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Comparative Analysis of Mapping Methods Used in Interior Space Organization and Experience Design

İç Mekân Organizasyonu ve Deneyim Tasarımında Kullanılan Haritalama Yöntemlerinin Karşılaştırmalı Analizi

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ABSTRACT

The necessity for new methods to gain insights into architectural interiors and user activity has sparked ongoing debate. Today, the possibilities offered by mapping methodologies serve as a bridge between architectural space and experience design. This research systematically explores the role of mapping methodologies in addressing a wide range of questions regarding the spatial behavior and movement of individuals or groups and how they orient themselves within and experience space. Detailed research of publications from academic databases spanning 1960 to 2024 reveals a lack of guidance in existing literature for practitioners on incorporating mapping methodologies into their design decision-making processes to enhance the organization and experience of interior spaces. The findings underline the advantages and potentials of each method, providing a comprehensive framework to guide practitioners on three categories of mapping methods: human centered, technology-based, and software-based. The study evaluates the advantages and limitations of mapping methodologies used in the past and present, revealing their fundamental contributions to spatial applications. As a result, this study proposes a guiding manual that brings together spatial mapping methodologies in the form of comparative modular information sets, enabling potential researchers/designers/practitioners to integrate the simultaneous use of these methodologies into their decision-making and design processes.

Keywords: Spatial design, spatial analysis, mapping methods, architectural visualization, interior spatial experience.

ÖZ

Mimari iç mekân ve kullanıcı etkinliğine yönelik iç görülerin geliştirilmesinde yeni yöntemlerin gerekliliği güncel bir tartışma alanı yaratmıştır. Günümüzde haritalama metodolojisinin sunduğu olanaklar mimari mekân ve deneyim tasarımı için bir köprü işlevi görmektedir. Bu çalışma, bireylerin veya grupların mekâna özgü davranışları, hareketleri ve mekânda nasıl yöneldiği ve deneyimlediği olmak üzere çok sayıda soruya yanıt verebilecek haritalama metodolojilerinin rolünü sistematik biçimde araştırmaktadır. Akademik veri tabanlarında 1960-2024 yıllarını kapsayan yayınlar ayrıntılı bir alan yazın taraması yoluyla incelendiğinde, mevcut literatürde iç mekân organizasyonu ve deneyimin geliştirilmesinde tasarım karar sistemine dahil edilebilir haritalama metodolojilerinin uygulayıcılara tanıtıldığı bir rehber çalışmanın olmadığı görülmüştür. Bulgular, her yöntemin avantajlarını ve potansiyelini vurgulamakta ve uygulayıcılara insan merkezci, teknoloji tabanlı ve yazılım tabanlı olmak üzere üç haritalama yöntemi kategorisi hakkında rehberlik edecek kapsamlı bir çerçeve sunmaktadır. Çalışma, geçmişte ve günümüzde kullanılan haritalama metodolojilerinin avantajlarını ve sınırlamalarını değerlendirerek, bunların mekânsal uygulamalara temel katkılarını ortaya koymaktadır. Sonuç olarak bu çalışma, potansiyel araştırmacıların/tasarımcıların/uygulayıcıların bu metodolojileri karar verme ve tasarım süreçlerine entegre etmelerini sağlayan, karşılaştırmalı modüler bilgi setleri şeklinde mekânsal haritalama metodolojilerini bir araya getiren bir rehber kılavuz önermektedir.

Anahtar Kelimeler: Mekân tasarımı, mekân analizi, haritalama yöntemleri, mimari görselleştirme, iç mekân deneyimi.

Introduction

Perception theories and environmental psychology have led interior designers to seek ways of designing experience in architectural space. Spatial experience involves developing an understanding of a designed environment through body movements and senses, together with perceptions and cognitive processes. In a general sense, the organization of interior space is related to a design process based on experience, as it is evaluated by human movements or orientations. Making design decisions shaped by user experience facilitates the process of people exploring and navigating architectural space. It also makes spaces accessible to users.

The adaptation of human-centered mapping methods based on a wide range of academic disciplinary backgrounds such as environmental psychology and cognitive science to interiors and public spaces has led to a focus on the concepts of “spatial interactivity” and “spatial experience” in design. In countless spatial applications, this mapping methodology is based on human perceptions, observations, experiences and decisions. With the inclusion of technology and computer-aided generative approaches in architectural design, the idea of developing unique mapping methods in space organization and experience has emerged. With the digital revolution, interior cartography has evolved into an optimized mapping methodology. This has enabled decision makers and interior designers to collaboratively capture, collect, process and visualize data from the physical space in a digital interface, including the organization and design of interior spaces, the life cycle of a building, and the simulation of possible space experience conditions. Mapping methodologies are thus decision support mechanisms that structure interior space organization and spatial experience, enabling the processing of material spatial data for meta-analysis.

According to James Corner (1999, p. 215), mapping, seen as a creative practice, is most productive through structural findings, its effectiveness coming neither from its reproducibility nor from its mission. It can reveal a previously unrecognized or unforeseen reality even in a deformed landscape. At this point, it can be said that mapping is important for discovering new potentials by reconstructing the territory, each time with updated and varied results. From this point of view, the effectiveness of mapping as a methodology in generating new information about the possible potentials of space has led to the emergence of creative mapping techniques.

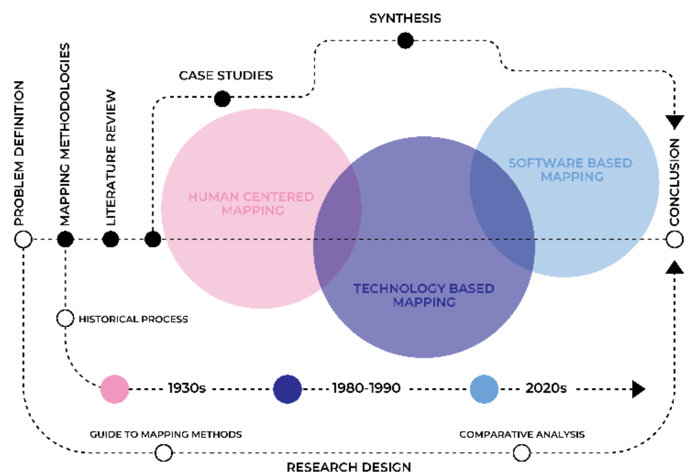
This study focuses on uncovering the main contributions and role of theoretical, technological and software-based mapping methodologies that can be applied to develop and evaluate insights in the experience and design of space in the AEC sector and interior architecture. The starting point of the research is the lack of a “methodological guide” in the relevant literature that sets out the spatial mapping methodologies that are intended to structure practitioners' information and serve as a decision support system tool in design. The collaborative and interdisciplinary usability of the methods among practitioners shows that basic and common spatial information can be used effectively in the design of experience-oriented interiors.

Methods

This chapter summarizes the research methodology adopted in the study to investigate the role of mapping methods in the design and development of place and experience as part of the AEC sector. In this direction, a literature review was conducted for the relevant literature from academic databases including Google Scholar, Scopus, Web of Science with keywords such as “mapping methods”, “spatial analysis”, “spatial mapping” and “architectural visualization”. The study aims to determine the basic characteristics, advantages, disadvantages, and application procedures of spatial mapping methods through a comprehensive synthesis of the literature. The research uses the case study approach from qualitative research methods (Figure 1). In this context, the use of mapping methods in interior design, architecture and engineering disciplines is examined with case studies at the spatial scale.

There is no methodological review in the current literature that defines spatial mapping methods together or reveals their basic characteristics. At this point, the methods remain within the scope of the field in which they were developed, thus limiting their use by the potential research community. The originality of this research lies in proposing a methodological guide consisting of summarised information sets that can guide future spatial research and applications on an interdisciplinary scale.

Figure 1.
Methodology of this research



Results: Mapping Methods Used in Interior Organization and Spatial Experience

In general terms, mapping methods have been applied in the relevant literature, within the disciplinary scope of each methodology, hardware or technical infrastructure requirements. In this research, methodologies are considered in a comprehensive perspective. Another importance of the study is that it emphasizes the holistic and interdisciplinary use of spatial data (inputs and outputs) of these mapping methods, which are taxonomized within the scope of the literature, especially in the architecture, interior architecture, engineering and construction sectors.

Human Centered Mapping Methods

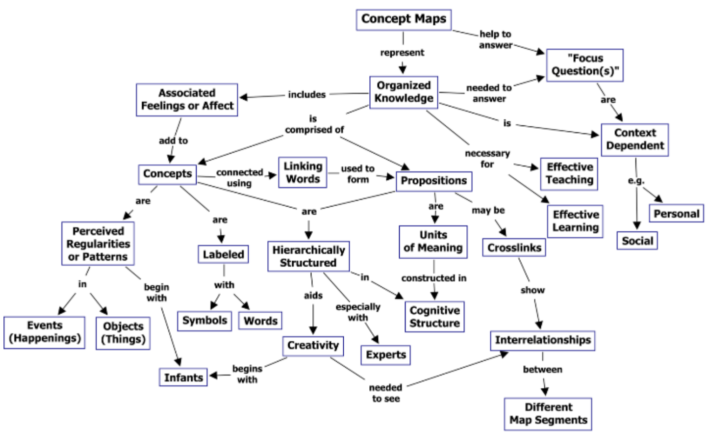
In the literature, human centered mapping methods are used in a wide variety of fields, such as learning models, psychology, and urban planning. In this study, however, the scope of the research topic has been limited to case studies under the headings of “interior space,” “public space,” and “spatial analysis.”

Conceptual Mapping and Personal Meaning Mapping (PMM)

According to Novak and Gowin (1984, p. 37), concept maps are representations that enable the expression of information in a graphical language and visualization of hierarchical relationships between concepts. They were developed to support better understanding, recall and presentation of complex information (Davies, 2011, p. 283).

A concept map usually consists of concepts enclosed in circles or rectangles, linking words that define the relationship between two concepts, and connecting lines (arrows) that construct the relationships. Linking words combine with two or more concepts enclosed in rectangles (or circles) to form the propositions of concept maps. There is also a hierarchical structure in these maps, with overarching and general concepts at the top and specific and specialized concepts downwards. Cross-links are used in maps to organize information systematically or to include different alternative answers to a question (Figure 2).

Figure 2.
A Concept Map showing the main features of concept maps (Novak & Cañas, 2008, p.2)



When the definitions and methodologies of "conceptual mapping" and "personal meaning mapping" methodologies are examined in the literature, it is seen that similar features are revealed. Methodologically, Personal Meaning Mapping (PMM) was developed from Novak and Govin's (1984, p. 105) concept maps. The main difference with concept mapping is that there is no basic "correct" map in personal meaning mapping. Another disadvantage of the method is that the researcher may request another interview to obtain long-term data after the meaning mapping process.

Figure 3.
Visualising Learning in Museums with Personal Meaning Mapping, Jewish Museum Berlin (Birkert, 2009, p.7)

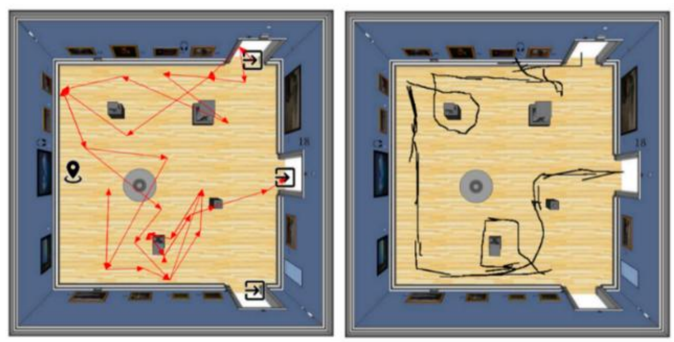
In the first stage of the PMM methodology, a keyword is circled in the center of a blank sheet of paper. With this keyword, visitors in the space are asked to freely write down the thoughts that come to their minds. The researcher then conducts interviews with the visitors and maps what the individual says, their post-experience notes at the end of the interview, and finally what they will say again in the follow-up interview. The researcher instructs the visitor to mark each stage of the interview with a different colored pen (Figure 3).

Social Meaning Mapping

Based on a method similar to behavioral mapping, this method is used to examine the movement routes, pauses and length of stay of visitors by marking them on a printed copy of the floor plans of the research area. It is a method preferred by museum staff and researchers to measure the success rate of curatorial efforts, especially those involving exhibition space design, during the museum visitor experience.

In Dimitra Christidou's (2020, p. 163) study, social meaning mapping methodology was integrated into a tablet application called "visitracker" and transformed into a digital data collection tool. The application includes a color digital floor plan of the gallery room to record the movement paths of visitors, their pauses in front of exhibitions, and the overall time the visitor spends in the painting and the exhibition. Visitors mapped their orientation in the museum through this application (Figure 4). However, some visitors have experienced problems with the digital tablet, using the application and drawing.

Figure 4.
Researcher's observation map (Left) and SMM map of a group (right) created with Visitracker App at the National Museum in Norway (Christidou, 2020, p.178)

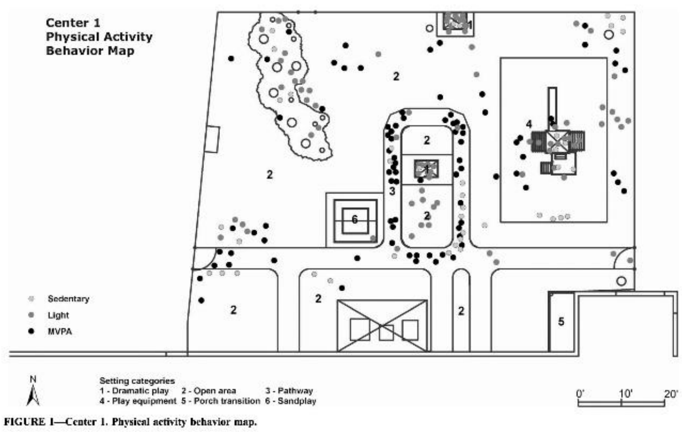


Behavioral Mapping

Bechtel and Zeisel define behavioral mapping as a technique used to convert human behavior and actions in a given area into systematic data as a subject of environmental psychology or similar disciplines (1987, p. 14). According to Sommer and Sommer (2002, p. 64), behavioral maps are divided into place-centered and individual-centered. In a place-centered map, people's behaviors are reported in the space and time intervals determined by the researcher. The aim here is to evaluate the use of the designated area. In the individual-centered map, on the other hand, the environment or environments that a person goes to in a specified time interval and their movements there are reported. For example, a researcher who wants to conduct a systematic study on where students spend their time after school and how they use this time can benefit from an individual-centered map.

An example of behavioral mapping is the study conducted by Cosco et al. (2010, p. 515) at two preschool play centers in Research Triangle Park in North Carolina to examine the behaviors of 3-5-year-old children in different activity areas such as play equipment and sandboxes in outdoor playgrounds. This study objectively assessed the relationship between child behavioral environments in outdoor playgrounds, their ground materials, and children's behavioral levels, and provided data to develop a standard that can guide the design of outdoor spaces in childcare centers (Figure 5). A limitation of the method is that additional observers may be required depending on the size of the space, and that observers may need to be trained in the observation procedure.

Figure 5.
Preschool play centre behaviour map (Cosco et al., 2010, p.515)



Cognitive Mapping

The Perceptual Form of the City research project initiated by American urban planner and academic Kevin Lynch with Gyorgy Kepes in 1954 and Lynch's 1960 book The Image of the City pioneered the cognitive mapping method. Lynch's book provided the opportunity to explain how we move through the city and how every experience in the city is organized as spatial information in the individual's mind over time. Lynch emphasized "readability" and "imaginability" in the formation of the environmental image.

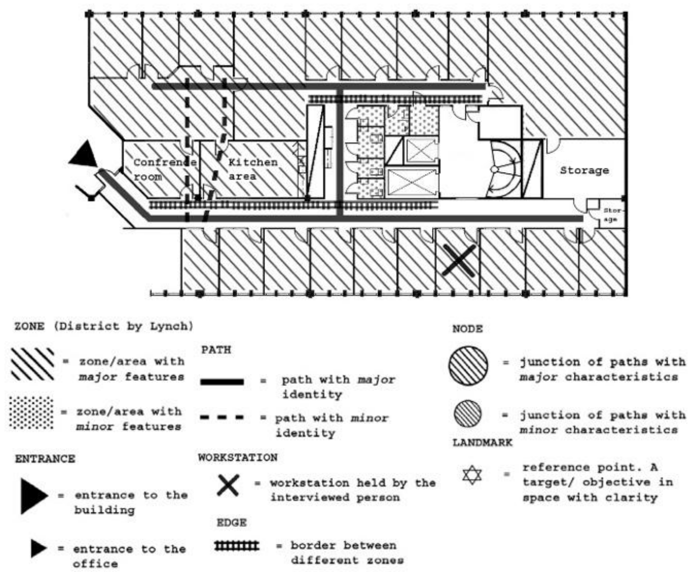
The potential symbolic value of the city for societies is strong. However, when this effect is emphasized with its visual identity, its meaning increases in the cognitive levels of individuals. The readability of an area increases the intensity of the experience of the people in that environment. The physical qualities of the environment structured by form, color and various arrangements are defined within the framework of the concept of "imaginability". Due to the vastness of the perceptual world, this can be grasped not only visually but also through the other senses, which are dominant in the context of "legibility and visibility" (Lynch, 1960, p. 2). Ultimately, these will produce their own characterization of the environment.

In the method he applied in Jersey City, Los Angeles and Boston, Lynch mentioned five different components that make up the urban image based on the physical elements in the urban space. These are paths, edges, districts, nodes and landmarks. (Lynch, 1960, p. 46). The use of these elements contributed to the visualization and universal language of cognitive maps.

The limitations of cognitive mapping include the potential observation of a weak correlation between individual mapping outputs and interview data, as well as the possibility that selecting participants who are familiar with the environment may restrict the sample size (Lynch, 1960, p. 144).

Although the elements are defined as different from each other, all elements should be evaluated together in the creation of the environmental image. Lynch explained the relationship between the elements as follows: "Districts are structured with nodes, defined by edges, penetrated by paths, and sprinkled with landmarks. Elements regularly overlap and pierce one another" (1960, pp. 48-49). Christina Danielsson's (2005, p. 69) study investigates the applicability of Lynch's theory in office environments with three different layouts. Accordingly, the research is based on understanding from a psychological perspective how employees perceive and use office environments. The study was conducted in one flexible type office with an open plan and two cubicle type offices consisting of individual workspaces. Accordingly, based on a verbal interview with the participant in the office and a mental map, diagrams linked to Lynch's method were created for each office plan layout (Figure 6).

Figure 6.
Map legends and cognitive map created in a cell type office (Danielsson, 2005, pp.72-73)



Sensory Mapping

In sensory mapping, there are sub-methodologies in which mapping is done from the five sensory systems or only for one sense, depending on the problem focused on with sensory experience. These are smell mapping, taste mapping, sound mapping, tactile mapping and visual mapping. These sub-methodologies of sensory mapping have separate evolutionary processes and individuality of perception. Accordingly, they involve generalizations about the common range of sensory perception of people who experience and map space in comparison to each other. While this may be considered a disadvantage, the inherently subjective nature of sensory perception also entails the possibility of collecting data that varies significantly between individuals.

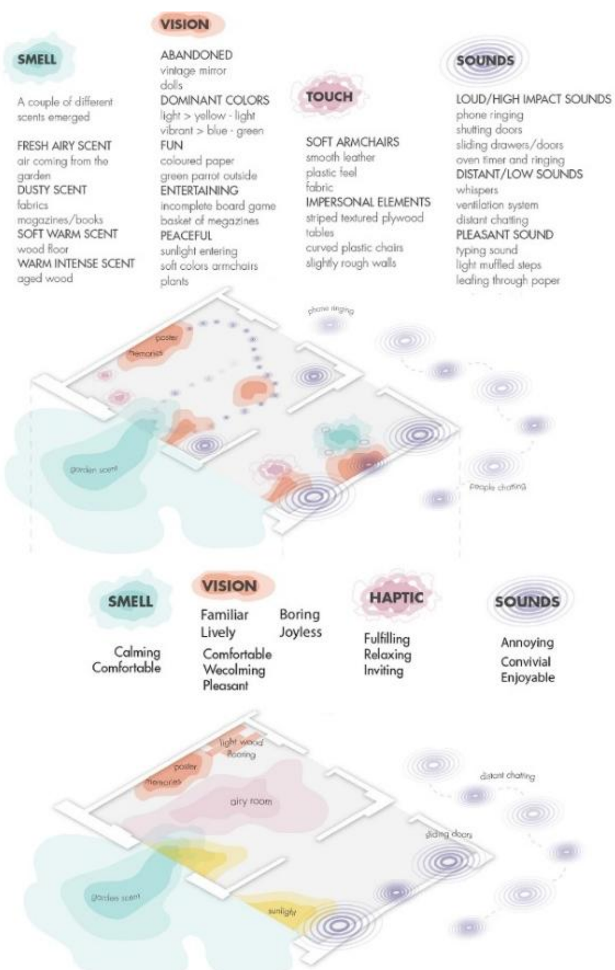
Two important concepts were encountered in the process of smell data collection and development: the smellwalk and the smellscape. Smellwalk is a sensory mapping methodology used only for the collection of odor data. Visual mapping of the olfactory smellscape is a way to open up the discussion of sensory awareness in an environment and to reveal human activity in that space as a tangible indicator. The scale and boundaries of the environment provide a guide to the combinations and diversity of odors that will form the legends of the map.

The physical link between flavors and maps is provided by the transformation of flavors specific to countries, cities or regions into spatial information as legends. Flavor maps also reveal social information such as the gastronomic identity and eating habits of a place.

A tactile map or Braille map is a tactile representation of public spaces such as countries, cities, neighborhoods, university campuses and museums, created with raised symbols and Braille alphabet on a plane (map) that can be touched by visually impaired user communities. These maps have a functional use in terms of accessibility. In museums, there are institutions that make use of this approach in order to provide spatial orientation and make architecture haptically accessible. For example, there are tactile floor plans at the entrance of the museum in the Jewish Museum in Frankfurt and at the Islamic Arts Department (Département des Arts de l'Islam) in the Musée du Louvre in France.

The mapping of the sensory integrity of sound is realized through sound walks. Numerous researchers have used the concept of soundwalking as a methodology for the study of environmental sound. This method can be described as conducting sound walks to identify soundscapes and their components in an environment and keeping audio recordings of the walks.

Figure 7.
Sensory map of students on the top, guests at the Piazza Grace Centre on the bottom (Mace et al., 2023, p.13)



According to Langley (1999, p. 700), visual mapping as a structured methodological tool is a graphical tool that facilitates the researcher in the expression, organization, analysis and sharing of large-scale data and information. Accordingly, the goal of the cartographer is to visualize spatial information and data. With this methodology, data can be collected in the field and the scientific inputs of data analysis can be conveyed in a universal and graphical language.

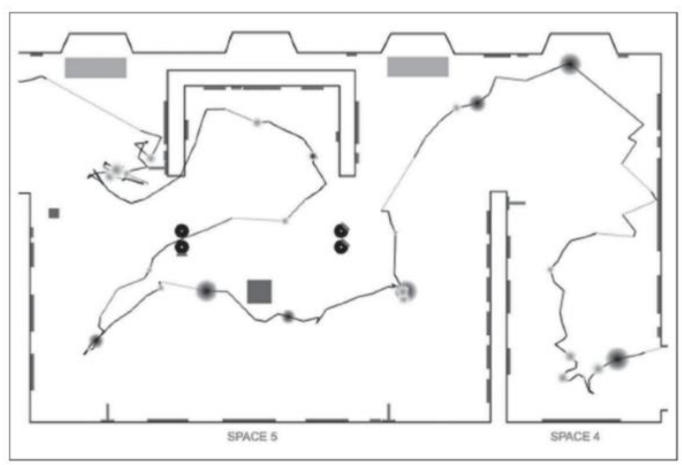
Mace et al. (2023, p. 2), who wanted to examine how interior architecture students would address space design by increasing their sensory awareness, conducted a sensory mapping study with the guests and students of Piazza Grace care home, where people with Alzheimer's and dementia stay (Figure 7).

Experiential Mapping

Merleau-Ponty's (2002, p. 162) approach that space can only be explored through experiences and Wunderlich's (2008, p. 126) definition of walking as a research method for experiencing a place and developing a sense of place help to explain the basis of experiential mapping.

Experiential mapping does not reflect a rule-based mapping methodology with its own basic protocols. This is because many researchers and designers continue to develop current and innovative methodologies to extract the network of relationships that make up the spatial experience. However, standardized procedures, which already have a theoretical background, can be used in combination with technological tools and software-based applications. eMotion: Mapping Museum Experience (Tröndle, et al., 2012, pp. 1-2) research project emerged in this context. In the project, it is aimed to measure the duration of the exhibition experience and the physiological activities of visitors to the St. Gallen Art Museum in Switzerland, who are interested in art or who are less predisposed to art, through location tracking in the museum and the data glove developed within the scope of the project (Figure 8).

Figure 8.
Exhibition experience map showing physiological reactions of 1 visitor in the 4th and 5th area of the museum (Tröndle et al., 2012, p.15)



Creative Mapping

Maps are colored representations of regions, continents or the world, as well as tools that reflect the philosophical, religious, social, political, scientific, aesthetic and artistic worldview drawn by cartographers (Pickles, 2003, p. 116). Creative maps may be based on subjective interpretations.

Some of the many examples of this type of map can be found in the four thematic techniques that Corner (1999, p. 100) has proposed to reveal new mapping practices in contemporary design and planning, namely drift, layering, game-board and rhizome. These include Debord's Psychogeographical Guide to Paris and Charles Joseph Minard's Napoleon Grande Armée. In addition, John Hejduk's site plan for the 1984 Prinz-Albert-Palais competition to build a memorial park on the site of a former Gestapo headquarters in Berlin, titled “Victims”, can also be cited as an example.

Technology-Based Mapping Methods in Space

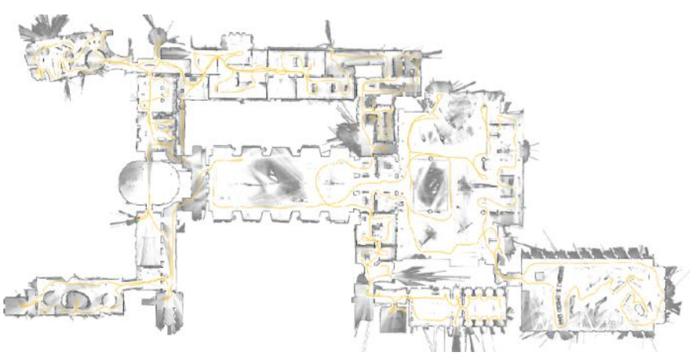
LIDAR

LIDAR is a remote sensing technology that uses the method of sending laser light to a target and measuring the light reflected from the target back to the sensor. It is a combination of laser scanner, IMU (Inertial Measurement Unit) and GPS data collection systems. Since Lidar consists of three different systems, it is important that these systems are compatible with each other (Baltsavias, 1999, p. 165).

LIDAR technology is classified into three systems as Aerial, Mobile Wearable and Terrestrial Lidar, depending on the vehicle in which it is placed and its use in space. The data captured by the lidar sensor is called a point cloud. The system that enables autonomous robots with LIDAR sensors to move independently in space and determine their own position is called SLAM (Simultaneous Localization and Mapping) method (Thrun, 2007, p. 13). The working principle of LIDAR technology is the same indoors as in open spaces. Thousands of laser beams are projected by the Lidar sensor onto the surfaces of walls, floors, ceilings, building elements and furniture in the interior, and the distance of the sensor to each surface is calculated by recording the return time of this light. The process continues as the sensor moves to capture each area of the interior. Cartographer, developed by Google engineers, is a mapping tool that allows a cartographer wearing a backpack equipped with SLAM LIDAR technology to walk indoors to create real-time floor plans (Figure 9).

The limitations of the method include the low quality of point cloud-based images, limited color and texture information in LIDAR systems, the need for careful installation on sensitive ground, and the high cost associated with intensive workflow requirements (Loosli, 2024).

Figure 9.
Cartographer ROS system map of the 2nd floor of the Deutsches Museum (Hess et al., 2016, p.5)

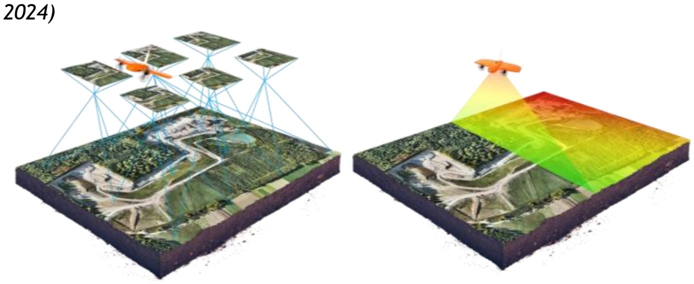


Photogrammetry

Photogrammetry, as another method, is a measurement technique that enables modelling of a three-dimensional space using two-dimensional images (Egels & Kasser, 2001, p.1). Methodological limitations include weather sensitivity, optical constraints, difficulty capturing upper structures, high UAV costs, and the need for technical expertise (Loosli, 2024).

With a photogrammetric analysis, planimetric detail and graphical maps, plans, digital geometric models of objects/structures, analogue or digitally corrected orthophotos, photomaps, photomontages and CAD models created with textures obtained from photographs, three-dimensional photomodels and their digital points in the coordinate system can be determined (Kraus, 2000, p. 1). Photogrammetry provides high quality and accuracy for the survey and preservation of historic architectural structures and monuments for mapping with complete scale-based documentation.

Figure 10.
UAV photogrammetry (left) and aerial LIDAR mapping (right) (Loosli, 2024)

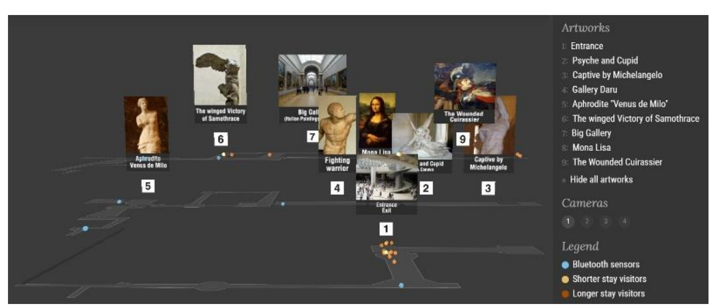


Bluetooth Sensors and Noise Monitoring Sensors

Sensors are lightweight and small autonomous devices that measure physical parameters (humidity, temperature, pressure, etc.) in an environment. Sensor nodes, which are placed randomly and in large numbers in the environment or system to be observed, constitute wireless sensor networks. A wireless sensor network (WSN) represents a set of collaborative nodes that provide sensing, data processing and communication over a wireless network. The method’s limitations include limited bandwidth and energy, interference, interoperability challenges, security risks, installation difficulties, and maintenance costs (Vijayalakshmi & Muruganand, 2018, p.1).

Today, the Bluetooth feature in the majority of mobile devices enables them to be detected by wireless sensors. In the project carried out by the MIT Senseable City Lab at the Louvre Museum, sensor and bluetooth tracking system technologies were used to collect data on visitor behaviour (Figure 11). The use of low-cost sensor networks as an alternative to sound level meters for noise monitoring is increasing.

Figure 11.
Art traffic at the Louvre, mapping visitor behaviour using bluetooth sensor data (Yoshimura et al., 2012, p.394)



Sound and Noise Level Meters

A number of basic devices are used in the measurement of sound and noise level. These are sound level meters (SLM), microphones, dosimeters, frequency analysers, acoustic calibrators and recorders. While making measurements to take measures against noise pollution, international and national standards, regulations, etc. The values specified as reference in legal documents are taken into consideration and methods for reducing and eliminating the noise level are developed accordingly. The device's limitations to consider include sensitivity to wind, environmental vibrations, and temporary sound interference (Casali, 2012, pp.641-647).

In IEC 60651, sound level meters are classified into four types (Type 0, 1, 2, 3) according to measurement accuracy. Increasing the type number from 0 to 3 indicates decreasing measurement accuracy. Type 0 is preferred for laboratory reference standard, type 1 for laboratory studies and close control of the acoustic environment, type 2 for non-laboratory field applications and finally type 3 for field noise research. Dose meters / dosimeters, which are small and lightweight portable devices, have been developed to determine the noise level to which people are exposed. A microphone is connected to the device by a short cable to measure the noise dose to which a person is exposed without interfering with daily work (Malchaire, 2001, p.130).

There are a number of procedures to be performed before, during and after measurement in sound level meter equipment. First of all, preliminary preparation process such as determining the measurement purpose and site, determining the measurement points and measurement time should be done. Before the measurement, the batteries in the sound level meter, the device indicator with the help of the calibrator and the device settings depending on the noise characteristics to be measured should be checked. At this stage, noise sources and reflective surfaces in the measured environment should be sketched.

Illuminance Meter Luxmeters

The unit of measurement of illuminance is defined as lux/lux (lx). Lux meters are used to measure the luminous intensity and illuminance reflected to the human eye to evaluate the lighting conditions in an environment. The device's limitations include variability from natural light and weather, influence of reflective surfaces, and effects of light properties like color temperature, direction, and shadows.

As there are many international and country-based standards and regulations in noise measurement and control, there are also certain standards for lighting. The illuminance level in an environment can be evaluated by comparing the measurement values made with luxmeter and lighting standards. If the researcher finds the measurement results insufficient, they can get support from simulation software such as DIALux to improve the lighting situation in the space.

Thermal Comfort Measurement Devices

Environmental factors (temperature, thermal radiant, humidity and air velocity) and personal factors (clothing and activity) combine to create thermal conditions indoors. However, personal thermal comfort levels are considered subjective. The device's limitations are as follows: measurements require regular intervals to avoid fluctuations, and researchers need equipment knowledge for proper setup and calibration.

There are two methods called PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) to assess the thermal comfort of people exposed to the thermal environment in a space. Within the scope of TS EN ISO 7730 Standard, PMV and PPD values enable the calculation of thermal comfort criteria, thus enabling a systematic evaluation of appropriate environmental conditions for general thermal comfort.

The thermal comfort measurement procedure starts with the determination of the standards to be taken as basis. These devices are variously labelled as thermal comfort meters and multifunctional HVAC meters. They are also equipment that require calibration protocols such as sound level meters. The measurement system consisting of probes and sensors is positioned in the space with the help of a tripod.

Wind Meter Device Anemometer

Today, anemometers utilise a range of new technologies to measure wind speed and pressure, including ultrasonic, LIDAR and Doppler technology and electrical currents. Anemometers are also used to investigate the air flow and ventilation system of indoor spaces. Researchers can use anemometer measurements and CFD simulations to develop passive design strategies to improve ventilation levels. The device's limitations are as follows: based on its operating principles, it can be prone to overheating, damage, measurement inaccuracies, and vulnerability to electrical interference.

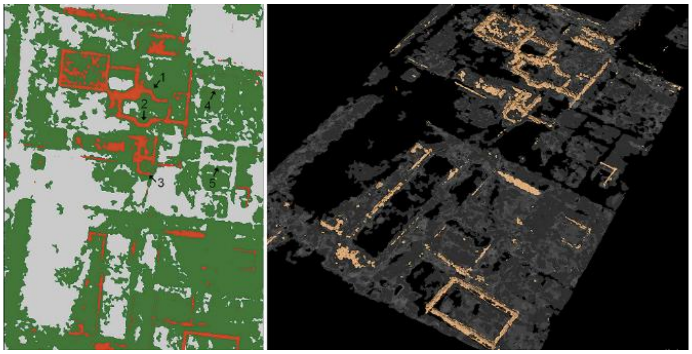
Ground-Penetrating Radar (GPR)

The ground penetrating radar transmitter sends pulses of electromagnetic energy into the subsurface to detect the structural characteristics of objects and materials beneath the scanned surface (Annan, 2002, p.253). The system sends different types of signals to the radar receiver as a result of detecting different materials in the subsurface.

Ground penetrating radar is a safe and high-resolution method of obtaining data without the need for destruction or excavation in the relevant area (surface). However, the device's limitations include high costs for small-scale research due to intensive workflows and reduced ground penetration under weather conditions like rain. A team of archaeologists from Cambridge and Ghent Universities used ground-penetrating radar to create a map of the entire ancient Roman city of Falerii Novi in Lazio, Italy, without any excavation. The study revealed public buildings such as a temple, macellum or market building, bath complex (Figure 12-13), palaestra (exercise area), theatre and public monument, as well as a network of water pipes throughout the city (Verdonck et al., 2020, p. 711).

Figure 12.
Map of explored sites in Falerii Novi (Verdonck et al., 2020, p.711)

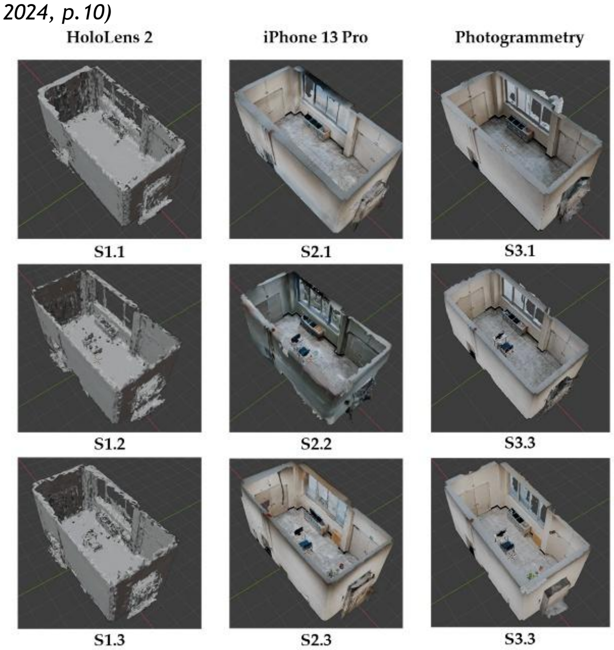
Figure 13.
GPR sections of the bath complex at Falerii Novi, walls in red, floor in green, and 3D representation of the data on the right (Verdonck et al., 2020, p.718)



Reality Technologies

Beyond physical reality, new digital realities are created through the perceptual state of the user with computers and technological equipment. In the literature, these digital reality technologies are divided into four groups as Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR) and Extended Reality (eXtended Reality - XR). Notable limitations of the device include high costs for devices, software, and application development, as well as ongoing maintenance expenses.

Figure 14.
3D spatial mapping models created with three different methods (Do et al., 2024, p.10)



VR involves the user experiencing only a virtual world simulated by a computer by blocking or abstracting the real world (reality). AR is the simultaneous embedding or adaptation of computer-generated virtual content into the reality in the physical world (Mann et al., 2018, p.1). The continuum of AR experiences linking real environments and digital environments is defined as mixed reality (MR). Therefore, AR technology is a form of representation of MR. The only difference between them is whether AR has a continuum state or not. MR and VR are completely different from each other in terms of representation (Milgram et al., 1994, pp.282-283). Paradiso and Landay (2009, pp.14-15) defined the mixed reality environment that emerges from the combination of the virtual and physical world through sensor/actuator networks placed in the physical world with VR as Extended Reality (XR).

Do et al., (2024, p.10) wanted to test the data accuracy level of MR in the real-world interior mapping procedure. In order to determine the spatial mapping procedure that provides the highest level of data accuracy for interior designers, a performance evaluation was performed using a head-mounted display, depth sensor in Microsoft HoloLens 2, built-in LIDAR sensor in iPhone 13 Pro, and photogrammetry. For this purpose, data were collected in three different experimental environments with different furniture conditions. It has been revealed that HoloLens 2 shows the most optimum performance in real time in line with the determined parameters. The file size is small and suitable for fast processing (Figure 14).

Software-Developed Mapping Methods

The invention of the World Wide Web (WWW) in the early 1990s and developments in computer-based information communication and network technologies made digital maps easily accessible (Peterson, 2003, p.1). In the following process, digital cartography has benefited from technological mechanisms such as spatial data capture technologies (GPS, satellite imagery, etc.), data processing (CAD, GIS, etc. software), data storage and rapid distribution (hard discs, servers, databases, data networks, etc.), transmission of data to the user, presentation or interactive collaboration.

Geographic Information Systems (GIS)

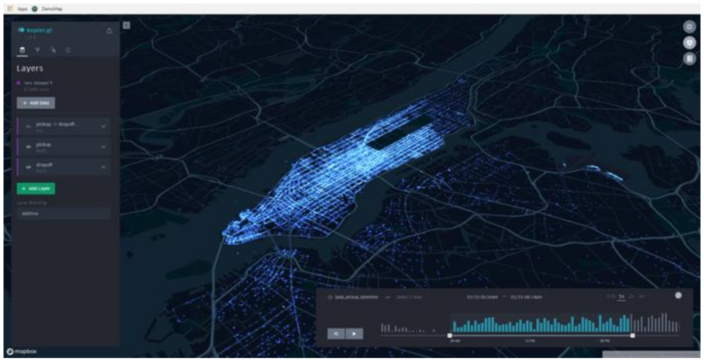
Geographic Information System (GIS) is defined as an organisational structure or system that integrates technology in a database and is carried out by experts with financial support in the process of collecting, storing, controlling, manipulating, analysing and displaying spatial data in the world (Carter, 1989, p.3). It can be said that GIS refers to a methodology based on geographic datasets, data management, computer hardware and computer software technology in mapping and analysing spatial information.

The method’s limitations include the risk of misinterpreting complex data, oversimplifying results, and depending on reliable infrastructure that is prone to technical failures (Okedu et al., 2024, p.5). It is necessary to mention the defined functions and advantages of GIS. GIS provides fast analytical analyses and digital maps as a result of storing large-scale geographical information in databases. In addition, it provides the opportunity to view or analyse multiple datasets together or separately in layers for new location-based and spatial information (Decker, 2001, p. 17).

There are many GIS software developed according to the sector and usage such as Google Earth, Google Maps, OpenStreetMap, Maperitive, QGIS, GRASS / GRASS GIS developed by the US military, ArcGIS belonging to Esri, NASA WorldWind, Maps.Me, CityMapper.

Kepler.gl, developed by the data visualisation team of Uber, a passenger transportation application, is a free web-based application that allows visualising and analysing large-scale geographic datasets with map layers. Using Mapbox Studio's infrastructure, Kepler.gl provides insights into human activities and location-based visualisation (He, 2018). In order to develop strategic and logistical recommendations, Uber collects instant and systematic data about the journey, such as drivers’ locations, passengers’ transport movements and time (Figure 15).

Figure 15.
Visualising the movements of uber drivers in New York City on a map Mapbox Studio, Kepler.gl (He, 2018).



Computer Aided Design (CAD)

Computer Aided Design (CAD) is a computer-based software technology that includes 2D drawing, 3D modelling and analysis of a design in design, engineering and architecture applications. Significant limitations of this method are the need for high-performance hardware due to large file sizes, reliance on licenses and updates, and requirement of plugins or external software for spatial scenario generation.

According to Groover and Zimmers (1984, pp. 1-2), it is the utilisation of computer hardware and software technology in product design. Computer Aided Manufacturing (CAM) is defined as the automation of production activities and processes by computer systems. In today's world, there are many areas and applications where CAM is used. CNC machines, 3D printers, laser cutting, robotic systems, etc. are some of these applications.

Figure 16.
A floor plan, AutoCAD

The capabilities and workflows of CAD software include the ability to design two- or three-dimensional solid body geometric modelling of a design, correcting errors with editing tools, scaling the design and drawing between layers with productive drawing tools and a large number of commands offered to users on the interface. At the same time, with the new opportunities offered by the IT industry, there are also functions such as integration between software, sharing of projects and designs between practitioners with data optimisation, and cloud-based data storage. AutoCAD (Figure 16), Autodesk Revit, Autodesk 3Ds Max, ArchiCAD, SketchUp, SolidWorks, Autodesk Fusion 360, CATIA, Rhinoceros 3D etc. are some of the CAD software used worldwide.

Design and Performance Simulation Software

Since the late 20th century, digital-based tools have helped architects and designers to develop and implement organic designs. As a result, design and performance simulations (acoustic, lighting, structural simulations, energy simulations, HVAC simulations, evacuation and fire dynamics simulations) have become increasingly important. Key limitations of these methods, are high processing requirements, software costs, reliance on accurate input data, and possible inconsistencies between simulations and real conditions. Acoustic simulation software, one of the performance simulations, is generally preferred in concert halls, auditoriums, live performance venues or recording studios where music is at the forefront. Simulation is also used in the construction processes of these structures.

Acoustic software such as Odeon, Catt Acoustic, CadnaR, Dirac, Ease, SoundPlan, Bastian, Pulse, Insul, dBInside and Rap-One II are software-based methodological tools for noise control, sound absorption reporting, architectural acoustic design and academic studies. In addition, meta-analyses can be conducted to examine the performance of these simulation software, to evaluate the accuracy of the simulations themselves, or to compare simulation and sound level meter measurements.

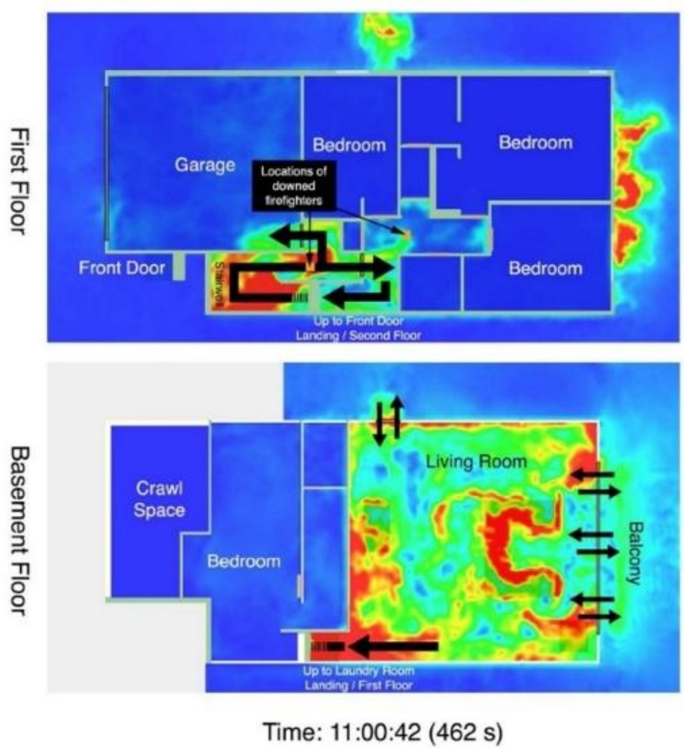
Lighting simulations refer to the modelling and simulation of light flow, light production and light management for various environments such as indoor, outdoor or road lighting in a computer-aided visual interface. The simulation helps the user to analyse the spatial effects of natural light or artificial light distribution, light reflections and shadow formation, taking into account weather and seasonal conditions (Hovestadt et al., 2020, pp.483-484). In addition, lighting simulation software are tools that provide insights to optimise energy efficiency in the building, provide lighting control in accordance with the regulations and standards in the country, and prevent design errors in application projects. Some of these tools are commercial software such as DIALux, Relux, AGI32, Lightscape, Lumen Designer, Radiance etc.

In the architectural design process, the horizontal and vertical load distributions of the structure, reinforcement layout and resistance design require especially detailed solutions and calculations in the project. The load case of the building should be calculated, and the effects of all structural forces should be analyzed. In addition to its own load resistance, the building may also be subjected to additional loads, including the interior, or to intense wind, severe weather conditions and seismic activities. Since these conditions may cause stresses in the structure to a greater or lesser extent, users utilize structural simulation technology. Structural simulation technology utilizes a numerical procedure known as Finite Element Method (FEM) to perform Finite Element Analysis (FEA).

FEM and FEA are basically numerical methods that involve breaking down complex physical problems into manageable simple units and reaching an approximate solution from the sum of the analyses of these units. In the construction industry, the advantages of the FEM method are utilized in the solution of many engineering problems, including truss frame structures and stress analysis of industrial equipment. Finite element simulation solutions include commercial programs such as ANSYS Workbench, Solidworks Simulation, Nastran, Dlubal RFEM, Dlubal RSTAB, Multiphysics, Midas FEA, Abaqus, COMSOL, FreeFEM, FEniCS Project, etc.

The development and design application of computational building performance simulation programmes in the disciplines of architecture, civil engineering, mechanical engineering and environmental physics has a major role as a research area. In addition, building energy performance management has sub-applications such as heat and mass transfer of the building envelope with its surroundings, indoor heating, cooling, air conditioning and thermal comfort, thermal and humidity (hygrothermal) building performance, indoor air flow and ventilation (Hovestadt et al., 2020, p.484). As a result of concerns for the environment and energy resources, international environmental standards, country regulations and certification systems have been developed, including recommendations for sustainable building construction and architecture, energy performance management. The international ISO 14000 and ISO 21930 standards, CEN/TC 350 and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) standards, and the LEED certification (Leadership in Energy and Environmental Design) of the United States of America are examples of legal and technical regulations. Energy simulation software such as DesignBuilder, Trace, EnergyPlus, eQUEST, BSim, Equa, (Integrated Environmental Solutions Virtual Environment) OpenStudio-EnergyPlus, Autodesk - Green Building Studio, HEED (Home Energy Efficient Design) etc. help users in building energy design and performance analyses.

Figure 17.
Simulated fire flow path in floor plans (Overholt et al., 2014, p.32)



HVAC (Heating, Ventilation, and Air conditioning) is a system that provides optimum thermal comfort and efficient indoor air quality for people in the environment. Airflow and CFD simulations used to improve HVAC systems are based on the principle of visually modelling local airflow, air temperature and pressure behaviour. There are many commercial and open-source software for CFD analysis such as Autodesk CFD, ANSYS Fluent, SimScale, OpenFoam, Comsol Multiphysics, FloVENT (Mentor Graphics), FloEFD HVAC, etc.

Evacuation simulations provide 3D modelling of the dynamics and movements of the human crowd in a possible emergency, enabling the development of different escape scenarios and insights in the structure. With the customisable analysis system of the software, users can include data such as the probable cause of the emergency (fire source, spread, smoke flow, flooding, explosives, etc.), the width and length of escape routes, the number (thickness, material and type) of doors on the escape route in evacuation scenarios. Fire dynamics simulation is based on a computational fluid dynamics (CFD) model and provides a visualisation representing the formation of fire gases and fire behaviour through physics-based calculations. These simulations (Figure 17) reveal a large number of data related to the fire resistance of the structure, total evacuation time or dynamic temperature calculation in case of possible fire and fire source (Overholt et al., 2014, p.32).

Building Information Modelling (BIM)

According to Eastman et al. (2011, pp.1-2), BIM is defined as a technology that includes the design, performance analysis, construction process and subsequent operation of a building's life cycle model with digital models in coordination with the project team in architecture, engineering and construction industry building applications. However, this method's limitations include substantial hardware requirements, inefficiencies in small-scale applications, international BIM standard discrepancies, and high licensing costs.

Various governments around the world see BIM as a strategic development and are trying to make it a mandatory application in public projects. In addition, professional organisations and international academic conferences define BIM as the future platform of the architecture, engineering and construction (Architecture, Engineering and Construction - AEC) industry. Practitioners in the AEC industry use a reference system known as the Level of Development (LoD) specification to structure the model content and information in the BIM project phase in a coordinated manner with other stakeholders. In order to facilitate the implementation of BIM in the AEC sector, many BIM standards and guidelines have been published by governments, institutes and organisations worldwide. By following these standards and guidelines, all practitioners can have a clearer understanding of their role in a BIM-based project.

In general, BIM design includes the digital representation of structures that have been built, are planned to be built or are still under construction. Users produce their digital representations with BIM software with a virtual interface. According to the Illinois Institute of Technology, there are more than 30 BIM programmes available today. Autodesk Revit and Navisworks, ArchiCAD, Bentley Systems, Dassault Systèmes and CATIA, Tekla and RIB iTWO are some of them. In addition, BIM software can perform structural simulation for spatial analyses, building energy simulation, lighting simulation, acoustic simulation, CFD simulation software for HVAC and data integration with CAD software. BIM technology is used to optimise the MEPF (Mechanical, Electrical, Plumbing and Firefighting system) design of buildings. BIM technology is used for documenting, preserving, restoring and analysing the performance of existing buildings of historical and architectural importance. This application, defined as HBIM, involves the creation of a digital representation by combining point cloud or image-based data created by technological devices such as LIDAR etc. with building historical data (Figure 18).

Figure 18.
3D laser scanning point cloud (left) and BIM model (right) for Notre Dame Cathedral Restoration (URL-1)

Digital Twin

Industry 4.0 represents digital and smart manufacturing initiatives, including next generation information technologies such as big data and analytics, Internet of Things (IoT), artificial intelligence (AI), cloud computing. However, there are difficulties in ensuring the integration of cyber and physical domains in smart manufacturing. Digital twin (DT) is a technology that can eliminate this challenge in smart manufacturing initiatives in the Industry 4.0 era (Tao et al., 2019, p. 2405). DT is a simulated digital/virtual twin of a real-world object or asset that can collect real-time data about it throughout its life cycle and process and interact with its physical twin in a dynamic way. The digital twin uses the data to mirror the real twin in the virtual interface, for remote access, real-time monitoring, prediction, optimization and maintenance. Among the reasons why the method is seen as part of Industry 4.0, there are many advantages such as prediction of problems and system planning, remote control and monitoring, improved maintenance and optimization of solutions, rapid prototyping, safe operation in smart manufacturing processes of hazardous industries, waste reduction in the prototyping process, easy data synchronization. Nevertheless, the method requires continuous data updates, incurs maintenance and technical support expenses, and can be costly for small-scale projects (Singh et al., 2021, pp. 6-7).

DT architecture consists of three main elements. These are: physical world, digital world and the connection between the two. Although different components can be integrated into the architecture according to the designer's requirements, a number of basic components are required. These include sensors and actuators in the physical twin for real-time data collection, edge computing capabilities, data security, data processing capabilities that can be enabled by machine learning (ML), artificial intelligence (AI), big data, etc., and communication interfaces such as internet, bluetooth, satellite, etc. (Botín-Sanabria et al., 2022, p.4).

DT is a digital mapping method that covers a range of technologies and software developed by various companies. For example, virtual geometric models are created with software such as SolidWorks, 3D Max, SketchUp, AutoCAD, CATIA, etc. Behavioural models enable the creation of a model that can respond to environmental factors and improve the simulation performance of the digital twin. In this regard, support is obtained from Twin Builder, ANSYS, SimuWorks, Dymola etc. software. In rule modelling, it improves the service performance of the digital twin and detects abnormal situations based on modelling the behaviour of the physical entity according to the laws and rules in the physical world. Software such as Thingworx, MindSphere etc. are used for these processes.

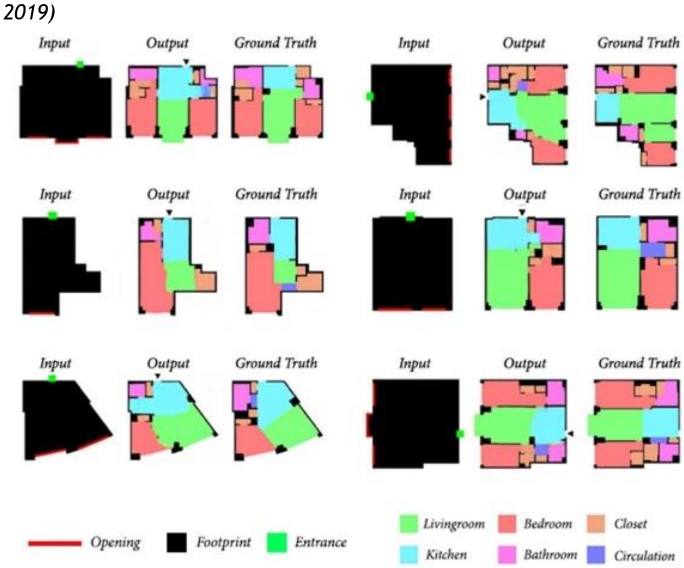
Artificial Intelligence (AI) and Machine Learning (ML)

Artificial intelligence (AI) is defined by Bellman (1978, p. 3) as the automation of skills associated with human intelligence, such as decision making, problem solving and learning. Many researchers focus on artificial intelligence and its research areas. This has led to various research areas related to artificial intelligence. Search algorithms, knowledge graphs, natural languages processing (NLP), expert systems, evolution algorithms, machine learning (ML), deep learning (DL) are some of them. Today, most of the artificial intelligence based intelligent systems are based on machine learning.

Due to the difficulties created by coding-based systems, there was a need for artificial intelligence systems with an autonomous learning capacity that can acquire and infer patterns from the training data defined in the system. The field of artificial intelligence with this capacity is defined as machine learning (ML). Deep learning (DL) is a special type of machine learning based on artificial neural networks inspired by the brain structure, which performs better especially in areas with high-dimensional data (Goodfellow et al., 2016, pp.2-3). In addition, these methods require data science and programming skills, multidisciplinary teams, maintenance costs, potential program-command mismatches, and significant time, financial, and technological investments (Khanzode & Sarode, 2020, p.34).

There are AI-supported design platforms and tools that optimise space design and develop 2D or 3D architectural proposals. These platforms are open and accessible to the user and provide the opportunity to perform meta-analyses in space. These include Coohom, ARCHITEChTURES, RoomSketcher, Space Designer 3D, HomeStyler, etc. There are many AI-based design tools. In addition, there are also platforms with GPT-4 supported chatbots that can answer real-time user questions on design and architectural issues. Planner 5D, OpenAI, Craiyon, Dall-E and Midjourney are some of them.

Figure 19.
Floor plan design with space functions as a result of inputs (Chaillou, 2019)



The work of data scientist and architect Stanislas Chaillou (2019) is to optimise the process of creating large and diverse floor plan designs, transforming them into sequential designs at building and urban scale, and finally providing design options to users. For this, the Generative Adversarial Network (GAN) model framework of machine learning is utilised. According to Wu et al., (2017, p. 660), the GAN model has many capabilities including realistic image generation, texture synthesis, image editing, colouring and synthesis, and resolution enhancement. In Chaillou's study, the system allows users to select the plan shape and window layout and main entrance locations for residential units and takes them as input, and the GAN model trained with a dataset of more than 800 floor plans creates designs using this database (Figure 19).

Space Syntax

This method aims to define space configurationally in a numerical and graphical language and to analyze all spatial complexes within the building at the level of this configuration (Major et al., 1997, p. 1). However, this analysis presents limitations such as substantial hardware requirements, sensitivity to incomplete or inaccurate spatial data, the need for high computational power in large-scale spatial analyses, and the necessity of repeated analyses due to temporal changes.

Hanson (1998, pp. 23-24) has shown that the arrangement of spaces, their combination in different ways and the relationships between them are important in people's spatial experiences. By analyzing the sequence of spaces with numerical techniques and graphics, researchers and designers can gain insight into the configurations of spaces. Bafna (2003, p. 17) refers to the transformation of a continuous space into another whole by combining it in different ways and thus associating it as space configuration. Hillier (1996, p. 22) visualizes the configurational relationships in spaces with a simple graph called a transition graph (Justified Graph - J-Graph).

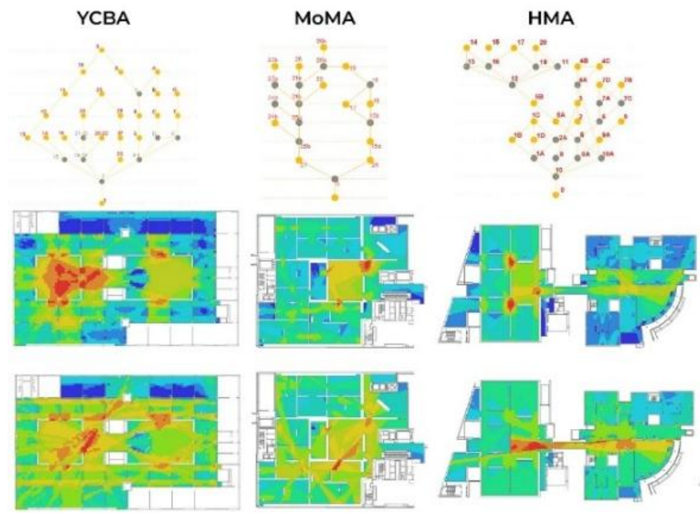
In syntactic analyses to analyze the configurations of structures, spaces are defined with mapping methods (axial map, convex map, visibility graphs-VGA and isovist map) other than transition graph. In these maps covering space syntax, spatial data are expressed with terminological concepts (parameters). The parameters used in the space syntax method include axial line, convex space, depth analysis and average depth, integration in relation to the transition graph. There are also other concepts and parameters such as connectivity, intelligibility, permeability, circularity, global or local radius, orientation, agent-based modeling (ABM), compactness, etc.

There are various software programs that can be used in space syntax studies to analyze the configurations of spaces. Axman, SpaceBox, Pesh, NewWave, OrangeBox, Pangea, Ovation, DepthmapX at University College London (UCL), Syntax2D at the University of Michigan, Grasshopper Space Syntax in Rhinoceros 3D program, Isovist_App, etc. help space syntax research. For analysis, AutoCAD program DXF and DWG format city plans, or floor plans can be transferred into the program in proportion to the actual plan dimensions.

Rohloff et al., (2009, p. 4) utilized space syntax methodology to examine the impact of the morphological structure of museum galleries on visitors' use and spatial experience. Researchers focusing on museums with interior gallery voids included the fourth floors of the Yale Center for British Art (YCBA), the Museum of Modern Art (MoMA), and the High Museum of Art in their study to determine the extent to which the visibility parameter can predict visitors' spatial usage (Figure 20).

Figure 20.

Justified graphs and visibility graphs of the YCBA, MoMA and HMA Galleries (Rohloff et al., 2009, p. 4)



Conclusion and Recommendations

Mapping methodologies, which have a wide range of use from macro to micro scale, can respond to the needs in space design patterns, procedures and decision-making processes. Rapidly evolving technology is helping to develop real-time design, data visualization, rapid and collaborative design solutions, but it also brings complex processes. This situation reveals the importance of new configurations supported by digital tools that can predict the user experience and combine it with the speed factor in future space designs. In addition, mapping methodologies can help to create a new analytical model that integrates qualitative and quantitative data in the process of space design. In this analytical model, which is based on a mixed methodology approach, the possibilities that each method, which is basically divided into three categories and some of which have their own sub-techniques, can offer to space design and experience are prioritized.

The data gathered within the scope of the study formed the basis for the methodological guideline in Table 1, Table 2 and Table 3 which outlines the possibilities, limitations and key characteristics of each methodology. As such, the study is a methodological guide that highlights the advantages of using mapping methodologies and introduces methodologies for future studies.

Human centered mapping methods focus on the efforts of individuals or groups who experience an architectural space, either verbally or in written form. The process of collecting data to be coded as systematic information on the map is undertaken by the person who experienced the space before or during the research. The difference from other mapping methodologies is that it is handled with the concept of interaction and all common or different spatial perceptions of individuals are put forward with an intellectual design model to create new approaches. Technological infrastructure can be used in graphic arrangements and data processing, but this does not change the data source in the human centered mapping method. All human centered mapping methods, except for conceptual and creative mapping, include observation procedures, interview questions, fieldwork, and survey procedures. Questionnaire and interview questions are optional depending on the research content.

Similarly, all methods except for two have prerequisites such as preliminary preparation, documentation (ethics form, institutional permission documents, or field notes), equipment/software support, and participant requirements. Methods such as cognitive mapping, social meaning mapping, PMM, experiential mapping, and sensory mapping reveal common disadvantages, such as the participant's direct or indirect creation of their own map, difficulty in drawing, and the need for an adaptation process to the equipment.

The data obtained from these methodologies is two-dimensional. Statistical data can also be obtained through common data identified by the researcher among participant maps. Human centered mapping methods are less costly than technology- and software-based mapping methodologies. However, depending on the research content, there are limitations such as generalization issues due to the small number of sample cases and participant consent for long-term data.

Table 1.
Comparison of spatial mapping methodologies: human centered mapping methods

METHOD	ADVANTAGES	DISADVANTAGES	APPLICATION	REQUIREMENTS AND TECHNOLOGIES
Conceptual Mapping & PMM	•Real-Time Data •2D Data •Analysis of Learning Skills •Conceptual Mapping provides a graphical representation of subjective and scientific information.	•PMM - Subjective data •The researcher may request an open-ended interview again to obtain long-term data on meaning maps.	•Meaning map - Hand drawing. •In PMM methodology, it is important to collect data in stages. The researcher requests the participants to create meaning maps with different colored pencils before and after their visits. •PMM - Observation procedure, interview questions, site study.	•PMM - Participant Requirement •PMM - Preliminary Study •Concept maps can be created with various computer software. CmapTools and CmapServers etc.
Social Meaning Mapping	•Real-Time Data •2D Data •Digital Data Collection •Analysis of visitors' movement routes and pauses within the space.	•The visitor may not know how to use digital equipment or software.	•Observation procedure, interview questions, site study and questionnaire. • The researcher asks the visitor or a member of the group to draw their own route of movement through the space. •Think Aloud Procedure	•Preliminary Study •Floor Plans •Participant Requirement •The researcher must obtain permission from the organization for personal data collection and site study. •Software Support
Behavioral Mapping	•2D Data •Documenting the real environmental activity and behavior of people in space. •Collect data with paper maps or digital maps. •Data correctness and systematic data.	•Additional observers may be required depending on the size of the space. •Observers may need to be trained in the observation procedure.	•Teamwork or Individual Researcher. •Visitors must be "unaware that they are being observed". •Observation procedure and site study. • (Optional) Questionnaire and interview questions.	•Preliminary Study •Floor Plans •Visitors and Observers Requirement •A system of codes or symbols should be designed to identify categories of behavior on the map. •Organizations should be asked for permission for site study.
Cognitive Mapping	•2D Data •Data correctness and systematic data. •Analysis of spatial memory and spatial behavior in individual's cognitive processes. •The method can be applied on different scales: city, space, etc. •Urban (spatial) image, Imageability and Legibility.	•Lynch's cognitive mapping procedure - limited to five physical elements. •Difficulty with hand drawing. •In some cases, a weak correlation may be observed between individual mapping and interview data. •Selecting participants who are familiar with the environment may limit the sample size. •Cognitive map - The problem of scale and some elements being overlooked.	• Teamwork •Observation procedure, interview questions, site study and questionnaire. •Think Aloud Procedure	•Preliminary Study •Participants and Observers Requirement •Lynch's five physical elements are defined as legends in cognitive maps. • Equipment and Software Support
Sensory Mapping	•2D Data •Collect data with paper maps or digital maps. •Tactile maps help people with disabilities in terms of accessibility in spaces.	•Subjective data (sound map, taste map, smell map, visual map).	•Teamwork or Individual Researcher. •Observation procedure, interview questions, site study and questionnaire. •Think Aloud Procedure	•Participant Requirement •Walking notes and obtaining participant signatures on ethics forms. •Equipment and Software Support
Experiential Mapping	•2D Data •Collect data with paper maps or digital maps. •Analysis of experiential actions based on body-environment interaction.	•Subjective data •It has non-fixed parameters based on the assumption that architectural elements and experience conditions may change.	•Observation procedure, interview questions, site study and questionnaire. •Think Aloud Procedure	•Preliminary Study •Floor Plans •Participant Requirement •Equipment and Software Support •Its methodological structure is adaptable. It can be used in conjunction with other methods, such as the Lynch method.
Creative Mapping	•2D Data •Real-Time Data •Collect data with paper maps or digital maps. •It can be used at all scales, from spaces to atlases. •It is a methodology that is open to representing any type of subject matter and has no procedural rules.	•Subjective data	•Individual Researcher	•Creative maps can be created with various computer software. Illusrator, Photoshop, Procreate etc.

For systematic and accurate quantitative data, it is recommended to choose expert researchers or teams with knowledge of system setup, equipment, and software in technology-based mapping methodologies. However, depending on the research content, the preferred system/equipment size in methodologies such as GPR, LIDAR, photogrammetry, sensors, thermal comfort measurement devices, and reality technologies may require teamwork.

However, small and lightweight equipment such as lux meters, sound and noise level meters, and anemometers enable researchers to perform individual measurements and create maps.

Photogrammetry and LIDAR systems, have many differences and common points in many aspects. Photogrammetry is a passive system using frame or linear geometric sensors. Geometrically and radiometrically high-quality images are obtained, but LIDAR is an active system using point sensors. Low quality images consisting only of point clouds are obtained. The common points of both methods are that they provide three-dimensional measurement, GPS/INS integration into the system, filtering, data reduction, data processing, object removal, image processing and analysis. Photogrammetry provides colour and texture information due to high quality imaging, but this is limited in the LIDAR system. Nevertheless, LIDAR is generally weather-compatible for data collection, but conditions such as fog and clouds affect the image quality in photogrammetry.

Table 2.
Comparison of spatial mapping methodologies: technology based mapping methods

METHOD	ADVANTAGES	DISADVANTAGES	APPLICATION	REQUIREMENTS AND TECHNOLOGIES
LIDAR	•2D Data •Real-Time Data •LIDAR is an active system using point sensors. •Three-dimensional measurement. •GPS/INS integration into the system. •Filtering, data reduction, data processing, object removal, image processing and analysis. •Weather-compatible for data collection.	•Low-quality images consisting of point clouds are obtained. •Color and texture information is limited in LIDAR systems. •Installation on sensitive ground. •High cost due to high workflow intensity.	•Teamwork •Site Study •Depending on its use, it is classified into three systems: Aerial, Mobile, and Terrestrial Lidar.	•Preliminary Study •Equipment Requirement
Photogrammetry	•2D Data •Real-Time Data •Documentation of historic buildings. •Passive system. •Geometrically and radiometrically high-quality images are obtained. •Three-dimensional measurement. •GPS/INS integration into the system. •Filtering, data reduction, data processing, object removal, image processing and analysis. •Colour and texture information. •Less expensive than LIDAR systems.	•Image quality is affected in foggy and cloudy weather. •Knowledge of equipment and software enables researchers to overcome problems they may encounter. •Optical properties are limited by buildings with challenging surfaces, lighting changes (shadows, glare, etc.) and repetitive textures. •Limitations in photographing the upper parts of buildings, such as roofs, in terrestrial photogrammetry. •The high cost of UAV photogrammetry for small-scale research.	•Teamwork •Site Study •Terrestrial photogrammetry and UAV photogrammetry.	•Preliminary Study •Equipment Requirement •Software Requirement: Reality Capture etc.
Sensors	•2D Data •Real-Time Data •Quantitative Data •These are small autonomous devices that measure physical parameters (humidity, temperature, pressure, etc.). •Low cost and high level of fault tolerance, durability, and high detection resolution.	• Limited bandwidth, processing and energy. Interference Issues. •There may be difficulties in inter-system interoperability. •Possibility of unauthorised access or electronic damage in wireless networks. •Installation Issues •Maintenance Costs	•Teamwork •Site Study •Installation in Difficult-to-Wire Areas: rivers, freeways, old buildings etc.	•Preliminary Study •Equipment Requirement •Each node requires one or more microcontrollers, memory, RF transceivers, and power sources. Various sensors and actuators can be added to this. •Wireless Standards and Range.
Sound & Noise Level Meters	•2D Data •Real-Time Data •Quantitative Data •Sound and noise measurement. •Identifying the spatial distribution of noise and developing mitigation strategies to reduce its impact. •They are small, lightweight, portable devices.	•Measurements are affected by windy weather and environmental vibrations. •Temporary sounds may interfere with measurements.	•Teamwork/Individual Researcher •Site Study •Sound level meters (SLM), microphones, dosimeters, frequency analysers, acoustic calibrators and recorders. •Preliminary preparations must be made such as determining the purpose of the measurement and the field, identifying the measurement points, and setting the duration. •Equipment calibration.	•Preliminary Study •Equipment Requirement •A measurement report must be prepared. •During measurement, reference values specified in international and national standards and regulations are taken into account.

Table 2.
Comparison of spatial mapping methodologies: technology-based mapping methods (continued)

METHOD	ADVANTAGES	DISADVANTAGES	APPLICATION	REQUIREMENTS AND TECHNOLOGIES
Luxmeters	•2D Data •Real-Time Data •Quantitative Data •They are small, lightweight, portable devices. •Assessment of the lighting level and intensity in an environment and measurement of indoor illumination quality.	•Measurements taken in naturally lit spaces may vary depending on the time of day and weather conditions. •Reflective surfaces can affect measurement results. •Colour temperature, light direction, shadow characteristics, colour perception of light, and measurements related to UV and IR rays must also be taken into account.	•Teamwork/Individual Researcher •Site Study •Simulation tools such as DIALux, Velux can be used to model and improve lighting conditions in a given environment.	•Preliminary Study •Equipment Requirement •During measurement, reference values specified in international and national standards and regulations are taken into account.
Thermal Comfort Measurement Devices	•2D Data •Real-Time Data •Quantitative Data •Analysis of indoor thermal comfort and factors such as temperature, humidity and air velocity in the environment. •Measurements are important in terms of workplace safety and productivity.	•Measurements should be taken at regular intervals to prevent fluctuations. •The researcher may need to have knowledge of the equipment in order to set up and calibrate the multifunctional measurement device.	• Teamwork/Individual Researcher •Site Study •Preliminary preparation is required for the measurement areas. •Equipment calibration. •The clothing and activities of users in the measurement environment are parameters that affect thermal comfort.	•Preliminary Study •Equipment Requirement •During measurement, reference values specified in international and national standards and regulations are taken into account.
Anemometer	•2D Data •Real-Time Data •Quantitative Data •Measurement of wind pressure and speed in an environment. •Ventilation efficiency and air conditioning system analysis.	•Depending on the type of device with different operating principles, there may be disadvantages such as heating, burning, measurement errors, and susceptibility to electrical environments. •Measurements should be taken at regular intervals due to changes in air flow.	•Teamwork/Individual Researcher •Site Study •Preliminary preparation is required for the measurement areas. •Equipment calibration.	•Preliminary Study •Equipment Requirement
GPR	•2D Data •Real-Time Data •Detection of buried historical buildings and artefacts. •A wide range of applications, including archaeological and geophysical research, space exploration, ancient cities and buried mine detection. •Safe, high-resolution data without the need for surface damage or excavation. •Use on different types of surfaces. •Enables rapid examination of large areas.	•Knowledge of GPR equipment and software enables researchers to overcome problems they may encounter. •High costs for small-scale research due to high workflow intensity. •Weather conditions (such as rain) can affect the ground surface and limit the penetration depth of GPR.	•Teamwork •Site Study •GPR data, which includes mapping of images beneath the surface, is referred to as a time-slice. Time-slices require interpretation by experts.	•Preliminary Study •Equipment Requirement •Software support is available for analysing GPR data, detecting anomalies and creating 3D visualisations.
Reality Technologies	•3D Visual Data •Real-Time Experience •Quantitative Data •Enables 3D visualisation of spatial data. •It offers remote access and ease of collaboration. •Optimum performance and fast processing. •Real-time spatial measurement, mapping, and spatial design proposal development.	•Devices (glasses, sensors), software, and application development processes are costly. •Maintenance Costs	•Teamwork •System installation, use of hardware and software, training and expertise are required.	•Preliminary Study •Technical infrastructure and equipment requirement. •Plugins compatible with game engines and CAD software.

In addition, LIDAR has a high cost compared to Photogrammetry because it requires precise ground installation and the workflow is intensive. Technologies such as LIDAR and photogrammetry may be limited for underground work. At this point, GPR technology is preferred. However, this technology can be costly for small-scale projects.

Although technology-based mapping methods offer advantages such as high-resolution, detailed, real-time data, measurement of physical parameters, optimal performance, and fast processing, they also have disadvantages such as the need for regular measurements depending on time, weather, or conditions, equipment calibration, external measurements, security vulnerabilities, external equipment and long-term system installation. In addition, technology-based mapping methodologies may require technical knowledge to interpret measurements or two-dimensional data.

Since the data output of mapping methodologies such as sensors, sound and noise level meters, lux meters, GPR, and thermal comfort measurement devices is two-dimensional and quantitative, software can be used to support three-dimensional graphical representations of the data.

Software-based mapping methods offer advantages such as simultaneous 2D and 3D data output, real-time and quantitative data at optimal speed, multi-analysis, and integration of programs with each other, compared to other mapping methods. However, these mapping methods have limitations such as licensing and software costs when they are not open source, operating systems may be insufficient for large file sizes, and external plugins or external data/file input may be required for analysis.

It can be said that collaborative software and algorithms using technologies such as AI & ML, Digital Twin, and BIM are costly in terms of maintenance and installation costs, require interdisciplinary expert researchers or teamwork, cause program incompatibility/integration issues, and are expensive for small-scale projects. Additionally, potential failures in external hardware can lead to incorrect interpretation of data.

In addition, depending on the software, there are also features such as cloud integration for data storage and updating, documentation of complex data, fast data output from online databases, visualization of complex spatial data, and the ability to work with layered and international standards and units of measurement. Among these mapping methods, only the Space Syntax method produces two-dimensional data output.

However, compared to software technologies such as AI & ML and Digital Twin, the preparation time is short because no external system setup (sensors, actuators, algorithm development, etc.) is required for the data. Similarly, the preparation time is also short for performance simulations, CAD, GIS, and BIM software.

In GPR, LIDAR, and Digital Twin methodologies, fieldwork with equipment is required to obtain results data. However, in software-based mapping methodologies such as Space Syntax, GIS, and CAD, fieldwork and observation procedures are either preferred or not preferred depending on the research content.

Since mapping methodologies yield different spatial analysis results, working with a mixed methodology in research or applications can provide multiple insights in architecture and design.

Interior architects, designers, or researchers may prefer human centered mapping methods to transform complex spatial information into a graphic representation, to reveal the experiences and learning abilities of space users, their spatial orientation, space-specific behaviors, spatial memory and imaginability, the sensory and perceptual state of space, and the shared body-space phenomena of groups, and transform ideas about space into artistic representations.

Table 3.
Comparison of spatial mapping methodologies: software based mapping methods

METHOD	ADVANTAGES	DISADVANTAGES	APPLICATION	REQUIREMENTS AND TECHNOLOGIES
GIS	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Location data analytics. •Multi-dimensional analysis capabilities with different data layers belonging to a location. •Fast analytical analyses as a result of storing geographic information in databases. •Efficient storage, retrieval, and updating of spatial data.	•High-resolution data and intensive layer usage can affect system performance. •There is a possibility of inaccurately interpreting or reducing complex data to overly simplistic conclusions. •Needs reliable infrastructure and vulnerable to technical failures.	•Individual Researcher •System installation, use of hardware and software, training and expertise are required. •(Optional) Site Study	•Preliminary Study •Software Requirement •Integrated use of photogrammetry, LIDAR, GPR and reality technologies to create 3D models and digital twins. •Web GIS and cloud integration. •Integration of data from different sources such as satellite images and sensor data.
CAD	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Highly accurate detail drawing, scaling and measurement capabilities. •Architectural designs can be visualised from every angle and with various materials. •CAM systems operate in a hybrid manner. •Drawings compliant with international standards and measurement systems •Optimum performance and fast processing.	•High file sizes require hardware and system requirements. •Dependence on licence and updates. •Plugins and external software are required for spatial scenario generation. DIALux, CFD, IES, Autodesk Insight, etc.	•Individual Researcher •Visualisation with rendering and animation. •(Optional) Site Study	•Preliminary Study •Software Requirement •Integration with BIM, GIS, photogrammetry, LIDAR, Space Syntax, etc. software. •Development of the latest version with AI-powered tools and cloud-based integration.
Performance Simulation	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Compliance with international standards and certifications (ASHRAE, US LEED, etc.). •Provide performance-oriented quick estimates and physics-based insights in a virtual environment for potential problem-solving suggestions regarding design and systems.	•Simulations require high processing power and RAM. •Licence and Software Costs •Accuracy Depends on Input Data •The conditions in the physical world may not be consistent with the simulation data. •The results may not be consistent if the correct data is not entered.	•Individual Researcher •Use of hardware and software, training and expertise are required. •Acoustic Simulation, Lighting Simulation, Static Analysis and Structural Simulation, Energy Simulation, CFD Simulation for Air Flow and HVAC, and Evacuation and Fire Dynamics Simulation Software.	•Preliminary Study •Software Requirement •Integration with CAD and BIM software. •Input data is required (climate file - energy simulation, interior surface materials - acoustic simulation, definition of loads and mechanical contact in the model - structural simulation, etc.).

Table 3.
Comparison of spatial mapping methodologies: software based mapping methods (continued)

METHOD	ADVANTAGES	DISADVANTAGES	APPLICATION	REQUIREMENTS AND TECHNOLOGIES
BIM	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Ensures that the process of designing, planning, documenting, constructing and operating buildings is carried out in a coordinated manner. •Processing point-based or image-based data using LIDAR and photogrammetry technologies. •Technologies such as Digital Twin, Reality Technologies, and cloud-based BIM platforms can be used together.	•High file sizes require hardware and system requirements. • The use of BIM in small-scale projects can be inefficient in terms of time and resources. •Each country or institution may have different BIM standards. Compatibility issues may arise in international projects. •Licence and Software Costs	•Teamwork •(Optional) Site Study •LoD Specification •Use of hardware and software, training and expertise are required.	•Preliminary Study •Equipment and Software Requirement •Integration with performance simulation software and CAD software. •Plugin Requirements for Simulations
Digital Twin	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Interactive real-time data collection with the virtual twin of a physical space using sensor and information technologies. •Providing recommendations for energy efficiency and performance optimisation. •Real-time analysis of the physical condition of the space.	•Need for Continuous Data Updates •Maintenance and Technical Support Expenses •Costly for Small-Scale Projects	•Teamwork •Site Study •System installation, use of hardware and software, training and expertise are required.	•Preliminary Study •Equipment and Software Requirement •Sensors, actuators, edge computing, data security, AI, ML, big data and the internet, Bluetooth, satellite and other communication interfaces are required. •When creating digital twins, numerous models are required, such as geometric, functional, behavioural, rule-based, and finite element analysis models.
AI & ML	•2D and 3D Visual Data •Real-Time Data •Quantitative Data •Calculation of long term and complex situations •Optimum performance and fast processing. •Various functions can done at a time. •Continuous Improvement	•Data science, statistics and programming knowledge are required. •Multidisciplinary expertise or team. •Maintenance Costs •Programme mismatch sometime done opposite to the command. •Require a lot of time and money, and technological dependency increased.	•Teamwork/Individual Researcher •System installation, use of hardware and software, training and expertise are required. • (Optional) Site Study	•Preliminary Study •Equipment and Software Requirement
Space Syntax	•2D Data •Real-Time Data •Quantitative Data •Through syntactic measurements, it examines how people actually use space and move around. •Visualisation of complex spatial data using colourful graphics that are easy for users to understand. •It offers the opportunity to analyse the morphology of spaces and the relationships between them through human interactions using numerical data.	•High file sizes require hardware and system requirements. •Analysing incomplete or incorrect spatial data affects the results. •High operating power and sufficient hardware may be required for the analysis of large-scale spaces. •Analyses provide insights into the current indoor morphology. Time-dependent changes (e.g., crowd density or changes in spatial organisation) necessitate the repetition of analyses.	•Individual Researcher •(Optional) Site Study •Various spatial analyses using parameters such as connectivity, intelligibility, permeability, circularity, agent-based modelling, compactness, etc.	•Preliminary Study •Software Requirement •Integration with CAD software.

Researchers and designers can use it for fast and highly accurate spatial measurement, high-resolution architectural documentation, measurement of noise levels and sound exposure in the environment, assessment of lighting conditions in accordance with relevant standards, examination of thermal conditions in the environment, assessing air flow and wind conditions, and visualizing underground spatial structures and elements, monitoring the life cycle of spaces, and interactive operations management.

Software-based mapping methodologies provide researchers and designers with real-time spatial data visualization through satellite imagery and location integration; real-time spatial data visualization to 2D and 3D design modeling, rendering, and animation; from building acoustics, noise control, sound transmission, and architectural sound absorption calculations in a virtual interface to natural and artificial light simulations; and from static and structural analysis of buildings to energy performance assessments. Additionally, environmental factors such as ventilation and climate control conditions, air quality, and wind comfort can be scientifically analyzed; in emergency scenarios, fire conditions and evacuation processes can be evaluated numerically and visually.

Furthermore, these software solutions support the coordination and documentation processes of building design, construction, and operation, while also enabling the collection of real-time data interactively through virtual twins of physical spaces and contributing to performance optimization. Furthermore, they enable the development of architectural strategies and the conduct of meta-analyses in the space by teaching specific tasks to the computer; through syntactic measurements, they play a significant role in analyzing how users use the space, how they move, and potential points of encounter.

Among the limitations of this study is the increase in the variety and number of mapping methodologies, along with new technological and software innovations. In this study, case studies and methodological approaches were obtained through a detailed literature review. Therefore, each case study includes mapping methodology proposals obtained from different locations. This constitutes the second limitation of the study. Researchers wishing to work on this topic may conduct mixed methodological studies to compare the results of various mapping methods between one or more locations, depending on the content of the study.

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