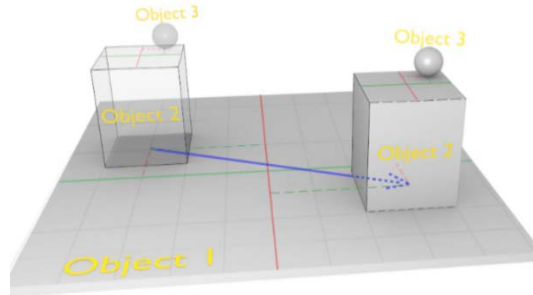


S2.1 pav. Konceptinė BIM, GIS ir žiniatinklio aplinkų integravimo schema, skirta MCDA atlikti (sukurta autoriaus)

Visi pasiūlyti metodai ir apibrėžtų problemų sprendimas buvo atlikti autoriaus sukurtoje internetinėje erdviųjų sprendimų palaikymo sistemoje.

Disertacijos 2.2 poskyryje aprašytas siūlomas objektų tarpusavio ryšio sekos nustatymo metodas leido perkompiliuoti BIM modelio vaizdą ir apdoroti jį taip, kad perskaičiuotos koordinatės galėtų būti panaudotos geoerdvinėje analizėje. Siūlomas metodas buvo pritaikytas kitose disertacijoje pateiktose analizėse.

Disertacijos 2.3 poskyryje pateikta nekilnojamojo turto patrauklumo veiksnių analizė ir parinkti kriterijai, kuriuos taikant trečiajame skyriuje atlikta pastato vietų daugiakriterė analizė. Čia taip pat aprašytas rodiklių reikšmingumų nustatymo procesas.



S2.2 pav. Objektų tarpusavio ryšių seka (sukurta autoriaus)

Disertacijos 2.4 poskyryje pateiktas daugiatislių metodų Fuzzy TOPSIS, Fuzzy COPRAS ir Fuzzy EDAS, taikytų daugiakriterėi alternatyvų analizei, aprašymas.

Disertacijos 2.5 poskyryje aprašyti etapai, taikyti daugiakriterėi analizei automatizuoti autoriaus sukurtoje internetinėje erdvių sprendimų palaikymo sistemoje.

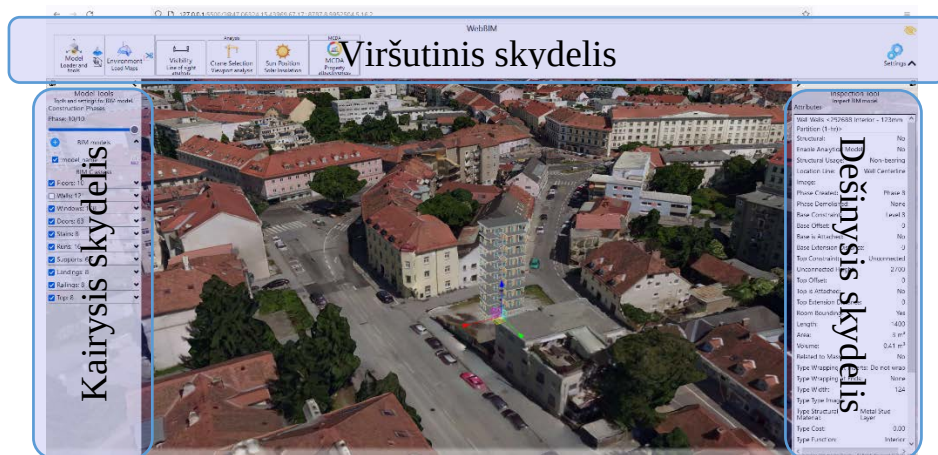
Disertacijos 2.6 poskyryje pateiktas autoriaus sukurtas QUVIAS metodas matomumo analizei atlikti integruojant BIM, GIS ir žiniatinklio aplinkas.

Disertacijos 2.7 poskyryje pateiktas autoriaus sukurtas krano valdymo metodas, kuris paremtas matomumo analize.

3. Konceptinio modelio taikymas racionaliems sprendimams modeliuoti statybos projekte

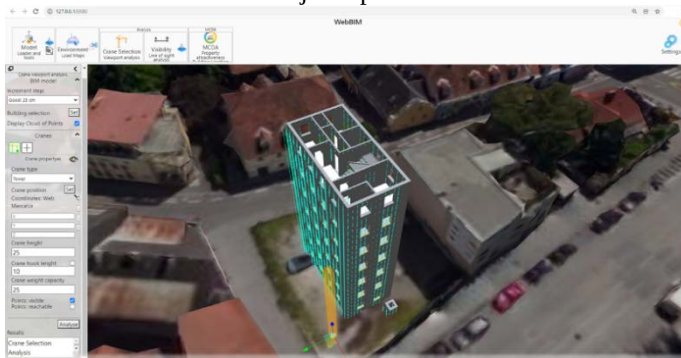
Trečiajame skyriuje autoriaus sukurti metodai pademonstruoti atvejo tyrimuose. Šiame skyriuje pristatoma:

- Trumpa informacija apie internetinės erdvinės sprendimų paramos sistemos (S3.1 pav.) kūrimą, įskaitant pagrindinį funkcionalumą, langų matomumo analizės įgyvendinimą, krano valdymo funkcionalumą, praktinį daugiakriterės sprendimų paramos analizės įgyvendinimą, įskaitant funkcionalumo, susijusio su duomenų rinkimu, aprašymą.
- Internetinės erdvių sprendimų paramos sistemos aprobavimas integruojant BIM, GIS ir žiniatinklio aplinkas, įskaitant optimalaus krano veikimo modeliavimą, matomumo ir geoerdvinės analizės panaudojimą turto patrauklumo ir pastato vietos parinkimo problemoms spręsti, daugiakriterį turto patrauklumo vertinimą.
- Daugiakriterė sprendimų analizė, atlikta naudojant sukurta internetinę sprendimų paramos sistemą, įskaitant Fuzzy TOPSIS, Fuzzy COPRAS ir Fuzzy EDAS metodų taikymą.



S3.1 pav. Sukurta internetinė sprendimų paramos sistema (sukūrė autorius)

Taikant pasiūlytus metodus atlikti atvejo tyrimai. Vienas iš jų – kranų valdymo analizė taikant matomumo koeficientą. Kranų matomumo koeficientas yra parametras, nurodantis pastato procentinę dalį, kuri gali būti matoma iš kranų kabinos. Pateikto pastato matomumo koeficientas nagrinėjame projekte yra lygus 95,01 %. Tiksliau, 51,94 % pastato buvo matomi iš pirmosios kranų vietos, o 49,7 % – iš antrosios kranų vietos. Tačiau 5 % pastato buvo nustatyta kaip nematoma abiem atvejais. Remiantis šiuo parametru, galima palyginti alternatyvias kranų vietas ir skirtingus kranų derinius, kad būtų užtikrintas didžiausias matomas objekto paviršius.

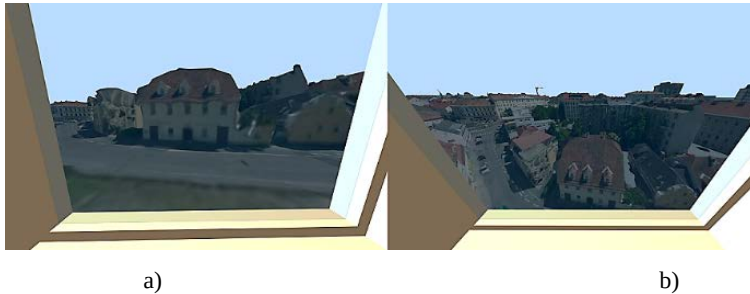


S3.2 pav. Kranų matomumo koeficientas: matomumo analizė statybos etape (sukūrė autorius)

Matomumo koeficiento ir geoerdvinės analizės panaudojimas išbandytas nekilnojamojo turto patrauklumui vertinti ir pastato vietos parinkimo uždaviniuose.

Nekilnojamojo turto patrauklumui vertinti vizualiai palyginti vaizdai iš antro (S.3.3a pav.) ir devinto aukštuose (S.3.3b pav.) esančių langų. Matyti, kad vaizdas pro devinto aukšto langą yra vaizdingesnis ir aiškesnis, palyginti su antro aukšto langais. Remiantis aktualios literatūros analize ir įvertinus vienodą kitų patalpų parametrų įtaką, devintame

aukšte esančios patalpos patrauklumas potencialiai yra didesnis, lyginant su antrame aukšte esančia patalpa. Tačiau toks palyginimas yra kokybinis ir negali būti naudojamas norint tiksliai nustatyti skirtumus tarp pateiktų vaizdų. Todėl buvo taikytas QUVIAS metodas. 3.3 poskyryje detalai aprašytas metodo taikymas šiam uždaviniui spręsti.



S3.3 pav. Siūlomos langų matomumo analizės praktinis tyrimas: a – vaizdas iš antro aukšto; b – vaizdas iš dešimto aukšto (sukūrė autorius)

Remiantis sankirtos taškų analize, vaizdas, kuris matomas iš antro aukšto lango, susideda iš 0,11266 (arba 45,6 % vaizdo) kelių, 0,03710 (arba 15 %) pastatų ir 0,01030 (arba 4,2 %) neapibrėžtų objektų, kurie nėra pateikti OpenStreetMap duomenų bazėje. Vaizdą pro dešimto aukšto langą sudaro 0,06509 (arba 16,1 %) kelių, 0,11671 (arba 28,8 %) pastatų, 0,00180 (arba 0,4 %) žaliųjų plotų ir 0,02469 (arba 6,1 %) nežinomų objektų, kurie nebuvo apibrėžti duomenų bazėje. Remiantis literatūros analize, tokia tiksli informacija gali būti labai vertinga vertinant turto patrauklumą.

Remiantis QUVIAS metodu ir matomumo koeficientais palygintos pastato alternatyvios lokacijos. Toks alternatyvių pastato vietų palyginimas gali padėti atlikti daugiakriterę sprendimų analizę, prognozuojant statybos projekto pajamas pagal tinkamiausią pastato vietą. Remiantis analizės rezultatais, antroji pastato vietos alternatyva yra priimtinesnė, palyginti su pirmąja, nes potencialiai tai gali lemti didesnę nekilnojamojo turto patrauklumą ir dėl to didesnes projekto pajamas. Siūlomas pastato vaizdo koeficientas gali būti įtrauktas į MCDA kaip parametras, apibūdinantis vaizdo kriterijaus kiekybinę vertę.

Bendrosios išvados

Apibendrinus literatūros analizės rezultatus, galima teigti, kad:

1. Remiantis mokslinės literatūros analizės rezultatais, BIM, GIS ir žiniatinklio aplinkų integravimo procesas susiduria su daugybe kliūčių, kur aktualiausios problemos yra susijusios su duomenų apdorojimo standartų ir metodų taikymu. Iš esmės ši problema yra susijusi su BIM modelio apdorojimu, nes nerasta vieno bendro standarto, kuris pateiktų duomenų saugojimo ir valdymo metodą, kurio pakaktų visoms trimis aplinkoms.

2. Siūlomas objektų tarpusavio ryšio sekos nustatymo metodas leido perkompiliuoti BIM modelio vaizdą ir apdoroti jį BIM būdu, kad perskaičiuotos koordinatės galėtų būti

panaudotos geoerdvinėje analizėje. Siūlomas metodas buvo ne kartą taikytas kitose disertacijose pateiktose analizėse. Remiantis rezultatais, pasiūlytas metodas pasirodė vertingas ir naudingas.

3. Taikant siūlomą kranų parinkimo ir valdymo metodą buvo gautas didelis skaičiavimo tikslumas, leidžiantis analizuoti pavienius kranus ir jų grupes. Remiantis analizės rezultatais, pasiūlytas metodas leido diferencijuoti kranų vietų alternatyvas, atsižvelgiant į matomumą iš kranų operatoriaus kabinos.

4. Taikant matomumo analizei pasiūlytą kiekybinio vaizdo įvertinimo (QUVIAS) metodą, leidžiantį apskaičiuoti vaizdą matematiškai, buvo gautas didelis skaičiavimų tikslumas ir jo aprobavimo pagrindu pateikiamos šios išvados:

a) Esamų matomumo analizės metodų palyginimas su pasiūlytu atskleidė pakankamą tikslumo skirtumą ir įrodė QUVIAS metodo vertę.

b) Lango vaizdo koeficientas leido tiksliai nustatyti skirtumą tarp langų vaizdų, tai įrodo siūlomo kiekybinio vaizdo vertinimo metodo tikslumą.

c) Siūlomas patalpų vaizdo koeficientas atskleidė reikšmingą skirtumą tarp dviejų patalpų vaizdų. Patalpų vaizdo koeficientas parodė, kad jis gali būti panaudotas vertinant patalpų patrauklumą.

d) Pastato vaizdo koeficientas atskleidė pakankamą skirtumą tarp dviejų vaizdų, susijusių su alternatyviomis pastato vietomis. Analizė parodė, kad pasiūlytas pastato vaizdo koeficientas yra tinkamas naudoti sprendžiant pastato vietos problemą, pateikiant kiekybinį vaizdo reprezentavimą į skaičiavimą.

5. Siūlomas daugiakriterės sprendimų analizės koncepcinis modelis ir metodika pritaikyta pastato vietos parinkimo sprendimo automatizavimo atvejo tyrime. Visas duomenų rinkimo ir MCDA sprendimo procesas buvo atliktas sukurtoje internetinėje sprendimų paramos sistemoje. Pasiekti rezultatai įrodė BIM, GIS ir žiniatinklio integracijos naudingumą sprendžiant statybos projekto problemas.

6. Sukurta internetinė sprendimų paramos sistema apima visus siūlomos metodus, sistemos veikimas patvirtintas atvejo tyrimais. Pagrindinė kliūtis atvejų tyrimuose buvo šaltinių iš GIS duomenų bazių, skirtų duomenims rinkti daugiakriteriui sprendimų priėmimo analizei, trūkumas. Ši problema susijusi su institucijų pateikiamais ribotais duomenimis. Duomenų bazės dažniausiai yra ribotos prieigos, nepasiekiamos, todėl trūko duomenų daugiakriteriui analizei atlikti.

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MULTIFACETED CONSTRUCTION PROJECT PROBLEMS

Doctoral Dissertation

Technological Sciences,
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STATYBOS PROJEKTŲ DAUGIALYPĖMS PROBLEMOMS SPRĘSTI

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