Enhanced 3D Visualization Techniques in Support of Indoor Location Planning

ABSTRACT:

Indoor environments are challenging spaces to handle in location analysis and Geographic Information Science. In this paper, new techniques to visualize solutions of location models used for the optimal indoor placement of emergency devices are proposed in support of location planning decisions. The analysis compares and contrasts extensions of traditional 2D visualization techniques to display diverse aspects of the service coverage of demand nodes by devices in the form of canonical and network-based spider maps, areal and volume coverage. Other innovative approaches are suggested to visualize the spatio-temporal relationship of multiple facilities serving multiple demand nodes across a multi-story building. User surveys suggest that the proposed 3D visualization techniques are preferred to their 2D counterparts in terms of quickness, effectiveness, easiness, and usefulness.

Keywords:

Visualization, Location Modeling, Facility Planning, Coverage Mapping, Three-Dimensional (3D), Space-time Representation

1. Introduction

Locational planning has been an important component of operational spatial sciences for a number of decades as location theory, which Church and Murray fittingly called the “science of ‘where it should be’” (2008, p. xiii), brought to applied research and practitioners an extensive toolbox of methods of planning and spatial optimization. When they are coupled with effective visualization techniques, location models do more than provide a set of optimal solutions. They offer a platform to address the partially unstructured nature of the problem at hand as well as the complexity and controversy that inherent uncertainties and the multiplicity of decision criteria impose on many location planning decisions (Armstrong et al., 1992; Andrienko et al., 2007). Armstrong et al. (1992) pointed out the lack of attention paid to communicating the spatial aspects of facility location planning to decision makers and stakeholders. Research on the content, design and production of visualization techniques suited to supporting locational planning has remained rather nominal (Andrienko et al., 2007). The focus of the paper is on geovisual support for locational problem-solving inside enclosed three-dimensional (3D) spaces. The analysis considers the case of locating devices at discrete places in a multi-story building so as to serve a demand whose distribution across the building varies temporally. The case of automated external defibrillators (AEDs) is used for this purpose. It extends and broadens recent research on the optimal placement of indoor Wi-Fi base stations (e.g., Plets et al., 2012).

The modeling of micro-scale spaces of the built environment has come to the forefront of the spatial sciences research agenda over the past decade (Thill et al., 2011; Worboys, 2011). This prominence certainly owes tremendously to the focused concern for emergency management, response and evacuation in the wake of the September 2001 attacks. Work by Kwan and Lee (2005), Lee and Kwan (2005), Meijers et al. (2005), Lee (2007), Vanclooster et al. (2012), Isikdag et al. (2013), Kim et al. (2014) and others is primarily geared towards the development of data models enabling such functionality. Personal movement within indoor spaces with or without explicit consideration for indoor way-finding or navigation has been the primary purpose of some other data models (e.g., Li et al., 2010; Mandloi and Thill, 2010; Thill et al., 2011; Vanclooster et al., 2012).

There is a very limited body of literature on optimal location modeling for 3D indoor environments in spite of cities being increasingly removed from two-dimensional (2D) graph representations due to their vertical expansion. Notable exceptions include Arriola et al. (2005) and Dao et al. (2012) in facility location planning and Plets et al. (2012) and Wölfle et al. (2005) in wireless network planning. In all these bodies of literature, there is scant consideration for visualization and cartographic representation. The present study is motivated by recent work (Dao et al., 2012) that proposed a space-time facility location model for the interior space of multi-story buildings. In their study, the authors underscore the scarcity of concepts and tools for the effective and comprehensive communication of locational information in 3D networked spaces. Therefore, this paper adds to the literature by proposing and implementing several 3D visualization techniques[1] to support locational planning in 3D indoor environments. Specifically, the research seeks to extend traditional 2D visualization approaches into 3D spaces on the one hand, and to create new visualization techniques tailored to the specific requirements of location

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[1] Strictly speaking, the space in our visualizations is 2.5D, and not true 3D, since different floors slice the volumetric space vertically.

planning in 3D spaces, on the other hand.

The main advantage of 3D representation lies in its ability to render the shape of complex objects due to the integration of dimensions (Kraak, 1988; Hodza, 2009; Aignier et al., 2011), providing a more familiar version of the world (Shepherd, 2007), and its potential to estimate absolute or relative object heights (Bleisch et al., 2008; Blaschke et al., 2012). Improved graphical rendering, efficient spatial indexing and faster computer processing have facilitated the visualization of complex features such as terrain models and detailed urban structures (e.g., Jobst and Germanchis, 2007; Spence, 2007; Bleisch et al., 2008; Brooks and Whalley, 2008; Aigner et al., 2011; Blaschke et al., 2012).

Space-time data can be visualized in a 3D environment where the z-axis is generally used to portray the temporal dimension (Kraak, 2003; Aigner et al., 2011; Nakaya, 2013). 3D visualization of geospatial information continues to present significant challenges (Pouliot et al., 2013). First, effective 3D scenes are difficult to construct (appropriate angle, color, transparency, lighting, texturing must be calibrated) (Card et al., 1999). Second, 3D representation may potentially lead to biased estimates of the position of objects, their sizes and their proximity to one another (St. John et al., 2001), although the accuracy of proximity estimates can be enhanced by the addition of a reference axis frame (Sheperd, 2007). Third, distortion in 3D environments can occlude data located further in the back of the image (Card et al., 1999; Tory et al., 2006; Brooks and Whalley, 2008). Fourth, response time in 3D environments may be increased when incorporating virtual landscapes, causing a distraction from the main objective (Bleisch et al., 2008; Wilkening and Fabrikant, 2013).

This paper builds on location and 3D visualization theories to propose a series of innovative 3D techniques to visualize solution sets from location and location-allocation (LA) models for the optimization of emergency devices placed in a three-dimensional built structure. Our attention is particularly focused on demand coverage issues, which convey the relationships existing between demand and supply and are more complex to visualize than other key elements of location problems. The proposed visualization approaches are also capable of representing the time-dependence of solutions and the quality of the service rendered so that they can better inform the locational planning process.

As pointed out earlier, facility location planning models have overwhelmingly been set in a 2D space and visual forms of location-allocation solutions use a 2D representation. When the problem domain is situated in a three-dimensional micro-scale environment characterized by space-time dynamics of demand and network impedances at a fine resolution, current visualization techniques appear to fall short in communicating solution results effectively and fail to exploit the potential of 3D visualization (Hanzl, 2007; Wissen et al., 2008). Therefore, our research is aimed at addressing a number of questions regarding visualization support in indoor location planning. A first point of interest is to identify visualization techniques developed for 2D LA problems that can be advantageously ported to the 3D domain. Also, to move the 3D visualization agenda forward, new visualization techniques are presented and discussed to meet and advance the needs of 3D LA modeling, especially within a GIS environment. Can current commercial-off-the-shelf (COTS) GIS software fulfill the new and emerging requirements of indoor location planning? Given the technical solutions that are presented, a use evaluation is also conducted to assess to what extent 3D visualization is preferable to 2D visualization from a user perspective.

Our paper is organized as follows. Section 2 reviews the state of the art in visualization techniques for location-allocation modeling that contributes to framing our core research questions to support indoor 3D facility location planning. Section 3 starts with a summary of the methodology used for the optimal placement of AEDs within a 3D environment. The rest of this section presents a suite of 3D cartographic displays developed to visualize the solutions of indoor LA models. Each visualization technique is illustrated with one or more examples derived from a case study. The suitability and effectiveness of the proposed techniques is compared to more conventional 2D representations in Section 4. The conclusion section acknowledges the challenges in visualization for 3D LA models and suggests avenues for future research.

2. Visualization Support for Location-allocation Modeling

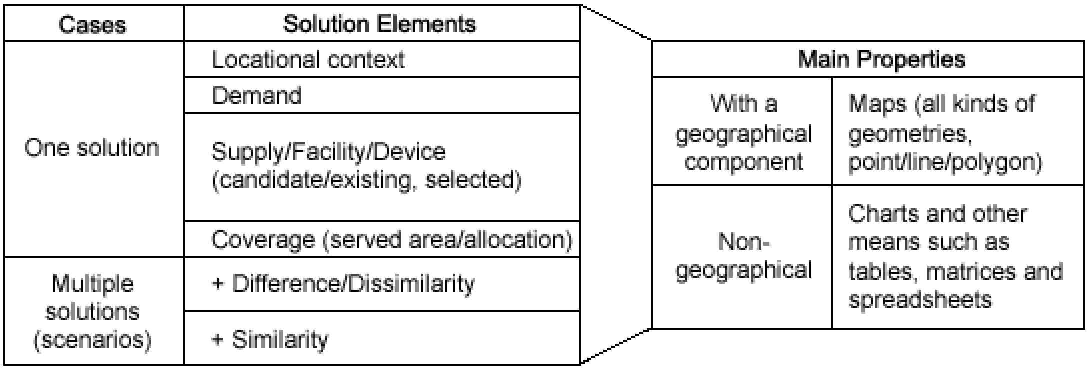
2.1 Visualization's Unique Contributions

Jones (1994) brought to light the unique contribution of visualization techniques in optimization research. Throughout the entire modeling life cycle, specific visualization techniques can be applied to gain further insight on complicated planning problems by producing appropriate representations of the models, the algorithms, the data and the solutions, respectively. One key issue in location modeling is to identify the cartographic displays that can best serve the various purposes during all three stages of the modeling and planning process (Armstrong et al., 1992), namely the problem research and definition, the generation of alternative solutions, and finally the selection of a plan of action. The integrated implementation of the full gamut of visualization techniques in a visual interactive modeling (VIM) environment is recognized in all domains of application as the ultimate goal to leverage to the greatest extent the benefits of each one (Harrison, 1986; Armstrong et al., 1991, 1992; Densham, 1994). In this paper, the study of visualization techniques for 3D LA modeling is restricted to the final stages of the modeling life cycle, namely solution analysis and result presentation. This specific focus is motivated by the fact that these stages are intrinsically spatial endeavors that often involve stakeholders and facility managers and directly support location planning.

2.2 Elements to Be Visualized

When they resort to location modeling, planners find themselves in the situation of either presenting a single solution or comparing multiple solutions under different scenarios (Figure 1). Under both modalities, several solution elements need to be presented separately or in combination, namely (Church and Murray, 2008):

- The locational context;
- The demand side; the demand is the spatially distributed target that facilities provide service to; demand existing at present as well as expected future demand may be sought to assist in making decisions.
- The supply side or facilities; these are the objects to be located in space and to which demand is allocated. They may differ from one another according to their role in the problem-solving task; some may already be operational, others may be potential sites for future supply, while some of them may in fact be selected for new facilities.
- The service coverage, which reveals the relationship between demand and supply and constitutes the core element in a solution.



Cases	Solution Elements
One solution	Locational context
	Demand
	Supply/Facility/Device (candidate/existing, selected)
	Coverage (served area/allocation)
Multiple solutions (scenarios)	+ Difference/Dissimilarity
	+ Similarity

Main Properties	
With a geographical component	Maps (all kinds of geometries, point/line/polygon)
Non-geographical	Charts and other means such as tables, matrices and spreadsheets

Figure 1. Elements in solutions to location-allocation problems

For the purpose of comparison of multiple solutions, a critical consideration is to characterize the dissimilarities and similarities among solutions at once, rather than focus on each solution in turn. Andrienko et al. (2007) as well as Armstrong and Densham (2008) have recently addressed the visualization challenges in collaborative spatial decision-making environments. Several types of synthetic maps are presented to assist parties involved in group decision-making to compare solutions to a problem and to further promote discussion and support group consensus-building activities.

2.3 Visualization Forms

Solution elements of any type may have spatial and/or non-spatial components in their attributes, for which different representation formats may be better suited (Figure 1). For geospatial properties, several types of maps are often employed by individual users to present results, including location maps, demand maps, supply maps, and spider maps, which all correspond to the elements in the one-solution case (Armstrong et al., 1991; Murray, 2010). Intuitively, demand maps and supply maps are used to provide information on the spatial distribution and magnitude or capacity of demand sites and facilities. Depending on the geographic unit accommodating the service demand and the data type of the variable being represented (e.g. ordinal or ratio), graduated-symbol maps or choropleth maps, or even purely point symbol maps, are applicable to node-aggregated, polygon-aggregated or disaggregate demands, respectively. For supply maps on the other hand, graduated point symbols are often used, although choropleth maps can be suitable if fixed service areas are given.

Spider maps are convenient representations to show the allocation of a dispersed demand to a smaller set of facilities. Depending on the way in which demand and facilities are linked, spider maps come in one of two types, canonical spider maps and network-based spider maps (Church and Murray, 2008). In a canonical spider map, each demand node is connected to its assigned facility by a straight line through which the relationship between demand and supply is very easy to read and can be rapidly generated and displayed. In contrast, a network-based spider map presents the actual paths taken through the network between each demand site and their assignment facility (e.g., Densham and Armstrong, 1993; Curtin et al., 2010). This more realistic representation can be extended to depict the demand flow merging into each facility along the paths by applying appropriate width and hue to each link (McKinney, 1991; Densham and Armstrong, 1993). Thus the flow and traffic consequences of selecting a particular locational configuration can be better understood by a facility planner or decision-maker.

In addition to spider maps, Armstrong et al. (1992) exemplify some other cartographic displays for showing coverage or allocation, including center-region, center-border, and nodalchromatic displays. The simplest version of center-region maps is to code the areas where demands are covered or not by any facility, and when a maximal covering location problem (MCLP) or a backup coverage location problem (BCLP) is concerned, primary coverage (area that is covered by one and only one facility) and multiple coverage (area that is covered by multiple facilities) are distinguished (e.g. Murray et al., 2007). However, this type of representation cannot inform the user on which facilities cover the same demand. When time or distance is crucial to determining the service area of facilities, network-based coverage areas derived in GIS as a variant of center-region display are often found in the literature (Goodchild, 1984; Schilling et al., 2000; Gutierrez and Garca-Palomares, 2008). In a more complex approach, Southworth (2008) uses a nodalchromatic display to show the allocation of the demand sites to optimal facilities represented by star symbols of different colors and sizes. Demand sites are grid cells in this work and are represented by dots of different colors and symbols.

For solution comparison purposes, delta maps (Armstrong et al., 1992) may prove useful by showing explicitly the difference between multiple solutions (usually two solutions), although they are not common in the optimization literature and side-by-side visual comparisons remain popular due to their convenient production. When they are explicitly derived, the differences in delta maps can be binary coded or color-coded after classification (Suomalainen, 2006). Another form of delta maps is to show two solutions simultaneously in a single graph by combining a spider map for one solution and a nodalchromatic map for another (Armstrong and Densham, 2008).

Contrary to traditional delta maps, synthetic map types are specifically designed for use in multi-user group settings, as suggested by Armstrong and Densham (2008). Reading a facility frequency map, a user can quickly know how many times a candidate facility location is chosen under alternative decision criteria or scenarios. Allocation consistency maps go one step further and reveal to the decision makers the common linkages among demand and supply across two or more scenarios. A network consistency map focuses on linkages between demand and supply: it conveys information on how many times a linkage is traversed between supply and demand. To evaluate the non-geospatial properties of a set of solutions, a star plot/radar plot can be effective at displaying their mean and standard deviation or value range, although this type of plot can also be used for presenting the values of multiple variables of each solution (Frank et al., 2000). Plotting the objective function values of multiple scenarios for *p*-median problems (Hakimi, 1964; Church and Murray, 2008) is a prevalent way of drawing comparison.

In summary, visualization is recognized to play a critical role in facility location planning. Various visualization forms for demand-side, supply-side, and allocation information in the geographic and solution spaces have been implemented, but the use of 3D visualization remain rather limited.

3. 3D Visualization Techniques for Indoor Facility Location Planning

3.1 Background

The example of spatio-temporal location modeling of AEDs within the confines of a multi-story building is used to motivate the study of 3D visualization techniques in support of indoor facility location planning (Thill et al., 2011; Dao et al., 2012). AEDs are devices that instrument the on-site treatment of persons in sudden cardiac arrest (SCA) by laypersons. Given that time is a critical factor for the treatment of SCA (Das and Zipes, 2003), a number of communities and public health organizations have resolved to sponsor programs to deploy AEDs as public access units at many locations where a sizeable population may congregate (e.g. shopping malls, airports). Because of the navigational complexity of indoor spaces and because of the limited visibility that may delay the discovery of an SCA victim, effective indoor AED deployment may benefit from planning based on a robust and efficient coverage optimization model. Due to space limitation, only the modeling features that are distinctively relevant to the discussion of the visualization of optimal device placement are summarized here. Further detail can be found in Dao et al. (2012).

- Traversable networks formed of hallways, rooms, stairs/elevators and exit doors are built in GIS to represent the indoor environment of a multi-story building, on which optimization is carried out. Travel time impedances (including detection time and response time) used for determining the facility coverage of a site are calculated on the basis of 3D network distances.
- The spatial and temporal variation of the distribution of the population at risk (potential demand) inside the building serves to capture the micro-level dynamics of the location problem. Assuming that the fluctuation of spatial demand is known at different time periods through the day, these considerations are captured by formulating a single aggregated weighted model with demand defined at each indoor position in each time period. The model gains in complexity when accounting for the temporal dynamics of indoor population distributions.
- All the visualization approaches are presented using a maximum covering location problem (MCLP), although the proposed techniques can be extended to other models, such as the *p*-median model. The MCLP places devices so as to maximize the total population being covered within a pre-specified time limit under the assumption that

the device that can be reached the fastest is used. The optimization modeling process is automated in a tightly-coupled system integrating ArcGIS^{TM} and the commercial solver LINGO^{TM}. The results are visualized in ArcScene^{TM} (ESRI, Redlands), where innovative visualization techniques are implemented for enhancing representations.

3.2 Visualization of the Key Elements

Visualization techniques for the four key elements mentioned in Section 2.2 are presented in this section, namely the locational context, the demand and supply of the system under consideration, and the service coverage associated to each run of the MCLP. Special attention is devoted to the visualization of the space-time variability of service coverage. Visualization forms of the similarity between solutions of alternative modeling runs are not treated in this research. All the visuals are in full color in the digital version of the paper.

Locational context

The interior space of the building used as example is abstractly represented by its 3D transportation network (Figure 2), which connects the hallways and other indoor passageways (blue lines) with the stair wells and elevator shafts (red lines), the exits and the rooms (represented as point symbols). Specifically, Figure 2 shows the position of the demand nodes (placed at room centroids or along hallways), of the candidate AED stations (placed along hallways), of the floor exits connecting floors to staircases (red straight segments of the network), and of the building exits accessing to outdoor environment and/or other buildings. The layout drawing of the building floors from CAD files can be an ancillary element to be included in the representation of the locational context.

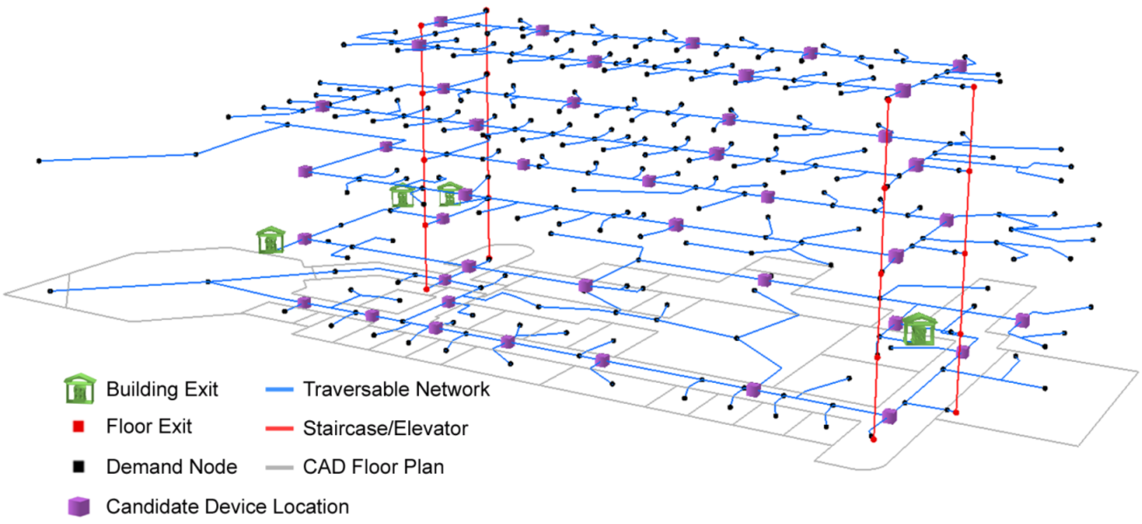


Figure 2. Locational context represented in 3D indoor environment

Demand and Supply

In line with established practices in LA modeling, demand nodes are the objects used to represent the population at risk aggregated in a room. The key attribute of demand is the number of individuals at a certain point in time. The distribution of potential demand can generally be expected to vary over time as usage of buildings fluctuates during the day. To capture this time-dependence, discrete time windows that are pre-defined over a typical twenty-four-hour period are used, under the assumption of invariance of the demand distribution within each time window. Furthermore, to provide decision makers with complete information on daily demand distributions at once, the demand attribute in all time windows is combined in a single representation. In our example, three time windows are defined: window 1, [08:00 – 18:00]; window 2, [18:00 – 22:00]; window 3, [22:00 – 08:00]. Many institutional buildings where AEDs would be deployed would exhibit patterns of usage with similar contrasts across a typical weekday. For each individual time window, demand distribution is displayed using 3D graduated symbols.

In Figure 3, an approach based on nested cubic symbols is proposed, in which the visual dimensions, size and transparency, are integrated to produce the desired effect. Although this approach may lose effectiveness when the number of time windows is large due to the marginal differences in transparency of nested symbols, three or four windows should be sufficient to represent the daily variation of demand in most practical cases. It also would be less effective if demand is fairly stable as cubes would hardly be distinguishable; little accuracy would be lost in this case by collapsing similar time windows. Some circular visualization approaches (e.g., Aigner et al., 2011) could also be implemented, but this may quickly become an impractical option in buildings with more than just a few demand nodes.

No special visualization is proposed for positioned devices, except that 3D symbols are used instead of 2D ones (Figure 3).

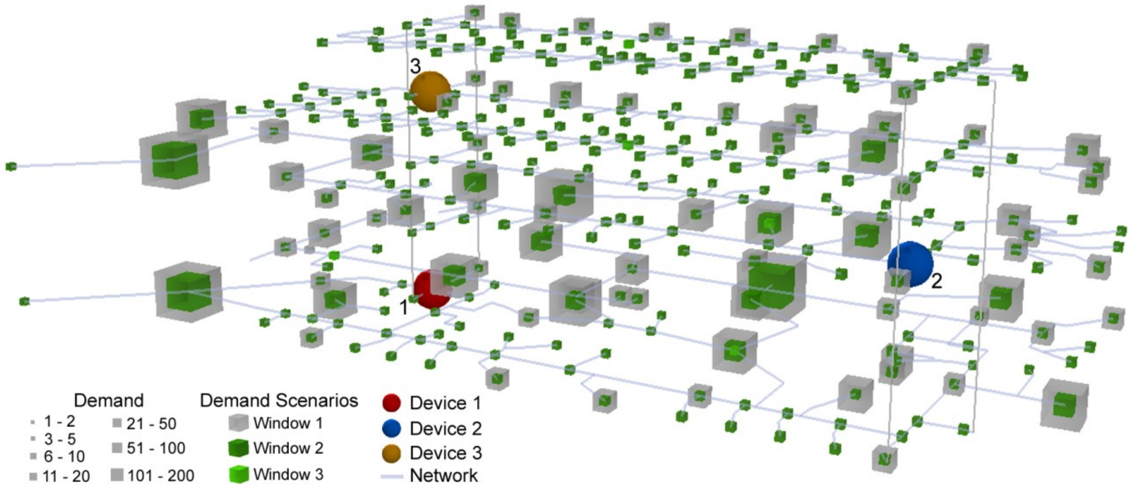
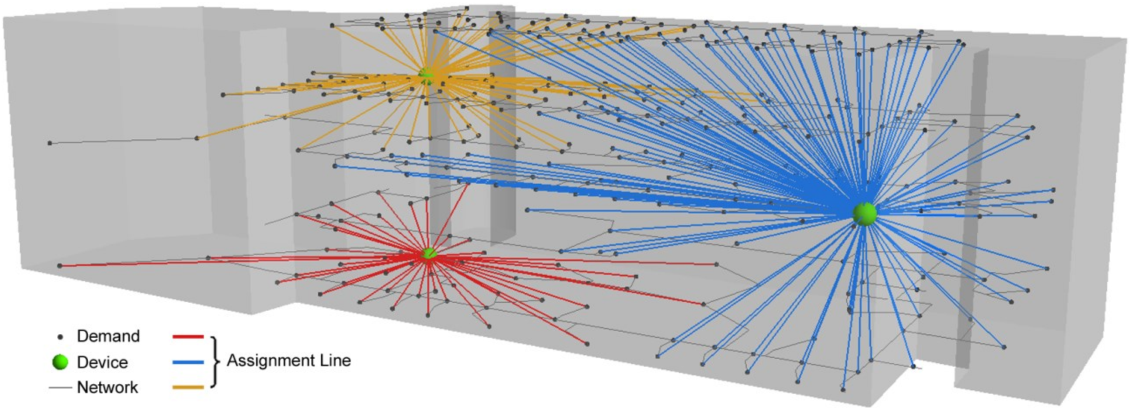


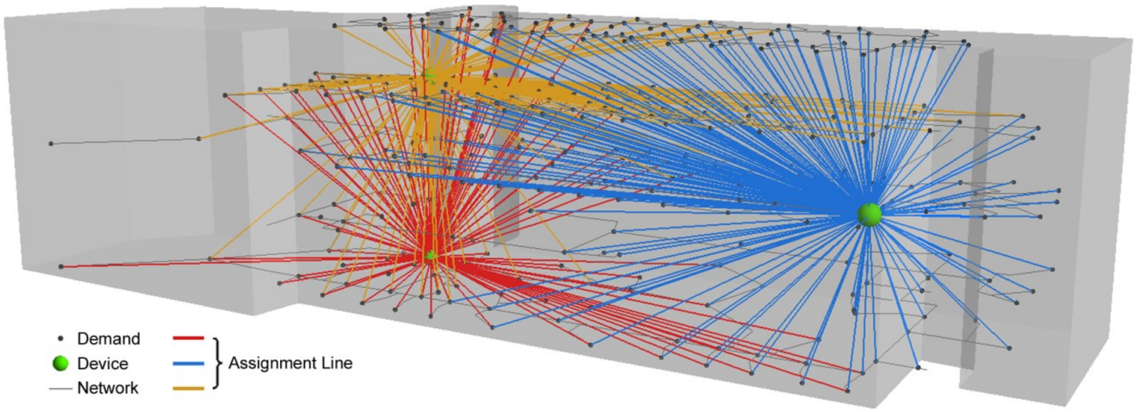
Figure 3. Demand distribution across multiple time windows and location of selected devices

Coverage

Multiple visualization alternatives are proposed to portray the relationship between positioned devices and demand nodes. The first illustrations are equivalent to spider maps, but in 3D space. In Figure 4a, a solution to the p=3 MCLP is presented using a 3D canonical spider map. Similarly color-coded lines are radiating from each AED position (highlighted green sphere) to all the demand nodes it serves. To strengthen the user's perception of the three dimensions of the building, the 3D network is shown to distinguish different floors and a partially transparent polyhedron demarks the volumetric boundary of the building. The user can easily see through the 3D spider map, particularly with regard to demand on the same floor or remote demand nodes on other floors. This representation may appear cluttered when more than a few facilities and their coverage area are depicted, or, when multiple devices serving one demand node are represented, as would commonly be the case with the set covering problem (SCP) or the complete demand allocation produced by the MCLP (Figure 4b). As seen in Figure 4b, many assignment lines may intersect or overlap with each other, thus hindering the readability of the graphic.



(a) The single most accessible devices are depicted for each demand node



(b) All serving devices are depicted

Figure 4. 3D spider map for the MCLP solution (p=3)

Since the building's traversable network is readily available, network-based 3D spider maps are straightforward to generate and offer an alternative to canonical spider maps. Figure 5 gives such an example, in which the path from each demand node to their nearest AED position is rendered in the same color as the serving AED. A distinct advantage of network-based 3D spider maps over canonical 3D spider maps is quite evident since they trace the exact path to reach the nearest device from any position in the building so as to minimize the chance of getting lost, especially when walking through an intricate indoor environment. This representation also explicitly indicates which portion of the network on each floor is covered by each AED. For example, in Figure 5, the space (and the demand nodes) situated on the two lowest floors of the building is split into two parts served by the red and blue AEDs, respectively, while most of the demand nodes on the middle floor are most accessible to the blue AED located on the same floor. Even as more devices are positioned, the network-based 3D spider map continues to convey effectively the information on network coverage of facilities. The only issue that may arise is that some segments of the shortest path between an AED and a demand node are hidden due to the overlapping of other paths through computer rendering. It should be noted that the same may happen in 2D network-based spider maps. To alleviate this drawback, a proposed alternative may be to represent the total demand traversing a particular link to reach a facility using variation in hue and/or line width to draw network-based spider maps, as is commonly seen in 2D versions. The variable hue denotes which demand node is served by which AED, while the width of the network line indicates the frequency a path is traveled.

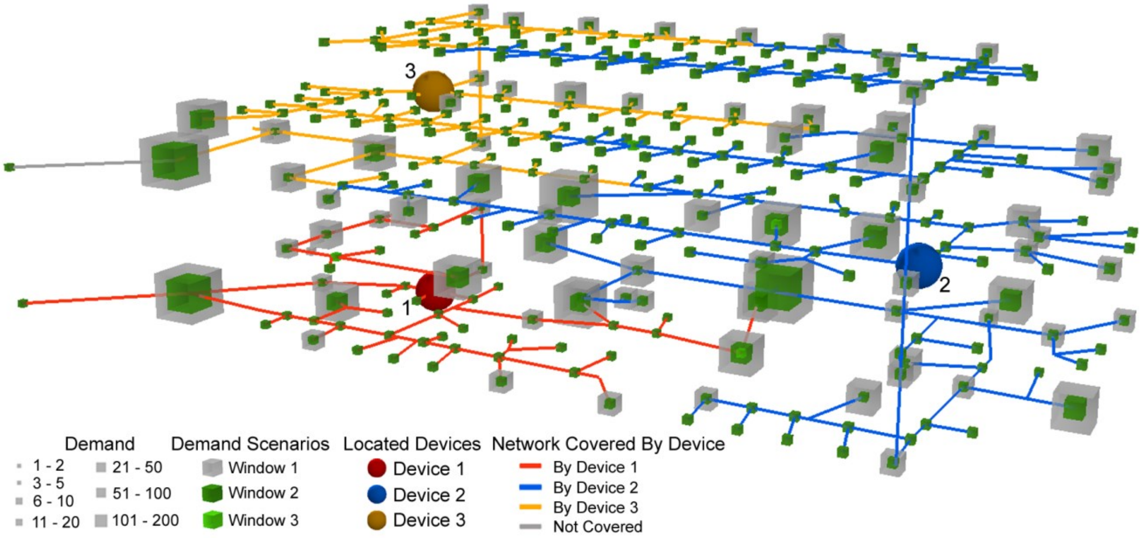
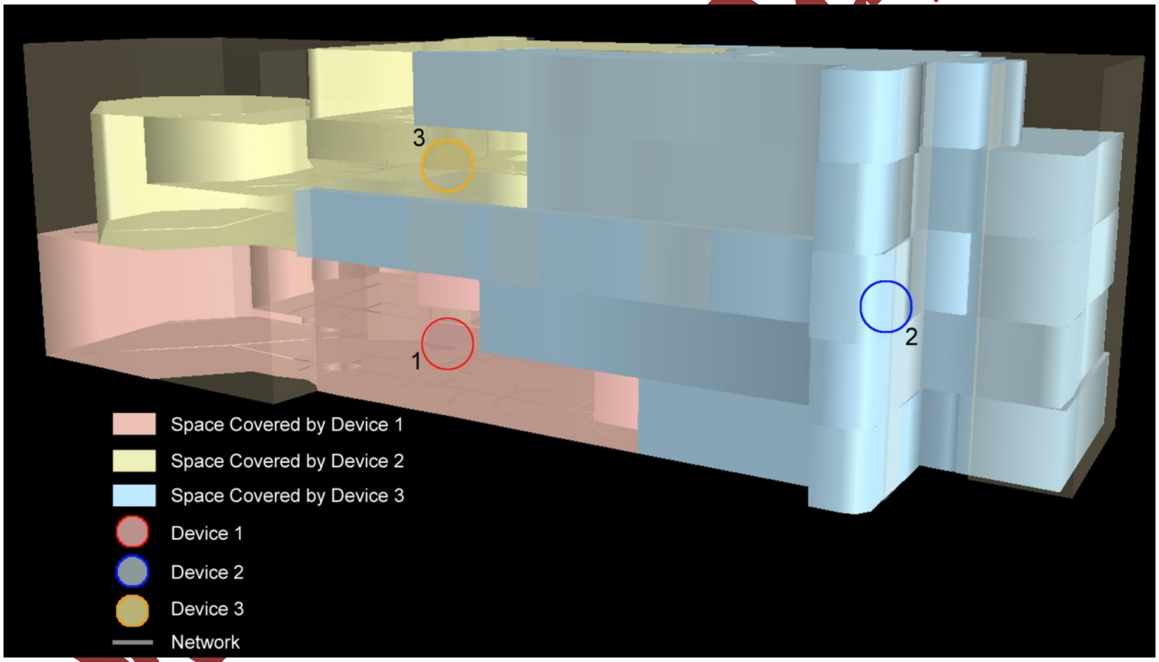
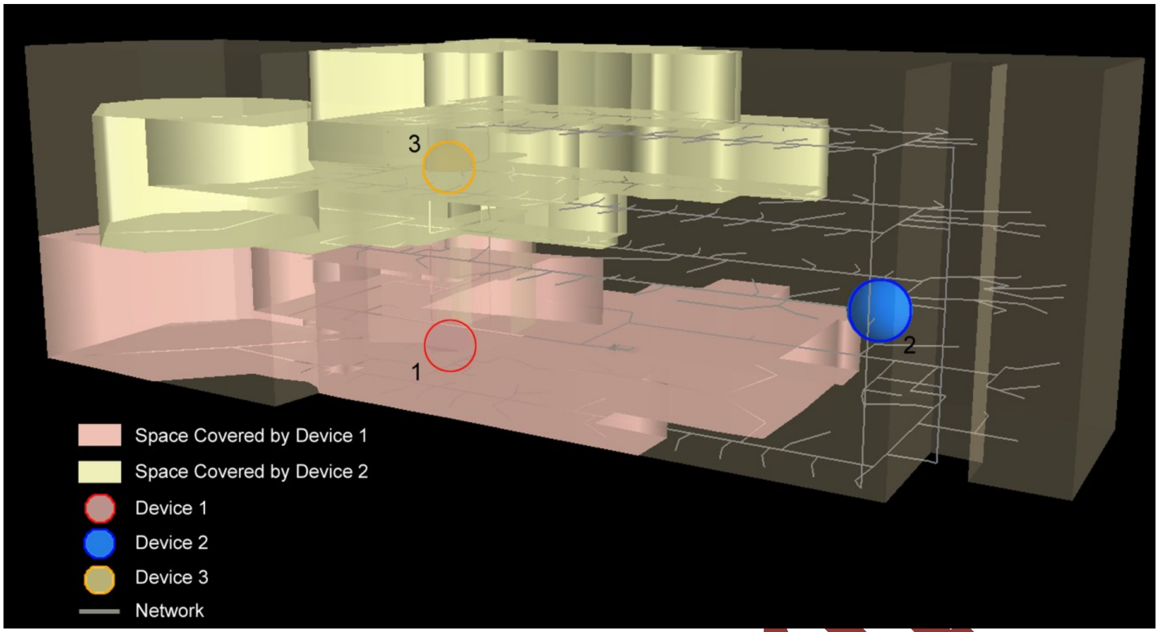


Figure 5. Network-based 3D spider map for the MCLP solution (*p*=3, most accessible devices only)

Volume coverage is a new 3D visualization form that is proposed to render information on demand allocation and coverage (Figures 6a and 6b). The challenges of this approach are the same that are encountered in the modeling and visualization of 3D cadastral systems, especially with regard to visual obstruction and concerns for translucence with a dense volumetric partition in complex buildings (Wang et al., 2012; van Oosterom, 2013). With this technique, a building is modeled as an exhaustive collection of polyhedrons that constitute the display units; each polyhedron represents a building component (i.e., a room) to which demand is aggregated. Each polyhedron can be the geometric representation of a room if detailed geometric and topological information is available. Alternatively, it can be approximated by the extrusion of each room’s Thiessen polygon. All the polyhedrons covered by the same AED are rendered in the same color and form an irregular-shaped 3D block. Thus the space occupied by the whole building is partitioned into a number of volumes according to the number of AEDs. This representation gives a crisp 3D visual perception of device allocations’ boundary. It can be regarded as a volumetric variant of a center-border or center-region display.



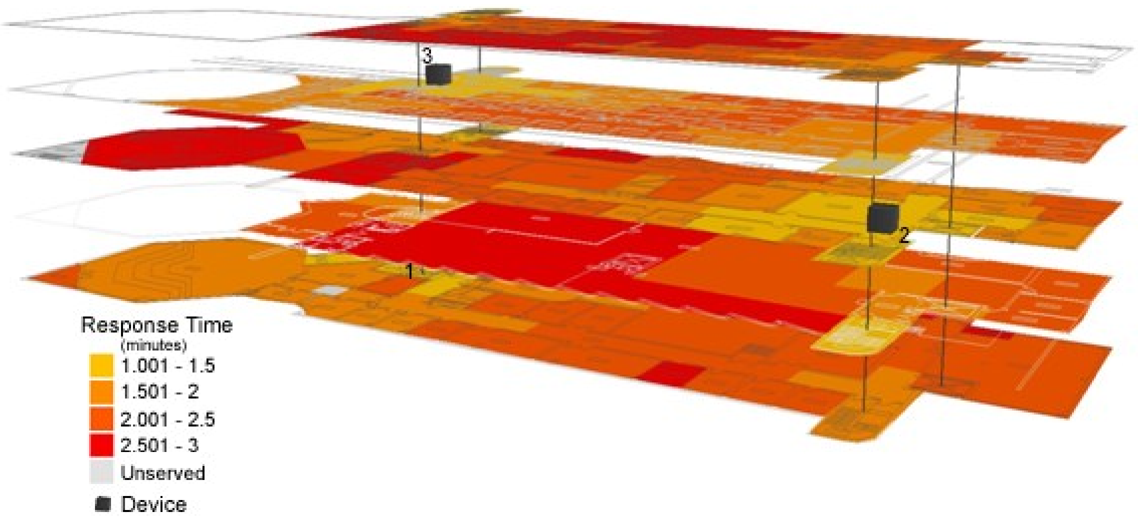
(a) For all serving devices



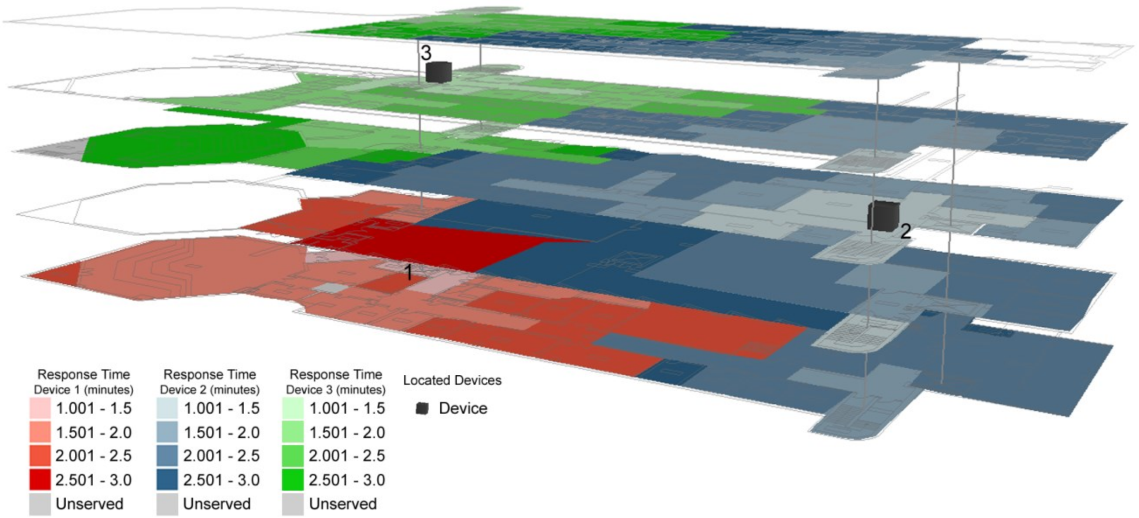
(b) Selective display of volume coverage: coverage of device 2 is hidden to reveal the structure of volume coverage of the interior of the building

Figure 6. Volume coverage for the MCLP solution (*p*=3, the single most accessible device for each demand node only)

Information on device coverage can be enhanced by also reporting the response time. This information is proposed to be represented as an areal coverage, where each display unit is the polygon to which demand is aggregated (Figures 7a and 7b). The response time can be computed between each demand node and each of the available AEDs, and then be classified into user-defined categories for rendering at the polygon level. In Figure 7a, response time to the most accessible device alone is represented by a simple map. In Figure 7b, the layered map communicates not only the specific response time, but also the service area of each device. The combination of choropleth displays for each of the three AEDs with three sets of graduated color (red, blue and green) is used for this purpose.



(a) Based on minimum (optimal) total response time



(b) Based on total response time

Figure 7. Areal coverage for the MCLP solution (*p*=3)

Because the MCLP is a covering model, each demand node can be assigned to multiple devices and this one-to-many relationship may need to be represented rather than just the relationship of each node to the most accessible device that covers it[2]. Two

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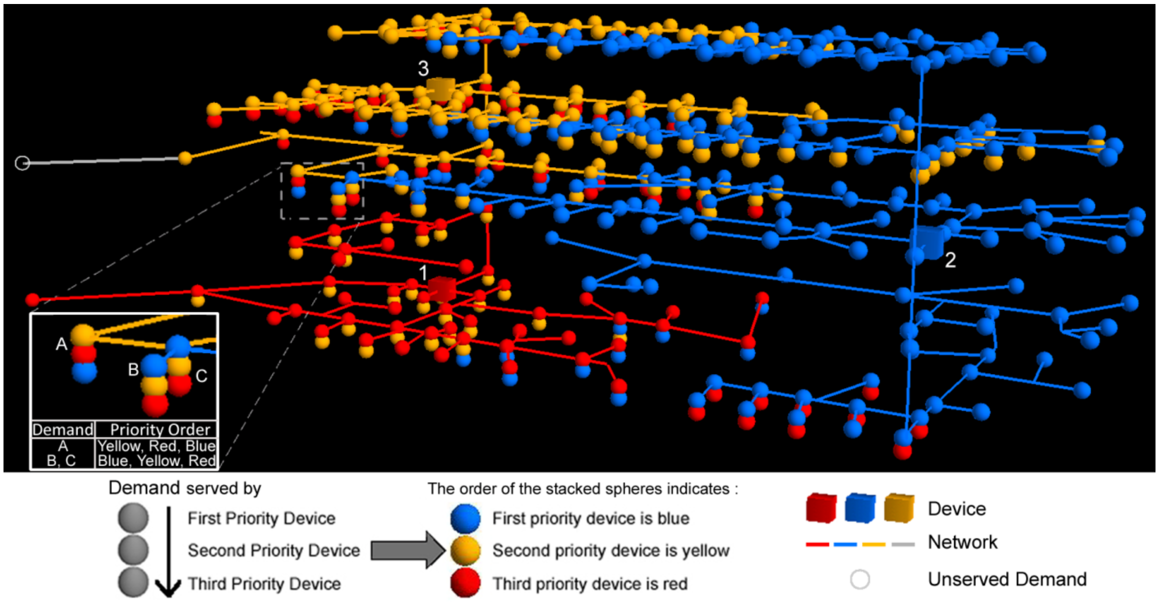
[2] Other location models such as the Set Covering Problem (Toregas et al., 1971) and the Backup Coverage

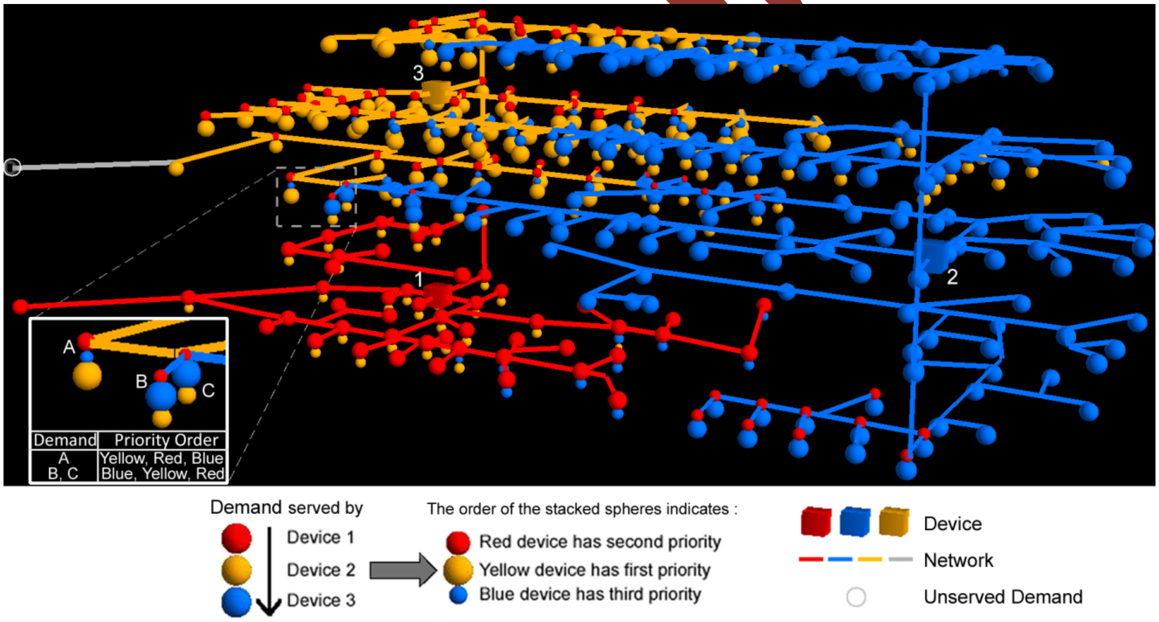
types of representations are proposed for this purpose (Figure 8). What is common between them is that multiple devices serving the same demand node are shown as a stack of symbols (spheres) hanging on that demand node, with each color-coded symbol representing coverage provided by a different device. This compact visual helps a user quickly find how many devices serve a specific demand node, as well as identify which ones. The two visualizations differ in terms of the arrangement of the spheres. In one representation (Figure 8a), the order of the spheres is determined by the response time, from the most to the least accessible from the top down. By scanning the top sphere at all the nodes, the user can tell the primary allocation of demand nodes to each device. This indicates which nodes a device should serve as a priority for the purpose of greater effectiveness. This representation also conveniently conveys the primary workload of each device and may point to concerns for the equitable distribution of workloads. It allows for fast communication of the priority order of devices to potential users at each node. The network in the visualization is color-coded to represent the set of paths from the demand nodes and their most accessible devices, respectively.

The second visualization of multiple serving devices keeps the order of the devices (spheres) in each stack constant across the map, but uses graduated symbols to imply the difference in total response time from multiple devices to a demand node. A larger sphere in a stack is associated to shorter response time. The entire allocation of demand nodes to each AED can be identified by looking at the corresponding layer in all the stacks of spheres.

Location Problem (Murray et al., 2007) share this property.



(a) Order in a stack is determined by response time



(b) Order in a stack is fixed; graduated symbols show total response time

Figure 8. Multiple devices serving each demand node (stacks of spheres denote the position of demand nodes)

Space-time coverage

Many location planning problems exhibit a fundamental temporal dimension (Aigner et al., 2011). In our test problem, not only is the spatial distribution of demand assumed to vary through the day, but response time does as well, since it encompasses the detection time which depends on the presence of people in the vicinity of a node. As such, coverage may be different at different times of the day. Novel visualization techniques are required to incorporate the time component into the 3D cartographic displays. Two general cases are identified here, depending on whether the interest is in the relationship of the demand to the most accessible device (one-to-one relationship) or in the relationship of the demand to all the devices available during a certain time window (one-to-many relationship).

To represent the one-to-one coverage relationship between demand nodes and devices, stacks of color-coded symbols are placed at each demand node, where the dimensionality of the stack is given by the number of time windows (Figure 9). Thus the spheres at the bottom and at the top of each stack correspond to the most accessible devices during the first and the last time window, respectively. Because some demand nodes cannot be served within the critical response time at certain times of the day, the corresponding service spheres are grayed out to communicate that service is not available at these locations during these time windows. By identifying the color of the spheres at a demand node, the user can identify which device is in service for a particular time window. The overall representation shows how the coverage of each device varies with the changing demand distribution during different time windows.

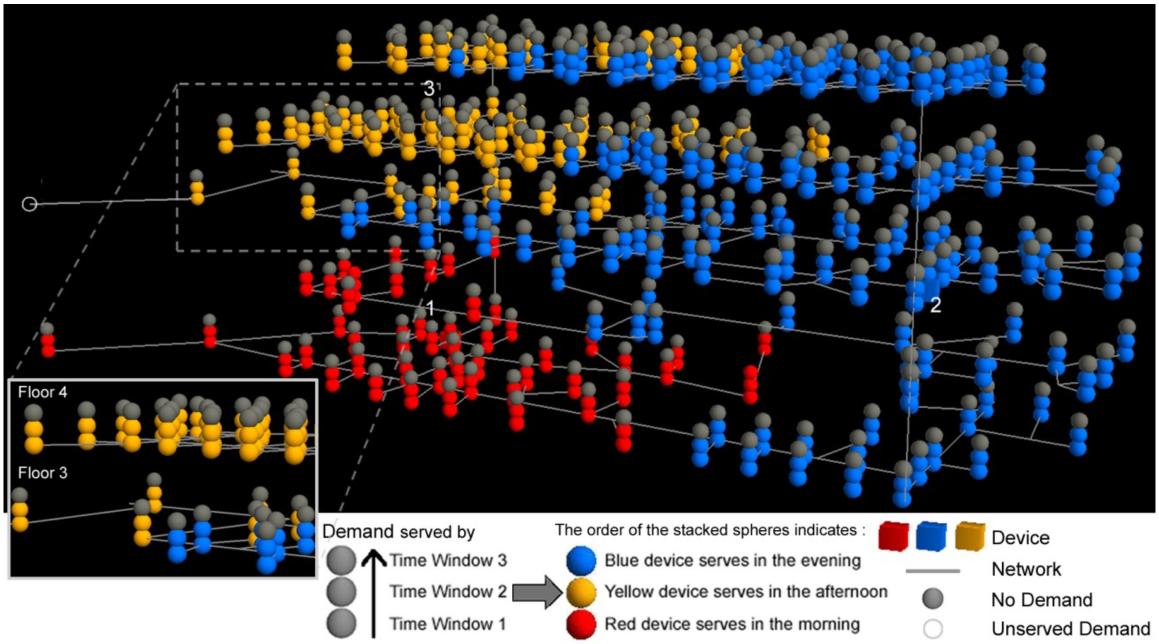
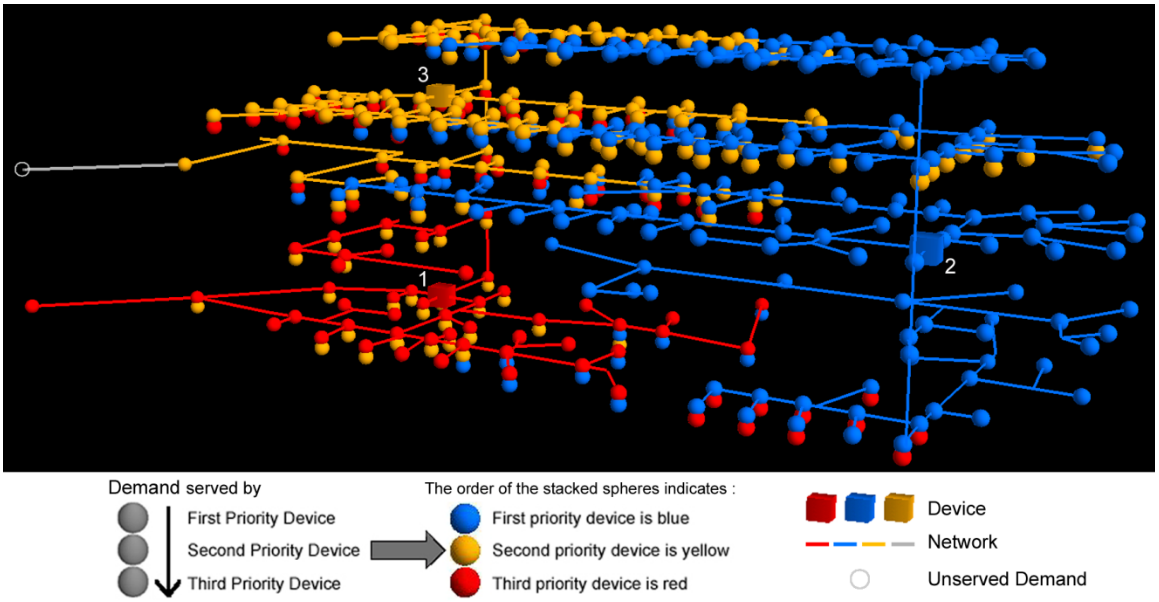
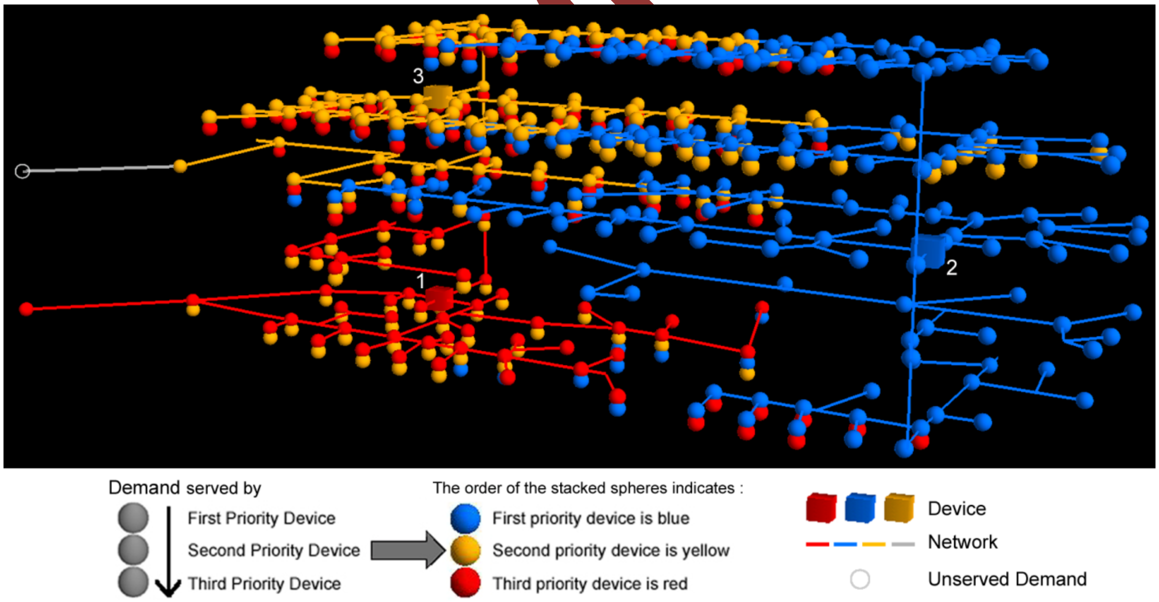


Figure 9. Demands in different time windows served by one facility (MCLP solution, p=3, most accessible devices only; the inset shows that, some of the demands on the third floor have the yellow device as most accessible device - serving in the morning and afternoon, while the blue device serves the others in the morning and afternoon)

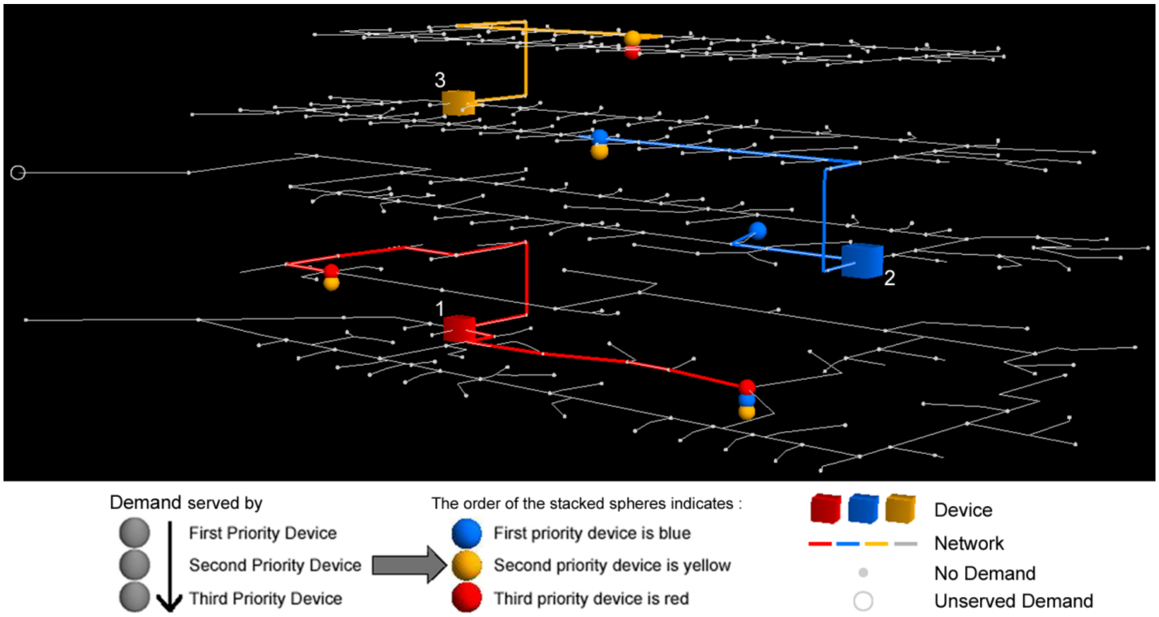
A property of the SCP and MCLP models is that a demand node may be covered by multiple devices. A straightforward visualization of time-dependent coverage consists in displaying multiple graphs side by side for this purpose, where each graph would be as in Figure 8a for each time window. In the following example (Figure 10), three separate graphs are generated to inform how all the demand nodes are served by one or more than one device in the respective time windows. Note that, in time window 3 (Figure 10c), very few nodes have a non-zero demand. Hence, only a handful of paths connecting nodes and their most accessible device are represented. The collection of time-dependent coverage graphs conveys information on the role of each device across all the time windows. Specifically, given a demand node, a user can determine which device should be the first choice and which other devices could serve as backup in case the first choice is not available.



(a) Time window 1: 08:00 – 18:00



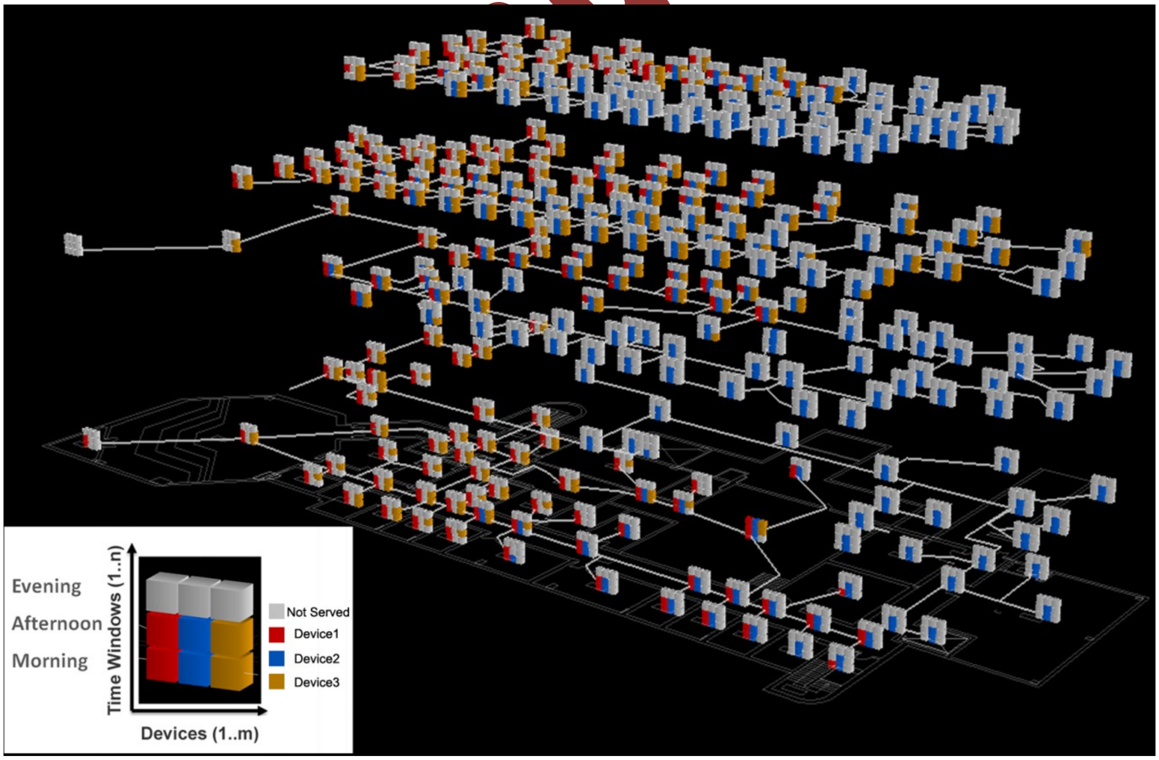
(b) Time window 2: 18:00 – 22:00



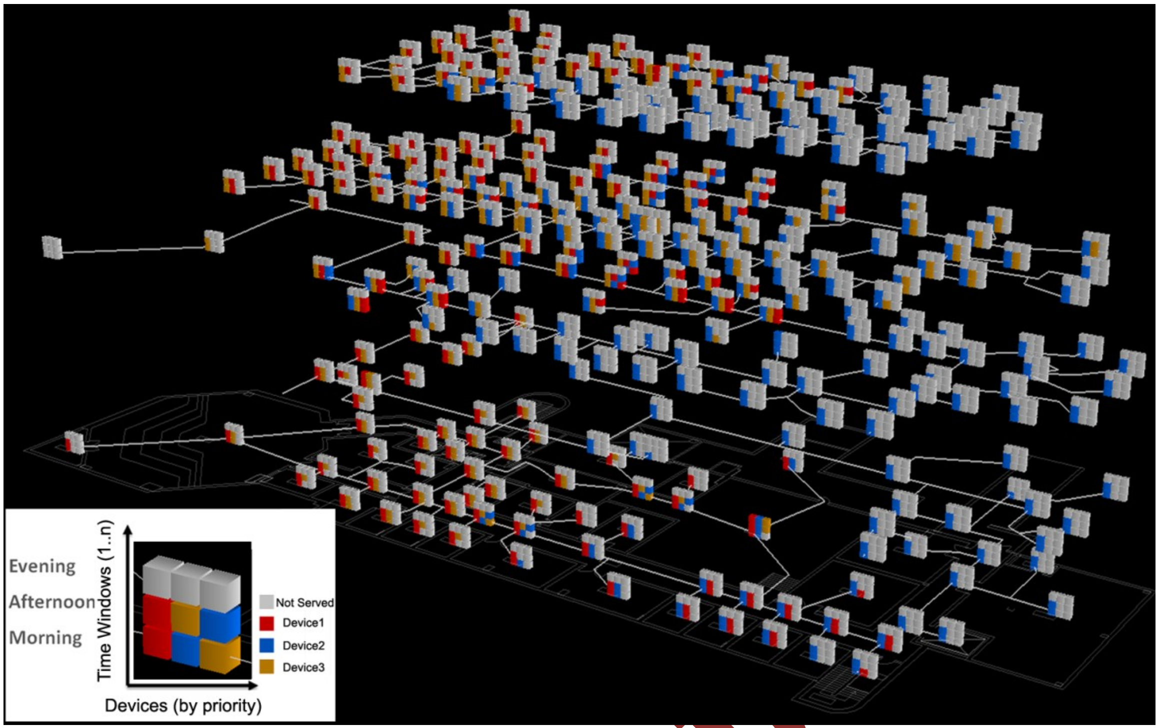
(c) Time window 3: 22:00 – 08:00

Figure 10. Demand in different time windows served by multiple devices (MCLP model, p=3)

Finally, the coverage information pertaining to all the time windows can be combined in a single visualization form. Each demand node is represented by a color-coded cube-matrix in which cubes are arranged along two axes (Figure 11). Devices can be placed along the horizontal axis either in a fixed order according to the device ID (Figure 11a), or in the order of priority given by the response time (Figure 11b). The vertical axis is for the sequential ID of time windows. A cube rendered in grey placed in row i and column j of the matrix means that device i is not accessible from the current location in time window j or that the demand at this location is null during this time window. When multiple devices are available during a time window, the respective positions on the row for this time window are color-coded after the serving devices. Different ways of placing devices in a cube-matrix convey different information to the user. When the order of devices is fixed and given by the device IDs (Figure 11a), it is quick to make out the service area of each device with a simple visual scan and which devices serve each demand node in particular, although one cannot determine the fastest device to reach. In contrast, when devices are ordered by ascending response time, the most accessible device (the one indexing the left column of the cube matrix) can readily be pinpointed; it is straightforward to differentiate the serving priority of all the serving devices. This way of ordering can help discovering whether the priority of serving devices changes across different time windows. For example, as seen in the legend of Figure 11b, the serving priority of yellow and blue devices (devices 3 and 2, respectively) are swapped between the morning and afternoon time windows. However, the cube-matrix visualization with the fixed ordering (Figure 11a) cannot support this type of query, because the pattern will be the same as long as the set of serving devices is the same across time windows.



(a) Devices displayed according to their ID



(b) Devices displayed according to response priority (high to low, from the left to the right of each cube-matrix)

Figure 11. Demand in different time windows served by multiple devices in a combined visualization (MCLP solution, *p*=3)

Dynamic visualization

All the visualizations described so far are static snapshots. The dynamic nature of both service demand and response time lends itself particularly well to the use of animations. Instead of showing many static cartographic displays for all the floors, it is attractive to provide the user with an animation in which the situation is presented first; the solution is then demonstrated floor by floor and for each time window, and an overall 360 degree rotation view is provided. Animations may be particularly effective when large and complex building structures are used, so that obstruction of the view is kept to a minimum thanks to multiple perspectives and zooming capability. An example of animation generated with ArcScene^{TM} accompanies this paper.

4. User Evaluation of the Proposed 3D Visualization Forms

4.1 Survey Design

A number of new 3D visualization forms are proposed in Section 3 to represent the results of LA models in indoor spaces for the purpose of supporting the optimal placement of AED devices. We now proceed to evaluate the relative quickness, usefulness, effectiveness, and user friendliness (easiness) of contrasting modalities of information visualization, particularly the new three-dimensional renderings (3D, two-dimensional plus height) and corresponding conventional 2D renderings. For this purpose, a survey of potential users was conducted following an approach similar to that of Bleisch et al. (2008). Respondents would ideally be facility planners or emergency response planners and coordinators, who have a good sense of space and navigation. This group is approximated here by surveying students with some knowledge or experience of geospatial technologies and therefore commensurate spatial thinking abilities.

The survey instrument consists of six groups of query tasks and an overall evaluation. Each task consists of a group of questions similar to the queries that a facility planner would engage in to assess the quality and value of an algorithmic solution, such as “In which part of the building is there no back-up service?” and “Which part of the building has the greatest disadvantage in terms of minimum service times from any device location?”; each task is associated with one of the six visualization forms. In each task, users answer several questions (two types, multiple choice options and open ended questions). All survey participants are presented both the 3D and 2D visuals for the same set of questions. In order to control for the effect of ordering of 3D and 2D visuals on users' learning process, two sets of instruments were designed according to a 2x2 within-subject design to randomize the order of the questions (Griffen et al., 2006). In Group 1 (half the respondents), the odd-numbered tasks present the visuals in the (3D, 2D) order while the even-numbering tasks present them in the (2D, 3D) order; vice versa for Group 2. In addition, the time taken to complete the 2D and 3D versions of each each task is also recorded.

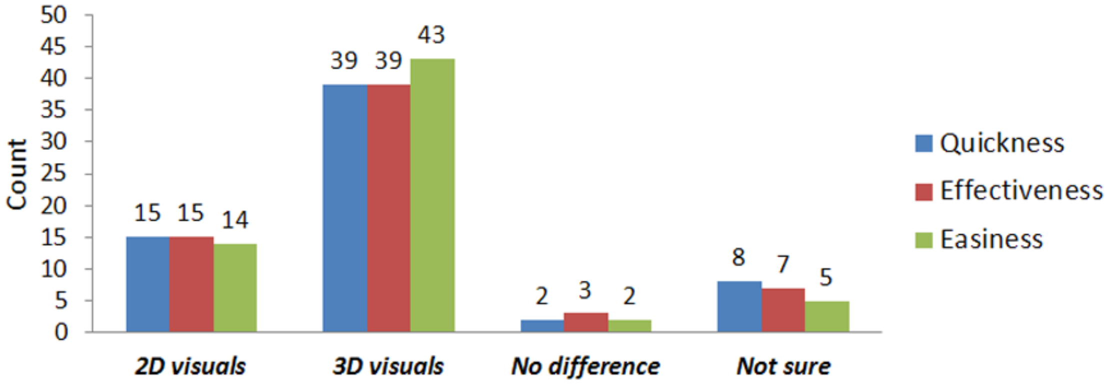
The overall evaluation is composed of five questions on a 5-point Likert scale that are designed to reveal the users' general experience with the 2D and 3D visuals from four perspectives, namely quickness, effectiveness, easiness and usefulness for the purpose of completing the assigned tasks. For the first three properties, 3D visuals are compared to 2D visuals, while the two types of visuals are assessed independently of each other as far as usefulness is concerned. Also three questions assess the degree of usefulness of three specific visualization techniques, including stacked balls representing how the demand nodes are served by certain devices in different time periods, how multiple devices serve demand nodes at one time period, and the cube-matrix representing how multiple devices serve demand nodes at different times of the day.

A total of 64 surveys (32 in each group, age range = 20 - 40) were completed by students in the Department of Geography and Earth Sciences at the University of North Carolina at Charlotte. In the interest of brevity, only overall evaluation results are reported here.

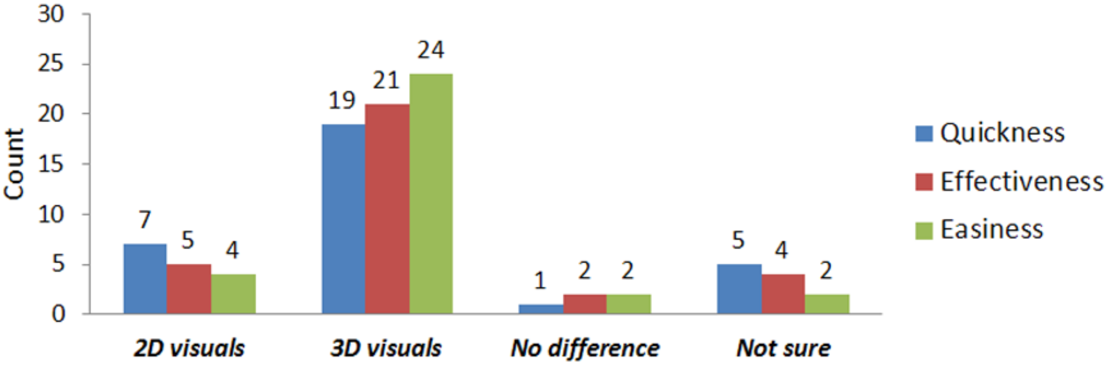
5.2 Evaluation Results

Pooling all responses together, 3D visuals are rated much higher than their 2D counterparts in terms of quickness, effectiveness, and easiness (Figure 12a). This also holds true when Groups 1 and 2 are examined separately (Figures 12b and 12c). The assistance of 3D visuals reduced completion time for similar task using 2D visuals. In fact, it is better by a 7% margin. 2D renderings offer a speed advantage in two tasks only, the most significant occuring in the task pertaining to space-time coverage using the cube-matrix construct. This particular construct has a richer information content but also requires more complex cognitive processing, which may explain the much longer time to complete the task. It should also be noted that the faster completion of assigned tasks does not lead to a lower quality of the responses and decisions; overall, no difference in accuracy can be discerned between situations where 2D or 3D visuals are used to complete the same tasks.

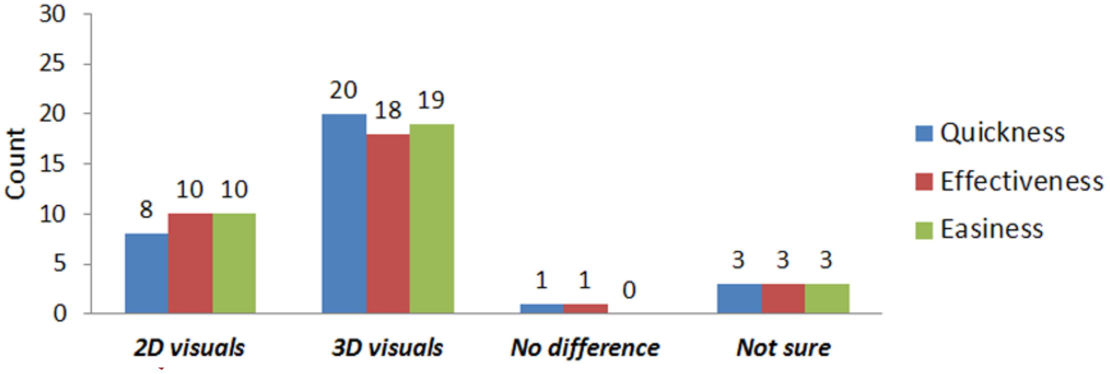
When respondents are prompted to evaluate the usefulness of 2D and 3D visuals independently of each other, the votes for agreeing or strongly agreeing that 3D visuals are very similar to those for 2D visuals (out of 64, 51 for 2D and 49 for 3D, Figure 13a). No significant differences exist either when respondents are segmented between Groups 1 and 2 (Figures 13b and 13c). It is worth noting that opinions on 3D visuals are more strongly positive than for 2D visuals. When usefulness is evaluated for specific types of visuals, these conclusions also carry over for the representation of device coverage over multiple time periods and cub-matrix representations (Figure 13). In contrast, visuals representing coverage by level of priority (as in Figure 8) are not found to be useful as frequently. Overall, respondents found 3D visuals to be useful to complete the assigned task.



(a) Pooled Sample

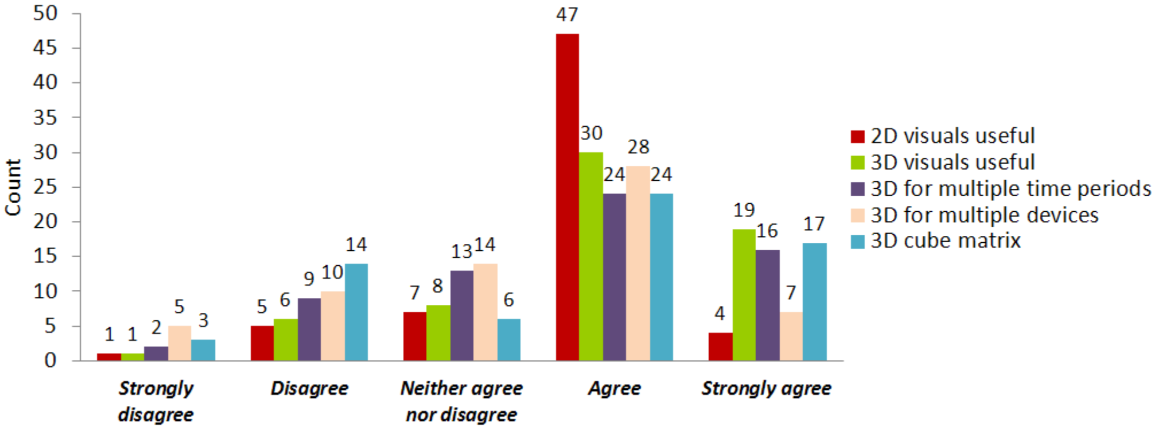


(b) Group 1 Respondents

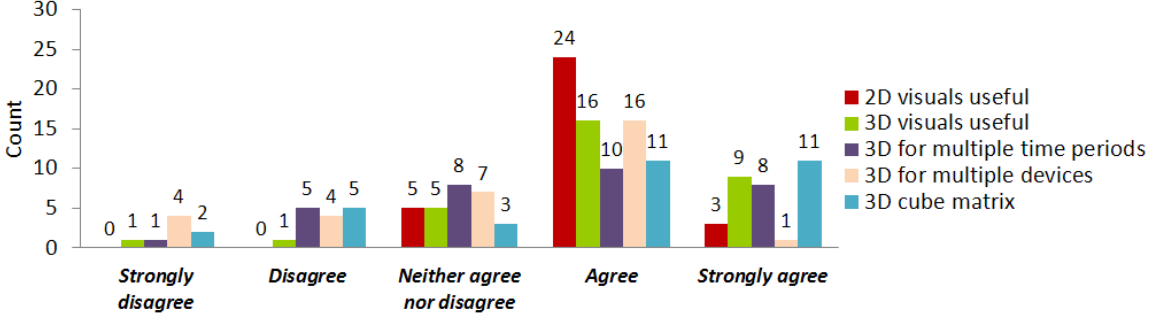


(c) Group 2 Respondents

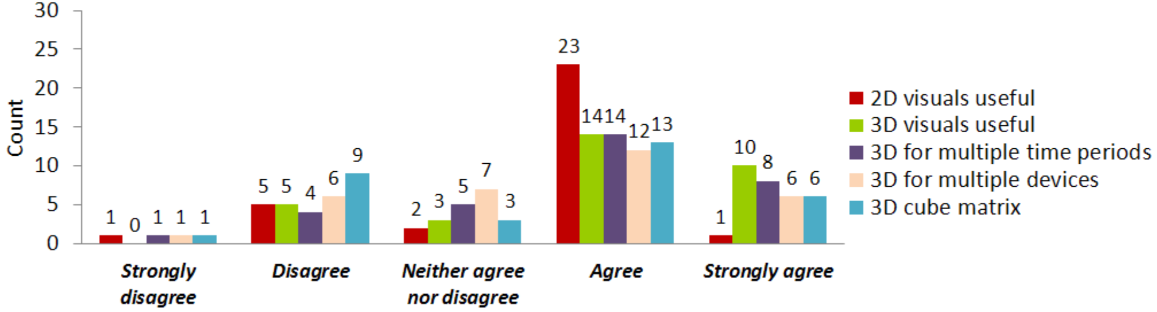
Figure 12: Overall evaluation results regarding quickness, effectiveness and easiness



(a) Pooled Sample



(b) Group 1 Respondents



(c) Group 2 Respondents

Figure 13. Evaluation of 2D/3D usefulness

5. Discussion and Conclusions

In this paper, we have discussed the visualization requirements of location planning in 3D indoor spaces. A number of innovative techniques were presented to facilitate the communication of results of location models in a 3D environment. The representations can be extended to other location models including the set covering problem (SCP), the *p*-median problem, the backup coverage location problem (BCLP), and variants of these models. We first compared and contrasted extensions of traditional 2D visualization techniques to display locational contexts and the spatial distribution of demand nodes and devices in 3D space, and illustrated the allocation or coverage using 3D spider maps and 3D network coverage in a GIS. The paper further suggested new 3D visualization forms called areal coverage and volume coverage to render information on the demand allocation and coverage through multi-story built structures traversed by hallways, passageways, staircases and elevators. A technique for visualizing the relationship of multiple devices serving multiple demand nodes was proposed, which can be applied to traditional coverage location modeling approaches. Also, space-time information on service demand and response times was accounted, which required novel 3D visualization techniques.

The visualization techniques suggested to support indoor locational planning in indoor spaces are not only technically implementable within a GIS environment, but also well received by users with regard to key properties of quickness, effectiveness, easiness, and usefulness, although they are generally found to be equally useful as their 2D counterparts. However, the proposed techniques share several shortcomings that are common to 3D visualization. The usability of 3D visuals for indoor visualization may suffer under increasing complexity (Worboys, 2011). There are different types of complexity involved, including: 1) indoor building complexity (shape, the number of floors, variation in vertical space) (Kim et al., 2014); 2) location problem size (number of demand nodes and devices); 3) temporal granularity (number of time windows). For instance, within the building featured in this paper, there are 316 demand nodes in total and, on average, about 60 demand nodes per floor. It is not a straightforward task to accommodate all the anticipated pieces of information in a single graph, even in this test building of rather moderate size. Further experiments will evaluate the merits of the proposed 3D visuals in the case of increasing levels of complexity, for instance through dynamic aggregation (Andrienko et al., 2008).

All 3D illustrations in the paper are displayed with a perspective, so that some objects far from the observer's point of view in a 3D scene may be hidden or obstructed by other objects in front or on top of them (Brooks and Whalley, 2008). Increase in the number of demand nodes may hamper visibility. Due to the short vertical distance between floors (about five meters for a typical building), the viewer may experience difficulties in distinguishing the objects belonging to one floor from another. One possible way of alleviating this problem is to amplify floor height enough to visually separate the objects on different floors, as it is done in Figure 11. This approach is not always effective and creates distorted spaces (St. John et al., 2001). Furthermore, the effect of perspective that makes objects in a far distance look smaller than their actual size is evident in all the representations. This is likely to increase the risk of misperceiving the properties of objects located further away. Similarly, the effect of illumination which is simulated by shades and unreal colors would induce wrong perceptions.

To address these challenges, an alternative consists in allowing users to interact with the results in a 3D, interactive environment (Wilkening and Fabrikant, 2013). Besides zooming in and out as in a 2D mapping environment, manipulations such as rotating, changing perspectives or angles, turning on/off different layers of objects (network, demand nodes by floor, by device or by priority level, etc.) are rather standard (See the sample animation available as supplemental material). More advanced interactivity such as customized one-click query, multiple dynamic or interactive windows (for viewing separate floors or time windows on demand), spatial summary or dynamic aggregation (similar to table summary, but using spatial components as aggregation units and automatically presenting summary results in display window, see Andrienko et al. (2008)), can enhance the functionality of the visualization system, particularly in order to cope with decision situations of greater complexity.

Our paper has provided a number of meaningful answers in addressing the research questions put forward in the introduction. Some of the traditional 2D cartographic displays have been ported to 3D environments successfully, including displays for locational contexts, demand and supply distributions, and canonical spider maps. For some other visuals, such as network-based spider mapping and areal coverage, the demand flows can be enhanced by color-coded links or graduated symbols to disambiguate the representation. As also echoed by Pouliot et al. (2013), transparency and color blending remain challenging issues in areal coverage displays when a polygon representing a room is covered by multiple devices. Volume coverage is an attractive adaptation to the three-dimensionality of indoor spaces, yet challenges remain to effectively represent complex coverage layouts (such as non-contiguity and non-compactness) as well as in the case of buildings with a large proportion of rooms without exterior walls. The paper also proposed several new visualization techniques to represent one-to-many relationships between demand nodes and devices. When the temporal dimension is brought into indoor locational planning, the imperatives to filter and communicate more information create complex representations. Stacked spheres depicting the multiple serving devices and arrays of cube-matrix for multiple time windows and multiple devices are novel elements in the proposed representations. These new visuals can become challenging when the complexity of the locational problem rises. Their structure can be simplified either by replacing the same pattern of stacked sphere or cube-matrix with simpler symbols which would be explained in detail in the legend, or by clustering these 3D visual structures and representing the clusters according to different levels of granularity of clustering.

The role of geospatial information technologies in the overall modeling process is well recognized. In this paper however, real limitations were encountered, particularly with respect to lightening, rendering, labeling, and transparency. The imperfection of the proposed visualizations implies the need for building interactivity or designing user interfaces into the modeling process. Greater benefits may ensue from a stand-alone system to support different stages of decision making, from the model-building stage to result representation, in which flexible and easy-to-use interactivity and user interface should be emphasized (e.g., Harrower and Fabrikant, 2008). Enabling turning-on/-off of different layers, defining the threshold value for visualizing and selecting individual objects (including demand nodes, devices and routes), and designing solution query to facilitate subset visualization (e.g. by floor, by building, or by device site) will form the basic aspects of such interactivity. Being interactive means, for example, that when a user clicks on a device, the system will display all the relevant information, such as the service performance, capacity, population served, and average total response time or network travel time. To ensure the success of users' interaction with the system, useful information that a decision maker could retrieve from the solution is also essential. The following properties derived from the solution are proposed. Based upon the relationship between demand and supply, average response time or travel time, and coverage/allocation changes among time windows could be generated for each demand node, while aggregated total demand and average response time or travel time are available to a specific device.

The various visualization forms presented in this paper can become the core elements of interactive visualization strategies. While 3D visualization is more complex that visualizing location modeling results in two dimensions, a broad collection of readily implementable techniques is available and their advantages were demonstrated. They offer a solid foundation for visual interactive modeling environments that will be more encompassing in the future. Advanced interactivity should also support sensitivity analysis for evaluating the solutions, and even the full-ranged modeling process, which would bring the system closer to the ideal visual interactive modeling environment.

More work is necessary to evaluate the proposed visuals comprehensively on pertinent audiences such as professional user groups (planners or modeling experts) in a real-world decision support setting (Andrienko et al., 2007). Common users are expected to have requirements that are quite different however, and further 3D visualization design work would be needed to meet the standards suited to this user group. For instance, a desirable enhancement may involve "pseudo" directional navigation from the user's location to the most accessible device via the layouts of devices (sphere symbols) and network by floor that are oriented to match the egocentric viewpoint of the user).

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