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Spatial subdivision of complex indoor environments for 3D indoor navigation

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ABSTRACT

As we realize that we spend most of our time in increasingly complex indoor environments, applications to assist indoor activities (e.g. guidance) have gained a lot of attention in the recent years. The advances in ubiquitous computing made possible the development of several spatial models intending to support context-aware and fine-grained indoor navigation systems. However, the available models often rely on simplified representations (e.g. 2D plans) and ignore the indoor features (e.g. furniture), thereby missing to reflect the complexity of the indoor environment. In this paper, we introduce the Flexible Space Subdivision framework (FSS) that allows to automatically identify the spaces that can be used for indoor navigation purpose. We propose a classification of indoor objects based on their ability to autonomously change location and we define a spatial subdivision of the indoor environment based on the classified objects and their functions. The framework can consider any 3D indoor configuration, the static and dynamic activities it hosts and it enables the possibility to consider all types of locomotion (e.g. walking, flying, etc.). It relies on input 3D models with geometric, semantic and topological information and identifies a set of subspaces with dedicated properties. We assess the framework against criteria defined in previous researches and we provide an example.

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1. Introduction

Compared to the outdoor where there are pavement and roads to organize navigation, buildings' interior has no formal classification of where is navigable or not (Becker *et al.* 2009, Walton and Worboys 2012). Indoor navigation will then only depend on whether there is free space and whether the moving subjects can fit in such space or not. Furthermore, public buildings such as train stations, hospitals and airports, which are supposed to shelter important amount of people and different services, are often big in scale and structurally complex. It then becomes a non-trivial task to find the way to a part of interest in such buildings, despite indications placed on site to help. In more critical scenarios such as fire, earthquake and other catastrophes (storms, terrorist attack, etc.) where a quick and reactive emergency response is required, a smart 3D indoor navigation system becomes a vital tool to support the potential victims as well as the first responders (firemen, police, etc.) (Kwan and Lee 2005).

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To enable such efficient and relevant indoor navigation systems, a 3D model representing the structuring of the space and containing semantic information of the elements it contains are needed, among several other components (Nagel *et al*. 2010, Brown *et al*. 2013, Russo *et al*. 2014, Zlatanova *et al*. 2014). In that sense, precise and detailed 3D description of complex indoor environments are offered by few standards that arise from Building Information Modelling (BIM) and Geographic Information Systems (GIS) fields. The most renown ones on both sides are geometric and semantic oriented and are the Industry Foundation Classes (IFC) from Building SMART International (2013) for BIM and the City Geography Markup Language (CityGML) from Open Geospatial Consortium (2012) for GIS. Additionally, they allow also to describe topological relationships between the building components. More recently, a standard named IndoorGML (Lee *et al*. 2014, Kang and Li 2017) and specially dedicated to 3D indoor navigation has been introduced. Thereby, those standards stand as a precious support to build smart indoor navigation tools.

Nonetheless, the spatial description provided by the standards is not readily adequate to fine-grained indoor navigation. Indeed, the indoor spaces in those models originally correspond to the layout provided by the structural components, meaning that a space is delineated by the walls, floor and ceiling surrounding it (Diakit´e and Zlatanova 2016). A consequence of such representation is that huge spaces such as halls in airport or train stations, could result in one single space entity for example. Therefore, it would be hardly possible to guide a user to a specific part of that space. Furthermore, despite the growing availability of those 3D models, most of the existing spatial models for indoor navigation rely on 2D and 2.5D representations of the indoor environment and focus on the generation of simple navigation paths, mainly for pedestrians. The few works relying on the 3D models generally consider empty buildings and allow in the best case to navigate from one room to the others. This is motivated by the assumption that human senses will compensate the missing information (positioning, obstacle avoidance, etc.), but this is a serious limitation in critical situations (emergency intervention) and for other types of locomotion (flying, driving, etc.).

In this work, we introduce the Flexible Space Subdivision (FSS), a framework that provides an automatic spatial partitioning scheme that fully considers the complexity of the indoor environment. It leads to 3D subspaces allowing to identify the free and non-free indoor spaces, based on the objects populating them and the activities that they host. The framework is flexible enough to consider the static as well as the dynamic changes of the environment. The produced subspaces are semantically meaningful and correspond to points of interest (POIs) or hosts for position nodes of a navigation graph. Thanks to their spatial linking, it is possible to generate navigation graphs that can reach up to a specific object inside a given room. Furthermore, combined with the proper inputs, the subspaces embed enough information to allow customized path derivation for the users. This opens possibilities for advanced features such as cognitive-based navigation; however, we limit the scope of this paper only to criteria based on the locomotion type and the space needed by a user. In order to show the applicability of the subdivision process, a use case on a BIM model is presented and discussed.

In Section 2, we discuss the works related to subdivision of indoor spaces for navigation. In Section 3, we detail the different principles of the FSS framework. The spatial interactions resulting from the sub-spacing process are analysed in Section 4.

Finally, a use-case analysis is elaborated in Section 5, before we conclude and discuss future improvements in Section 6.

2. Related work

Space subdivision for the purpose of indoor navigation has been regularly investigated in the literature. The common approach is using the well-defined building construction spaces like rooms and corridors, establishing the connectivity between the spaces utilizing their semantics and applying Poincaré Duality to derive navigable network (Lee and Lee 2001, Lee 2007, Stoffel *et al*. 2007, Boguslawski and Gold 2009, Boguslawski *et al*. 2011). In this context, a number of semantic models have been developed to support the identification of spaces and the creation of the navigation network (Richter *et al*. 2009, Liu and Zlatanova 2011, Worboys 2011, Isikdag *et al*. 2013). Specific constraints and scenarios such as obstacles avoidance, navigation of disabled people or indoor evacuation were also investigated (Swobodzinski and Raubal 2009, Liu *et al*. 2015). All those works have provided high level of automation especially for regular buildings. Interesting reviews can be found in Afyouni *et al*. (2012) and Zlatanova *et al*. (2014). However, these approaches, in addition to relying on 2D representations (Yang and Worboys 2015) or assuming completely empty indoor spaces when they use the 3D models, they do not consider any further subdivision of the indoor spaces that are physically defined in their input models.

The problem of additional subdivision has been motivated by the consideration of the functional and organizational aspects of indoor spaces in addition to their structural aspects (Richter *et al*. 2009, 2011). Furthermore, the need to provide more accurate identification of parts of rooms and corridors discussed by Goetz and Zipf (2011) and Sithole and Zlatanova (2016) also helped to emphasize the need, mainly for large public buildings such as airports, offices, hospitals, etc. The authors pointed out the limitations involved in considering big spaces as single space units during a navigation. Such spaces might need to be delineated either because of human (e.g. perception) or environmental (e.g. unsafe area), technological (e.g. sensors) or functional criteria (e.g. waiting area) for example. In consideration of all those parameters, the concept of sub-spacing has been adopted in the IndoorGML standard as well (Lee *et al*. 2014). Nevertheless, neither subdivision guidelines nor the spatial properties of the eventual subspaces have been addressed in (Goetz and Zipf 2011), the focus being put on extraction of routing graph with obstacle avoidance.

In Becker *et al*. (2009), the authors proposed a framework for semantic space identification which allows to link conceptually different subdivisions of indoor space in a multi-layered representation. These indoor space subdivisions can be guided by topography, security, sensor, property, etc. considerations, which can be independent from building structure (for example, Wi-Fi signal, RFID tag system). Applying Poincaré Duality layers, a network can be derived for each layer and between the layers. The framework however does not provide a guiding mechanism to create the subdivisions. Khan and Kolbe (2013) later relied on that framework and proposed a sub-spacing approach of indoor 3D models, but they focussed on graph extraction and considered unfurnished indoor environments. Afyouni *et al*. (2010) also proposed a spatial representation of indoor spaces with focus on the possibility of precise sensor coverage estimation and fine indoor localization. The functional aspect of the indoor objects is considered but because of the focus on the location precision, the approach is based on a regular grid subdivision of 2D floor plans similar to the work of Li *et al*. (2010). Therefore, the model is limited to floor-related locomotions (e.g. walking) and adopts a computationally expensive approach, as stated by the authors.

Another framework for indoor subdivision is presented in Zlatanova *et al*. (2013), which takes into consideration the building environment, agents using the environment, the targets of interest and the events that might impose changes. Even though the framework proposes a clear classification of the different parameters that may be involved in the design of an automatic subdivision approach, the characteristics of the subspaces and their interaction are not addressed. An application of the latter framework is presented in Krüminaité and Zlatanova (2014) where the authors propose and test a method to delineate functional spaces, which are used to specify more precisely indoor navigable areas. But here again, the work is oriented on 2D indoor representations with a focus on human perception of the space.

In summary, the need to exploit the wide potential of 3D models, to consider the objects populating the indoor spaces and their functions and to perform further subdivision of the spaces based on relevant criteria is clearly acknowledged in the existing literature. This would enable the possibility to consider the global complexity of the indoor environment and compute paths for any type of locomotion, in order to target any indoor objects. This would also enable the ability to consider the accessibility of those objects for the specific navigating clients. However, there is, to our best knowledge, no 3D compatible approach that practically addresses the aforementioned space subdivision in an automatic fashion while providing a clear definition of the resulting subspaces and their interactions. We therefore introduce a framework that considers the 3D configuration of the indoor environment with the objects it may contain, and perform an automatic subdivision of the space by relying on the indoor objects and their functions.

3. Principles of the FSS framework

The purpose of the FSS framework is to provide a spatial abstraction of the 3D indoor environment that fully reflects its complexity so that suitable navigational areas can be automatically identified for a given user. The output of the framework is meant to serve as a support for adaptive route estimation and path planning in buildings. In order to understand the principles on which the framework relies, it is necessary to discuss few observations regarding the indoor environment, and analyse them from a navigational point of view.

Depending on the types of building, the indoor environment is different in size, spatial configuration and purpose. It contains many different objects that, for the purpose of our framework, we will distinguish on the basis of their mobility, meaning their ability to change independently their location. We introduce the following notions:

- *static* (*S-objects*) as objects that can neither move by themselves nor be moved (e.g. construction elements such as walls, columns, stairs, etc.);
- *semi-mobile* (*SM-objects*) that cannot move by themselves but can be moved (e.g. furniture, machines, etc.);

- *mobile* (*M-objects*) that can move by themselves (e.g. humans, animals, autonomous robots, etc.).

The above-defined objects influence the indoor environment and therefore the navigation. Generally, they can play several roles in the navigation process: a role to be navigated (*agent*), a role to be the start and target location (*resource*), and a role to be an obstacle. Although M-Objects can freely move, they can also adopt a stationary position for specific purpose. Under such situations, we will refer to them as *M_{St}-objects*.

The S, SM and M_{St}-objects guide the space subdivision independently of the building type. They are used to define geometry, semantics and topology of the subspaces that they occupy physically or require for their access or usage. Their placement determines the space that is free for navigation or that has to be avoided. For example, a room can be judged unsuitable for navigation due to its high M_{St}-objects occupancy or due to the nature of its SM-objects (e.g. flammable objects under emergency situation like fire).

On the basis of those observations, our framework proposes a subdivision of the indoor environment as follows:

Definition 3.1 **(The subdivided indoor environment)** *I_{sub} is a spatial partitioning of the indoor environment such that $I_{sub} = (O, F, R)$, where O stands for object space (O-Space), F for functional space (F-Space) and R for remaining space (R-Space) and*:

(1) *O-Space* is the subspace occupied by SM-objects; it is non-navigable.
(2) *F-Space* is the subspace dedicated to the usage of SM-Objects or activities of M_{St}-objects; it is navigable under conditions.
(3) *R-Space* is the space available for navigation; it is freely navigable.

The O, F and R spaces are non-overlapping and compose a complete subdivision of the indoor environment. Figure 1 illustrates the configuration of a room and the subspaces

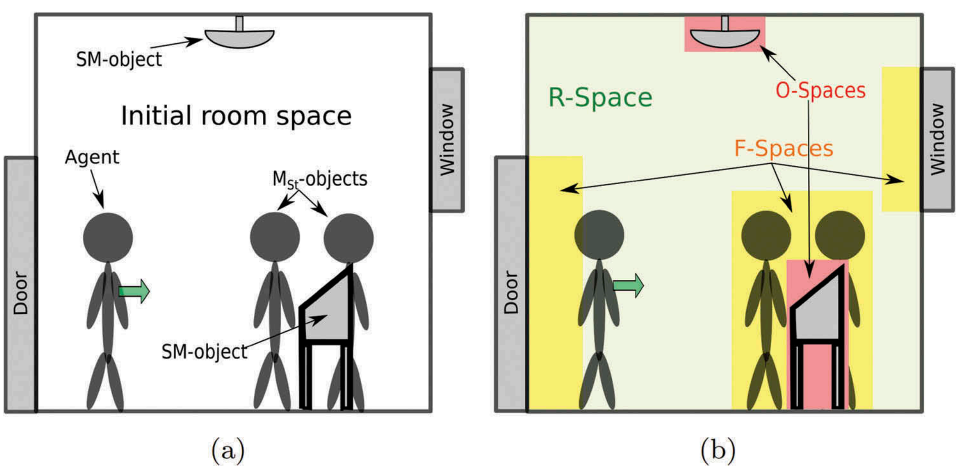

Figure 1. Different subspaces created during the FSS. (a) A populated room (the green arrow symbolizes an M-object in motion). (b) Subspaces generated on basis of SM and M_{St}-objects: O-Spaces (red), F-Spaces (yellow) and R-Space (light green).

resulting from the FSS. It identifies the O-spaces first, then the F-spaces related to the function of the SM-objects and the activities of the M_{St}-objects populating the indoor environment.

Each subspace is geometrically defined, possesses semantic information and interacts with its surrounding subspaces (topological links) through adjacency relationships. From a navigational point of view, each subspace type has its own specificities in terms of size, availability and accessibility as well. Furthermore, on the basis of the objects they are related to, some subspaces require less update, thus are convenient for storage and others require a more dynamic estimation. We discuss the specificities of each subspace in the following subsections, and we detail their spatial interactions in the next section.

3.1. *Object spaces (O-Spaces)*

In order to identify the free spaces that are really suitable for indoor navigation, it is necessary to first identify the spaces occupied by the SM-objects populating the indoor environment. That binary partitioning of the spaces into navigable and non-navigable spaces motivates the creation of O-Spaces. The latter do not concern the S-objects because they are meant to permanently occupy the space where they are located, thus they are, by default, excluded from the potential free space.

An O-Space corresponds to the space that the SM-objects occupy physically, and it is the first subspace to be created in the FSS framework. The geometry of an O-Space entirely depends on the one(s) of its related object(s), similarly to its semantic attribute. It can be a **POI** for a navigating agent, but due to the notion of physical occupancy implied, an O-Space is by definition a non-navigable subspace.

Figure 2 illustrates different possible geometries of O-Spaces for a furnished room. At their finest representation level, the O-Spaces directly correspond to the original shapes of their objects, as it is the case in Figure 2(b). Nevertheless, coarser geometries can be used to represent the O-Spaces as well (see Figure 2(c)). Indeed, coarser representations may be more adapted for vector models because the shape complexity of the SM-object can be very elaborated. A direct consequence of such simplified geometries is the encompassing of part of the immediate free space surrounding the SM-objects, as well as intersections between the O-Spaces (Figure 2(c)). While the former issue can

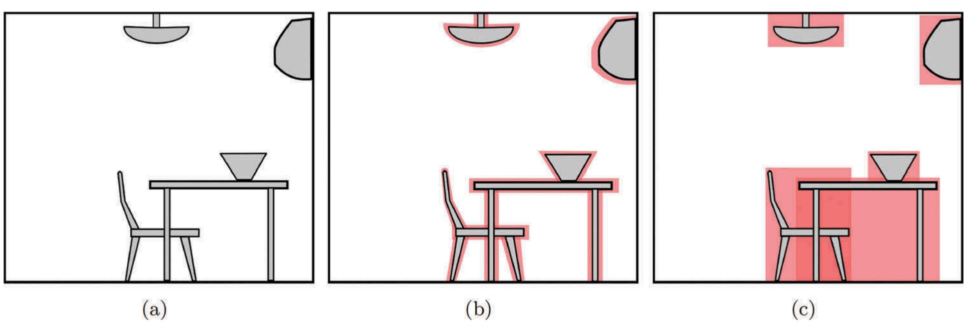

Figure 2. Creation of O-Spaces (light red). (a) A room with several equipments. (b) O-Spaces with refined geometries. (c) O-Spaces with coarse geometries.

be reduced by making coarse O-Spaces fit to their contained SM-objects as much as possible, the latter issue can be solved by processing to aggregation of the intersecting subspaces, as discussed later in Section 4.1.1.

Since their non-navigability is clear, the semantic information attached to the O-Spaces should be only related to the elements they encompass. Therefore a list of relevant criteria of the corresponding SM-objects can be determined (e.g. name, description, weight, etc.). A reference to the objects in the input BIM model can also be considered. Furthermore, O-Spaces are meant to be stored and directly excluded from the navigation path estimation. This is made possible by their unlikelihood to change position unless they are moved, case in which they fall into another subspace category related to the activity of their users. The creation of O-Spaces provides a first binary partitioning of the indoor structural spaces into navigable and non-navigable spaces. Now, we will consider the functional occupancy of the free spaces involved by the interaction between the elements populating the indoor environment.

3.2. *Functional spaces (F-Spaces)*

The notion of functional space is widely discussed in recent conceptual frameworks for indoor spaces organization (Richter *et al*. 2011, Krüminaité and Zlatanova 2014, Zlatanova *et al*. 2014). The concept is consequently a very relevant criterion that has to be considered in the subdivision.

3.2.1. *Definition of an F-Space*

An F-Space is a subspace allowing to define an area of function necessary to perform specific tasks or to reach and interact with an SM-object (see Figure 3). While the O-Spaces focus on the physical aspect of the SM-objects, the F-Spaces consider mainly their functions and the space occupancy induced by the M_{St}-objects. They are intended to provide localization and destination nodes to the navigating agents. We distinguish two sorts of F-Spaces:

- a *fixed* one (*F_f-Space*) needed for a direct interaction with an SM-object (e.g. ordering on a coffee machine);
- a *monitored* one (*F_m-Space*) for the activities of M_{St}-objects (e.g. informal gathering for discussion).

The first type is the regular functional space implied by the direct use of an SM-object. It is fixed in the sense that it can be determined a priori, independently of its actual physical occupancy and is always attached to the SM-object it is related to. For those reasons, F_f-Space should be stored similarly to O-Spaces. Figure 3(a,b) illustrate the representation of such subspace for features like openings, for which the function requires a directed movement in the space. Figure 3(a) shows also an F_f-Space attached to the O-Space of a coffee machine representing where an M_{St}-objects shall be positioned to operate on it. In Figure 3(b), although the function of the board is purely informative, it allows to give a location to the space dedicated to meetings. The geometry of such F_f-Space can be estimated empirically or heuristically, by considering the specificities of the function of the related SM-object. For Example, Figure 3(c) shows a case where both a human working on a desk and a drone performing operations on the air conditioner fit into their respective F_f-Spaces. It is noteworthy to mention that some SM-objects may have several functions (e.g. a table can be designed to handle dinners as well as pool game). But even in such cases, the activities closely related to an SM-object are generally held in its immediate surrounding. Therefore, an F_f-Space can still be estimated, for example, based on the most common or most spacious activities.

The F_m-Spaces are meant to represent the activities of M_{St}-objects in the indoor environment. This is motivated by the fact that M-objects become static generally for specific purposes and thereby turn the subspace they occupy into a functional space dedicated to their activity. They can then be joined or left by other M_{St}-objects interested in them or their activity. Contrarily to the F_f-Spaces, the location and size of such subspaces can hardly be known a priori as they are not directly related to SM-object, they can happen anywhere in the free indoor space and they involve a potential change of spatial occupancy in time. Thus, F_m-Spaces will change accordingly and for those reasons, they are not suitable for storage but should be monitored at the time of navigation instead. Figure 3(d) illustrates F_m-Space for a group of people holding a discussion in still position. Figure 3(e) shows a case requiring the formation of an F_m-Space representing a queue because someone ordering a coffee is already occupying the F_f-Space.

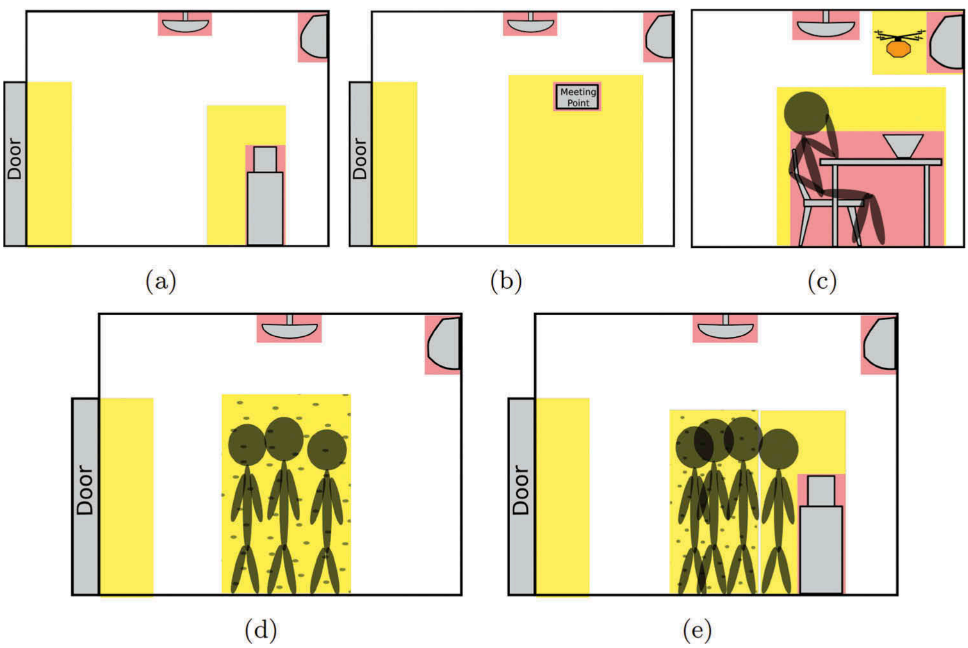

Figure 3. F-Spaces (yellow) in FSS. (a) A door having an F_f-Space in the direction of its opening movement and a coffee machine having one in the direction of its potential use. (b) An F_f-Space attached to a board indicating a meeting area. (c) M_{St}-objects using SM-objects (a human working on the desk and a drone maintaining the air conditioner) and their corresponding F_f-Spaces. (d) An F_m-Space (with dots) representing an informal gathering of M_{St}-objects. (e) F_f-Space for the coffee machine and F_m-space for the queue related to it.

Consequently, due to the large variety of possible functions and activities, the semantic information attached to the F-Spaces should help supporting advanced analysis. More precise semantics can be used to clearly specify the type of occupancy expected in F_f-Spaces (e.g. check-in area) or involved in F_m-Spaces (e.g. coffee-machine queue). This can be used to decide either an agent interested in an SM-object should be navigated towards it directly or towards the end of the queue if any.

3.2.2. *Navigability issues of F-Spaces*

The navigability of an F-Space depends mainly on its type and also its interest for the navigating agent. An F_f-Space is by definition navigable as it is not necessarily occupied at the time of navigation. However, it is not a preferred subspace for navigation when there is R-Space available and suitable (cf. next subsection). Therefore, approaches that include F_f-Spaces only when they offer a more satisfactory results to the constraints of the navigating agent can be considered. Regarding the F_m-Space, they should always be considered as obstacle, as they stand for a physical occupancy, unless they are targeted in the navigation. In the latter case, they will host the destination node of the agent. Particular situations could involve the need to cross F_m-Spaces (e.g. because they may consequently occlude the space on a path). For example, a queue in front of a coffee machine could cut a corridor in two parts. In such situations, the assumption of the possibility to cross the F_m-Space will rely on the M_{St}-objects occupying it (e.g. humans could slightly move to let the agent pass through).

3.3. *Remaining free space (R-Space)*

The R-Space is by definition an obstacle-free subspace of the indoor environment, in which all types of locomotion are allowed as long as they are suitable for a given agent and the latter can fit in it. Its availability will therefore depend on the other subspaces already identified in the subdivision process. Similarly to the F-Spaces, we identify two types of R-Spaces:

- a *fixed* one (*R_f-Space*) corresponding to the remaining space after subtracting the O-Spaces and the F_f-Spaces;
- a *monitored* one (*R_m-Space*) corresponding to the remaining space after subtracting the F_m-Spaces from the R_f-Space.

It can be seen that this categorization results mainly from the effect of the F-Spaces on the indoor environment. This makes the R_f-Spaces adequate for storage. Since the activities implying the creation of F_m-Spaces will be necessarily localized in them, routes taking into account such activities will therefore rely on the R_m-Spaces.

Figure 4 illustrates an example of R-Spaces resulting from the scene of Figure 3(b). The R_f-Space initially considered the different O-Spaces, the F_f-Space of the door and the one of the coffee machine (Figure 4(a,b)). But the two pedestrian agents are not yet considered in the subdivision as they are dynamic in location (M-objects). Once they reach the coffee machine and become static (M_{St}-objects), some of them fit in the predefined F_f-Space of the coffee machine (one person in this example) and the rest will form a queue. The latter results in an F_m-Space which will change according to the

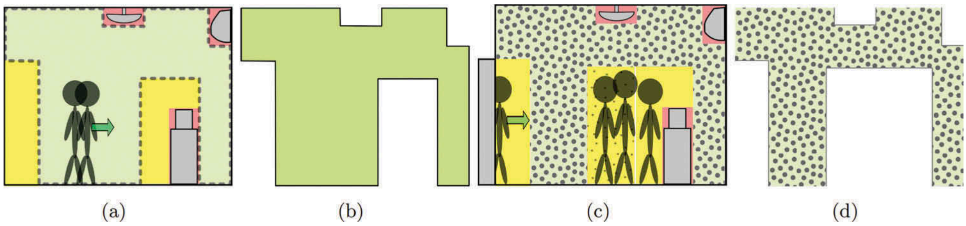

Figure 4. R-Spaces of a room (light green). (a) The R_f-Space (blank space with dashed boundary). (b) It does not consider the moving agents. (c) The R_m-Space (white and dots). (d) It considers the M_{St}-objects through their F_m-Space.

crowd (Figure 4(c)). Thereby, the R_f-Space of the room is reduced to the R_m-Space illustrated in Figure 4(d). R-Spaces are then a good indicator of the occupancy of the indoor spaces, as their availability will reflect the possibilities to navigate through or perform a task inside that environment.

3.4. *Agent spaces (A-Spaces)*

The agents are the main dynamic actors considered in the FFS. The A-Spaces aim at considering their dimensions and the spatial clearance they need during the estimation of a path, and also during the navigation process. *An A-Space is therefore defined as a clearance space that encompasses one or several agents, as well as the SM-objects they carry, if any*. While its geometry helps to know what the dimensions of the agents are, its semantic helps in determining specificities such as flexibility or limitation of movement of the agent. It intervenes at three stages of a navigation process:

(a) at the origin, for the estimation of the spatial constraint required by the agent(s),
(b) at the path computation, to select only navigable cells in which the agent(s) can fit,
(c) at the destination for the evaluation of the accessibility of the resource or place.

Figure 5 provides an illustration of such A-Spaces. The geometry of an A-Space can be of minimal size, considering the minimum incompressible size of the agent or it can be

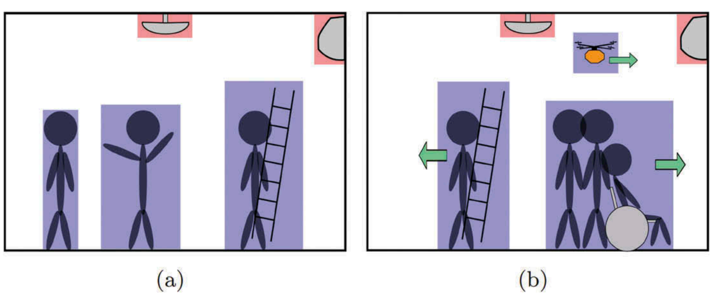

Figure 5. Different A-Spaces for different moving subjects. (a) From left to right: a minimal A-Space for a pedestrian, an A-Space considering the motion abilities of the agent and a final one including the tool carried by the agent. (b) A-Spaces of multiple agents depending on their destination.

large enough to anticipate the motion possibilities and the carried objects (Figure 5(a)). Since the suitability of the paths will rely on it, the risk in relying on a minimal size is to allow paths that are too narrow while in the contrary, convenient paths could be discarded. Several studies dedicated to humans' perception of the space reveal that there is a need to consider more space around them than the actual physical space that they may occupy (Hall 1966, Sommer 1969). Thus, such studies could be used, e.g. to define A-Spaces for pedestrian agents, along with consideration of specific security distance between the agents and targeted indoor objects. An interesting overview regarding constraints on human way-finding can be found in Krüminaité (2014) (Section 2.1).

Furthermore, an A-Space can describe a group's navigation, assuming that the agents in the group are spatially close and are willing to navigate towards the same destination. Based on the constraints that will be specified for the group, a more adequate path can then be considered. An example is illustrated in Figure 5(b), where a single A-Space encompasses three people including a disabled one on a wheelchair. Since they are all heading together to the same destination and knowing that one of them has a hard accessibility constraint, adequate route for disabled people and spacious enough for the three of them will be sought in the indoor space. In case of strong difference of scale or nature of locomotion, the use of a distinct A-Space is better. It is the case for example of the group of people and the drone. The latter being a flying agent, smaller compared to humans, its spatial and navigational constraints are very different from pedestrian ones. However, if they are meant to navigate together (e.g. the drone guides a group of people), then a route satisfying the most important constraint could be determined. A different A-Space is needed for the pedestrian carrying a ladder as well, since (s)he is taking a different direction.

4. Spatial interaction between the subspaces

The FSS framework involves maintenance of 3D spatial relationships induced by the subspaces' interactions. We can distinguish two categories of spatial interactions:

- one involving conflicting situation between the subspaces;
- one related to their neighbouring links.

Those categories are further discussed in the following subsections. We will also discuss the specific case of the A-Spaces in relation to the subspaces of the subdivision.

4.1. *Conflicting situations*

The subspaces resulting from the framework correspond to a partitioning of the indoor structural spaces. This means that any subspace created is a part of that limited space initially available. Therefore, there may be situations leading to spatial conflict between them when it comes to their creation. The two main subspaces concerned are the O-Spaces and the F-Spaces. There is no conflict possible between the two types, because O-Spaces, as physically occupied spaces, have always priority on F-Spaces. However, O-Spaces or F-Spaces may face conflicting situation between them. In the case of the O-Spaces, the conflicts can be solved by aggregation operations and in the case of the F-Spaces, either aggregation is considered or priority rules between the subspaces.

4.1.1. *Aggregation of O-Spaces*

SM-objects are implicitly related by their nature, their functions and their positions in the space. For those reasons, they can be gathered and considered as belonging to a same group based on two types of criteria: the geometric one, related to their spatial placement and the semantic one, related to their nature and function.

The geometric-based aggregation considers the spatial proximity of a set of SM-objects. Two SM-objects which are close enough are then aggregated under the same O-Spaces. The intersection between O-Spaces is one clear sign of their closeness, as illustrated in Figure 2(c). Therefore, such configurations directly lead to their aggregation in the FSS framework. The resulting O-Space encompasses entirely the corresponding SM-objects as shown in Figure 6(a). A closeness parameter could also be determined by computing the shortest distance between two vertices of the tested O-Spaces, in a constrained direction (e.g. using the minimum translational distance approach (Cameron and Culley 1986)). A threshold could then be determined based on the A-Space of an agent. Since spaces where the latter fits are important during the navigation, O-Spaces can be aggregated if their separating space is not enough to let the agent go. Figure 6(b) illustrates that the chair is not aggregated with the table, because the agent can fit between them.

The semantic-based aggregation considers the nature and the purpose of the SM-objects in order to group them. For example, a sofa, a couch and a table considered together may refer to a living room furniture; a chair, a table and all the objects on it may be considered as a working desk, etc. Such rich semantic attributes, if available, should be kept by the O-Space resulting from an aggregation. If the O-Space of a 'chair' is aggregated to the O-Space of a 'table', a list of the information related to 'chair' and 'table' should be maintained or reference to them provided in their input. The semantic attached to the resulting O-Space can then be, e.g. 'chair+table', or 'desk', etc.

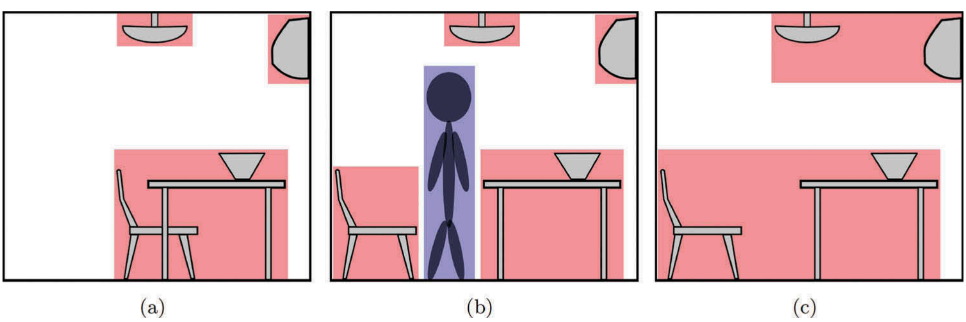

Figure 6. Several scenarios of O-Spaces' aggregation. (a) The table, the chair and the vase are aggregated. (b) Only the table and the vase are aggregated, because an agent can fit between them and the chair. (c) Aggregation of the table, the vase and the chair (desk objects), and another aggregation of the lamp and the air conditioner (electrical equipments), leading to a substantial loss of navigable space.

However, because the O-Spaces represent physical occupancy, the use of geometric criteria for aggregation is more relevant. Indeed, gathering SM-objects based on semantic criteria may lead to the encompassing of substantial free spaces as shown in Figure 6(c). But combined with the geometric criteria, more optimal aggregations can be made, e.g. aggregation of close SM-objects sharing similar purposes. For that last type of operations, it is noteworthy to mention that the semantic level of the actual standards (BIM or CityGML) are not yet elaborated enough to allow their stable implementation.

4.1.2. *Aggregation and priority rules between F-Spaces*

F_f-Spaces are closely related to the O-Spaces' aggregations. When these latter are based on closeness and similarity of purpose of the SM-objects, it also makes the definition of an adequate common F_f-Space easier. In the case of two SM-objects with independent F_f-Spaces, there is no possibility of volume intersection between them because they rely on the free space available and the last one generated have to deal with the space left by the first one. However, since the F_f-Spaces stand as access points for their SM-objects, there is a need to define priorities among them.

For that purpose, weights can be attributed to the SM-objects based on their need, frequency of usage, etc. For example, the F_f-Space of a working desk is likely to have priority on the one of a nearby cupboard. In situations where the weights are similar and the SM-objects spatially close, their aggregation under a common F_f-Space can be considered. The latter will then contain functional information of both resources and any agent targeting one of them can be guided there.

Regarding F_m-Spaces, their aggregation depends on the precision of the monitoring techniques used. In general spatial closeness is likely to end up in an aggregation of all the concerned M_{St}-objects. However, if more discriminative features can be identified among them, they can result in separated F_m-Spaces and therefore priority rules can be defined (e.g. F_m-Space for the bigger group in priority, etc.).

4.2. *Neighbouring relationships*

The spatial relationships are critical information in the FSS. Here also, the relationships between the fixed subspaces can be stored and those related to the monitored ones need to be determined at the navigation time. Furthermore, because we consider the whole space in 3D, one subspace can have several different neighbours on a same side.

An O-Space is spatially related to R-Spaces (of all type) and/or F_f-Spaces. Figure 7(b), illustrates an example. Due to the aggregation involved in their creation process, they do not have direct contact with other surrounding O-Spaces. The spatial link with the R-Space is a critical piece of information when there is a need to generate an F_f-Space for the SM-object(s) represented by the O-Space. Therefore, if there is no spatial link with an R-Space from any side of the O-Space (e.g. because it is surrounded by the F_f-Spaces of other SM-objects), it can be assumed that the functional use of the targeted resources cannot be satisfied for a given agent. Consequently, when there is a spatial link, the area of contact between the two types of subspace can also give information about the suitability of the F_f-Space that will be generated (e.g. not high enough, not large enough, etc.). The spatial link with an F_f-Space also provides important information

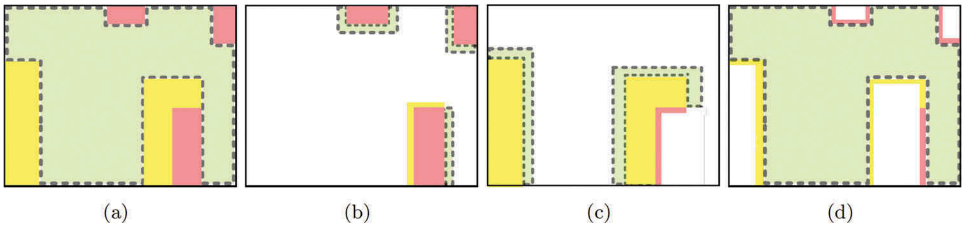

Figure 7. Interaction between the (fixed) subspaces. (a) Three O-Spaces, two F_f-Spaces and one R_f-Space. (b) Links for the O-Spaces, (c) the F_f-Spaces and (d) the R_f-space.

during the navigation process. For example, it gives an insight of the functional side of a resource (e.g. a ticket machine), or it tells the parts of the SM-object that are already occupied. An O-Space could also be spatially connected to the F_f-Space of another O-Space. In such case, the side of the spatial link becomes inaccessible for a given task, unless the SM-object has priority on the other which the F_f-Space is originating from.

An F_f-Space, as illustrated in Figure 7(c) can be spatially linked with O-Spaces, R-Spaces (of all type) or other F_f-Spaces as well. The most important links are those with the R-Spaces, since the accessibility of the F_f-Space by an agent will depend on them. The links with other O-Spaces than its original one means either that those O-Spaces have no F_f-Spaces or that the considered SM-object has priority on them.

An R_f-Space is generally linked to all the fixed subspaces in its surrounding (Figure 7(d)), unless these latter are covered entirely by other fixed subspaces (for example an O-Space entirely covered by an F_f-Space). Being the space where all types of locomotion is allowed and where navigation is possible for all agents, its spatial links allow to parametrize the navigation itself (e.g. the walk-able surfaces detection based on the links between R-Spaces and the floor).

Regarding the monitored subspaces, the R_m-Spaces can be spatially linked to all subspaces, while F_m-Spaces can only be linked to R_m-Spaces in which they are necessarily located, thereby having indirect links with the rest of the subspaces.

4.3. *Relations between the A-Spaces and the other subspaces*

As mentioned earlier, the A-Spaces are not part of the spatial subdivision and provide just assistance in estimations related to the navigation process. In that sense, an A-Space may have impact on O-Spaces only if its size is considered to decide whether two resources should be aggregated, as illustrated in Figure 6(b).

F-Spaces are the main subspaces than can be affected by the A-Spaces because information from the latter can be used, for example, to predefine adequate F_f-Spaces for SM-objects. Inversely, comparing A-Spaces and F_f-Spaces can reveal if the agent is guaranteed to fit (e.g. for F_f-Spaces of openings, etc.). Additionally, F_m-Spaces can be updated based on A-Spaces, as illustrated in Figure 8. Because there is an F_m-Space between the R_m-Space and the F_f-Space of the coffee machine (symbolizing the presence of M_{St}-objects queuing), the agent is navigated towards the boundaries of the F_m-Space (Figure 8(a)) and the size of the latter will be updated accordingly (Figure 8(b)).

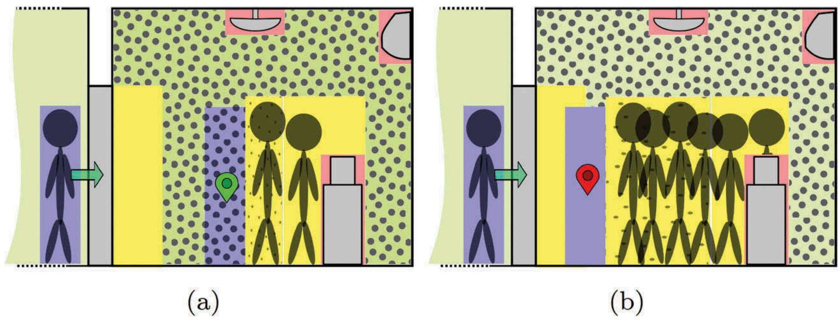

Figure 8. Accessibility derivation based on the A-Space. (a) There is possibility to make room spacious enough for the agent at the destination (green point). (b) Due to the crowd, the F-Space increased and the agent is not guaranteed to fit in the space at the destination (red point).

Those changes on F-Spaces affect the R-Spaces, determining the space remaining for further activities. For example, the R_m-Space in Figure 8(b) reveals that there may not be enough space for an agent after checking its A-Space at its destination. An alternative in such case could be: either to guide the agent towards the F_m-Space anyway or towards the closest navigable subspace to the resource where the A-Space fits. The first decision assumes that the crowdedness can be rearranged (e.g. in case of human) and the second one is more adapted for sensitive navigation.

5. Data model and use case example

5.1. *Example of a data model*

The FSS framework can fit in existing data models such as IndoorGML (Lee *et al.* 2014). Although it will require a slight extension, the actual version of the standard includes necessary mechanisms to implement the FSS properly. Figure 9 illustrates the UML diagram that integrates the subspaces resulting from the framework to existing classes of IndoorGML. Only the fixed subspaces are considered as they are the one that will be stored. IndoorGML being based on a cellular modelling of the indoor spaces, each subspace is a generalization of the *CellSpace* class which can be defined as *Navigable* or *NonNavigable*. The standard considers several other semantic classes related to indoor navigation as well (e.g. different types of spaces such as transition, anchor, connection spaces, etc.). In order to provide even more advanced semantics, *function* and *usage* attributes based on the OmniClass construction classification system (OCCS Development Committee *et al.* 2002) can be associated to space cells. IndoorGML does not consider physical objects populating the indoor environment, therefore, the *objects* attribute associated to the O-Space class is an addition to consider them. It can present a list of all the SM-Object encompassed by the subspace.

Furthermore, IndoorGML gives the possibility to link the cells to external references. This makes it possible for a specific subspace to link it to other components from richer semantic models such as CityGML of IFC. Information from those models can then be integrated in the FSS framework as well. Additionally, the standard rely on a multi-layered space representation, enabling the possibility to store several different layers of

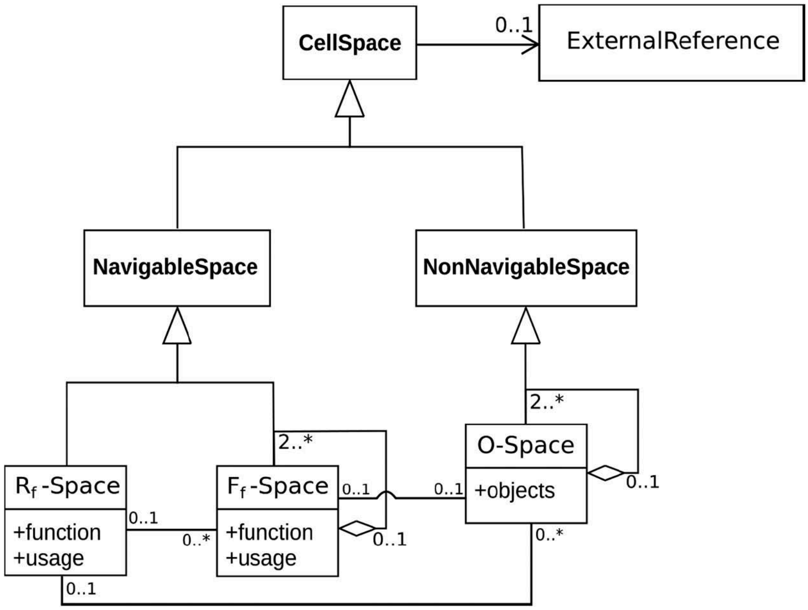

Figure 9. UML diagram of the FSS integrated to IndoorGML.

the same indoor environment. The basic space subdivision in a BIM model could then be the first layer and the FSS would stand as a more detailed subdivision layer for the purpose of fine-grained indoor applications.

5.2. *Application to a BIM model*

In order to illustrate better the advantages of the FSS framework, we applied it to a 3D BIM model (see Figure 10(a)). The model corresponds to a single floor and fully furnished office building, with 4 rooms and one corridor. The rooms are populated by regular office equipments, but also some humans are represented to reflect the M-objects' activities going on in the indoor environment. Figure 10(b) illustrates the structural indoor spaces as they would be provided in most BIM models. While these are the spaces on which the existing 3D approaches would rely, considering them empty, it can be clearly seen that they do not reflect the reality of the indoor environment. In contrast, by applying the FSS, the real navigable spaces appear. Here, we limit the example to the extraction of the fixed subspaces.

The structural spaces serve as a basis for the subdivision and stand as the maximum indoor free space possible. We start considering the SM-objects contained in them by defining the O-Spaces (Figure 10(c)). Some SM-objects have been aggregated while some others were not, following the aggregation rules discussed earlier for the O-Spaces (e.g. the desk and chairs in the lower office room vs. the upper one, on the left side of the building). Any SM-objects occupying the spaces physically is then encompassed inside an O-Space. The definition of the functional spaces is illustrated in Figure 10(d), where F_f-Spaces are generated for openings and SM-objects. Not all the SM-objects are concerned, e.g. no cupboard has an F_f-Space, but all the openings have F-Spaces considering their opening

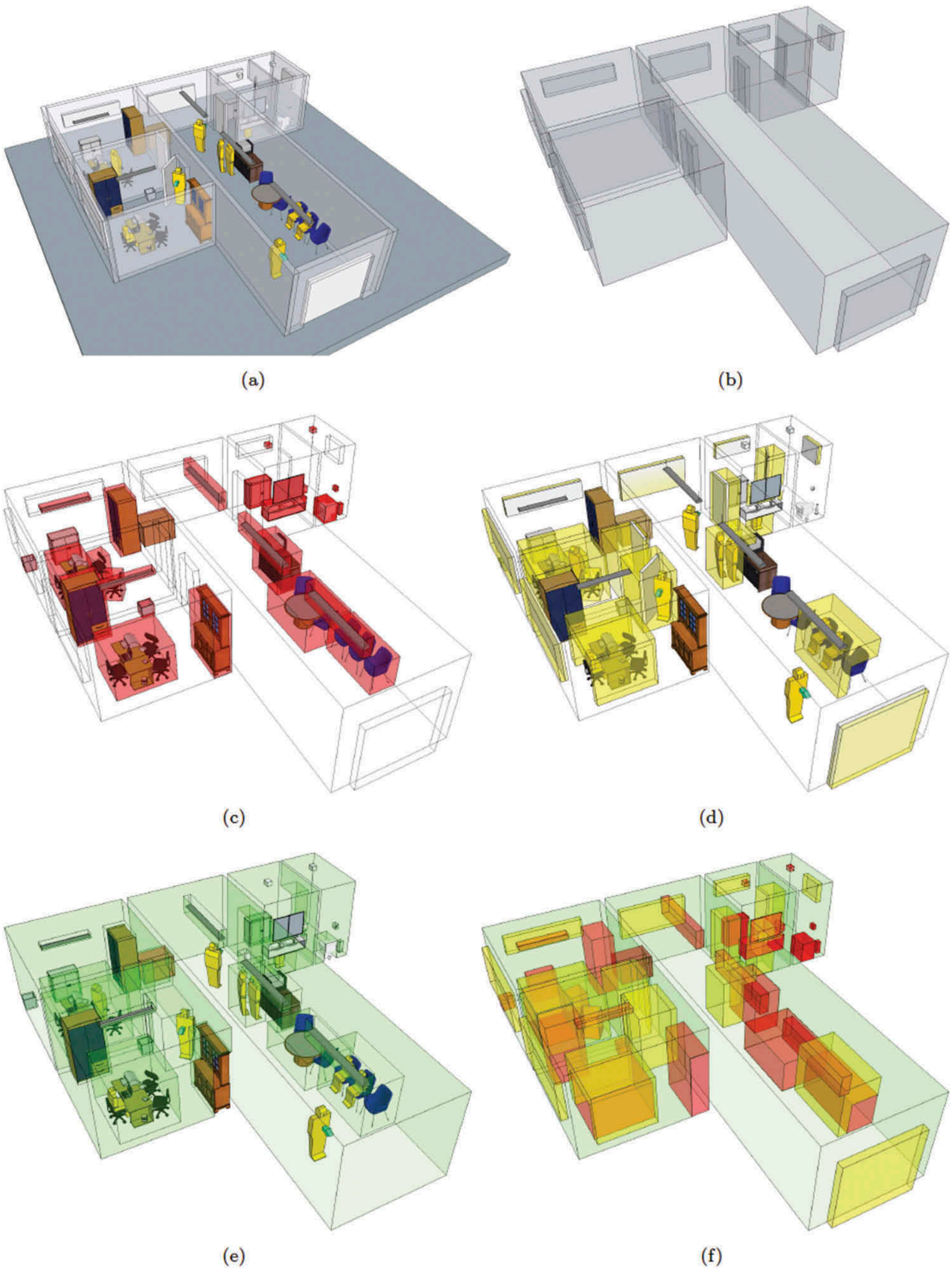

Figure 10. FSS of a BIM model. (a) Furnished office model. (b) Structural spaces resulting from the structural layout. (c) O-Spaces resulting from the SM-objects' configuration. (d) F_f-Spaces reflecting the processing areas of the SM-objects. (e) R_f-Spaces resulting from the O-Spaces and F_f-Spaces generation. (f) All the fixed subspaces resulting from the spatial subdivision.

motion, as specified in Section 3.2.1. Some of them are considered as sliding doors or windows (e.g. the main entrance and the windows), therefore their F_f-Spaces are limited to their natural opening spaces (meaning the void in the S-objects hosting them).

There are three agents represented in this example. It can be seen that they are not affecting to the R_f-Spaces that consider only the O-Spaces and the F_f-Spaces (see the green subspaces in Figure 10(e)). Figure 10(f) shows all the subspaces resulting from the subdivision framework, and clearly emphasize the complexity of the indoor environment compared to Figure 10(b). Thanks to the R_f-Spaces, the navigable spaces on which agents can rely inside the building are identified.

5.3. *Derivation of a navigation path*

The suitability of the R_f-Spaces to provide proper navigation spaces is illustrated in Figure 11. The subdivision provides a configuration making it easy to extract specific navigation paths in a straightforward manner. The corridor and one office room of the model are used to estimate the navigable spaces for a pedestrian aiming to navigate from the entrance to the office desk. The walkable surface between those two spaces is obtained by simply considering the bottom surface (in touch with the floor's slab) of the R_f-Spaces and the F_f-Spaces that necessary, such as the openings (Figure 11(b)).

Nevertheless, it can be seen that the R_f-Spaces, as they result from the subdivision, may not be directly suitable for graph extraction. Indeed they are often highly non-convex subspaces (see Figure 10(e) and Figure 11(a)). It can also be the case for F_f-Spaces as well. This could be a limitation for the extraction of navigation graphs that require the definition of position nodes that must be located in their corresponding space. The common approach is to rely on the centroid of the space units, but there is a high risk to obtain nodes out of them if they are non-convex. Therefore, a further step is the application of a convex subdivision of such navigable non-convex subspaces in order to guarantee proper position nodes inside them. It also enhances the granularity level of the navigable spaces, thus improving the precision of the path that can be reached. Figure 11(c) illustrates the result of a simple convex subdivision of the R_f-Spaces of Figure 11(a) based on the approach of Chazelle (1984). The only constraint enforced on the partitioning is the vertical direction (following the Euclidean *z*-axis) in order to produce simple convex space units that considers the walkable surface layout.

Based on the convex subdivision, the connectivity graph that represents the links between neighbouring subspaces can be derived as shown in Figure 11(d). The centroids of the convex subspaces are considered as the nodes and edges link every connected pair of centroids. The graph at that stage appears fuzzy because it considers all the subspace units and implicitly represents all the possible paths from any centroid to another. It is the basis from which the proper navigation graph will be determined for a given agent. For the navigation purpose of the agent in Figure 11, the subspace units providing the shortest walkable route towards the destination were identified (Figure 11(e),f)). Several approaches are dedicated to the computation of the shortest paths (Goldberg and Harrelson 2005). Here, we relied on a simple estimation of the smallest distance between the departure and destination nodes, based on the connectivity of the space units. Furthermore, the A-Space of the agent allowed to pick a string of connected spaces such that the agent can fit all along its path (Figure 11(f)). Of course, different constraints on the navigation could result in a different path, for example for considering flying

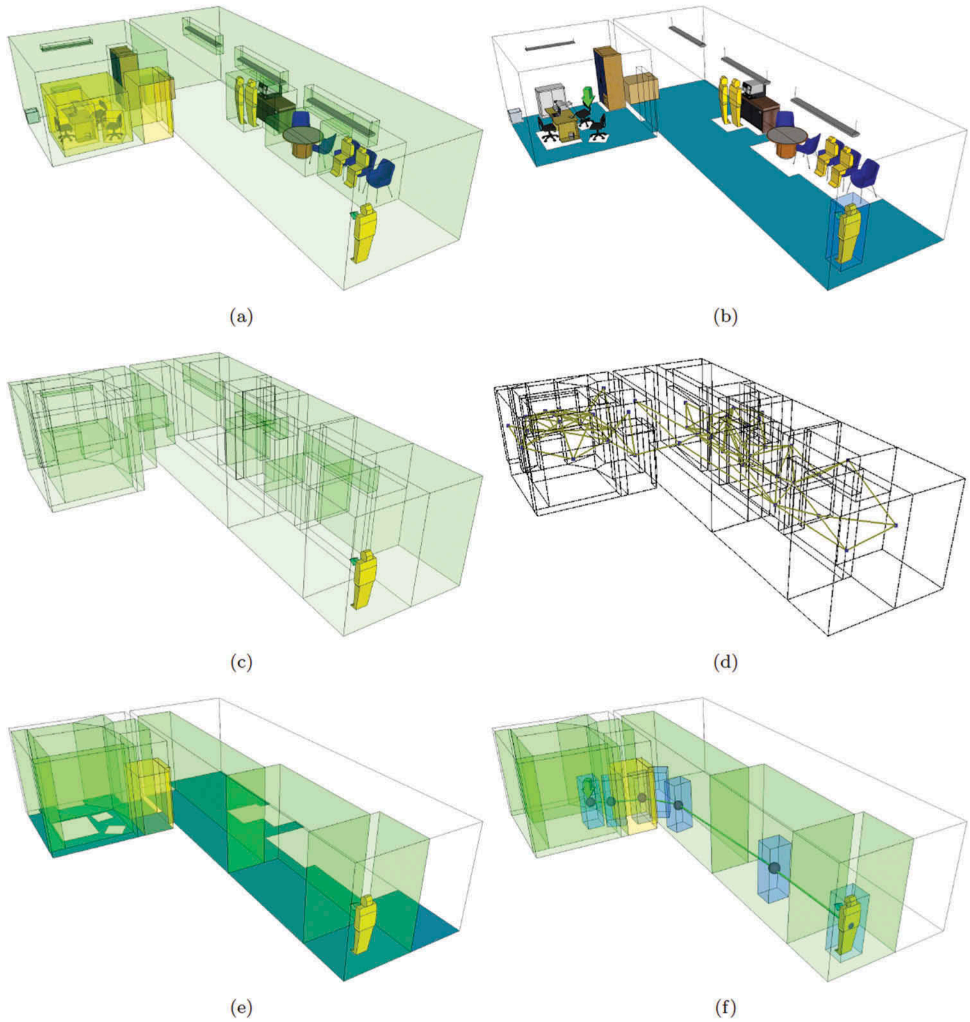

Figure 11. Example of navigation graph extraction for an agent aiming to reach an office desk. (a) R_f-Spaces and F_f-Spaces of the corridor and the office room. (b) Walkable surface (dark cyan) inferred from the subspaces. (c) Full convex subdivision of the R_f-Spaces. (d) Full connectivity graph between the convex R_f-Space entities. (e) R_f-Spaces and F_f-Spaces which connectivity allows to reach the target. (f) Selected part of the connectivity graph to navigate the agent.

objects. In that case, we would rely on the part of the R-Space closer to the ceiling and we could constraint the convex subdivision in an horizontal direction instead.

6. Discussion and future work

An efficient indoor navigation system needs to be flexible, precise and to offer a coherent description of the space in which the navigating agent is supposed to circulate. It is only by considering the real free space in 3D that a system can perform navigation while accounting for the agent's specific constraints. The spatial representation of the indoor navigable space proposed in this paper clearly makes it possible to go for a deeper exploration of the space for finer navigation purpose. The FSS framework provides an adapted subdivision of the 3D space, and considers the resources, the agents and all the parameters necessary to provide a proper navigation for any type of locomotion.

A considerable benefit of the framework lies in the fact that, thanks to the subdivision it provides based on mobility patterns that compose the indoor environment, all the subspaces do not have to be computed from scratch every time. From a 3D BIM model of a building, the fixed subspaces (namely the O, F_f and R_f-Spaces) can be computed and stored in a database. Providing a path will then amount to estimating the F_m and R_m-Spaces. This reduces the complexity of the path estimation problem by narrowing down the specific parts of the scenes requiring an update. On the agent's side, the latter can request an itinerary to a room or an SM-object in the building from a device connected to it (e.g. smartphone). Thus, a request considering the destination and the agent's profile (we have mainly discussed the locomotion here, e.g. pedestrian, etc. but deeper cognitive aspects could be considered) will be sent to the building's server. The latter will then send the latest R_f-Spaces and F_f-Spaces suitable for the request and the path can be computed by the agent's device, favouring this way a good responsiveness of the building's server. Furthermore, the fixed subspaces only enable advanced analysis already (e.g. R_f-Spaces can tell whether a room is suitable for crowd evacuation in emergency or whether a specific furniture can fit in it, etc.).

In the assessment table of symbolic spatial models proposed in Afyouni *et al.* (2012), the navigational abilities of object-oriented models relying on BIM is qualified as limited for fine grained indoor navigation. The authors mentioned the lack of connectivity between indoor spaces and the indirect suitability of such models for the task. After the application of the FSS, those limitations are overcome and the model becomes highly suitable for navigation thanks to the subspaces and the spatial relationships they are maintaining.

Since focus is made on vector models in this work, the spatial granularity that can be reached with the framework allows already to perform precise navigation. We have also shown that the granularity can be further deepened when necessary, mainly regarding the R-Spaces, e.g. in order to provide more adequate support to graph's nodes and customized paths extraction. Another improvement of that granularity can also consider and address the free spaces that are encompassed by the O-Spaces, due to their geometric representation. A proper simplification could allow to recover useful free spaces (e.g. below chairs or table) that could still be useful to some navigating agents (cleaning robot, crawling agent, etc.).

The approach highly relies on semantic information available in the building models. Indeed, that information is crucial for any automated approach aiming to deal with the space organization, as numerous objects characterize the indoor space in general, and without semantic distinction, the definition of the subspaces is limited but not impossible. BIM models that are targeted in this work generally offers the semantic information level necessary to handle an adequate subdivision based on the SM-objects (namely the fixed subspaces). However, those models do not provide yet any support for handling the dynamic activities such as monitoring the M_{St}-objects or the moving agents, and they are not primarily intended to do so. Therefore, other solutions need to be considered in order to properly build the F_m-Spaces and R_m-Spaces or dynamically estimate the A-Spaces. This could be, for example, the use of surveying camera linked to the BIM model and allowing to estimate the indoor motion activities (Zhao *et al*. 2008).

However, several aspects still need to be investigated deeper and solved. The first one concerns the integration of monitoring techniques to consider the monitored subspaces in order to provide even more accurate path planning. After this, the possibilities for the extraction of navigation graphs on such model needs also to be explored, as the potential can be considerable. Specific user-oriented subdivisions could be applied to the R-Spaces to enable cognitive and person-centric navigation (e.g. provide the path that offers the most visibility and spatial comfort to a pedestrian). Means to integrate advanced agent profiles through the A-Spaces could help in providing such navigation networks and optimized paths after our spatial subdivision.

Another aspect that needs to be considered in future work is the dynamic changes that can occur in the scenes. Indeed, the furnitures represented in the models have different mobility that can affect the precision of the extracted subspaces. For example a chair is most likely to be moved than a cupboard or a desk. Theoretically, such dynamic changes can be represented by our approach too. But to be able to consider such aspects, more information on the semantic of the furnitures and moving object will be required in the input models (e.g. dynamic weight on the furnitures).

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References

Afyouni, I., Ray, C., and Claramunt, C., 2010. A fine-grained context-dependent model for indoor spaces. *In*: *Proceedings of the 2nd acm sigspatial international workshop on indoor spatial awareness*. New York, NY: ACM, 33–38.

Afyouni, I., Ray, C., and Claramunt, C., 2012. Spatial models for context-aware indoor navigation systems: a survey. *Journal of Spatial Information Science*, 1 (4), 85–123.

Becker, T., Nagel, C., and Kolbe, T.H., 2009. A multilayered space-event model for navigation in indoor spaces. *In*: J. Lee and S. Zlatanova, eds. *3D geo-information sciences*. *Lecture Notes in Geoinformation and Cartography*. Berlin, Heidelberg: Springer, 61–77.

Boguslawski, P. and Gold, C., 2009. Construction operators for modelling 3D objects and dual navigation structures. *In*: J. Lee and S. Zlatanova, eds. *3D geo-information sciences*. *Lecture Notes in Geoinformation and Cartography*. Berlin, Heidelberg: Springer, 47–59.

Boguslawski, P., Gold, C.M., and Ledoux, H., 2011. Modelling and analysing 3D buildings with a primal/dual data structure. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66 (2), 188–197. doi:10.1016/j.isprsjprs.2010.11.003

Brown, G., *et al*., 2013. Modelling 3D topographic space against indoor navigation requirements. *In*: J. Pouliot *et al*., eds. *Progress and new trends in 3D geoinformation sciences*. *Lecture Notes in Geoinformation and Cartography*. Berlin, Heidelberg: Springer, 1–22.

Building SMART International, 2013. Industry Foundation Classes (IFC), IFC4 [online]. Available from: http://www.buildingsmart.org/standards/ifc [Accessed 4 November 2016].

Cameron, S. and Culley, R., 1986. Determining the minimum translational distance between two convex polyhedra. *In*: *1986 IEEE international conference on robotics and automation. Proceedings,* 7–10 April 1986, San Francisco. Vol. 3, 591–596.

Chazelle, B., 1984. Convex partitions of polyhedra: a lower bound and worst-case optimal algorithm. *SIAM Journal on Computing*, 13 (3), 488–507. doi:10.1137/0213031

Diakit´e, A.A. and Zlatanova, S., 2016. Valid space description in BIM for 3D indoor navigation. *International Journal of 3-D Information Modeling (IJ3DIM)*, 5 (3), 1–17. doi:10.4018/IJ3DIM.2016070101

Goetz, M. and Zipf, A., 2011. Formal definition of a user-adaptive and length-optimal routing graph for complex indoor environments. *Geo-Spatial Information Science*, 14 (2), 119–128. doi:10.1007/s11806-011-0474-3

Goldberg, A.V. and Harrelson, C., 2005. Computing the shortest path: a search meets graph theory. *In*: *Proceedings of the sixteenth annual ACM-SIAM symposium on discrete algorithms*. Philadelphia, PA: Society for Industrial and Applied Mathematics, 156–165.

Hall, E.T., 1966. *The hidden dimension*. 1st ed. New York: Doubleday & Co.

Isikdag, U., Zlatanova, S., and Underwood, J., 2013. A BIM-oriented model for supporting indoor navigation requirements. *Computers, Environment and Urban Systems*, 41, 112–123. doi:10.1016/j.compenvurbsys.2013.05.001

Kang, H.K. and Li, K.J., 2017. A standard indoor spatial data ModelOGC IndoorGML and implementation approaches. *ISPRS International Journal of Geo-Information*, 6 (4), 116. doi:10.3390/ijgi6040116

Khan, A. and Kolbe, T., 2013. Subspacing based on connected opening spaces and for different locomotion types using geometric and graph based representation in multilayered space-event model (MLSEM). *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 13, 173–185. doi:10.5194/isprsannals-II-2-W1-173-2013

Krüminaité, M., 2014. *Space subdivision for indoor navigation*. Master's thesis. Delft University of Technology, The Netherlands.

Krüminaité, M. and Zlatanova, S., 2014. Indoor space subdivision for indoor navigation. *In*: *Proceedings of the sixth ACM SIGSPATIAL international workshop on indoor spatial awareness*. New York, NY: ACM, 25–31. doi:10.1145/2676528.2676529

Kwan, M.P. and Lee, J., 2005. Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments. *Computers, Environment and Urban Systems*, 29 (2), 93–113. doi:10.1016/j.compenvurbsys.2003.08.002

Lee, J., 2007. A three-dimensional navigable data model to support emergency response in microspatial built-environments. *Annals of the Association of American Geographers*, 97 (3), 512–529. doi:10.1111/j.1467-8306.2007.00561.x

Lee, J., *et al*., 2014. OGC® IndoorGML. *Open Geospatial Consortium standard* [online]. Available from: http://www.opengeospatial.org/standards/indoorgml [Accessed 10 February 2017].

Lee, S.H. and Lee, K., 2001. Partial entity structure: a compact non-manifold boundary representation based on partial topological entities. *In*: *Proceedings of the sixth ACM symposium on solid modeling and applications*. New York, NY: ACM, 159–170. doi:10.1145/376957.376976
Li, X., Claramunt, C., and Ray, C., 2010. A grid graph-based model for the analysis of 2D indoor spaces. *Computers, Environment and Urban Systems*, 34 (6), 532–540. doi:10.1016/j.compenvurbsys.2010.07.006
Liu, L. and Zlatanova, S., 2011. Towards a 3D network model for indoor navigation. *In*: *Urban and regional data management, UDMS annual*, 28–30 September, Delft, the Netherlands. CRC Press, 79–92.
Liu, T., *et al*., 2015. A GIS-oriented location model for supporting indoor evacuation. *International Journal of Geographical Information Science*, 29 (2), 305–326. doi:10.1080/13658816.2014.969271
Nagel, C., *et al*., 2010. Requirements and space-event modeling for indoor navigation. *Open Geospatial Consortium*. Available from: http://www.opengeospatial.org/docs/discussion-papers
OCCS Development Committee, *et al*., 2002. OCCS net, The Omniclass Construction Classification System [online]. Available from: http://www.omniclass.org/ [Accessed 17 August 2017].
Open Geospatial Consortium, 2012. City Geography Markup Language (CityGML) encoding standard, version 2.0.0. [online]. Available from: http://www.opengeospatial.org/standards/citygml [Accessed 4 November 2016].
Richter, K.F., Winter, S., and Rüetschi, U.J., 2009. Constructing hierarchical representations of indoor spaces. *In*: *2009 tenth international conference on mobile data management: systems, services and middleware*, 18–20 May 2009, Taipei, Taiwan. 686–691. doi:10.1109/MDM.2009.117
Richter, K.F., Winter, S., and Santosa, S., 2011. Hierarchical representations of indoor spaces. *Environment and Planning B: Planning and Design*, 38 (6), 1052–1070. doi:10.1068/b37057
Russo, D., Zlatanova, S., and Clementini, E., 2014. Route directions generation using visible landmarks. *In*: *Proceedings of the sixth ACM SIGSPATIAL international workshop on indoor spatial awareness,* 04 November, Dallas/Fort Worth, Texas. *New York, NY: ACM*, 1–8. doi:10.1145/2676528.2676530
Sithole, G. and Zlatanova, S., 2016. Position location, place and area: an indoor perspective. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 4, 89–96. doi:10.5194/isprsannals-III-4-89-2016
Sommer, R., 1969. *Personal space. The behavioral basis of design*. New Jersey: ERIC.
Stoffel, E.P., Lorenz, B., and Ohlbach, H.J., 2007. Towards a semantic spatial model for pedestrian indoor navigation. *In*: *International conference on conceptual modeling*. Berlin, Heidelberg: Springer-Verlag, 328–337.
Swobodzinski, M. and Raubal, M., 2009. An indoor routing algorithm for the blind: development and comparison to a routing algorithm for the sighted. *International Journal of Geographical Information Science*, 23 (10), 1315–1343. doi:10.1080/13658810802421115
Walton, L.A. and Worboys, M., 2012. A qualitative bigraph model for indoor space. *In*: N. Xiao, *et al*., eds. *International conference on geographic information science*. Berlin, Heidelberg: Springer, 7478, 226–240.
Worboys, M., 2011. Modeling indoor space. *In*. *In*: *Proceedings of the 3rd ACM sigspatial international workshop on indoor spatial awareness. New York, NY: ACM*, 1–6. doi:10.1145/2077357.2077358
Yang, L. and Worboys, M., 2015. Generation of navigation graphs for indoor space. *International Journal of Geographical Information Science*, 29 (10), 1737–1756. doi:10.1080/13658816.2015.1041141
Zhao, T., Nevatia, R., and Wu, B., 2008. Segmentation and tracking of multiple humans in crowded environments. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 30 (7), 1198–1211. doi:10.1109/TPAMI.2007.70770
Zlatanova, S., *et al*., 2014. *Space subdivision for indoor applications*. Delft, Netherlands: Delft University of Technology, OTB Research Institute for the Built Environment.
Zlatanova, S., Liu, L., and Sithole, G., 2013. A conceptual framework of space subdivision for indoor navigation. *In*: *Proceedings of the fifth ACM SIGSPATIAL international workshop on indoor spatial awareness*. New York, NY: ACM, 37–41. doi:10.1145/2533810.2533819