3D Visualization of Cadastre: Assessing the Suitability of Visual Variables and Enhancement Techniques in the 3D Model of Condominium Property Units

Thèse

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Résumé

La visualisation 3D de données cadastrales a été exploitée dans de nombreuses études, car elle offre de nouvelles possibilités d'examiner des situations de supervision verticale des propriétés. Les chercheurs actifs dans ce domaine estiment que la visualisation 3D pourrait fournir aux utilisateurs une compréhension plus intuitive d'une situation où des propriétés se superposent, ainsi qu'une plus grande capacité et avec moins d'ambiguïté de montrer des problèmes potentiels de chevauchement des unités de propriété. Cependant, la visualisation 3D est une approche qui apporte de nombreux défis par rapport à la visualisation 2D. Les précédentes recherches effectuées en cadastre 3D, et qui utilisent la visualisation 3D, ont très peu enquêté l'impact du choix des variables visuelles (ex. couleur, style) sur la prise de décision.

Dans l'optique d'améliorer la visualisation 3D de données cadastres, cette thèse de doctorat examine l'adéquation du choix des variables visuelles et des techniques de rehaussement associées afin de produire un modèle de condominium 3D optimal, et ce, en fonction de certaines tâches spécifiques de visualisation. Les tâches visées sont celles dédiées à la compréhension dans l'espace 3D des limites de propriété du condominium. En ce sens, ce sont principalement des tâches notariales qui ont été ciblées. De plus, cette thèse va mettre en lumière les différences de l'impact des variables visuelles entre une visualisation 2D et 3D.

Cette thèse identifie dans un premier temps un cadre théorique pour l'interprétation des variables visuelles dans le contexte d'une visualisation 3D et de données cadastrales au regard d'une revue de littéraire. Dans un deuxième temps, des expérimentations ont été réalisées afin de mettre à l'épreuve la performance des variables visuelles (ex. couleur, valeur, texture) et des techniques de rehaussement (transparence, annotation, déplacement). Trois approches distinctes ont été utilisées : 1) discussion directe avec des personnes œuvrant en géomatique, 2) entrevue face à face avec des notaires et 3) questionnaire en ligne avec des groupes ciblés. L'utilisabilité mesurée en termes d'efficacité, d'efficience et de degré de satisfaction a servi aux comparaisons des expérimentations.

Les principaux résultats de cette recherche sont : 1) Une liste de tâches visuelles notariales utiles à la délimitation des unités de propriété dans le contexte de la visualisation 3D de condominium ; 2) Des recommandations quant à l'adéquation de huit variables visuelles et de trois techniques de rehaussement afin d'optimiser la réalisation d'un certain nombre de tâches notariales ; 3) Une analyse comparative de la performance de ces variables entre une visualisation 2D et 3D.

Abstract

3D visualization is being widely used in GIS (geographic information system) and CAD (computer-aided design) applications. It has also been introduced in cadastre studies to better communicate overlaps to the viewer, where the property units vertically stretch over or cover one part of the land parcel. Researchers believe that 3D visualization could provide viewers with a more intuitive perception, and it has the capability to demonstrate overlapping property units in condominiums unambiguously. However, 3D visualization has many challenges compared with 2D visualization. Many cadastre researchers adopted 3D visualization without thoroughly investigating the potential users, the visual tasks for decision-making, and the appropriateness of their representation design. Neither designers nor users may be aware of the risk of producing an inadequate 3D visualization, especially in an era when 3D visualization is relatively novel in the cadastre domain.

With a general aim to improve the 3D visualization of cadastre data, this dissertation addresses the design of the 3D cadastre model from a graphics semiotics viewpoint including visual variables and enhancement techniques. The research questions are, firstly, what is the suitability of the visual variables and enhancement techniques in the 3D cadastre model to support the intended users' decision-making goal of delimitating condominium property units, and secondly, what are the perceptual properties of visual variables in 3D visualization compared with 2D visualization?

This dissertation firstly identifies the theoretical framework for the interpretation of visual variables in 3D visualization as well as cadastre-related knowledge with literature review. Then, we carry out a preliminary evaluation of the feasibility of visual variables and enhancement techniques in a form of an expert-group review. With the result of the preliminary evaluation, this research then performs the hypothetico-deductive scientific approach to establishing a list of hypotheses to be validated by empirical tests regarding the suitability of visual variables and enhancement techniques in a cartographic representation of property units in condominiums for 3D visualization. The evaluation is based on the usability specification, which contains three measurements: effectiveness, efficiency, and preference. Several empirical tests are conducted with cadastral users in the forms of face-to-face interviews and online questionnaires, followed by statistical analysis. Size, shape, brightness, saturation, hue, orientation, texture, and transparency are the most discussed and used visual variables in existing cartographic research and implementations; thus, these eight visual variables have been involved in the tests. Their perceptual properties exhibited in the empirical test with concrete 3D models in this work are compared with those in a 2D visualization, which is derived from a literature-based synthesis. Three enhancement techniques, including labeling, 3D explosion, and highlighting, are tested as well.

There are three main outcomes of this work. First, we established a list of visual tasks adapted to notaries for delimiting property units in the context of 3D visualization of condominium cadastres. Second, we describe the suitability of eight visual variables (Size, Shape, Brightness, Saturation, Hue, Orientation, Texture, and Transparency) of the property units and three enhancement techniques (labeling, 3D explosion and highlighting) in the context of 3D visualisation of condominium property units, based on the usability specification for delimitating visual tasks. For example, brightness only shows good performance in helping users distinguish private and common parts in the context of 3D visualization of property units in condominiums. As well, color hue and saturation are effective and preferable. The third outcome is a statement of the perceptual properties' differences of visual variables between 3D visualization and 2D visualization. For example, according to Bertin (1983)'s definition, orientation is associative and selective in 2D, yet it does not perform in a 3D visualization. In addition, 3D visualization affects the performance of brightness, making it marginally dissociative and selective.

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Chapter 1 Introduction

> *"New symbol systems are being developed constantly to meet the needs of a society increasingly dependent on data. Once developed, they may stay with us for a very long time, so we should try to get them right"*--Colin Ware (2012)

1.1 Context

3D visualization is currently a basic part of many geospatial solutions, for example, commercial Geographic Information System software such as ArcScene and CityEngine. Also, it is a hot topic in the academic world as geospatial researchers try to improve it using new software (Ribeiro, Almeida, & Ellul, 2014), new visualization strategies (Sieber, Hollenstein, & Eichenberger, 2012), and through applications to geospatial sub-domains (Ross, Bolling, Döllner, & Kleinschmit, 2009). It is also a realm that reflects the cross-domain nature of geospatial research, as researchers try to integrate knowledge or research methods from a wide spectrum of research outside the geospatial domain, like information visualization (Bleisch & Nebiker, 2008), cognitive science (Wood, G.Pearson, Calder, Miller, & Tinto, 2005), and human-computer interaction (Popelka & Dolez, 2015). The common features of 3D visualization, which could refer to either an environment or a computer system, can be identified here as: first, it uses a 3D model, namely the volumetric representation of real world objects; and second, it enables the perception of the volumetric representation from different angles with an illusion of depth. In this dissertation, 3D visualization only refers to those on a monoscopic display like 2D LCD (liquid crystal display) or CRT (cathode ray tube). Despite the availability of stereo 3D devices, 2D displays like LCD and CRT are still widely used.

As a geospatial sub-domain, cadastre is also starting to adopt 3D visualization, as can be seen in the discussion of first, second, and third 3D cadastre workshops (Aditya, Iswanto, Wirawan, & Laksono, 2011; Jeong, Jang, Lee, & Hong, 2012; Vandysheva et al., 2012). Cadastres play a significant role in modern society, as they register immovable properties and provide necessary information for land administration, tax calculations, real estate transactions, and mortgages (Stoter, 2004). The term cadastre, as used herein, may refer to the cadastre system and/or the cadastre map (called the cadastre plan in Quebec, Canada). A cadastre system is a property information system that is based on immovable property units and is up-to-date. A cadastral map is normally one part of a cadastre, and it supports cadastre information visualization.

According to the review of different countries' responses to a 3D cadastre questionnaire issued by Van Oosterom[1], modern mainstream cadastre visualization does not have 3D visualization capabilities except in Germany and in ShenZhen, China. However, the registration of overlapping properties, where the property

[1] Available at http://www.gdmc.nl/3dcadastre/participants/

vertically stretches over or covers only one part of the land parcel, may require a special graphical representation in order to facilitate cadastre registration, updating, and communication (Khoo, 2011; MRNF, 2003; Shojaei, Kalantari, Bishop, Rajabifard, & Aien, 2013). 2D visualization approaches such as floor plans, cross-sections, and isometric diagrams may have limits. For example, in Quebec, for overlapping situations, Complementary Plan (PC), as shown in Figure 1.1, is provided to represent the cadastre survey for 2D visualization. The PC uses floor plans for each floor and a vertical profile of all the floors together to visualize the condominium situation. As indicated by Pouliot et al. (2011), it requires considerable mental effort and a certain level of experience for the user to understand the spatial arrangement of property units with PC.

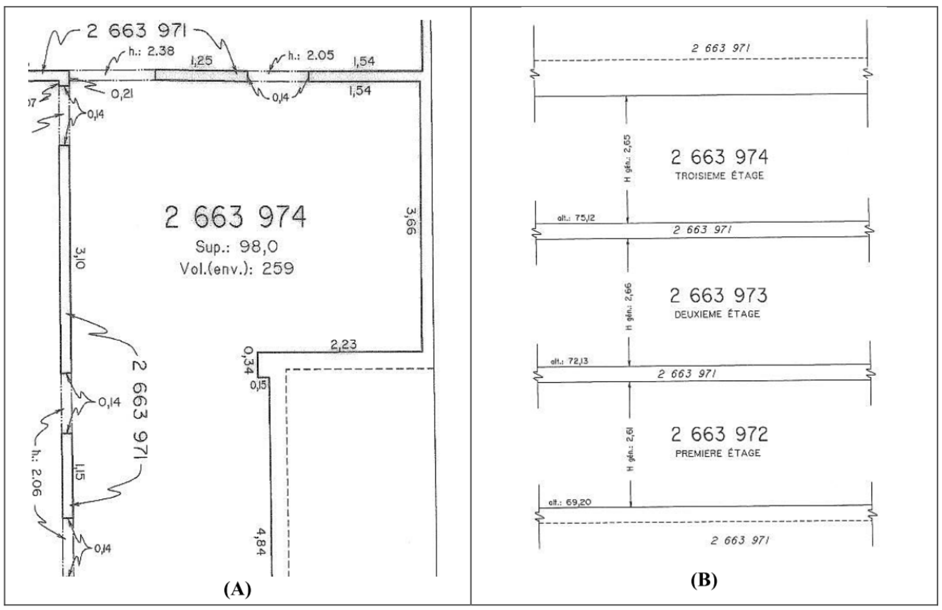


Figure 1.1. Complementary Plan for condominium property unit in Quebec (Pouliot, Vasseur, & Boubehrezh, 2012)

1.2 Problematic

The interest of using 3D visualization to face some limits of the 2D visualisation of property boundaries is clearly identified in the literature (Aditya et al., 2011; Guo et al., 2013; Jeong, Kim, Nam, Li, & Cho, 2011; Karki, Thompson, Mcdougall, Cumerford, & Oosterom, 2011; Shojaei, 2012; Vandysheva et al., 2012). However, many issues are yet to be addressed.

The third dimension is a double-edged sword (Elmqvist, Assarsson, & Tsigas, 2007). Despite the existence of rich literature regarding the advantages of 3D visualization and many positive examples in the cadastre domain, 3D visualization has some negative influences on human perception. Van Oosterom (2013) mentioned that occlusion in 3D visualization may be an obstacle to a user's perception of property units in a complex building or in underground construction. Meanwhile, regarding information visualization, Ware (2012) mentioned that shadows, which are common in 3D visualizations, may sometimes be confusing to users. Moreover, since the volumetric representations could be aggregated together as a complex structure in three dimensions, a saliency-guided approach may be necessary to help users focus on relevant sub-region for details (Kim & Varshney, 2006). These examples demonstrate that 3D visualization has shortcomings and limits.

Additionally, the designers and researchers should consider factors other than visualization technology. MacEachren and Kraak (2001) formulated five issues associated with visual representation (data, semiotics, map uses, map users, and technology) in geo-visualization, and technology is only one of them. In the discussion of information visualization challenges, Chen (2005) mentioned other factors, including prior knowledge, aesthetics, usability, and elementary cognitive tasks. 3D visualization of properties is one application of geo-visualization, but it may require a specific visualization approach since research suggests that visualization design and implementation are largely ad-hoc (Rogowitz, Treinish, & Bryson, 1996). Intended users, their tasks, and attitudes towards 3D visualization are also critical factors. The result of a 3D visualization approach may largely be task dependent (Taylor, Herbert, & Chen, 2015) and influenced by end users' cognitive capabilities and preferences (Haklay, 2010). Usability, which is a benchmark indicating how easily, efficiently, and satisfactorily users achieve their visual tasks with a human computer interface, is an important criterion for the evaluation of visualization and, thus, should be considered as well. According to ISO 9241-11 (1998), usability could be evaluated using three factors: the effectiveness and efficiency of the user's visual tasks with the interface and the user's subjective satisfaction. It has already been argued by a few researchers that this is a fundamental benchmark for 3D visualization of a cadastre (Shojaei et al., 2013; Van Oosterom, Stoter, & Ploeger, 2011).

Despite the expectations of 3D visualization, most recent research regarding cadastres simply mentions the implementation of 3D visualization as being one part of a prototype system, without thoroughly discussing the reasoning and decision-making behind the designs and implementations. Based on a review of over 100 pieces of literature published since 2011, fewer than 10 articles primarily focused on 3D visualization and 3D representation (Pouliot & Wang, 2014), and most discussed it from a technical aspect. Many research studies were feasibility studies of technology and 3D cadastre system design. For instance, Shojaei et al. (2012) developed a 3D visualization system based on Google Earth for 3D ePlan/LandXML data to be used in overlapping property situations. Shojaei, Rajabifard, Kalantari, Bishop, and Aien (2014) then established a web-based 3D cadastral visualization system with a comprehensive review of functional visualization requirements and the applicability of 3D visualization platforms. Aditya et al. (2011) developed two 3D cadastre web map prototypes based on KML with Google Earth and X3D with ArcGIS online, respectively, and Olivares García, Virgós Soriano, & Velasco Martín-Varés (2011) explained how to use KML and Google Earth to visualize a volumetric representation of property units in condominiums. Much of their research, as evaluated here, indicates that current technical capability has reached a point that most of the 3D visualization functions required by cadastre could be well supported.

Moreover, intended users and their tasks are the preliminary concerns in visualization research (Chen & Czerwinski, 2000; MacEachren & Kraak, 2001; Plaisant, 2004). However, there is minimal current research in the 3D visualization of cadastre, except for Elizarova et al. (2012) and Shojaei et al. (2013), as they discussed those in a comprehensive way and embedded the direct participation of the end user. Since 3D visualization of cadastre is novel compared with the current 2D approach, the end user's opinion of it, their capability to use it, and the real value gained from it remains obscure. Based on a literature review, the only cases that cooperate with users for design, implementation or evaluation are in the pilot system of Russia and Victoria, Australia. In the Russian pilot system, experts in Rosreestr (the Russian cadastre institution) and other cadastral engineers are invited to evaluate the pilot system in the form of a questionnaire (Elizarova et al., 2012). Moreover, in Victoria, Australia, the visualization requirements of professional users are discussed in detail (Shojaei et al., 2013). Twenty academy and industry experts in cadastres have participated in evaluating the prototype. In summary, in order to support cadastre-related tasks, the design and application of 3D visualization in cadastres of overlapping properties should consider not only the pros and cons of 3D visualization but also other factors, such as the cadastre domain context, the intended users, their tasks, and the usability of the visualization results, which a number of current research papers failed to do.

In a 2D context, the visualization framework that involves visual variables and graphic semiotics is a representation framework that is influential among both cartographers (Roth, 2012) and researchers in information visualization such as Carpendale (2003), Voigt & Polowinski (2011), and Zuk (2008). This could be the groundwork upon which a user's interaction is based. Research studies involving visual variable-based theories reveal much experience in and knowledge about the suitability of visual variables and graphical semiotics. There are many visual variables, but the most often discussed are size, shape, brightness, saturation, hue, orientation, texture, and transparency. Each visual variable performs differently, depending on the characteristics of the intended visual tasks (Bertin, 1983; Carpendale, 2003; Halik, 2012).

Considering the impact of visual variable-based theories in the research of cartography and information visualization in 2D visualization, a careful design of a 3D cadastre model that considers the suitability of visual variables and graphic semiotics may also be valuable. An example is the study of Jobst and Döllner (2008). They discussed how to use cartographic-oriented design to construct a 3D city model considering semiotics, symbols, and visual variables. The 3D models in 3D visualization are also termed three-dimensional cartographic models by Terribilini (1999) and graphic aspects of 3D Map by Haeberling (2002), from an aspect of the semiotics of graphics.

Much cognition research suggests that human perception of visual variables may greatly change in a 3D situation compared with that in 2D; thus, the conclusions and principles regarding the capability of visual variables and semiotics of graphics in 2D visualization to communicate information should not be applied to 3D visualization readily. For example, Todd (2004)'s work disclosed that the perception of visual variable shape in a 3D context is influenced by other visualization factors such as occlusion contours and edges of high curvature. At the same time, shape perception is relatively straightforward in a 2D context. Tory et al. (2006)'s research concludes that precise orientation and position perception is hard in a 3D context. 3D visualization also gives more capability to the visual variable transparency. In 3D visualization, transparency could not only represent underlying data but also be a visual enhancement to ease the occlusion. The viewer's judgment of transparency may change, too. For example, using variations of brightness and hue to create transparency illusions, as shown in the studies of D'Zmura, Colantoni, Knoblauch, & Laget (1997) and Metelli, Da Pos, & Cavedon (1985), is applicable to 2D visualization. However, it is no longer feasible in 3D visualization since the viewer could perceive the surface from multiple angles. As a result, investigating the suitability of visual variables in a 3D context for cadastral tasks is the preliminary step for a meticulous study of the 3D visualization from a graphic semiotics' view. However, there is no such research paper placed in the cadastre domain and very few in the geospatial domain, except Hardisty (2001) (preliminary evaluation of visual variables in 3-D visualization), Fosse, Veiga, and Sluter (2005) (preliminary assessment of color hue in 3-D visualization), and Jobst and Döllner (2008) (non-photorealistic 3-D city).

Besides visual variables, visual enhancement techniques like labeling and highlighting have been used in interactive visualization and provide convincing profits like an attention guide (Robinson, 2009). They also provide the capability to address some drawbacks of 3D visualization (Elmqvist et al., 2007; Trapp, Beesk, Pasewaldt, & Döllner, 2011). The most discussed visual enhancements include labeling in order to represent data that is hard to encode to visual variables, occlusion management in order to mitigate visual obstruction like objects detaching, and visual highlighting in order to guide viewer's attention. They are based on representation with symbols and visual variables but diverge from conventional graphic semiotics to help user's perception. For example, use text for annotation (Métral, Ghoula, & Falquet, 2012b; Shojaei et al., 2013), unevenly change the scale of the 3D scene to create fisheye view (Elmqvist, 2007), or add an new symbol of arrow above an original symbol to attract viewer's attention (Trapp et al., 2011). In sum, an investigation of visual enhancement techniques in the 3D visualization of cadastre may be beneficial, yet no dedicated research has been implemented in the cadastre context.

Stemming from the misuse of visual variables and enhancement techniques, many of the current representation designs may be insufficient for unambiguous communication with the viewer about the overlapping properties in condominiums to support decision-making. Taking the prototype of Russian 3D cadastre for example, in figure 1.2, the 3D visualization of a condominium combines properties with its physical counterpart together. Moreover, this representation uses visual variable colors to indicate different property units as well as physical objects. However, it is hard to unambiguously distinguish which color or which group of colors corresponding to the physical objects, notably those without an ordinary shape of a wall, like the frames in this model. Furthermore, this representation could not depict the inside structure of this building about the property units. For occlusion issues, they used visual enhancement techniques to move the floor model to enable users to drag out one floor along with the 2D floor plan, as shown in figure 1.3. However, "drag out" changes the horizontal position of the property unit, thus hindering the perception of the spatial relationship between property units with land parcels and with property units of other floors. Additionally, in figure 1.2, the highlighting of a wall's boundaries by using the visual variable color "red" is confusing since viewers may doubt whether it highlights the outer wall or just its boundaries and whether there is a relationship between the red used for highlighting and the property units that are colored red.

Figure 1.2. Representation of condominium property units in Russian 3D cadastre prototype (Elizarova et al., 2012)

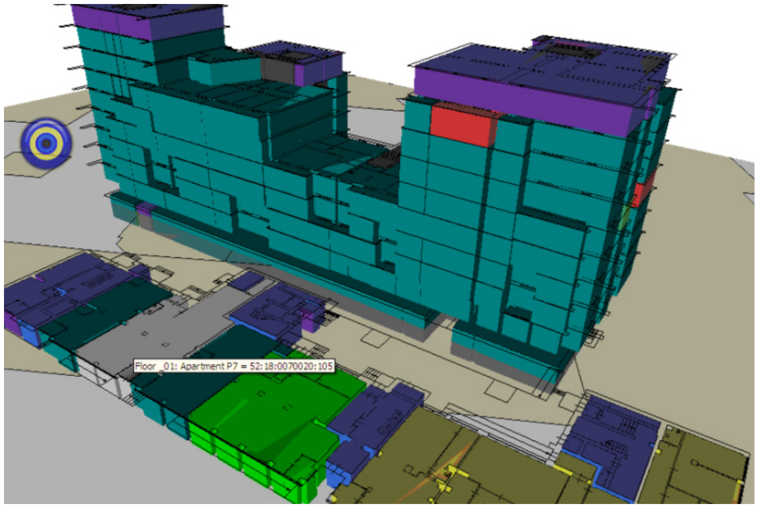


Figure 1.3. Move-floor-model for 3D visualization of property units in Russian 3D cadastre prototype (Vandysheva et al., 2012)

To sum up, insufficient investigation of 3D visualization in cadastre research, especially in relation to visual variables, graphic semiotics, and enhancement techniques, may bring about the risk of producing 3D visualization solutions that do not support the user's decision-making. Currently, researchers, system developers, and end users are not aware of or do not pay enough attention to the hazards of unsuitable 3D visualization solutions. Inadequate 3D representations may reduce the perceptual efficiency of their end users. Furthermore, they may trigger user misunderstandings and mistakes and, thus, damage cadastral integrity and the interests of property stakeholders. Comprehensive 3D visualization research that considers the factors mentioned above is urgently needed. In an era in which 3D visualization is relatively novel in the cadastral domain, users' adaptation of 3D visualization to existing 2D solutions will be determined by their experience with specific 3D solutions, e.g., whether they can unambiguously and efficiently achieve their goals with a particular design to a great extent. It is also a period in which design conventions and users' habits have not yet been established; thus, 3D visualizations that come out first may influence later designs and user expectations, whether with a good impact or a bad one.

1.3 Research Questions

Considering the problematic, **the general research subject of this work is how to improve 3D visualization of condominium property units, considering intended users and their decision-making goals**. The focus of this dissertation is on the 3D cadastre model from a semiotics of graphics aspect, namely visual variables and visual enhancement techniques. Two research questions are identified:

1. **What is the suitability of visual variables and visual enhancement techniques in the 3D visualization of condominium property units to support users' decision-making goals?**

2. **Do the visual variables in the 3D visualization of condominium property units exhibit the similar visual variables' perceptual properties, as in 2D visualization?**

Here, suitability refers to the capability of a visual variable or enhancement technique to represent the underlying data in order to enable viewers to accomplish their decision-making goals or their visual tasks. There are multiple indicators of the suitability of a specific visualization design, for example, appreciation, usability, usefulness, and the appropriateness of adoption (Van Velsen, Van Der Geest, Klaassen, & Steehouder, 2008). The selection of the indicator will be further discussed in the following sections as a part of the research methodology.

1.4 Objectives

The general aim of this work is to improve the 3D visualization of condominium property units while considering the intended users and their decision-making goals. This dissertation addresses the subject of the 3D cadastre model from a semiotics of graphics point of view, in which visual variables and enhancement techniques are applied to perform 3D visualization. Considering the great number of the applicable visual variables, visual enhancement techniques, and the potential user, it is recommended to establish the objectives of the thesis based on a pre-selection set of graphic elements and decision-making. The list of visual variables and visual enhancement techniques is selected from current cartographic and information visualization research. It includes eight visual variables (size, shape, brightness, saturation, hue, orientation, texture, and transparency) and three enhancement techniques (labeling, object detaching, and highlighting), as they are the most used and discussed in the literature. Besides the usage of a specific visual variable, the detailed settings of the visual variable may also affect the suitability. Due to the time limit of this dissertation, only one visual variable is selected for detailed tests of its settings. We select transparency, because, first, of its importance in 3D visualization as an occlusion management, and second, the viewer's perception of transparency in 3D visualization greatly changed from 2D visualization.

Among all potential cadastre visualization users, such as surveyors, urban planners, and property owners, the potential users considered are mainly notaries and notarial students since the notaries' work directly ensured the integrity of property transaction and registration in Quebec. In order to limit the investigation, this research considers one main decision-making goal: to delimitate property units in condominiums.

Three objectives are specified to answer the previous research questions:

1. **To evaluate the suitability of a preselected list of visual variables and visual enhancement techniques for performing unambiguous delimitation of overlapping property units in condominiums in the context of 3D visualization.**

2. **To evaluate the suitability of transparency with different transparency settings for performing unambiguous delimitation property units and their physical counterpart in 3D visualization.**

3. **To compare the perceptual properties of visual variables exhibited in 3D visualization of condominium property units with those in 2D visualization.**

The overall intention of these research objectives is to improve the design of the 3D model of condominium property units considering intended users and their decision-making goals in order to promote good practices of 3D visualization of cadastre.

1.5 Methodology

As stated in the research question and objectives, the research is placed in a context of condominium, which is one common type of overlapping property units. Figure 1.4 demonstrates the general workflow of the research in this dissertation. A comprehensive review of the reliable literature is the starting point of this research, and it accompanies the entire research process for information synthesis and results comparison. These are the main methods for synthesizing visualization concepts and identifying potential cadastre data and users. It also supports the comparison between 3D and 2D visualization by listing conclusions in other studies. Studies on a similar scale -- for example, those in an urban context with a scale ranging from a city to a single building -- are favorable. For reliability, best evidence synthesis (Slavin, 1986) has to be used due to the massive amount of literature and its varying credibility. The selection of reliable literature in this work uses four pieces of evidence: (1) controlled experiments, (2) empirical tests with credible test design, (3) logical reasoning with examples, and (4) widely accepted articles with external validation.

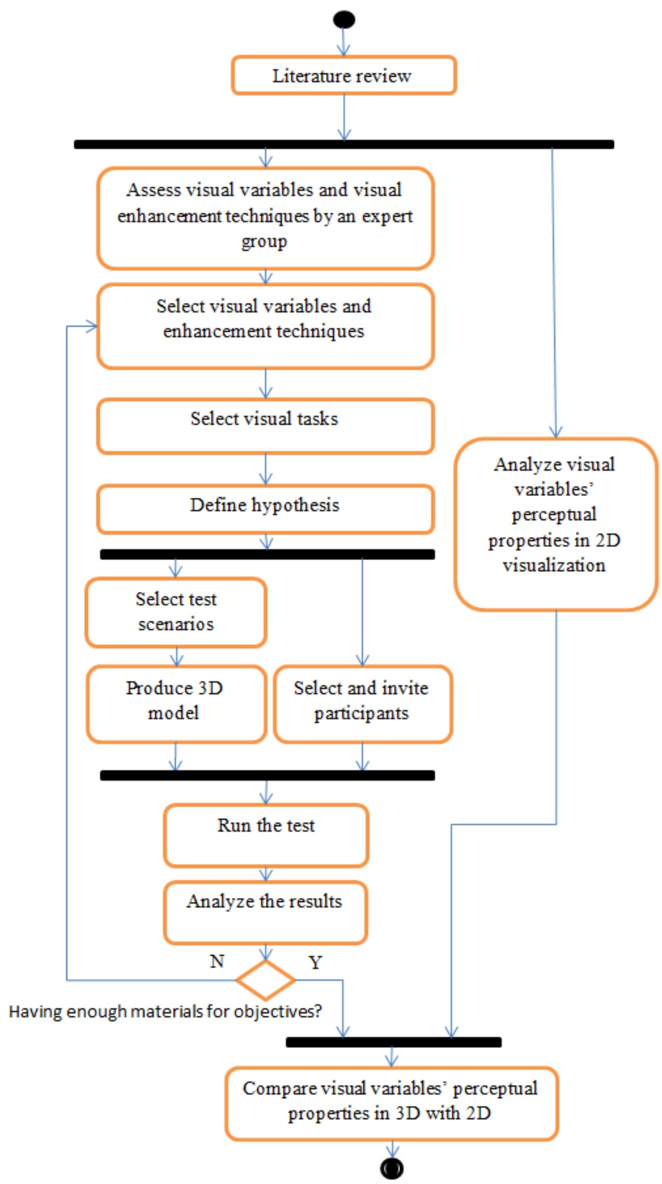


Figure 1.4. Research steps of this work, by UML activity diagram

In order to evaluate the suitability of visual variables and enhancement techniques, the dissertation uses the expert group method to determine feasibility. All of Bertin's visual variables are tested, including position, size, value, color, orientation, shape, and texture. For the visualization enhancement technique, information labeling is tested. The expert group consists of two professors and four graduate students in our 3D research groups at Laval University. They first determine the five visualization requirements necessary to support the decision-making goal of delimitating property units based on a literature review and their experience. Then, more than 200 3D models were constructed and evaluated. In each 3D model, only one visual variable or only one enhancement technique is used to encode underlying data, and the other visual variables and environment settings are kept largely constant. The assessment of the suitability of each 3D model is largely subjective but based on the expert reviewers' knowledge and experience, and the conclusions are derived from their evaluations with thorough reasoning and discussion. This step is helpful for us to limit the following evaluation by providing preliminary knowledge about the feasibility of each visual variable and visualization enhancement technique and by quickly eliminating the non-feasible or obviously feasible solutions.

This dissertation then performs the hypothetico-deductive scientific approach to empirically evaluate the suitability of the selected visual variables and enhancement techniques. The empirical test process is the center of this dissertation. In each test, it establishes a series of hypotheses to be falsified by empirical studies. Using empirical study is not only a requirement of the hypothetico-deductive scientific approach but also a fundamental need to achieve user-centered design (Wallach & Scholz, 2012). Many researchers have evaluated their visualization design empirically like Bleisch (2012) for geospatial visualization, MacEachren et al. (2012) for information visualization, and Shojaei et al. (2013) for cadastre visualization. Compared with simple subjective evaluation and analysis, empirical studies could more precisely evaluate the suitability of a visualization design (Green, 1998).

The evaluation criteria are the benchmark of a specific visualization design's suitability. They are the measurements that empirical evaluation tries to access, and the design process aims to improve. Among all the evaluation criteria, such as those listed by Van Velsen, Van Der Geest, Klaassen, & Steehouder (2008), the usability is selected to be the main suitability indicator in the test of this dissertation as it seems tightly linked with both the visualization design and the viewer's reaction. It has already been discussed in 3D visualization research of cadastre by a few researchers as a fundamental requirement for 3D visualization of cadastre (Shojaei et al., 2013; Van Oosterom et al., 2011). According to the usability specifications in ISO 9241, the experiment assesses the visual variables' and visual enhancement techniques' usability based on the observation and analysis of the user's effectiveness, efficiency, and preference with 3D models. However, due to the experiment limits, as different geometry of 3D model may influence the efficiency measurement, some of the tests only consider the effectiveness and preference.

The empirical test of the suitability of visual variables and enhancement techniques is a recursive process. In each round of test, the first step is to select a few visual variables and enhancement techniques to be empirically tested. Then, the precise visual tasks for determining the decision-making goals are devised. The selection of visual variables and visual tasks is based on the conclusions of the experiments performed during the preliminary test. The selection also considers the length of the test, as its duration should not be too long. The test then produces a series of hypotheses regarding the suitability of visual variables and enhancement techniques. Each hypothesis involves one visual variable for only one visual task. Then, the test scenarios are designed, and the 3D models are constructed according to the hypotheses. Meanwhile, a group or a few groups of participants are selected and invited to participate in the tests. The analysis of the test results may support or reject the hypotheses and, thus, may contribute valuable material to fulfill the research objectives of suitability evaluation. Each round of empirical tests will contribute valuable information, and each subsequent round aims to solve the new research questions that are prompted by previous rounds. For this dissertation, there will be a preliminary evaluation with an expert group and two rounds of empirical tests centered around the first research objective of eight visual variables (size, shape, brightness, saturation, hue, orientation, texture, and transparency) and the second research objective of transparency. In a preliminary evaluation of the visual variable's suitability, we only evaluate by the criterion of feasibility, which is the effectiveness subjectively assessed by experts. The selection of the participants is largely a convenient sampling, which means we chose all notarial participants we could find. During the empirical test, some of the user's attributes, such as their educational background and their experience with 3D visualization, are collected and analyzed. However, more focus is placed on visualization design rather than on users.

In order to achieve the third research objective, we identify the perceptual properties involved in each tested visual task and then synthesize the performance conclusion for each visual variable. Current theories and evaluation of visual variable's' perceptual properties in 2D visualization differ, and it may be impossible to tell which one is better since they are addressed from different aspects. As a result, this thesis compared the perceptual properties exhibited in the test with eight different research papers respectively, and six different theory frameworks are involved. General changes are spotted and synthesized at the end of this research together with the knowledge derived from the current research of information visualization and cognitive science.

1.6 Contributions of the work

The main contributions of this research include:

1. A 3D geo-visualization framework from an aspect of semiotics of graphics.
2. A list of visual tasks for delimitating property units in 3D cadastre visualization of condominiums that has been validated by notaries, for example, distinguishing the limits of property units from the associated physical limits of building construction in 3D visualization.
3. A statement about the suitability of eight visual variables (size, shape, brightness, saturation, hue, orientation, texture, and transparency) of the property units and three enhancement techniques (labeling, 3D object detaching and highlighting) in the context of 3D visualisation of condominium property units based on the usability specification for delimitating visual tasks. For example, brightness

only shows good suitability in helping users distinguish private and common units in the context of 3D visualization of condominium property units.

4. A statement about the differences, with respect to eight visual variables' perceptual properties, between 3D visualization of property units in condominiums and 2D visualization. For example, orientation is selective in 2D, yet it is not selective in the 3D visualization of property units in condominiums.

To complete this list of contributions, the outcomes of the thesis may also be recognised as foundation for further developments such as:

1. Designing a guide for best practices of 3D cadastral visualization.
2. Establishing methodological benchmark for empirical approach to test the suitability of visual variables and visual enhancement techniques in 3D cadastre model.
3. Improving current visualization theories in geo-visualization and cartography domains.

1.7 Thesis organization

This first chapter presented the research context, the problematic, research questions, research objective, and the methodology. Five chapters are afterward proposed:

- Chapter 2: *3D Visualization: Concepts, Theories, and Challenges*. This chapter gives a literature review of current visualization concepts and theories that are capable of being applied to the research in 3D geo-visualization. The concepts mentioned in chapter 1's introduction are further developed and precisely defined, for example, the terms "3D visualization" and "usability." In this chapter, we also present a 3D geo-visualization framework containing symbols and visual variables to support the literature review and discussion in the following chapters. This chapter also investigates the general challenges and current solutions of 3D geo-visualization in order to contribute background knowledge of 3D geo-visualization for further tests.

- Chapter 3: *3D Visualization of Condominium Property Units: Data, Users, Usages, and 3D Cadastre Model Designs.* First, this chapter examines the important terms used in cadastres and the inventory of cadastral data that cadastral visualization may contain in the condominium situation. Then, it discusses the users and their goals concerning visualization of condominium property units. Moreover, it reviews existing representation designs in 3D visualization adapted to the cadastral domain. The aim of reviewing current designs is to yield knowledge about the suitability of visual variables and enhancement techniques in 3D cadastral visualization.

- Chapter 4: *Suitability of Visual Variables and Enhancement Techniques for 3D Visualization of Condominium Property Units*. This chapter has two parts. The first part presents the assessment of the suitability of the visual variables and enhancements techniques while the second part compares the results with those from literature in 2D visualization. Regarding empirical tests, this chapter describes a preliminary evaluation of visual variables' feasibility in the research. Then, it describes the design, implementation, and results analysis of an empirical test of the suitability of visual variables in the form of face-to-face interviews with notaries. The comparison with 2D visualization starts with identifying the perceptual properties involved in the tested visual tasks. Such a comparison is carried out using seven current studies of visual variables in 2D visualization. In the end, this chapter discusses general conclusions about the suitability of visual variables and enhancement techniques in the 3D visualization of condominium property units and the influence of using the third dimension.

- Chapter 5: *Transparency for Delimitating Property Units with Physical Counterparts.* This chapter describes the design, implementation, and results analysis of an empirical test of the suitability of transparency for demarcating legal and physical sections in condominiums in the form of an online questionnaire. The purpose of this test is to address the second research objective. For the result analysis, necessary statistical methods are used.

- Chapter 6: *Conclusion and Future Research*. This chapter summarizes the process of this research, the main discovery, and its deficiencies considering the research questions and objectives. Then, it discusses the research results and contributions in a more general context of 3D geo-visualization, leading to the suggestion for future studies.

Chapter 2 - 3D Visualization: Concepts, Theories, and Challenges

Several concepts of visualization, like usability and visual variables, were briefly discussed in Chapter 1 but must be precisely defined to enable the following discussion of this research. This is of particular importance for this work as there are diverse models and theories such as pipeline model (Haber & McNabb, 1990), semiotics of graphics (Bertin, 1973, 1983), and data state model (Chi, 2000). A wide spectrum of disciplines including cartography, information visualization, human-computer interaction, computer graphics, and cognitive science contains visualization studies. We do not pretend to present an extensive analysis of all current visualization theories, but only those applicable to this research, which is a special application of geo-visualization in 3D geospatial domain. This chapter only presents application independent knowledge, and the next chapter will go further into the application dependent knowledge of cadastre and of condominium property units.

2.1 Introduction to the general theory of visualization

Visualization is a process that expresses data through the interface of images, diagrams, and animations to allow user's discovery, exploration, and visual analysis in order to acquiring insight of the data for particular purpose (Jones, 1996; Mcnamara, 2010; Tory & Möller, 2004). It has been used long in human history containing a huge amount of forms from characters and paintings to diagrams and scientific drawings. There is extensive research to explore the potential of visualization in a quite wide variety of topics like visual arts, computer graphics, information visualization, science visualization, cartography, and geo-visualization. There is no "correct" model for visualization. The visualization theory is always in accordance with the epistemological view of different disciplines and is designed for divergent purposes. Various models of visualization have been proposed by different researchers and groups to facilitate research in various domains under diverse topics, for example, semiotics of graphics (Bertin, 1983) for information visualization, Gestalt (Koffka, 1935) for perceptual science, and three-dimensional cartography model (Terribilini, 1999) for 3D geo-visualization. Voigt and Polowinski (2011) divided visualization research into seven different subfields including data, domain, graphical vocabulary, graphic representation, task and interaction, user, and system. They argued that many visualization theories only address a small subset of these fields. For example Tory and Möller (2004)'s user model in visualization discussed only the visual task and viewer's interaction, and Chi (2000) proposed an influential data-state reference model centered on the data part. Here, this chapter defines the visualization theory that involves data, graphic, and viewer together to be a general theory. There are many general visualization theories. For example, in the domain of information visualization, Pfitzner, Hobbs, and Powers (2003) presented an information visualization taxonomy that includes data, task, interaction, user's skill and operation context. Voigt and Polowinski (2011) proposed an ontology for the entire visualization process. In the domain of cartography, Häberling (2005) defines the design process of a 3D map with three design aspects including modeling, symbolization, and usability tests with users.

As a general theory, the pipeline model introduced by Haber and McNabb (1990) is a widely accepted epistemological interpretation of visualization process in current information visualization research (Voigt & Polowinski, 2011). This model interprets visualization as a series of transformation from data to display image. Many researchers (Card, Mackinlay, & Shneiderman, 1999; Chen & Jänicke, 2010; Malyanov, d'Auriol, & Lee, 2013) used pipeline model as the general visualization theory in their works with necessary extension including the human perception part like user's profile, their visual tasks, and their interaction with computer interface. Pipeline model is in accordance with the cartography and geo-visualization related research, since they all view the visualization process as a series of transmission. As a result, it has also been adapted in geo-visualization domain, termed portrayal pipeline (Doyle & Cuthbert, 1998) or geo-visualization pipeline (Open Geospatial Consortium, 2010). The pipeline model helps to explain the role of semiotics of graphic and visual varaibles in the entire visualization process. Among various pipeline models, this chapter adapted that of Chen and Jänicke's work (2010), as their pipeline contains not only the process of visualization from data to display but also perception process from display to human knowledge. However, minor modifications are necessary since Chen and Jänicke's pipeline model addresses visualization process from the aspect of signal transmission theory. Figure 2.1 shows the pipeline model of visualization where two groups of actions may be recognised: (1) the representation processes from data to display image and (2) the perception processes from display image to user's knowledge. In this figure, the different stages of visualization and perception are color blue while the transformation between stages is colored red.As visualization consists of converting the information to human knowledge through means of graphic representation, describing the procedure how the graphics created and how users perceive the graphics are both important. The visual design should consider the human sensory capabilities to ensure a quick and unambiguously perception of elements and patterns (Ware, 2012).

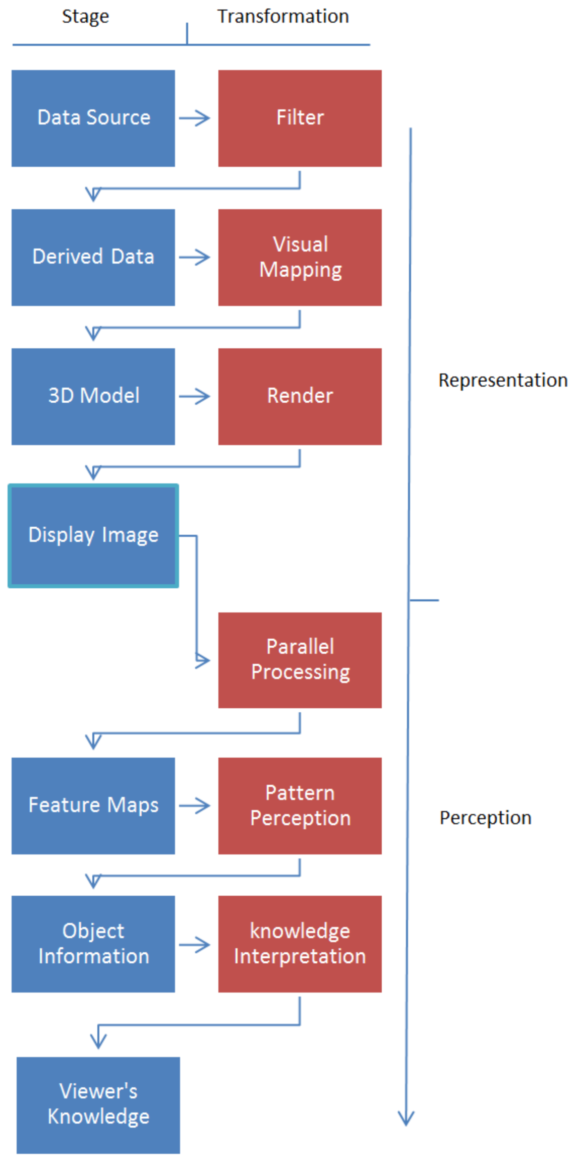


Figure 2.1. The pipeline model of visualization from data to viewer's knowledge, adjusted from Chen and Jänicke (2010)

In the representation part of the pipeline model, the data goes through transformation steps of filter, visual mapping, and rendering to the final display images. Graphic semiotics is carried out in visual mapping step. The display images are the end of representation process and the starting point where the viewer's perception begins. In the perception part, the display image is perceived and interpreted in three transformation steps of parallel processing, pattern perception and knowledge interpretation into the final viewer's knowledge (Treisman & Souther, 1985; Ware, 2012). The pipeline model is static; however, it is important to emphasize the dynamic and iterative nature of visualization and human perception. For human perception, pattern perception step could not process the entire scene at a glance. Instead, it is an iterative procedure consisted of a number of steps

(Milner & Goodale, 1995; Rensink, 2002; Ware, 2012). Answering a visual query may lead to several new visual queries in which other selections of objects are needed. On the other hand, the visualization process from data to display image is also becoming a dynamic process as state-of-the-art computer based visualization tools like Google Earth, Arcscene, and Blender enable user to interact with the visualization result and customize the visual mapping process to fulfill their visualization demands.

As a conceptual model, the pipeline model separates the 3D model with final visualization realization, and divides the visualization process from the human perception process. It only represents a static profile of the dynamic visualization and perception process. The pipeline or part of it will repeat and iterate until the visual purpose is fulfilled. It is a general description of the entire visualization process. Many detailed components concerning graphic semiotics process, like the data and design possibilities, are excluded. The user's role in visualization process should also be demonstrate to support the following argument in this thesis, which involves direct user study. Thus, the following sections discuss the data, the user, and the design space in 3D geo-visualization.

2.2 Data in visualization

Data are the starting point of visualization process according to the pipeline model. Derived data is also the basis of the graphic semiotics. It is a critical factor for both viewers and computers that involved in the visualization process (Pfitzner et al., 2003). In addition, it is the starting point of several visualization research like the data state reference model (Chi, 2000) and data-centered theory (Purchase & Andrienko, 2008). Moreover, the interpretation of data pattern and structure is one of the essential goals of user's perception and analysis (Demiralp, Scheidegger, Kindlmann, Laidlaw, & Heer, 2014).

In geo-spatial domain, researchers tend to categorize data into spatial data and non-spatial data, as demonstrated by Longley, Goodchild, Maguire, & Rhind (2011) in their famous book "Geographic information systems and science". Spatial data, which is the measurement of spatial variables (location, geometry shape and spatial relation) of the spatial object is the basis of many geo-visualization and cartography research like that of Schilling(2014) and Häberling, Bär, and Hurni (2008). Non-spatial data is either the attribute data of the non-spatial object, or the descripive data of spatial object, such as the lot number of a land parcel. For the non-spatial data, four scales of measurements proposed by Stevens (1946) have been used in geo-visualization research like Kraak & Ormeling (2011) and Slocum (2009) for assessment of visual variables. In addition, some of the studies in information visualization evaluate the visualization results considering the data scale, like Rogowitz, Treinish, and Bryson (1996), Lohse, Min, and Olson (1995), Ware (2012), and Borland and Taylor (2007). The four scales of measurements are:

- *Nominal data*: The measurements of this data are differentiated by its qualitative classification or naming. Sometimes numeric measurement will be used to represent naming or classification. However, in this circumstance, they do not represent any quantitative meaning, any ordinal direction nor distance difference. For example, the nominal scale could be “Montreal”, “Toronto”, or “Quebec”. It could also be “0” or “1” which represent a Boolean measurement.

- *Ordinal data*: The ordinal data are those data measurements that could be ranked but have unequal distance between them. For example, Likert scale (Likert, 1932) is widely used in user survey to measure subjective attitude. A typical Likert scale contains five degrees: Strongly disagree, disagree, neutral, agree and strongly agree. It is a formal way to rank the result; however, the distance between different levels could not be esteemed equal.

- *Interval data*: They are those data measurements that could be ranked and the distance between them could be measured. For example, temperature data. However, any scale calculation is impossible for interval data because they do not have a true “zero” point. For example, 30 degree Celsius is not three times hotter than 10 degree Celsius.

- *Ratio data*: Data with measurements that allow ranking, measurement of distance and with a true “zero” point. For example, angle, duration time and latitude.

Bertin (1981) proposed two fundamental characteristics of data: data value and data structure. We evaluate that Bertin’s proposal of two parts of data could further extend its data structure into data model for more structural and digitized expression. Data value is the real digit or string that stored like -3.4, 1, A+, or "Quebec". It could represent the real world phenomenon only in combination with a data model. Data model is a structural specification of a set of data and their relationship for representing parts of the real world in a digital system. It decides what data is collected, how these data is organized meaningfully to describe the reality, what their meanings are, and how they could be processed in a digital system. The same data value, for example, "2.0" could be interpreted as a measurement of temperature, an amount of money or a position over axis Z according to the underlying data model.

Both data model and data value are influential factors that a visualization research should consider. For example, 3-dimensional (3D) geospatial data model and 2-dimensional (2D) geospatial data model may require different visualization strategies. For data value, the range of data value, the amount of different measures and the value distribution are considered influential in visualization discussion. For example, each visual variable like color or size can represent three to five distinguishable values (Carpendale, 2003; Ware, 2012). When there are more values, the designer should either use multiple visual variables or add a numerical scale.

Besides data value and data model, there are many other data taxonomies. Shneiderman (1996) proposed a taxonomy with seven data types: 1-dimensional, 2-dimensional, 3-dimensional, temporal, multi-dimensional, tree and network. Roth and Mattis (1990) characterized data by data type and relational structure. Their theory contains three characteristics of data type: "Set ordering: nominal, ordinal and quantitative", "Coordinates versus Amounts", "Domain of Membership", and three properties of relational structure: coverage, cardinality and uniqueness. Ware (2012) evaluated that data could be categorized by the attributes of entities and their relationships. He proposed that the classification includes, but not limits to "Data Dimensions: 1D, 2D and 3D" and "Types of numbers: Nominal, Ordinal, Interval, and Ratio". Viewed from the classification of data value and data model, the above-mentioned data taxonomies are mainly based on data model rather than data value, as they all concern the interpretation of data under certain data model. There are also data value based taxonomies. For example in the domain of the database, data is classified into integral data, decimal data, and string data.

2.3 User and User's Visual Tasks

While data is the starting point of visualization, user is the ultimate receiver of the information that transformed by visualization process. It has been recognized as a critical factor in current research of cartography (Virrantaus, Fairbairn, & Kraak, 2009), geo-visualization (MacEachren & Kraak, 2001; Robinson, Chen, Lengerich, Meyer, & MacEachren, 2005) and information visualization (Plaisant, 2004). In an era of computerized visualization, user's requirement, cognitive capabilities and preferences greatly influence the visualization design (Haklay, 2010). User research with empirical experiment is the key to access the visualization (Anderson, 2012). The capability, pros and cons of a visualization design could be exposed through user studies. Meanwhile, by user studies, the designer could understand more about users' requirements, their perceptual capability, and how they interact with the display. Moreover, many existing elementary visualization knowledge and design principles of visualization are derived from the direct user research. For example, CIE 1931 XYZ color space is a reference color space adopted by International Commission on Illumination. It has been used directly or with transformation in the research of scientific visualization (Moreland, 2009) and cartography (Brewer, MacEachren, Pickle, & Herrmann, 1997). User experiments with a large number of participants are the basis of CIE 1931 XYZ color space's creation (Guild, 1932; Wright, 2002).

Considering the importance of user in visualization, a few researchers advocated or employed a user-centered visualization design like Haeberling (1999); MacEachren and Kraak (2001); Shojaei, Kalantari, Bishop, Rajabifard and Aien (2013). The user-centered design is a doctrine that highlights user's need and involves the intended user in the design process (Abras, Maloney-Krichmar, & Preece, 2004). It was proposed in the domain of human-computer interaction, but has also widely discussed in the research of information visualization (Chen, 2005; Koh, Slingsby, Dykes, & Kam, 2011) and cartography (Elias & Paelke, 2008; Tsou, 2011). For a system easy to learn, useful and pleasant to use, Gould and Lewis (1985) recommended three implementation principles, which have then been evaluated essential for user-centered design (Wallach & Scholz, 2012). The three principles are:

- *Early focus on users and tasks*: designers should understand user's cognitive capabilities, its knowledge background, its decision-making goals and visual tasks at very early stages in a design process.

- *Empirical measurement*: the evaluation of visualization design will be based on observation, register and analysis of intended users' objective performance with the design and their subjective opinions.

- *Iterative Design*: the design will be a cycle process in which the visualization designs and the understanding of intended user will improve through multiple tests with the user, analysis of results, and re-design.

A user model is the collective information of a particular user or user group that can be used to adjust the system(Domik & Gutkauf, 1994; Van Velsen et al., 2008). It contains attributes that differentiate the user for specific purpose, like the user identification and domain for Windows login, the address and payment information for an online shopping site, and the gender, age, weight for a medical survey. In the visualization research, there are multiple influential factors in user model including user's discipline, their socio-demographic attributes, their physical and psychological situation, and their visual tasks (Domik & Gutkauf, 1994; Schulz, Nocke, Heitzler, & Schumann, 2013).

Many researchers divided users by their disciplines like Shojaei et al. (2013) and Schulz, Hadlak and Schumann (2011). It is reasonable to argue that users from different disciplines may use visualization system for different purposes. For example, surveyors may use cadastre visualization for survey related tasks and government employees use it for the tax calculation purpose. Users from the same domain may also differ in their knowledge, experience, socio-demographic attributes, and physical, psychological situation. These attributes may also influence their effectiveness and preference when using a visualization design. Domik and Gutkauf (1994) listed a few user's socio-demographic attributes and psychological situation that could affect their perception including gender, age, color perception, color memory, and fine motor coordination. Brewer, MacEachren, Pickle, and Herrmann (1997) emphasized that cartographic design aiming for general public should consider the user with color perception deficiencies, as statistically 8 percent of males and 0.4 percent of females have color perception deficiencies (Wyszecki & Stiles, 1982).

User's visual tasks are the goals and perceptual activities that a user tried to achieve with the visualization display. A list of intended users' visual tasks is the basis of user-centered visualization design according to user-centered design principles (Abras et al., 2004). A framework of user's visual tasks is imperative for both visualization design and visualization evaluation (Tory & Möller, 2004), as it gives a common vocabulary for designers to describe, understand and evaluate the visualization regarding end user's tasks (Amar, Eagan, & Stasko, 2005). However, there is no widely accepted framework to describe visual task currently. Evaluating the features of influential theories of visual tasks backs the choice of an appropriate vocabulary system to describe precisely the intended visual tasks for this research in the following research process.

Many researchers allocated visual tasks in different perception levels. For example, Roth (2013) proposed two levels including goals and objectives. Amar, Eagan, and Stasko (2005) divided user's visual analytic tasks into high-level goals, which is more objective centric, and low-level goals, which is more visual query centric. Lee, Plaisant, and Parr (2006) suggested three task levels containing low-level tasks, graph tasks, and high-level analytic tasks based on Amar, Eagan, and Stasko's model. High-level visual tasks are general goals, and the low-level tasks are detailed operations to accomplish the general goals. Zhou and Feiner (1998) characterized a list of visual tasks by their visual accomplishments (the presentation intent that visualization has to achieve) and implications (the perceptual action a viewer carries out). In visual accomplishment, they listed 15 low-level visual tasks by their visual intents like "inform", which contains “elaborate” and “summarize”, and "enable", which contains “explore” and “compute”.

Current description of user’s visual tasks also differs in other aspects. For example, they could be operation oriented like Tory, Kirkpatrick, Atkins, and Möller (2006) or exploratory oriented like Andrienko and Andrienko (2006). Operation oriented visual tasks follow a predictable routine to achieve a particular goal, while exploratory visual tasks contains dynamically evolving subsequent tasks for a general goal. They could be centered on viewer’s perception like Shneiderman (1996) or visualization implementation requirements like Shojaei et al. (2013). Some researchers address visual tasks domain independently and theoretically, like Zhou and Feiner (1998), while the other addresses these visual tasks for visualization system in a particular domain, like Shojaei et al. (2013) for the visualization of 3D cadastre. Many researchers discuss visual tasks with the consideration of underlying data. Bertin (1983) argued that "there are as many types of questions as components in the information", and Shneiderman (1996) suggested a task-by-data-type taxonomy, based on seven data types. The previous review showed many of current visual tasks theories and frameworks. The choice among them should consider the specific research purpose and context.

In sum, understanding intended user's personal attributes and visual tasks is critical for user-centered visualization design and evaluation. Aiming more pertinent visualization results, designers often differentiated users by their discipline as well as their knowledge background, experience, socio-demographic attributes, and physical, psychological situation. Pertinent design strategy also calls for a list of clearly defined visual tasks to describe, understand and evaluate the user's potential usage. There are many description frameworks.

2.4 The 3D geo-visualization design space

2.4.1 Introduction

The user-centered design process could provide contextual knowledge for visual design, as well a posteriori evaluation. Nonetheless, how to produce a usable visualization design based on the knowledge of data, the intended user, and its usage is still a challenge since it may require the domain knowledge and design experience. A design space consists of a series of visual design dimensions like visual variable, symbol, transform algorithm, and model in which designers can make design choice (Baudel & Broeskema, 2012; Card & Mackinlay, 1997; Javed & Elmqvist, 2012; Schulz, Nocke, Heitzler, & Schumann, 2013). Because design space enables the definition of the visualization design borders to prevent inappropriate solutions (Simon, 1996), global understanding of visualization design space may greatly facilitate designer's decision-making.

Many different design spaces have been proposed by researchers. For example, Baudel and Broeskema (2012) constructed a design space including order, size, chunk for a specific class in model algorithms of treemap, and Javed and Elmqvist (2012) devised a composite visualization design space based on visualizations, spatial relation and data relation. Card and Mackinlay (1997) have formed a comprehensive design space to describe the visual design in information visualization. Their design space involves variables, data types, recorded data types, control processing, mark types, retinal properties, position, view transformation and widget. For each visual design dimension, vocabulary, and grammar are also formulated. There are many theories, international standards, and implementation specifications of design space addressing geo-visualization from an aspect of semiotics of graphics, for example Bertin (1983)'s theory, ISO 19117 Portrayal, OGC Symbology Encoding, and CartoCSS. These frameworks highlight the separation of visualization representation from original data and an algorithm of transformation between them. Bertin's design space, which is termed semiotics of graphics, consists of symbols and their visual variables. It is defined from a theoretical aspect. In contrast, OGC symbology encoding and ISO 19117 Portrayal (ISO, 2009) defines the geo-visual mapping process from a more practical way. ISO 19117 Portrayal lists a comprehensive set of graphic symbols, their structure and their organization to represent geospatial features. Its specification is documented in Unified Modeling Language (UML) in order to provide more structural expressiveness compared with terminology and taxonomy narrowed in nature language. OGC Symbol encoding is an implementation specification that normally works together with Web Map Service to provide customization. It covers a subset of ISO 19117's schema. All the frameworks mentioned above provide systematic ways to describe the design space of visual mapping process in a software platform independent (not medium independent) form. ISO 19117 and OGC Symbol Encoding, as a structure defined by

UML, could also support related system implementation. Beside explicitly defined theories, some cartographical software imply a design space, for example, CartoCSS[2], which is supported by Mapbox and Openstreetmap Similar example includes ESRI's lyr file, which is used inside ArcGIS platform.

Shortcomings of these design space theories and framework of visual mapping when applied to 3D geo-visualization have been spotted. First, all these theories or frameworks are based on 2D visualization. Extending the scheme to describe visual mapping process for 3D geo-visualization is a necessity. Many efforts have been made to extend them into 3D recent years (Haist, Figueiredo Ramos, & Reitz, 2007; Neubauer & Zipf, 2009). However, they are still in an early developing stage. Second, the ISO 19117 portrayal and OGC symbol encoding specification do not structurally include the visual variables. Instead, they only list them as possible attributes of symbols. The deficiencies of current frameworks may hinder their expressive capability for visual variables based cartography design and evaluation. Moreover, they could not describe the dependencies and interaction between different visual variables.

In consideration of the incapability of current design space theories for 3D geo-visualization, this work synthesizes a framework of 3D design space for geo-visualization based on the semiotics of graphics and visual variables in order to guide the following investigation. The center of this framework is a **3D cartographic representation** (**3DCR**), a 3D model which is the result of a visual mapping process and the main content in a 3D scene. The purpose of using the term 3DCR instead of general 3D model is to highlight the semiotics of graphic in the model creation and the application of geospatial. Not all 3D model could be view as a 3DCR, like those used for CAD, painting and animation. In a highly dynamic and interactive 3D scene, 3DCR could also be used to describe the representation design of a temporary state. The dynamics and interactions in 3D geo-visualization are also design dimensions in 3D visualization. However, they will not be considered in this research since the main focus of this work is on the 3DCR, rather than the interaction as stated in the first chapter. Similar to Haeberling (2002)'s graphic aspects of 3D maps and Terribilini (1999)'s three dimensional cartography model, 3D cartographic representation is a static three-dimensional and platform-independent description of static 3D representation design from a semiotics of graphic's point of view. Visual mapping is the transformation from data to 3D model by making design choice along representation design dimensions in a design space. The 3DCR's design dimensions consist of 3D symbols, their different visual variables, and are influenced by environment settings like projection, lighting, shading, background, and atmosphere. 3DCR describes the portrayal characteristic of a 3D model that represents underlying data, thus data and data model are the premises of the creation of a 3D model. Moreover, same underlying data could produce multiple 3DCRs to meet diverse design goals. 3DCR is not the final visualization result. It is realized by rendering process on different software platforms

[2] https://www.mapbox.com/tilemill/docs/manual/carto/

and different devices. For example, the same 3DCR could be viewed in a monoscopic 3D device like 2D projector, a stereoscopic 3D device like 3D LCD and even a CAVE (Cave Automatic Virtual Environment)(Krevelen & Poelman, 2010). The following chapters still use the term 3D model or 3D cadastre model, which may be easier for readers to keep the track of reading. However, readers should keep in mind that the 3D model in this dissertation is only refer to a 3D cartographic representation which we build the model from an aspect of semiotics of graphics with visual variables for geospatial application, and it is only a subset of all 3D models.

The following sections detail the design space centered in 3DCR from three parts: symbols and visualization primitives, visual variables, and environment settings.

2.4.2 Symbols and visualization primitives

In the research domain of visualization, and from an aspect of semiotics of graphics, symbol is the graphic element that represents an object and its attributes (ISO, 2009; Ware, 2012). It could be a faithful representation of the objects outline. It could also be an abstract image, like parking sign that represents a location for parking. Symbol differs in complexity. It could be simple ones like boundaries, or complex ones like a building model or a terrain model. A complex symbol may consist of a few simpler ones. For example, in figure 2.2, the door, helicopter sign (H), heart sign and the geometry of the building are all symbols. However, together they constitute a symbol of a cardiovascular hospital with an indication of its door open direction and helicopter landing capability.

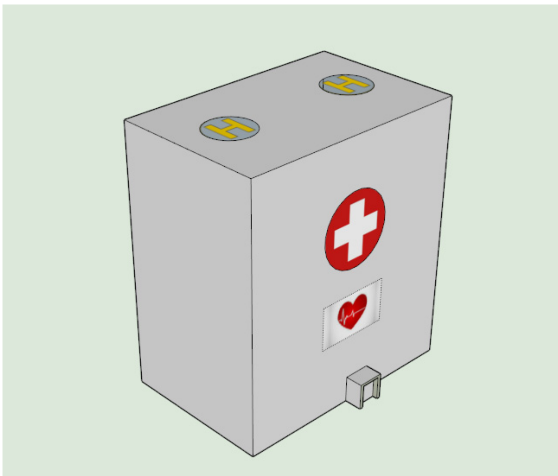


Figure 2.2. An example of complex 3D symbol of a cardiovascular hospital

Here visualization primitives are defined to be the basic graphic unit and the finest symbol in 3D model. Similar to Carpendale (2003)'s work, this work defines four visualization primitives including point, line, surface, and volume. Their definitions are as follows:

- Point: A zero dimension visualization primitive locates in a 3D space but with no occupation of space in any dimension. A point is perceivable when the size of the graphic used for it is big enough for user's perceptual system. In a static 3D model, the point symbol will not change its display on 2D screen with the change of environment setting and camera movement.

- Line: A one dimension visualization primitive locates in a 3D space and only has a length as its dimension. A line is perceivable when the size (width) of the graphic used for it is big enough for viewer perception. In a static 3D model, the line symbol will not change its display except its orientation on 2D screen with the change of environment setting and camera movement.

- Surface: A two dimension visualization primitive locates in a 3D space and has length and width as its dimensions. The surface symbol will change its display on 2D screen with the change of environment setting and camera movement. Visual thickness is sometimes used to enable viewers to perceive surface. In a static 3D model, the surface symbol will not change its visualization thickness with the change of environment setting and camera movement.

- Volume: A three dimension visualization primitive locates in a 3D space and has length, width and height as its dimensions. The volume symbol will change its display on 2D screen with the change of environment setting and camera movement.

Defined in 3DCR, visualization primitives are different from geometric primitives of geospatial data, which are the basic geometrical units to represent the real-world geospatial phenomenon. Visualization primitive can be produced from geometry primitives of geospatial data by visual mapping; however, it is not limited to the same geometry type of underlying data. In a cartographic representation, the transformations from geometric primitives to visualization primitives concern generalization and symbolization processes, and such transformation is normally for specific visualization purpose (Häberling, 1999; Wolf, 2009). Theoretically, any visualization primitives could represent a geometric primitive. For example, a volume ball, a surface of a star, or even a cross symbol composed of two line primitives could all be used to represent a geometry point in a 3D model.

2.4.3 Visual variables

Visual variable, sometimes also called graphic variable and visual attribute, is the perceivable characteristic of a symbol or a combination of symbols that could be used to transmit information. It has firstly been proposed by Bertin (1973) and then been widely accepted as a fundamental notion in the domain of cartography and information visualization (Roth, 2012; Yilmaz & Duzgun, 2011). In Bertin's theory, there are seven visual variables including position, size, value, texture, color, orientation and shape. Bertin divided them into two categories: Planar dimensions (X, Y) and retina variables (size, value, texture, color, orientation, and shape).

Bertin’s definitions of retina variables are:

- Size: height of a column, area of sign and number of equal signs
- Value: the various degree between white and black
- Color: Using repertoire of colored sensation with equal value
- Orientation: the orientation of a line or line pattern
- Shape: different shape with constant size
- Texture: a variation in the fineness or coarseness of the constituent of an area.

Although Bertin’s seven visual variables are still widely used in current cartography and information visualization research based on the literature review of Halik (2012) and Andrienko & Andrienko (2006), its definition is from the point of view of map designer in 1970s. Due to the technical advancement and studies in cartography, information visualization and cognitive science since then, some researchers gave the interpretation of Bertin's seven visual variables from different aspects. For example, Green (1998) interpreted visual variables from a perceptual point of view. The list of visual variables has also been extended. For example, MacEachren (1995) proposed to separate Bertin’s color into color hue and color saturation; Carpentale (2003) adds two visual variables: pattern and grain; and Slocum (2009) proposed the list of visual variables to include spacing, perspective height, orientation, shape, arrangement, lightness, hue, and saturation. This is the list of a few extensions proposed by other researchers:

- Material (Carpendale, 2003): the textile, or matter of a symbol when it perceivably resemble a real life surface
- Grain (Carpendale, 2003): the granularity of the symbols in space or structures that consist the surface
- Transparency (MacEachren, 1995): the translucency of a symbol
- Pattern (Carpendale, 2003): the shape of the symbols in space or structures that consist the surface
- Arrangement (Morrison, 1974): the way symbol are organized.
- Sketchiness (Boukhelifa, Bezerianos, Isenberg, & Fekete, 2012): the degree of the sketchiness of the symbol.
- Crispness (MacEachren et al., 2012): the degree the symbol is blurred
- Resolution (MacEachren, 1995): the pixel density of a symbol

The previously mentioned literature of visual variables is originally proposed in 2D visualization. However, several cartography and visualization research in 3D visualization are still centered on Bertin's seven visual variables, like Halik(2012) (Navigation with 3D visualization) and Hardisty (2001) (3D cartography). 3D visualization may bring in more visual variables in the list and need new interpretations of existing ones. Carpentale (2003) extended the visual variable "position" to be a 3D position. Slocum suggested "Perspective height" to be a visual variable in 3D visualization. In addition, Häberling et al. (2008) listed animation, light source, and camera view to be 3D specific visual variables. Yilmaz and Duzgun (2011), from a practical point of view, defined 2D visual variables' 3D equivalent all under categories of "material" and "texture". They also suggested that visual variables in 3D will be more complex like color contains the diffuse color, emissive color, and specular color. Despite these research efforts, till now, there is no consensus on the list of visual variables among different researchers in both 2D and 3D.

Visual variables have different suitability when considering specific visual tasks. Some researchers try to generalize their ad-hoc suitability to perceptual properties. Bertin's four perceptual properties of visual variables, which he termed "level of perception" implies the suitability of visual variable for four different visual tasks: visual isolate, visual grouping, visual classing and visual distancing. Their definitions by Bertin (1983) are:

- Selective: immediately isolate all the correspondences belonging to the same category, (the same category but not necessary the same group).
- Associative: grouping of all the correspondences differentiated by this visual variable
    - Dissociative: an attribute that negate the selective of other variables
- Order: immediate visual classing of its steps
- Quantitative: immediately perceived visual distance between categories

Besides Bertin's definition, we recognized five other evaluation frameworks of visual variable perceptual property. First, in Carpendale (2003)'s theory of visual variables, selective is defined as "*a mark changed in this variable alone makes it easier to select that changed mark from all the other marks*", and associative is defined as "marks that are like in other ways can be grouped according to a change in this visual variable". Halik (2012) used the same definition of selective and associative of Carpendale, but have a different inventory of visual variables and suitability evaluation conclusions. Halik placed his conclusion in virtual environment context; however, his conclusion is based on 2D visualization based literature rather than empirical tests.

Second, in Green (1998)'s interpretation about the suitability of visual variables, selective "*permits the viewer to select one category of a component, perceive locations of objects in that category, and ignore others*". His perceptual property selective is similar to Bertin's dissociative and selective combined. In his theory, associative means "*allowing grouping of all elements of a variable in spite of different values*", which is similar to Bertin's associative.

Third, MacEachren (1995)'s definition used a mixture of data scales with perception properties. It contains five axioms in the visual variable syntactic including numerical, ordinal, nominal, visual isolation and visual levels. He claimed that the “visual isolation” and “visual levels” are corresponding to Bertin’s selective and associative respectively. Nonetheless, based on his discussion in chapters 2 and 3 of his book, as argued here, MacEachren’s definitions are closer to Carpendale’s selective and associative.

Fourth, some of the researchers evaluated the suitability of visual variables directly by four scales of non-spatial data including nominal, ordinal, interval and ratio, like Kraak & Ormeling (2011), Slocum (2009) and Mackinlay (1986).

Finally, Garlandini and Fabrikant (2009) empirically evaluate the effectiveness and efficiency of visual variables to guide viewer’s visual attention for change detection in geo-visualization. Their research is an attempt to embed cognitive science with cartographic theories concerning Bertin’s perceptual properties. They also provide empirical evidence supporting Bertin’s evaluation of visual variables in 2D visualization.

The shortcomings of current visual variable based theories have to be mentioned here to precise the research limitation from a theoretic point of view. Although visual variables has been widely used to describe the design and implementation of cartography and information visualization as mentioned before, they fails to embed the knowledge from psychophysics and cognitive science (Garlandini & Fabrikant, 2009; Green, 1998). Some deficiencies of current frameworks of visual variables have been spotted through this research. Firstly, rather than the perceptual magnitude, the value of certain visual variables are defined by their computational graphic properties rather than a perceptual magnitude in current theories. For example, the brightness value 100 in HSL color space is not perceptually four times brighter than the brightness value 25. The empirical research of visualization is often perception based; at the same time, the visualization implementation is often physical attributes based. Thus, an algorithm that mapping certain visual variable from physical attribute to perceptual stimuli strength is helpful to link the research and implementation. Secondly, visual variables may interact with each other. For example, the perception of size is dependent on symbol's shape. It is hard to compare precisely the size of two symbols with different shapes. Some researchers have listed possible interactions between visual variables, like Green (1998) and MacEachren (1995), but they failed to provide a structural theory to synthesize the knowledge. Their conclusions, as evaluated here, are fractural and sometimes vague with many exceptions. Ware (2012) gave a comprehensive discussion of visual variables and their interaction in the context of glyphs, an independent visual object that depicts attributes of data recorded (Borgo et al., 2013). His conclusion is similar to channel theory that has a firm neuro-physical basis. Nonetheless, his discussion only considered the interaction between visual variables that is used for information encoding within the same symbol, and the interactions of visual variable with non-information-encoding graphic attributes, with visual variables of other symbols, and with the environment settings have not been discussed. Furthermore, as mentioned in Ware's argument, there are still many exceptions that his theory failed to explain. For example, his visual variable conjunctions could not explain all possible situations. In 3D context, only Jobst, Kyprianidis, and Döllner (2008) gave a non-empirical qualitative analysis of the interaction between visual variables, as well as between visual variable and environment settings. In sum, current visual variable based geo-visualization theories fall short in embedding knowledge from perceptual science and depicting the interaction between visual variables. This dissertation, which is built upon current visual variables' theories, will also share this theoretical restriction.

2.4.4 Environment settings

One of the differences between 3D visualization and 2D visualization is that the former contains environment settings that could greatly alter the appearance of the final display result. According to research in 3D visualization like Haeberling (2002), Jobst et al. (2008), Ware (2012) and Döllner (2005), six influential environment settings have been identified.

A. 3D Projection

The 3D projection defines the algorithm to map the 3D cartographic representation onto 2D screen. Among all different types of 3D projection, two types of projection are oftenly used in 3D visualization: orthographic projection and perspective projection. Orthographic projection is the projection that all the projection line is parallel and has no distance effect, which means object nearby does not appear larger than the remote object with the same size. In contrast, perspective projection considers distance effect, and the object nearby appears larger than the remote object with the same size. Projection settings will influence the perception of some visual variables, for example, orientation and shape. Figure 2.3 is a good example to demonstrate the influence of projection on the perception of visual variables. In figure 2.3, the object in the 3D scene is a cuboid. Orthographic projection makes that the top surface and the bottom surface has an identical area, however, it gives an impression that the top surface is smaller than the bottom one. In contrast, the model with perspective projection has a larger upper surface. However, it gives a more natural impression of a cuboid. The orientation of the boundary changes between these two projections too. It is a good example to demonstrate how our perception system manipulates the original visual signal to create an illusion that is sometimes different from the real physical reality. The research in cognitive science gives theoretical explanations: the perspective clue is an important cue for object positioning, orienting, and scaling (Wanger, Ferwerda, & Greenberg, 1992).

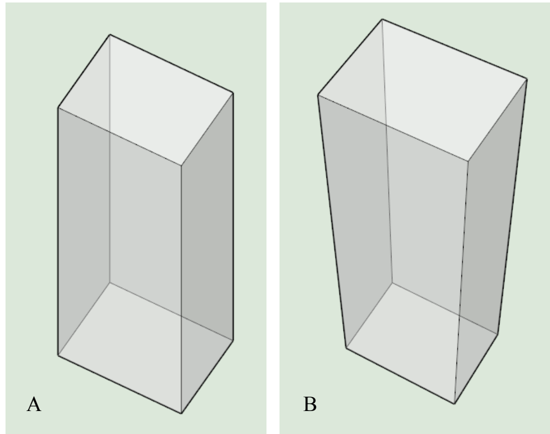


Figure 2.3. Same 3D scene with different projection: A, orthographic projection; B, perspective projection

B. Lighting

The lighting defines the type of light, its intensity, hue, and location in a 3D scene. The commonly used light types are Ambient lighting, Diffuse lighting, and Directional lighting. Ambient lighting is to apply brightness to the objects in a 3D scene globally; diffuse lighting is to simulate the light that reflected or re-emitted by objects surface; and directional lighting is to depict light that only emitted following given directions. Figure 2.4 shows how the change in light source position of a directional lighting will alter the brightness of surfaces.

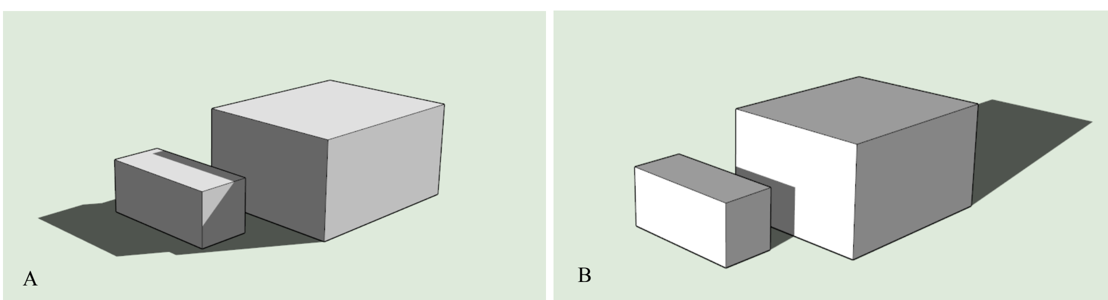


Figure 2.4. Different directional lightings and the shadows influence the brightness of surfaces. A: the light source is placed on the right, B: the light source is placed on the left. The two images use a same 3D model.

C. Shading

Shading is a visualization enhancement that uses brightness changes on a surface or surfaces to create depth perception of a surface or a volume. There are many different shading algorithm including Phong shading (Phong, 1975) or cartoon-like illumination shading (Jobst et al., 2008). Ware (2012) concluded that shading could enhance the depth perception of a 3D symbol, and Haeberling (2002) described that it "gives life to a 3D map". Figure 2.5 demonstrates the importance of shading effect for shape perception in 3D. However, shading may cause misunderstanding of information encoded in the visual variable of brightness, as it unevenly changes the brightness both between surfaces and within a surface.

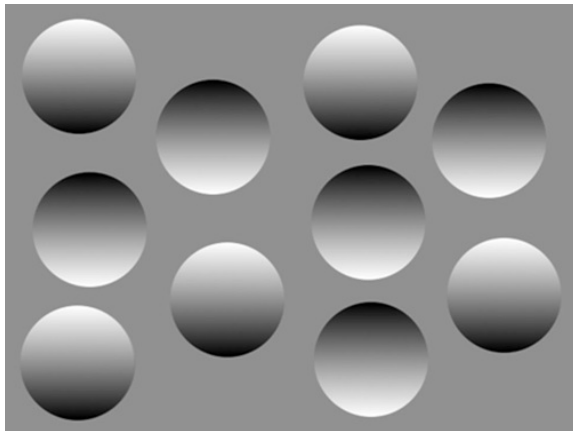


Figure 2.5. Shading effect changes the perception of a symbol's shape. The circle with brighter top illustrates a shape of convex and the circle with darker top shows a shape of concave.

D. Shadowing

Shadowing is largely decided by lighting and the arrangement of symbols in a 3D model. Shadowing could enhance the perception of the spatial relationships between 3D symbols (Wanger et al., 1992). However, similar to shading effects, it may affect the perception of brightness, hue, saturation, and shape. Sometimes it is more harmful than helpful in 3D visualization (Ware, 2012). Figure 2.4 shows how the shadow changes the brightness of surfaces.

E. Background

The background is the infinite end of a 3D model. Its visual variables will influence the perception of 3D symbol's visual variables. For example in figure 2.6 the two boxes have equal size. However, the right one appears larger than the left one because of the background texture.

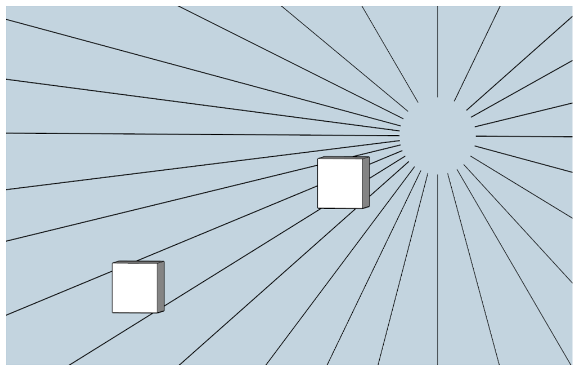


Figure 2.6. Background influences the perception of symbol's size

F. Atmospheric effect

By changing the scattering, and distance fall-off of the lights in the 3D model, designers could create atmosphere effect of fog or other effects like dust and haze. The perception of some visual variables will be influenced by atmospheric effect. For example, brightness, hue, and saturation will be influenced by atmospheric effects like fog (Hagedorn & D'Zmura, 2000; Jobst, Kyprianidis & Döllner, 2008). The atmospheric effect's influence on visual variables is decided not only by the settings of atmosphere but also the location of the symbols and the location of the camera together. For example, in figure 2.7 with atmosphere effect of fog, the identical symbols in 3D model may appear differently in the final display due to their distance with the camera: the further ones appear dimmer.

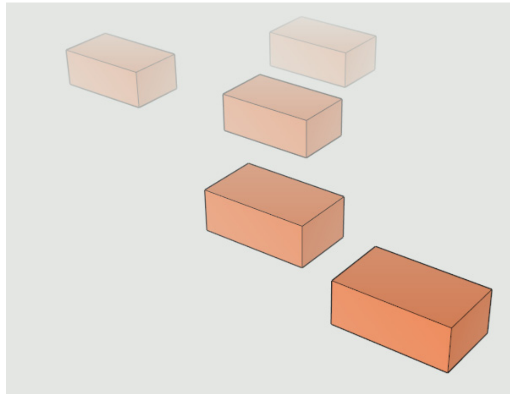


Figure 2.7. Atmospheric effect fog makes the further symbols dimmer

2.5 3D geo-visualization challenges

2.5.1 A review of challenges

3D geo-visualization brings new design possibilities as demonstrated in the design space for visual mapping; at the same time, it bears challenges. Figure out these challenges may be helpful for visualization designers to design usable result. The specific challenges may largely be ad-hoc since each design should consider particular data, user, and visualization purpose. However, general challenges could be identified, as there are common issues for graphic design in 3D geo-visualization that researchers and system designers have to address.

Some of the challenges in 2D visualization, like **keeping the optimal information density** and **using the appropriate visual variables**, remain pertinent in 3D visualization context (Resch, Wohlfahrt, & Wosniok, 2014), but may still have to be re-evaluated considering the specialty of 3D. For example, the suitability of visual variables in 3D may differ from in 2D, as previously discussed in chapter 1. For information density, the metric depends on the nature of the interface (Woodruff, Landay, & Stonebraker, 1998). In 2D cartography, the metric of information density is defined as the number of object at a given scale according to Töpfer's Radix law (Töpfer & Pillewizer, 1966), and Frank and Timpf (1994) extended it in term of viewing area rather than map scale. With 3D perspective, the information density will increase if measured by viewing area (Robertson, Card, & Mackinlay, 1993). Moreover, Jahnke, Krisp, and Kumke (2011) defined the metric of information density in a 3D context to be “the number of features per unit of area” rather than the number of objects, thus the texture of 3D object should also to be considered in the calculation of information density as well.

Occlusion management: 3D visualization also has special challenges. The most notable challenge is the occlusion. Occlusion is inevitable in a 3D situation with high object density and may be detrimental to viewer's perception (Elmqvist, 2007). For example, in a condominium situation, where the property units in the building are normally clustered together, the nearer (by depth from the display) property units may block the further ones, either partially or entirely. Occlusion hinders user's perception of the further property units. Changing the viewing angle by rotating the camera of the 3D scene may sometimes help as it could change the relative position of objects with the camera, however, more time and mental effort may be required for this interaction. When come to the cadastre situation where one property unit is covered by other property units, like the pillars and interior walls inside a room, camera rotation cannot guarantee a clear perception. Occlusion has adverse effects on viewer's perception; on the other hand, it contributes to the viewer’s understanding of 3D model, as it is the most fundamental depth clue (Ware, 2012). It is also evaluated as the basic factors in human's perception of visual variables of brightness (Zaidi, Spehar, & Shy, 1997), shape(Todd, 2004) and transparency (Cheung, 2011) in 3D context. How to mitigate occlusions’ adverse effect while taking advantage of its perceptual influences on visual variables is a challenge for 3D visualization researchers and practitioners.

Spatial relationship perception, the distance and position: Besides occlusion, another design question is how to assistant user's perception of spatial relationships between objects in the 3D visualization. Fulfilling this requirement is a challenge in 3D context for researchers and system developer, as many empirical studies confirmed that 3D visualization will influence user’s perception of distance and position. For example, St John, Cowen, Smallman, and Oonk (2001) argued that 3D visualization impedes viewer's determination of relative position including direction and distance through complex empirical tests. Tory, Kirkpatrick, Atkins and Möller (2006) concluded the influence of 3D visualization: it is effective for approximate relative positioning tasks while ineffective for precisely relative positioning tasks.

Spatial relationship perception, 3D topological relationship: Helping viewer perceive the 3D topological relationships, like intersection or cover, is also a challenge if required by the intended user. The calculation and determination of 3D topographical relationships is a process of 3D spatial analysis that involves the underlying geospatial data structured in topological models (Ellul & Haklay, 2006) with various data operations (Zlatanova, Rahman, & Shi, 2004). However, the result has to be communicated to the user through visualization approaches (De La Losa & Cervelle, 1999). Clustering and occlusion that comes with the third dimension may make viewer's perception of topological relationship difficult, and thus representation approach should assist viewer’s perception. In figure 2.8 (C), there are in fact three objects (red, orange and green), and the orange and red ones are intersected. The intersected part is applied slash line in Figure 2.8 (C). However, in the view A and B, it is impossible to perceive the topological relationship among property units in this 3D scene.

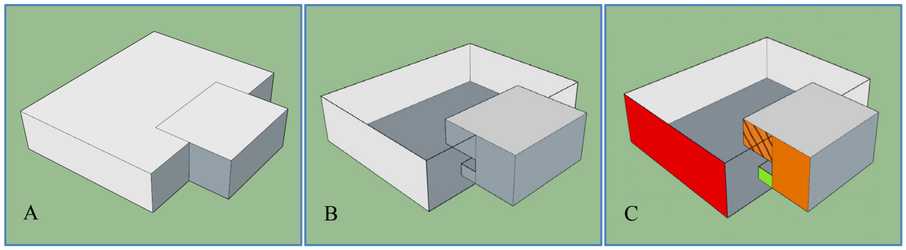


Figure 2.8. Representation of 3D topologic relationship: three different representation designs. A. Black boundary, white surface; B. Black boundary, white surface, transparent surface; C. Different color for the surface of different property units, transparent surface.

3D Navigation and orientation: Navigation and orientation (here means understanding surroundings) in 3D context are not a trivial task for even the professional user (Glander & Döllner, 2009; Grant & Magee, 1998; Omer, Goldblatt, Talmor, & Roz, 2006; Popelka & Dolez, 2015). This may prevent user from linking the 3D representation with the real world to acquire the spatial knowledge demonstrated in the 3D visualization, which is supposed to be a 3D visualization advantage towards 2D visualization approaches (see Chapter 1). Thus, 3D representation design should also be optimized for the viewer's navigation, and orientation. However, it is a challenge for both researchers and system designers, since the human cognitive and behavior concerning navigation and orientation in a 3D visualization context have not yet been well investigated (Taylor, Nash, Edwards, & Thompson, 2009).

3D Cartographic standardization: How to maintain a consistent result among different visualization scenarios is also a challenge since in an urban context, the user of cadastre may deal with a huge amount of buildings with divergent physical structure and legal situation rather than only one case. With different graphic design, the user has to immigrate between different models with an extra consideration of each model's symbology, and may encounter misunderstanding and confusion. For example, if the representation design for scenario A applies red for privately owned units and green for commonly owned units, and the representation design for scenario B applies a reversed strategy, say red for common owned and green for private. When a user is dealing with these two scenarios together, it will need to pay attention for the change in symbology. Worse, error may be inevitable if it fails to notice the difference. Similar to 2D map series, which is normally constructed with a same cartographic specification, cartographic standardization is worth considering in 3D geo-visualization too. The standardization challenge can be divided into two parts: the technical challenge that how to implement cartographical representation specification in a 3D context and the design challenge that how the specification is devised considering the possible scenarios, for example overlapping property units in cadastre.

This section discusses the most pertinent challenges in 3D geo-visualization, including optimizing information density, using the appropriate visual variables, maintaining the suitable symbol density, occlusion management, spatial relationship perception, navigation and orientation, and standardization. This list is not an exhaust challenge inventory and there are still many general challenges out there for example how to guarantee an aesthetic representation in a 3D context.

2.5.2 A review of current solutions

Many literatures give an insight of the possible solutions considering the general challenges of 3D visualization mentioned in previous section. **Optimizing information density** in 3D visualization could be addressed from three aspects: firstly chose the proper information density level with the consideration of user's perception capability (Bazargan & Falquet, 2009; MacEachren & Kraak, 2001), secondly realize the chosen information density, and thirdly maintain it constant among different scales (Woodruff et al., 1998). For realizing intend information density, generalization is a core approach in cartographic and geospatial domain (MacEachren, 1995), and it is often used in both 2D and 3D context as in the literature of Fabrikant & Skupin (2005) and Jahnke et al. (2011). It is a geometrical, graphical, or (and) semantical simplification process to maintain desired information density by eliminating unnecessary elements and characteristics, distortion, and abstraction (Agrawala & Stolte, 2001; Jones, 1996; Wolf, 2009). In order to maintain consistent information density among different scale in an interactive context, researchers and designers frequently use various levels of generalization, commonly referred as level of detail (LOD), in 3D cartography, geo-visualization, and information visualization (Bowman et al., 2003; De La Calle, Gómez-Deck, Koehler, & Pulido, 2012; Engin, Bozkaya, & Balcisoy, 2009). Using LOD is also driven by other metrics like the suitability (Forberg, 2007), thematic, and data attributes (Biljecki, Ledoux, Stoter, & Zhao, 2014). The appropriate density in a given context largely depends on the specific application scenario (Bertin, 1983), and could be calculated dividedly with overall density and local density (Tullis, 1988). Bertin (1983) has claimed that ten signs per cm^2 is the maximum density for symbols; however, his argument came without any empirical evidence. Moreover, to our knowledge, there is no investigation of whether his conclusion could be applied to 3D geo-visualization. To our knowledge, investigation of proper information density in 3D geo-visualization is still rare.

For **occlusion management**, the enhancement techniques by altering the viewing direction, objects and depth clue, may increase the spatial awareness of viewer in order to addressing the obstruction challenge in 3D visualization and to support viewer's visual tasks (Elmqvist & Tsigas, 2008). Elmqvist and Tsigas (2008) gave a comprehensive review of 50 occlusion management approaches including multiple viewports, virtual x-ray tools, and projection disorder. Moreover, their usability tests in an information-rich 3D environment with user confirmed that there is no omnipotent solution, and the choice of a particular method is largely visual tasks dependent (Elmqvist, 2007). A careful design considering the visual tasks and user's perception capability may be necessary for researchers and designers to choose or devise proper occlusion management approach. Furthermore, as argued before, empirical evidence acquired from direct user study is indispensable for accessing the occlusion management's capability for specific visual tasks.

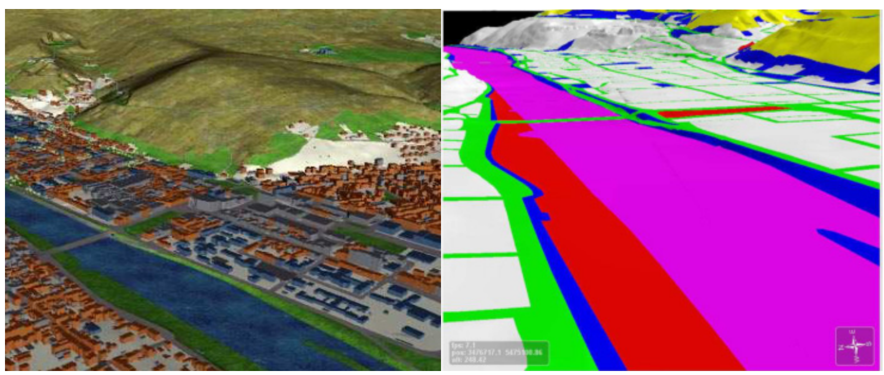
For **spatial relationship perception**, artificially adding visually salient depth clues (monocular) like transparency, occlusion, size-scaling gradient & texture, shading gradient, and cross-reference have been used by researchers and system designers to improve the relative positioning and distance estimation in static and dynamic 3D visualization. Possible design solutions include additive transparency, size scaling of rendered surface, ground plan grip, and alternative perspective (Furmanski, Azuma, & Daily, 2002; St John et al., 2001). Using shading, global illumination, and image stylization could also preserve depth cues in 3D visualization (Engel & Semmo, 2013). For precise distance perception, labeling with precise distance text is pertinent (Furmanski et al., 2002; Shojaei et al., 2013; Wang, Pouliot, & Hubert, 2012). On the other hand, the **visualization of topological relationship** in 3D context is rarely touched.

Landmark, which is a visually salient object assisting user's orientation, navigation and mental mapping (Feiner, 1985; Golledge, 1999), has been used in 3D geo-visualization to support **viewer's orientation** in 3D city modeling (Elias & Paelke, 2008; Jobst & Döllner, 2008; Trapp et al., 2011). Researchers used many highlighting techniques to aid viewers' perception of landmark, like abstract facade texture (Engel & Semmo, 2013), and to guide their attention towards landmark, like forcing a front-view (Jobst & Döllner, 2008). Besides landmark, multi-viewport is also a common solution to improve the viewer's orientation in the 3D (Terribilini, 1999).

For a **3D geo-visualization standardization**, most of the current studies are addressed from a technical aspect, and they imply the specifications for the 3D design space. For example, ISO19117 (ISO, 2009) portrayal gives a standardized description of the design space from a semiotics point of view. Haist, Figueiredo Ramos, and Reitz (2007), and Neubauer and Zipf (2007) tried to extend the OGC Symbology Encoding to the third dimension. CityGML, a well-accepted 3D city data model, also provides specification for the semiotics of graphic aspects: appearance of CityGML features (Open Geospatial Consortium, 2012).

Non-photorealistic representation have been discussed, evaluated, and advocated by many researchers for the visualization of the 3D city (Döllner, 2005; Giudice & Li, 2012; Jobst et al., 2008). It refers to a representation design that does not fully contain the features and visual variables of the real world objects like the geometry, structure, position, color, and texture, but uses symbolic features and visual variables (Döllner, 2005). Thus, this dissertation may fall in the category of non-photorealistic representation. Figure 2.9 shows a comparison of photorealistic representation with non-photorealistic representation for a same district. Although several studies indicated that users from architecture sectors and general public prefer realistic displays (Taylor et al., 2015; Tress & Tress, 2003), empirical evidences clearly show it affects user's performance (Giudice & Li, 2012; Hegarty, 2008; Hegarty, Smallman, Stull, & Canham, 2009). Jobst et al. (2008) collected the limitations of photorealistic visualization: higher load of data, burdensome thematic information integration, more distracting details, less design range for symbology, and higher suitability demand for visualization platform. In contrast, non-photorealistic design provides artificial coloring, shading, lighting & shadowing, more symbols including edges & silhouettes, and more texturing possibilities (Döllner, 2005). Designers could directly manipulate visual variables to produce cartographical representation in non-photorealistic representation (Jobst et al., 2008), and user studies indicate higher acceptance of non-photorealistic representation for urban planning due to its clarity and conciseness (Döllner, 2005). Regardless of the discussion of photorealistic and non-photorealistic, it is worth emphasizing that there are no clear boundaries between these two representation designs, and in each group, the levels of realism are quite different. Many representation designs fall in a gray area between these two categories, as they contain both photo-realistic features like remote sensing image and geometry accurate building models and non-photo realistic texture. Examples include the representation designs in the research of Jobst and Döllner (2008), Trapp, Beesk, Pasewaldt and Döllner (2010), Neubauer and Zipf (2007) and representation designs of Korea and Spain's 3D cadastre pilot system (Jeong, Kim, Nam, Li, & Cho, 2011; García, Soriano & Martín-varés, 2011).

A



B

Figure 2.9. A comparison of the photorealistic (A) and non-photorealistic (B) representation (Neubauer & Zipf, 2007)

Depicting non-spatial data is an important requirement in 3D geo-visualization (Bazargan & Falquet, 2009). Besides encoding non-spatial information into visual variables, visual enhancement techniques could also be used to illustrate non-geometrical data. Bazargan and Falquet (2009) reviewed 7 enhancement techniques used to depict the non-spatial information in 3D virtual environment, including illustrative shadows, virtual PDA, croquet 3D windows, croquet 3D interactor, 2D media layer, sidebar, and 3D labels. Some of these approaches reviewed in their research may be readily used in a 3D virtual environment in an urban context, as many of their examples are presented on a metropolitan scale. Moreover, among these approaches, 3D labeling, as shown in Figure 2.10, is highlighted for a virtual city visit. Bazargan and Falquet (2009) argued the choice of the enhancement technique should be based on specific application context, such as the objects number and types, their semantic relations to display, and geometric situation of the selected object.

Figure 2.10. 3D labeling for non-geometrical information (Bazargan & Falquet, 2009)

As demonstrated previously, the environment settings largely influence the final display result of 3D model. Engel & Semmo (2013) empirically evaluated the impact on user's perception that is caused by different rendering techniques. They also accessed the color mapping approaches used for information encoding. Four rendering techniques (edge enhancement, abstract façade textures, scree-space ambient occlusion, blinn-phong shading) and four color mapping methods (monochrome, continuous, single hue, de-saturated black-body, diverging) have been examined in accordance with four visual tasks (mental mapping, distance estimation, point-wise value estimation, and area-wise value estimation). Their study confirmed that some rendering techniques may capable to improve the thematic color mapping perception in 3D, yet their performance changes according to the visual tasks. The performance demonstrate a trade-off of performance between the visual tasks of orientation, navigation, mental mapping, and the visual task of thematic data (quantitative) estimation.

2.6 Summary

Following visualization pipeline model, this chapter reviews the general concepts and relationships of data, the user, and their usages in 3D geo-visualization. This chapter also investigates the 3D visualization opportunities and challenges. The content of this chapter provides valuable context of the current research of 3D geo-visualization, and indicates how visual variables and enhancement techniques may contribute to the general 3D geo-visualization challenges. I am fully aware of the discrepancy and limits of current theories of visualization, especially in 3D visualization. My discussion in this chapter does not intend to develop new theories. Instead, pipeline model and Bertin's semiotics of graphics have been chosen since firstly they meets the context of this research, and secondly they enable the comparison with existing research in the domains of cartography, geo-visualization, and information visualization. The current review is of general geo-visualization. The next chapter will propose a complementary literature review focusing on the application domain: the data of cadastre visualization, the user's profile, and cadastre related visual tasks.

Chapter 3 - 3D Visualization of Condominium Property Units: Data, Users, Usages, and 3D Cadastre Model Designs

To complete the literature review done in the previous chapter, the cadastre domain should be examined to answer what are cadastre data, the potential users and usages, and current 3D cadastre visualization design. First, this chapter reviews the cadastre and its data involved in the visualization of condominium situation. Then, it discusses in the specific context of 3D visualization, the potential cadastre users and their usage to delimitating property units of condominiums. Finally, in order to expose the challenges and the suitability of visual variables and enhancement techniques in current practices, this chapter reviews the existing application of 3D visualization of 3D cadastre systems in seven countries.

3.1 Introduction to cadastre

Cadastre plays a significant role in modern society, as it registers immovable properties and provides necessary information for land administration, tax calculation, real estate transaction, and mortgage (Stoter, 2004). Generally speaking, the term "cadastre" refers to the information system that registers the immovable properties, its subjects, and rights. For example, international federation of surveyors (FIG, 1995) defines:

> "*Cadastre is normally a parcel based, and up-to-date land information system containing a record of interests in land (e.g. rights, restrictions and responsibilities). It usually includes a geometric description of land parcels linked to other records describing the nature of the interests, the ownership or control of those interests, and often the value of the parcel and its improvements. It may be established for fiscal purposes (e.g. valuation and equitable taxation), legal purposes (conveyance), to assist in the management of land and land use (e.g. for planning and other administrative purposes), and enables sustainable development and environmental protection.*"

However, since the legislation and organization situation varies among different countries, the exact meaning of cadastre may vary from one country to another. The Netherlands cadastre and Land Registry Agency, which is termed "Kadaster", contains a land registration and a cadastre registration (Stoter, 2004). In “Kadaster”, the land registration records all notarial deeds chronologically, and the cadastral registration documents the parcel boundaries and legal status, administrative data, and mortgage information. In Quebec, the immovable property's transaction are registered in land registration infrastructure maintained by the Ministère des Ressources Naturelles; while the term cadastre mainly refers to cadastre plan or a graphic representation of lots (MRNF, 2003; Pouliot, Roy, Fouquet-asselin, & Desgroseilliers, 2011). The term “lot” corresponds to an immovable property unit, for example, a land parcel, and an apartment unit. Quebec cadastre plan also includes lot number, geometric boundaries (points and lines), and official measurements (like length, height).

The previous definitions of cadastre are all centered on the concept of "property"; something owned like land parcels and property units in condominium. Property, from a legal point of view, is more than possessory interest, as it could be the subject of rights like tenancy, servitude, usufruct, emphyteusis, and is limited by legal restriction and responsibility (*Quebec civil code, art. 948*). According to Quebec civil code (*Quebec civil code, art. 899*), property could also be classified as immovable property (ex. Land, building) and movable property (ex. furniture, computer). If not specified, the term "property" in the following discussion of this dissertation will refer to the immovable property.

To be noted that, the term cadastre, as argued here based on the Netherlands and Quebec case, may refer to the cadastre system and/or the cadastre map (cadastre plan in Quebec). In this thesis, Cadastre system will refer to an immovable property units based and up-to-date official property information system. It contains first the registration of the property geometric and second the property number that could be linked to other related information. That information could be rights, restrictions and responsibilities attached to properties, subjects, and transaction information to support multiple property related tasks. Cadastral map is normally one part of the cadastre system to support information visualization as can be seen in Netherlands (Stoter, 2004), and Quebec (MRNF, 2003).

3.2 Cadastre data in condominium situation

As stated in chapter 2, data is the starting point of the visualization pipeline. The data used for visualization greatly influences what the user can achieve and how the representation is designed. In cadastre system, comdominium is a common situation containing overlapping property units. To give a general understanding about which cadastre data is required to visualize a condominium situation, this section reviews the specific cadastre data involved in the visualization of property units in condominiums with case studies. These case studies are located firstly in Quebec, a Canadian province, then in Netherlands, Singapore, and Australia. Such review process is based on current 2D visualization solution already implemented for the overlapping situation like in Quebec and Singapore; but it also includes the suggestions for future 3D solutions like in Netherlands and Australia. The main focus of following case study was on condominium situation. The data is classified into spatial data and non-spatial data. Remind that spatial data corresponds to data referring to objects having a position or a geometry like legal objects (e.g. boundary of the property unit), or physical objects (e.g. boundary of the walls). While non spatial corresponds to data referring to the values of attribute of these objects, like unique identifier, height, length; no matter if this attribute indicates geometric information or not. Introducing this differentiation helps the following discussion of visual variables and enhancement techniques, since spatial data can be represented by geometries in 3D visualization, and non-spatial data have to be coded into visual variables or enhancement techniques in order to be perceived by viewer. It is worth mentioning here that the data involved in the visualization of condominiums is only a subset of all possible cadastre data.

3.2.1 Quebec Province, Canada

This case study is based on a real condominium situation that involves overlapping property units in Québec City, Canada. There are two types of property units. According to Quebec Civil Code (1991, c. 64, a. 1010; I.N. 2014-05-01): one is common unit, which each owner has a share of the right of ownership and the restricted right of use, and the other is private unit, which specific owner has an exclusive right of ownership. There are two types of data involved in the Quebec case of the visualization of the condominium property units: spatial data and non-spatial data.

The spatial data in the current cadastre plan and Complementary Plan (PC) in Quebec includes the boundaries of the property units, the boundaries of land parcel, and the boundaries of physical objects (like walls).

The non-spatial data observed in the Quebec cadastre plans are the lot number and the official measurements like length of boundaries, surfaces, height, and volume of a property unit. Lot number is the unique identifier of each property units, which corresponds to a basic administrative unit in LADM (Land Administration data model) (Pouliot et al., 2012). It could be used to refer to other related information not displayed or stored in cadastre like the ownership, transactions, and taxes.

The previous analysis is based on PC currently in use in the province of Quebec. On the other hand, from the aspect of user's expectation, Boubehrezh and Pouliot (2012)'s survey with professional users in Quebec recognized nine types of desired data in the context of 2D visualization of property in overlapping situation, and eight of them are supported by more than 50% participants:

Spatial data:

- The boundaries of 3D property unit
- The boundaries of buildings and infrastructure
- The boundaries of the usage that overlaps (ex. Servitude. Possible between 3D property units and 2D land lot)

Non-spatial data:

- The information that distinguish common and private property units
- The volume measurement of property units
- The length of property units' limits
- The surface measurement of property units

- The data relating to 3D relative position with neighboring properties, for example 3D neighboring relationship: the two property units touch each other over the vertical direction.

The survey of Boubehrezh and Pouliot proves that the existing cadastre data used in PC may still be pertinent in 3D visualization. Moreover, it suggests the topologic relationship like neighboring relationship may be useful for the intended user, either between 2D land lots and 3D property units or among 3D property units.

3.2.2 Netherlands

In Netherlands, according to Stoter (2004), at the time of 2004, the Dutch cadastral map only presented the boundaries of the ground parcel and building outline on the ground level. The spatial data of property units in condominiums was not yet included. For 3D visualization in future, Stoter, Oosterom, and Ploeger (2012) proposed a list of “minimum information”, which has not yet been realized. They include:

Spatial data: the boundaries of the 2D ground parcel, of the 3D legal space, and of overlapping parts between 3D legal space and 2D ground parcel; elevation of terrain; and the spatial objects for reference and orientation like landmarks.

Non-spatial data: the unique identifiers of the apartment units in the cross-section view

3.2.3 Singapore

Singapore cadastre uses Strata Certified Plan to represent overlapping properties of condominiums (Khoo, 2011). Strata Certified Plan contains three plan types[3] including site plan, elevation sketch of building, and story plan. The following cadastre data are involved:

Spatial data: the boundaries of property units (land lots[4], strata lots, accessory lots) and of the physical objects.

Non-spatial data: the attribute indicating the distinction between the common and private ownership of strata lots, the unique identifier of property units, the room number of strata lot, and the surrounding roads’ name, the official measurement (the surface and the height) of land lots and strata lots.

[3] The example of Singapore Strata Certified Plan is available at http://www.sla.gov.sg/Portals/0/SurveyServices/sm/CPST.pdf
[4] A lot in Singapore cadastre refers to a property unit.

3.2.4 Australia

Australia cadastre uses subdivision plan, land survey plan, and cross-section plan to depict overlapping situation (Shojaei, 2014). Shojaei (2014) in his research of visualization of 3D cadastre argued that three types of spatial data are necessary for cadastre 3D visualization:

Spatial data: (1) the boundaries of physical object (buildings, building footprints, digital terrain models, car parking, building utilities, urban utility networks, building facades' photorealistic textures, underground transport routes, and city structures). (2) The boundaries of legal object (parcels, lots, common properties, roads (one class of parcels), easement, restriction, crown land, depth and height limitations, survey marks, and administrative boundaries). (3) The boundaries of the zones and overlays inside the planning schemes (a plan that is used to control the land use and development within a city).

Non-spatial data: property attributes, surveying report, and addresses

The previous review shows that cadastre data in the visualization of overlapping property units in Quebec, Netherlands, Australia, and Singapore shares many common items. I suggests a core set cadastre data for 3D visualization of condominium property units based on the review.

For Spatial data: the boundaries of property units in condominium (all the four cases), the land lot the condominium located (all the four cases), the surrounding land lots (Quebec, Singapore), and physical objects (Quebec, Singapore and Australia).

For non-spatial data: the attribute indicating the distinction between the common and private ownership of the property units (Quebec and Singapore), unified identification number of property unit (all the four cases), the official measurements of the property units (Quebec, Singapore, and Australia).

Some researchers also suggested the spatial relationship between property units and 2D land lots (Boubehrezh & Pouliot, 2012; Stoter et al., 2012) and between different property units (Boubehrezh & Pouliot, 2012) could assist user's perception and thus may better be explicitly presented in 3D visualization of overlapping property units.

3.3 Cadastre Users and Usages

Cadastre user is the ultimate receiver of the cadastre visualization. Thus, the objective of cadastre visualization is to support their requirements. Cadastre system serves a wide variety of users. In Singapore, Khoo (2012) listed the possible users of cadastre including: financial institution, land agencies, property owners, development agencies, planning agencies, statistics department, property agencies, utilities companies, and general public.

In Australia, Majid (2000) listed that the potential user of a multi-purpose cadastre contains federal, state, local governments, private firms, individual, academia, and regional bodies. Also in Australia, Shojaei (2014) classified the users into the direct user who contributes to cadastre data and the indirect user who only benefits from cadastre data. In Quebec, Boubehrezh (2014) surveys users of cadastre in the specific context of municipalities management. He recognized three types of user: taxes evaluator, land manager, and land surveyor.

The user of 3D cadastre visualization is only a subset of all potential users since not all of them deal with overlapping situation. Boubehrezh (2014)'s survey with Quebec cadastre user showed that only 57% cadastre user uses Complementary Plan. Boubehrezh gave explanations based on his survey data to the relative low usage of the complementary plan compared with cadastre plan: this is due to that some user may not encounter an overlapping situation in their region. In contrast, 84% of participants who manage overlapping properties in their area used Complementary Plan and 81% of them expressed interested towards a volumetric representation of the overlapping situation. Since no real 3D visualization with volumetric representation have yet implemented in Quebec cadastre, and considering Boubehrezh's survey result, it is reasonable to deduce that the intended users of 3D visualization in future will be those currently use PC to deal with overlapping situations. It seems no need to pursuit a new 3D solution for users that do not need to deal with the overlapping situation.

For cadastre usages, Boubehrezh (2014)'s survey recognizes four most mentioned usages. They are taxation, construction permission, delimitating, urban development, and planning. These four usages recognized by Boubehrezh are the general decision-making goals. They could only be accomplished by finishing a series of visual tasks with perceivable contents of the symbol and visual variables in a 3D model.

Other researchers address the cadastre usage elaborately. As mentioned in the previous chapter, the user's usages and requirements could been addressed from two related aspects: one from the system design and implementation aspect of 3D models and visualization functions, and the other from perception aspect of the visual tasks and interaction process carried out by viewers. However, much of current literature explicitly addresses the 3D visualization usages from the aspect of system design and implementation.

In Russia, Vandysheva et al. (2011) identified a list of functional requirements for the 3D visualization of cadastre based on case study.

- Visualization of layer with 3D cadastral objects
- Visualization of layer with the 3D terrain
- Visualization of layer with 3D reference objects
- Visualization of underground objects

- Visualisation Separate layers for different types of 3D cadastral objects
- Rendering the terrain with raster map/image
- Visualization of Layers with results of calculations
- Visualisation Separate layers for different types of 3D reference objects
- Select and highlight 3D cadastral object
- Display attributes of selected 3D cadastral object in browser
- Validate geometry
- Check for 3D overlap between 3D cadastral objects
- Calculate the intersection of 3D cadastral objects with terrain
- Calculate projection of 3D cadastral object on terrain

In Australia, Shojaei, Kalantari, Bishop, Rajabifard and Aien (2013) registered an inventory of user's requirements towards 3D visualization of cadastre based on a prototype evaluation with professional users.

- Visualizing ownership boundaries in 3D Land registry
- Understand 3D legal boundaries
- Searching lots using plan numbers
- Retrieve ownership information for each lot
- Easements and common properties
- Examine and validate a 3D spatial unit
- Property management in 3D
- Digital representation of the physical environment

In Netherland, Van Oosterom (2013) mentioned several requirements of 3D cadastre visualization based on the discussion of 3D cadastre workshop. Some of them imply the visual tasks of user:

- Display bounded and unbounded properties
- Include earth surface and reference objects

- Provide depth clue for subsurface properties related to utilities

In this section, a wide range of potential users and their four general decision-making goals have been recognized based on Boubehrezh's survey and literature review about 3D visualization of cadastre. It provides necessary material for synthesizing the 3D visualization requirements and the viewers' potential visual tasks in the following test.

3.4 3D cadastre visualization design: state of the art

Cadastre data, users and users' usage are critical context information; however, they could not directly suggest the proper representation design. As previous chapter stated, the suitability of visual variables and enhancement techniques, and necessary design experience in 3D visualization for cadastre should be considered. However, there is currently no dedicated research in cadastre domain, only some implementations in 3D cadastre pilot system. In order to yield the knowledge about visual variables and enhancement techniques, for example, which of the visual variables are widely used to encode cadastre related information, and how it performances, we review 3D visualization designs in 3D cadastre pilot systems from seven countries including Netherlands, Turkey, Australia (Victoria), Korea, China (Shenzhen), Spain, and Russia based on the openly accessible literature. We list the usage of visual variables and enhancement techniques in each country. The intended user and their tasks are included since they are important design factors. It helps the reader to understand in which context the graphic design is carried out. The result could contribute to the formation of the following empirical tests in this research.

A. Netherlands (Stoter, Ploeger, & van Oosterom, 2013)

Netherlands's 3D cadastre pilot system used four different views together to support the 3D cadastre visualization in condominium: (1) artistic impression with photo-realistic texture, (2) perspective view of 3D property units with different colors, (3) cross section view of vertical profile, (4) floor plan of the 1st floor.

- User: not specified
- Tasks: not specified
- Visual variables:
    - Color: the representation uses different colors for property units in order to separate them visually. It uses the colors that are similar to the real color of the building and objects. This may provide the user a feeling of reality and may help them link the 3D scene with the real situation.

    - Transparency: transparency is used to overcome the occlusion.
- Enhancement techniques:
    - Four different views of a scenario
    - Labeling of non-geometry information
    - Providing a navigation panel to help user's orientation in the 3D scene

B. Turkey (Döner, Thompson, & Stoter, 2011)

The 3D visualization in Turkey's pilot 3D cadastre system includes the representation of underground pipeline together with surface parcels and volumetric representation of buildings' geometries.

- User: not specified
- Tasks: not specified but in cadastre domain concerning utility networks
- Visual variables:
    - Color: The representation of property uses three colors to represent building, pipeline, and land parcel.
- Enhancements techniques:
    - Labeling parcel numbers and pipeline identifications.

C. Victoria, Australia (Shojaei, 2014)

Shojaei constructed two prototypes for 3D cadastre visualization. The first prototype is a desktop based and the second one, which is rebuilt based on the challenges encountered in the first prototype, is web based. The following evaluation is based on his second prototype.

- Users: not specified, but evaluated by experts from industry and academic
- Tasks:
    - Visualizing ownership boundaries in 3D Land registry
    - Understand 3D legal boundaries
    - Searching lots using plan numbers
    - Retrieve ownership information for each lot
    - Easements and common properties
    - Examine and validate a 3D spatial unit

  - Property management in 3D
  - Digital representation of the physical environment
- Visual variables:
  - Color: the 3D model uses different colors to represent various types of object (not specified).
  - Texture: a photo-realistic texture has been applied to the terrain to create mixed reality.
- Visual enhancement:
  - Highlighting: the visualization uses different color, together by adding extra symbol (a red rectangle) to achieve the highlighting of the geometry of the selected property unit.
  - Labeling: the model could label the semantic information of selected property units.

D. Korea (Jeong et al., 2011)

The City of Seoul in Korea implemented a 3D cadastre pilot project as a preliminary step for the future 3D cadastre implementation.

- User: they claimed that they had investigated the needs of users, however, no specific user or user group have been mentioned in their paper
- Tasks: land management, no detailed visual tasks mentioned
- Visual variables:
  - Color: they used different colors to represent different groups of objects and different floor, yet without the explanation of the semiotics of their designs
  - Texture: photo-realistic texture to create mixed reality
- Enhancement techniques:
  - Different views (2D+3D).
  - Navigation panel with 2D map to help the orientation in 3D scene
  - Using different value (brightness) to highlight the underground part in some of the 3D scenes

E. Shenzhen, China (Guo et al., 2013)

The Shenzhen municipality of China has implemented a 3D cadastre system and imbedded it in current cadastre system. The following evaluation is based on the visualization part of their 3D cadastre system.

- User: not specified
- Tasks: administration of land space, no detailed visual tasks

- Visual variables:
    - Transparency: high transparent surfaces represent the boundaries of 3D space extended from the land parcel while building constructions use low transparency.
    - Color: properties inside building are colored with yellow and the property space extended from land parcel is color blue.
- Enhancement techniques:
    - Labeling of official measurement
    - Orientation aid with symbol
    - 2D view (cross section, orthogonal) +3D view

F. Spain (Olivares García et al., 2011)

The Spanish General Directorate for Cadastre (SDGC) generated volumetric 3D models of the property units by automatically extruding the plan of each floor in condominiums. The model is stored in KML format and visualized in Google Earth, a virtual earth software.

- User: general public (any user via the internet)
- Tasks: not specified
- Visual variables:
    - Color: The representation uses different colors to differentiate buildings and land parcels and to differentiate different property units.
    - Texture: photo realistic texture to create mixed reality.
- Enhancement techniques:
    - Transparency: buildings are applied semi-transparent appearance.

G. Russia (Elizarova et al., 2012)

Russian-Dutch joint project developed a pilot 3D cadastre system for Russian Federation. The following review is based on the visualization part of this pilot system.

- User: not specified, but the specialists from Rosreestre (Russian cadastre) system and cadastral engineers participated in the pilot system development.
- Tasks: they described the requirements from the system design and implementation aspect, mostly about the data
    - A topographic base map

  - A digital terrain model
  - Geometry of properties
  - Registration information of properties
  - Technical documentation
- Visual variable:
  - Color: the design uses different colors to differentiate property units in the condominium.
- Enhancement techniques:
  - Move-floor-model to enable user drag out the property units in one floor along with the 2D floor plan
  - Highlighting a wall's boundaries by using visual variable color "red"

In sum, the visual variable color and transparency have been extensively used in the representation design of these seven pilot systems (color: all of these pilot systems; transparency: three of these pilot systems). For visual enhancement techniques, labeling, occlusion management, and highlighting have been widely used. However, current designs have not explicitly discussed the visual variables' and enhancement techniques' suitability in 3D models and the graphic semiotics. As a result, some of their design, like that of Russian pilot system as evaluated in the problematic section of Chapter 1, may be confusing for the reader.

3.5 Summary

This chapter describes the main concepts of cadastre and lists the cadastre data, user, and usage. The recognized list of cadastre data supports the visualization requirement synthesis in the following empirical test. On the other hand, the vast majority of user and usages identified are only background information in this thesis, since the following discussion is only centered on the notary user and one usage: delimitating property units in condominium. However, it will be valuable knowledge for the 3D cadastre visualization practice in future.

For the visual variables and enhancement techniques, the literature review of current pilot systems described in this chapter contribute to the selection of targeted visual variables and enhancement technique in the following investigation. It shows that visual variable color and transparency as well as the enhancement techniques of occlusion management, labeling, and highlighting have been extensively used in current 3D cadastre visualization. Nonetheless, none of current representation designs tested their suitability. The next chapter thus describes our empirical tests with them.

Chapter 4 Suitability of Visual Variables and Enhancement Techniques for 3D Visualization of Condominium Property Units

This chapter is the core of this thesis and presents the experiments in two parts: (1) an empirical evaluation of the suitability of visual variables and enhancement techniques in 3D visualization of condominium property units, and (2) a comparison of the assessment results of visual variables with existing conclusions in 2D visualization. The first part tries to answer the first research objective, namely, to assess the suitability of visual variables and the enhancement techniques for user to unambiguously delimitate the condominium property units. The previous chapters demonstrate that few research of 3D cadastral visualization has empirically tested the suitability of visual variables and enhancement techniques with intended user groups. Empirical test could contribute more precise conclusions compared with simple subjective evaluation and analysis (Green, 1998) and is a fundamental requirement of user-centered design (Wallach & Scholz, 2012). This is why the empirical evaluation method is used here. Two phases of test are involved: (1) a preliminary evaluation inside our cadastre research group in Laval University for a quick insight of the suitability of visual variables, and (2) a face-to-face interview with notaries for a direct contact with end user. The results of the two steps contribute to the discussion of the suitability of eight visual variables, and have been published in two peer-reviewed conferences (Wang, Pouliot, Hubert, 2012; Pouliot, Wang, Hubert et. al., 2014). Based on the empirical evidences, the second part of this chapter tries to answer the third research objective, say, to compare the perceptual properties of visual variables exhibited in 3D visualization of condominium property units with those in 2D visualization. The comparison is carried out with seven current studies of visual variables in 2D visualization.

Note that all tests will be presented as follows: objectives, methodology, selection of participants, selection of visual variables, selection of visualisation requirements, test setup, and results.

4.1 Empirical tests of the suitability of visual variables

4.1.1 A preliminary evaluation of visual variables' feasibility

Testing all visual variables with different settings for each visualization requirement may exceed the possible length of a user's test. As a result, the preliminary evaluation aims a quick assessment about the feasibility of each visual variable and enhancement technique. It contributes a brief insight to which of the visual variables and enhancement techniques are feasible in 3D for a specific visualization requirement, and which visual variable settings are viable. In addition, by eliminating the visual variables that are obviously feasible or non-feasible, the preliminary evaluation could help us limit the following empirical test to a reasonable length. We also understand that this pre-selection may add a certain bias, and this point will be discussed further.

Methodology

The general methodology used is the expert group method(Lazar, Feng, & Hochheiser, 2009) by employing a group of academic investigators to examine subjectively the clearness and ambiguousness of using certain visual variable to fulfill specific visualization requirement. Academic investigators investigate a large number of 3D models, which are constructed to cover preselected visual variables, enhancement techniques and visualization requirements. Also, they inspect different value settings. The process is a cognitive walkthrough: the evaluator goes through the 3D model as an ordinary user and then gives evaluation. The evaluation criteria of the suitability here is feasibility, which refers to a subjective effectiveness evaluation without empirical test with the end user.

Selection of participants

For a quick feedback, and considering the amount of tests, the expert group of academic investigators are the members of our research group in Laval University. It has four graduate students and two professors with proficiencies in 3D visualization, cartography, and cadastre. The assessment is based on the thoroughly viewing, reasoning, and discussion among them.

Selection of visual variables and enhancement techniques

Bertin (1983)'s list of visual variables marks the beginning of the relevant research, and its content are still widely discussed like in the research of Engelhardt (2002), Carpendale (2003), and Yilmaz and Duzgun (2011). At this preliminary research stage, this work adapts Bertin's list of visual variables including position, size, value, color, orientation, shape, and texture. The tests should assess the visual variables with different visualization primitives like point, line, surface and volume. However, some of the visual variable and visualization primitive pairs, for example, changing the position, size, orientation, and shape of the surface with a clearly defined boundary, may be infeasible. On the other hand, for partial bounded property units, the undefined part can be altered by its size, shape, and position without confusing the viewer, since there is no defined geometry. The visual enhancement labeling is also evaluated since it is used in many 3D pilot cadastre systems like in Australia (Shojaei, 2014).

Selection of visualization requirements

The decision-making goal considered in the preliminary evaluation is to delimitate property units. Delimitating property units requires more than simply distinguish the boundary. It may concern, as evaluated here, locating the lots, settling its properties, and precisely measuring the boundaries. Five detailed requirements for delimitating property units are defined here based on the previous literature review of cadastre data, user study, and the discussions in 2nd, 3rd, and 4th 3D cadastre workshop (Banut, 2011; Felus, Barzani, Caine, & Blumkine, 2014; van Oosterom, 2013). This list is from the point of view of visualization system functions, as its items are stated in an aspect of what should be represented or labeled in a 3D model, rather than what a viewer will try to interpret. The five requirements are:

1. **Represent bounded and partial bounded 3D property units**: A 3D property unit could be bounded when its boundaries construct a well-defined volume and partially bounded when its boundaries cannot define a finite volume. An example of partial-bounded 3D property unit is the ground parking yards as they do not have limits in the vertical dimension. Stoter and van Oosterom (2005) named it infinite parcel columns. These partial-bounded 3D legal units should be represented in a way that people can unambiguously recognize its bounded and unbounded parts.

2. **Represent the relationship between 3D property units and 2D land parcels**: Since the property registration in almost all cadastral systems are still mainly 2D parcel-based (van Oosterom, Stoter, & Ploeger, 2014), the explicit description of the correspondence between the property units in a condominium and the land parcel may be useful for the examination and validation of 3D property units, for example hatching overlapping area (Stoter et al., 2012). The terrain information (DEM) is also necessary content where the elevation varies dramatically, for example in Greece (Tsiliakou & Dimopoulou, 2011).

3. **Represent the spatial relationship of 3D property units with corresponding physical objects**: The property unit does not necessary correspond to a physical object, but normally it is tightly attached to the physical construction of apartments or underground facilities. As a result, physical objects may contribute to cadastre data visualization since they may act as landmarks, which are recognizable by human in relation to real world object. Landmark supports viewer's navigation, orientation, and mental mapping (Feiner, 1985; Golledge, 1999). Moreover, the geometry of a physical object (e.g. a bona fide boundary) is easier to measure, to establish, comparing to the geometry of the property units (e.g. a fiat boundary) that exist relative to a particular legal interpretation or artificial demarcation (Smith & Varzi, 2000). Besides including physical objects in a 3D scene, explicitly representing the spatial relationship between property units and physical objects could further help the user understand how the property units are demarcated in considering the physical construction. For example, the 3D visualization could explicitly represent that the 3D property units' boundaries "touch" the boundary of physical objects with the help of extra symbols and distinct visual variables. The importance of visualizing legal objects and physical counterparts together is also supported by Shojaei et al., (2013) and Aien et al. (2013), and such design exists in many current 3D cadastre visualization designs like in Russia (Vandysheva et al., 2012), Korea (Jeong et al., 2011), and Turkey (Döner et al., 2011).

4. **Represent spatial relationships among 3D property units**: The spatial relations of property units, which include topological connexion, adjacency, distance, intersection as well as those non-topological relationships like "above" and "below", have to be unambiguously comprehended by the viewer. For

example, the common parts (e.g. wall, ceiling) of a condominium must be connected. Thus, explicitly represent the spatial relationship of “touch” may greatly facilitate user’s understanding of the connection.

5. **Label with official measurements**: Official measures of the length of the boundary, area, height and volume of the property units’ boundaries are required by the expert user in Quebec according to Boubehrezh (2014)’ survey. This information is acquired and certified by officers like land surveyors or notaries (MRNF, 2003). For labeling official measurement, visual variables are applied on the text label rather than primitives in order to differentiate three types of measurements of a property unit: the length of segments of boundary, the area and the volume. Changing the orientation of the labeling text may hinder viewer's reading, thus it is not applicable. The visual variable texture is also not applicable because in most cases, the text is too small to apply a texturized font.

Test setup

For each visualization requirement, several 3D models are constructed to be evaluated by the academic investigators. In order to accelerate the research process, the producing of 3D models did not wait until the data of a real condominium case is acquired. Instead, demonstrative examples have been used. Over 200 3D models have been tested inside our research group. Appendix 1 lists some examples for each visualization requirement. Simple volumetric geometries, mostly hexahedron, are used to represent the property unit in condominiums. Most of them are hand drawn in Sketchup, a 3D modeling software. In each 3D model, only one visual variable or enhancement technique is used to encode underlying information (other than geometry coordinates) for a specific visualization requirement. At the same time, the other visual variables are maintained constant.

Visual variable value settings are largely subjective with careful tune up to eliminate infeasible result, while cover a wide range of the potentially capable setting combinations. They follow two general setting strategies. The first setting uses visual variable for the primitive of surfaces in contrast with black (boundary) and white (surface) representation, for example use lower brightness for unbounded surface while keep bounded surfaces white. The second setting applies different values of a visual variable, for example use lower brightness for unbounded surface and use higher brightness for bounded ones.

Running the test

All these 3D models are evaluated inside our research group with four post-graduate students and two professors. They all have sound knowledge and much experience of 3D geo-visualization. The results are concluded based on the thoroughly viewing, reasoning and discussing by the academic investigators. They are the consensus among all investigators.

Test results

Table 4.1 gives an overview of the feasibility of visual variables deduced from the preliminary test. They are organized along the five visualization requirements. The evaluation results have three feasibility levels:

- **Yes** = The visual variable is evaluated feasible to meet the requirement;
- **No** = The visual variable is evaluated not infeasible to meet the requirement;
- **Maybe** = The visual variable may provide a feasible solution to meet the requirement but with deficiencies and limitations sometimes. It needs further evaluation and no clear decision can be stated.

Table 4.1. The preliminary evaluation of the visual variables' feasibility for each visualization requirement

Visual Variables / Requirements	Position	Orientation	Size	Shape	Brightness	Color (Hue and saturation combined)	Texture
1. Represent bounded and partial bounded 3D legal units	Yes	No, perspective view may cause ambiguity	Yes	Yes	Maybe, shading effect will cause ambiguity	Yes	Maybe, depends on the natural of the texture
2. Represent the relationship between 3D legal units and 2D land parcels	No	Maybe, perspective view may cause ambiguity	Yes	Yes	Yes	Yes	Maybe, depends on the natural of the texture
3. Represent the relationship of 3D legal units with corresponding physical object	No	No, perspective view may cause ambiguity	Yes	No	Maybe, shading effect will cause ambiguity	Yes	Maybe, depends on the natural of the texture
4. Represent spatial relationships among 3D legal units	No	No, perspective view may cause ambiguity	Yes	No	Maybe, shading effect will cause ambiguity	Yes	Maybe, depends on the natural of the texture
5. Labeling the official measurements	Maybe, hard to perceive and implement	No, hinder viewer's reading	Yes	Yes	Yes	Yes	No, texture is barely perceivable on the label font

The overall evaluation of each visual variable is as follows:

- **Position**: Change position of the unbounded surface could drive viewer's attention and give an "open" feeling.
- **Orientation**: Using different orientations of the surface's texture is not effective in 3D visualization. Users may be confused of whether the difference of orientation is caused by symbol or by perspective

projection. Only when all the orientation changes are carried out on a same plane, as shown in the second visual requirement, the change in orientation can be unambiguously perceived.

- **Size**: A change in the size of boundary (width) is feasible and unambiguous in every requirement it tested. We can quickly and easily view the surface that surrounded by broader boundaries. This conclusion is in accordance with other researchers' results. In 2D visualization, size has a perceptual properties of dissociative as it changes the visibility of symbol, making this symbol hard to ignore by human perception system (Reimer, 2011). It could also be used as an enhancement technique of highlighting in 3D virtual city (Robinson, 2009).

- **Shape**: Using different shapes as an extra symbol on surface is promising to aid the viewer's perception. However, shortcomings have been spotted. It could not be used for small surface, such as the physical objects like pillars. Moreover, when applied for multiple surfaces, it is sometimes distracting.

- **Brightness**: If there is a directional lighting and shading effect in 3D cadastre visualization, brightness of surface is not always a promising choice. The light source and shading effect may unevenly change the perceivable value of each surface. Using the ambient lighting or self-illuminating without shading effect could reduce the ambiguity of the value estimation, since they don't change the visual variables of the surfaces unevenly, but on the other hand, they may affect viewer's perception of depth clue and orientation in 3D model. The importance of shading and shadowing for depth perception in 3D has been confirmed in the literature of Engel and Semmo (2013) as reviewed in chapter 3. Moreover, many cognition research suggested that human's perception of brightness is not based on absolute value, but largely depends on the contrast with surrounding objects' and the background (Ware, 2012; Zaidi et al., 1997). This is confirmed in this preliminary evaluation as background brightness clearly influenced the perception of foreground cube's brightness. As a result, using value of surface to encode information in 3D context is not a feasible choice, or at least should be used with great caution.

- **Color**: A change in color of surface is feasible in every requirement tested. Color is a widely used visual variable in current 3D model for overlapping property units in condominium as reviewed in the previous chapter. Many researchers in 2D visualization argue that it is selective, which means it helps user separate the different correspondence in a same category (Bertin, 1983). The preliminary test shows that no specific color ambiguous occurs in 3D visualization. However, using visual variable color to construct feasible 3D model should also consider the visualization context, the value of the visual variables, and the background color. For example, the color series of “red” and “green” gives a significant different reading influence compared with color series of “red” and “blush red”.

- **Texture**: Using different textures of the surface is feasible for all tested visualization requirements. However, the conclusion may only in accordance with the textures tested since according to the statement of Carpendale (2003), texture could be altered in multiple ways, including pattern, grain, and material. Further evaluations are still necessary aiming more precise conclusion.

Through the preliminary evaluation, the initial knowledge about the feasibility of visual variables has been acquired. The results show that 3D visualization affects the perception of some of the visual variables, such as the orientation and brightness. The visual variable orientation is obviously not feasible while size is feasible when applied with boundary lines. In addition, the modeling building experience demonstrates that the visual variable color contains multiple dimensions and should better divided into color hue and color saturation for further research. It is necessary to highlight the test limitations. First, for a quicker testing process, it has used simple volumetric geometries instead of a real overlapping situation in condominium. Second, it has only assessed the visual variables' feasibility for five visualization requirements, rather than a robust usability test, and there is no comparison between different visual variables' feasibility in each visualization requirement. Finally, the evaluators are limited to our research group, rather than the real user of cadastre visualization. The evaluation, even with discussion inside the expert group, is subjective. Thus, the judgment may contain bias, yet, it is still an indispensable step since we could not test 200 models with the end user.

4.1.2 Empirical tests visual variables in the face-to-face interview with notaries

Following the preliminary evaluation, and addressing its limits, this research then implements empirical tests with intended cadastre users based on a real overlapping situation in condominium in a form of face-to-face interview.

Methodology

Empirical tests are placed in a face-to-face interview with notaries to evaluate the suitability of visual variables for specific visual tasks. The empirical test follows the hypothetico-deductive scientific method, and uses evaluation criterion of usability. This is because that hypothetico-deductive method is the scientific foundation of all experimental test, and usability is widely used as an evaluation criterion in the research of human computer interaction and computer science. Multiple hypotheses are constructed, and each one of them corresponding to a group of visual variable/enhancement techniques and a visual task. According to hypothetico-deductive’s definition, the hypothesis could never be proved, but only be rejected. As a result, we formulate the hypotheses in a negative form of "Visual variable X does not have good usability for visual task A". According to ISO 9241

Part 11, usability should be evaluated from the effectiveness, efficiency and satisfaction of users to carry out specific visual task. Thus the hypothesis could be:

- Hypothesis example 1: Visual variable transparency does not have good effectiveness for identifying the property units' boundaries.
- Hypothesis example 2: Visual variable hue does not have good efficiency for distinguishing the private and common property units.
- Hypothesis example 3: Visual variable brightness does not have good preference for distinguishing the property units with its physical counterparts.

In order to support or reject the hypotheses, we construct multiple 3D models of property units in condominium to test with participants based on the data of a real case condominium in Quebec. The data is provided by a private land surveying company (Groupe VRSB) that routinely conducts condominium survey and mapping for the delimitation of property rights. The building under study, as shown in Figure 4.1, is approximately 30m in width, 32m in length, and 36m in height. It has ten floors.

Figure 4.1. The building under study that contains overlapping condominium property units

In each 3D model, only one visual variable or enhancement technique is used to encode task related information other than geometry coordinates, while other visual variables are kept largely constant. Also, one 3D model is tested only for one visual task. User's navigation in the 3D model is not the main concern of this evaluation, and the time constraints have to be controlled considering that participants may not have the willing to spend more than 1 hour in this interview. Therefore, this test uses animation videos to present 3D models. In a video, the 3D model is turned up-down, and zoomed in-out, and each video shares a same animation process. Using video here reduces the impact of participants' different learning curves of 3D navigation and their different navigation strategies on test results, yet at the same time, it enables viewing 3D model from different prospects, which is a fundamental 3D visualization feature.

Selection of participants

The selected participants are notaries. The reasons are: firstly, notaries drafting the deeds and examine the title in cadastre. According to the civil code of Quebec, notary is a public officer that shall prepare and authentic legal document like real estate mortgage. In the case of buying a property, it is critical to invite a notary to evaluate the property and prepare the legal documents. Their work directly ensures the integrity of the property transaction and registration. Secondly, mainly trained for cadastre from legal professions, notaries are not experts in 3D graphics, surveying and architecture. Reading 3D visualization may even be a novelty for them. This has been further confirmed in our research (Pouliot, Wang, & Hubert, 2014). Moreover, since notaries are not visualization experts, they may not be aware of the potential risk of misinterpreting the visualization. Finally, test with notaries could largely eliminate the influence caused by the lack of basic cadastre knowledge since most of them are familiar with cadastre data. With the help of a private land surveying company (Groupe VRSB), we invited multiple notaries that have cooperated with this company through email. Finally, only four notary participants in our interview. For information purposes, Quebec City currently has 220 notaries, among whom approximately only 20% are working on co-ownerships (condominiums). Even with four notarial participants, the validity of the test result is trustworthy. Since first, four participants is already overpassed the suggestion of Nielsen and Landauer (1993), which they claimed that only 3.2 users is appropriate if considering the efficiency. Meanwhile, Virzi (1992) claimed that five users are enough to find 80 percent of the usability problems. Second, besides empirical evidence, there are other testimonies to support the conclusion, including examples, literatures, and reasoning. Finally, interviewing with four participants with usability test is already a big improvement of the result's credibility compare with much of other visual variable related research. Other works, such as those of Bertin (1983) and MacEachren (1995), have only examples without any direct empirical proof.

Selection of visual variables and enhancement techniques

The preliminary test uses Bertin (1983)'s seven visual variables for a quick evaluation. However, with the experiences gained during the preliminary evaluation, extending Bertin's list seems necessary. Firstly, Bertin's color should better be separated into color hue and color saturation. The preliminary test shows the detailed color setting greatly influence the visualization result. The change of color hue, like "green", "red" compared with the change of color saturation, like "red" and "blush red", could yield different impression. MacEachren (1995)'s argument also supports the separation of hue and saturation. He indicated that the color saturation has been used in many map designs for its perceptual property of order. Moreover, the separation could be feasibly implemented since the current color picking function in many graphic designs and geospatial software like CAD (computer-aided design) and Sketchup enables the separate control of hue and saturation. Secondly, transparency should better be included in the list. MacEachren included transparency in his list of visual variables, since it has already showed effectiveness in Treinish (1993)'s work. Other literature from information visualization research (Cheung, 2011; Colby & Scholl, 1991; Viola, Kanitsar, & Groller, 2004) also demonstrates the capability of transparency. Moreover, in 3D visualization, it could also be one of the occlusion management methods (Elmqvist & Tsigas, 2008).

Changing position and shape of the property units' representation may be inappropriate in the experiment since in the condominium case all the property boundaries are spatially defined. As a result, the empirical test with notaries does not consider position and shape as visual variable. Position of the boundary surfaces of a property unit may change due to the visual enhancement of object detaching; however, it is more a visualization enhancement technique than a visual variable that encodes underlying cadastre related data. Also, the visual variable size has not been tested, since it is clearly effective when used with line primitives as showed in the preliminary tests.

Finally, this chapter extends the list of visual variables for tests. The tested visual variables and their definition in this chapter are:

- Brightness: the measure of the perception of a color's brightness
- Hue: the categorical definition of a symbol's color to be "Green", "Red", "Yellow" and so on. Or the degree of similarity to these color name.
- Saturation: the intensity of a symbol's color
- Orientation: the direction of a symbol, its shape, or texture
- Transparency: the perceptual degree of a symbol's translucency
- Texture: the surface quality of a symbol, when it consists of finer symbols or structures

Three enhancement techniques (labeling, object detaching or transparency for occlusion management, and highlighting) are tested, as they have been extensively used in existing 3D visualization research in both cadastre and other domains as stated in the previous chapters. In addition to the preliminary evaluation, occlusion management is also tested. The reason is some of the following empirical tests involve multiple floors, in which situation the occlusion management is indispensable to aid viewer's perception.

Selection of visual tasks

The five visualization requirements previously tested in the preliminary evaluation are from an aspect of visualization implementation about which types of data should be visualized. However, the empirical tests with notaries are based on the evaluation criterion of usability, which is a term evaluated by the viewer's perception and human-computer interaction. As a result, detailed visual tasks for the goal of delimitating property units from an aspect of user's perception seems more pertinent compared with five visualization requirements. Taking advantage of the literature review in previous chapters about the user and usage of cadastre map in condominiums, and with the result of Boubehrezh and Pouliot (2012)'s survey with professional cadastre users in Quebec, we recognize eight visual tasks for delimitating property units:

1. Identify the geometric limits of the property units
2. Locate a specific property unit inside the building
3. Distinguish the limits of the property units and the associated building parts
4. Distinguish the private and common parts of the condominium
5. Associate property units with its surrounding units
6. Associate building part with 2D land parcel and compare their geometric limits
7. Identify the official measurements of property units
8. Background the condominium with its surrounding environment

This inventory of visual tasks have been fully agreed by all the notarial participants in the following interview process. For a formal and unambiguous description, this list uses the vocabulary proposed by Zhou and Feiner (1998): "identify", "locate", "distinguish", "background", and "associate", among other schema listed in the previous chapter. The reasons are: firstly, their theory systematically explains the relationship between visual tasks and more general visual intents, and links visualization requirements with perceptual visual implications. Secondly, their definitions of 15 visual tasks, as evaluated by this work, are domain-independent and simple to communicate with the intended user and other researchers. The vocabulary they used, for example, visual task "locate", is similar to its meaning in natural language. In contrast, for instance in the taxonomy of Andrienko and Andrienko (2006), the visual task "locate" should be expressed as an inverse lookup task that uses the value of attributes to find the corresponding values of the location referrers. This definition may be too abstract for end users to validate and hard to communicate with other cadastre researchers.

Test setup

In each 3D model, only one visual variable or one enhancement technique is used to encode task related information other than geometry coordinates, while other visual variables are kept largely constant. The detailed list of tested 3D models is placed in Appendix 2. For example, the property units have been applied different hue to encode their categories of legal or physical, while other visual variables like the transparency of surfaces and the brightness of surfaces are kept the same. Also, each 3D model is designed and tested for a specific visual task. The black and white (B&W) representation (boundary lines in black and surface in white) is also tested since it is the simplest form without any information encoding other than boundary geometry. It could be used as a comparison with those 3D models using visual variables for information encoding. The 3D models for each visual task should be built on different floor(s) of the condominium in order to minimize the carry-on effect (an effect that the knowledge of current test context influences the participant's performance in further tests). The final set contains 35 3D models designed to represent the overlapping property units in condominium. Some 3D models show only one floor, while others present many (depending on the visual task), as demonstrated in figure 4.2.

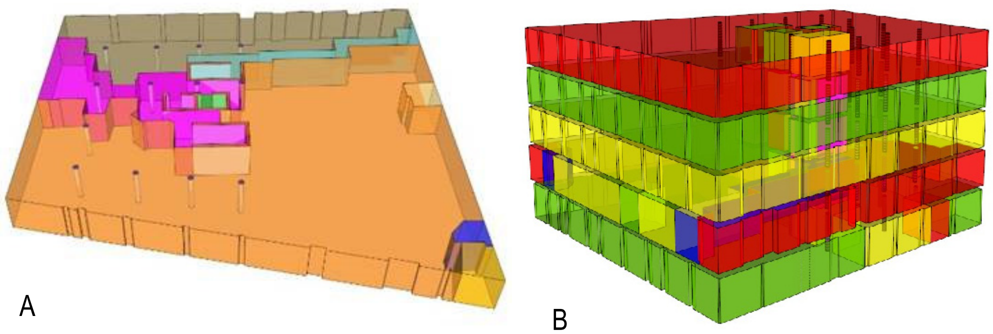


Figure 4.2. Two 3D models using the visual variable color to encode different property units for visual task 1, identify the geometric limits of the property units. A: one floor, B: multiple floors together. Transparency is used as a visual enhancement to manage occlusion

Not only the choice of visual variable for semiotics, but also its detailed settings (Green, 1998) as well as environment settings influence the appearance of the 3D model and thus may alter the test results. However, since the number of possible combinations of settings is infinite, a pre-selection has to be performed to find feasible and appropriate settings for each 3D model, if not the best. Such pre-selection is based on the comparisons between different settings, and the decision is largely subjective considering the clarity and ambiguity of the display results. As a result, each hypothesis, test, and conclusion about the usability of visual variable or enhancement technique in this empirical test with notaries is in fact based on an appropriate setting of visual variables' value and environment. The value settings of visual variable may differ between different tests. On the other hand, the environment settings in each visual task are kept untouched to a great extent in order to permit comparison. However, all these setting changes will not damage the credibility of the result. Based on the core idea of "hypothetical-deductive" scientific method, merely one positive example is enough to reject the hypothesis of "not good usability", and get the conclusion "visual variable may have good usability for specific visual tasks"; even such conclusion may not be applicable under all circumstances and settings.

In the tests, the effectiveness and satisfaction are measured for all visual tasks except visual task 8 background the building with the surrounding environment, which is more about the user's subjective choice of contextual features. However, efficiency is only evaluated for task 2 locating a property unit and task 7 identify the official measurements, since for the other visual tasks, the property units' geometry greatly changes between different 3D models, making the efficiency assessment meaningless.

In order to gauge the effectiveness, one question regarding task related facts of the 3D model is formulated in the tests of each 3D model. Here is the list of questions asked to notarial participants:

- Task 1: How many lots are you able to count?
- Task 2: At which floor is lot 5 252 285 located?
- Task 3: Considering a specific lot, is it an administrative unit or the building itself?
- Task 4: Considering a specific lot, is a private or a common part?
- Task 5: Which corners of the condo overlap the land parcel?
- Task 6: How many lots touch the lot presented in red (upper side and adjacent)?
- Task 7: What is the volume of lot 5 220 398?

For task 8 background the condominium, only the preference between three solutions (photorealistic, non-photorealistic vector, and mixture) has been evaluated. Users are also required to evaluate the necessity of certain feature types in 3D models, including 3D building geometry, PC number, neighbouring land parcels geometry, neighbouring land parcels number, road number, and land marks. Participants could suggest any other feature types that they evaluate helpful for viewer's orientation.

The correctness of user's answer to a question can be used for objectively evaluating the effectiveness of a 3D model in order to reject or support the hypothesis. If most of the participants gave a correct answer, the hypothesis is thus rejected, and the 3D model will be evaluated effective, and if most of them made error, the 3D model is evaluated ineffective under current settings. However, hypothesis that the visual variable is not usable could never been proved according to the hypothetical-deductive scientific methods.

For task 2 locating property units and task 7 identifying official measurement, the time a user spent to answer the question is registered in order to measure the effectiveness of the tested visualization solution. The quicker a correct answer is given, the more efficient the tested 3D model is evaluated. The time lapse registered for incorrect answer will not be considered, since efficiency for a non-effective 3D model is worthless.

Participants have to answer a series of preference questions for each visual task after they finish all the test and effectiveness questions. The snapshots of each group of 3D models tested for this visual task are presented, and participants are asked to indicate their preference between them. They are also allowed to indicate no preference.

Running the test

The interviews are carried out in the office of notaries. The notarial participant seats in front of the computer with limited interventions on the part of supervisors. Before real tests, the objectives of this interview, and the general procedure of all the tests are explained. They are also informed that all their comments and the time spent for answering the questions will be recorded. With their consent, a trail test is demonstrated to help notarial participants understand the exact test form. It contains, same as a real test, a video animation with a 3D model, and examples of questions.

The notarial participant then goes through all the tests for each of the eight visual tasks. In each test, all the video of 3D model will be displayed. Once the participant finishes watching the video animation of 3D model, the question regarding task related fact in 3D model is presented. He is allowed to rewind the video in order to view 3D model from a desired camera position and distance. The time lapse for him to submit the answer is recorded if necessary. Participant can give any subjective comments after finishing the question for each video. Once it has finished all the videos and effective questions for one visual task, the preference tests are presented, covering each pair of the tested 3D models for this visual task. The participant could also freely express its feelings concerning the visual task and the tested 3D models after the preference test is finished. Finally, when he finishes all the visual tasks in this interview, the notarial participants are invited to discuss: 1) if they already performed co-ownership establishment in condominium situation; 2) if they have 3D visualization experience, and 3) if they are interested in 3D cadastral modelling. They can also openly express their feelings and suggestions concerning the entire list of visual tasks, the tested 3D models, and the general topics of 3D visualization of cadastre. An interview normally lasts around 1 hour.

Test results

Scheduling interview with notaries turned out to be a big challenge since they are highly engaged. Despite our effort to invite notaries; only four notaries have been interviewed and tested with 3D models. This prevents us from statistically analyzing the results; however, valuable outcomes could also be acquired according to each visual task. The test results are placed in Appendix 3. We reject the hypothesis and evaluate the visual variable or enhancement technique effective, efficient, or preferable for a specific visual task if more than two participants give promising responses. If only two participants give favorable responses, the conclusion is marginal effective, efficient, or preferable. Less than two favorable responses indicate that the visual variable or enhancement technique is not effective, efficient, or preferable. The results are as follows, and the number following each item means how many participants gave promising responses (1/4 means one person in the four participants).

- **Task 1**: Identify the geometric limits of the property units
    a. B & W design is not effective (1/4).
    b. Brightness is marginal effective (2/4), and not preferable (0/4)

  c. Color is an effective solution (4/4) and preferable (4/4).
  d. In 3D visualization obstruction could affect the perception of the 3D model, this will be more critical when visualizing multiple floors together. Thus, we tried enhancement of transparency (40% opacity) here. However, the result is not very effective (lesser than 2/4 in multiple 3D models) and not preferred (0/4 in multiple 3D models). One participant commented that transparency may cause ambiguity in this situation.
  e. The enhancement technique of object detaching (detaching floors) is effective if not combined with transparency (4/4) but marginal preferable (2/4).

- **Task 2**: Locate a specific property unit inside the building
  a. Hue (other than white) of the surface is not a preferable characteristic when using labels (1/4).
  b. Higher transparency could improve the perception efficiency of the label that locates inside the 3D lot (average time 21 seconds compare with 29 seconds).
  c. Using different boundary color from font color (black) improves the effectiveness (3/4 compared with 4/4) and efficiency (15 seconds compared with 21s).
- **Task 3**: Distinguish the limits of the property units and the associated building parts
  a. All participants believed that they could distinguish the difference. However, the correctness varies: texture (4/4) > saturation (3/4) > brightness (2/4), and saturation is the most preferable (4/4).
  b. In this situation, even B&W with 40 % transparency is effective (4/4).
  c. Some textures give a feeling of the physic objects (mentioned by one participant).
  d. Texture may be hard to perceive when applied to very small geometries (mentioned by one participant).
- **Task 4**: Distinguish the private and common parts of the condominium
  a. Brightness is effective (3/4) and preferable (4/4) in this test.
  b. Using different transparency to represent private part and the common part is effective (4/4), but not preferable (0/4).
  c. Using special texture to represent common part is effective (4/4), but not preferable (1/4).
- **Task 5**: Associate property units with its surrounding units
  a. Adding virtual walls for the land parcel, and making interaction with 3D building model is effective (3/4) and preferable (4/4). However, one participant insists that presenting footprint is visually better.
- **Task 6**: Associate building part with 2D land parcel and compare their geometric limits
  a. When visualizing multiple floors, object detaching is effective for observation of the center part (3/4) and marginal preferable (2/4), but may affect the effectiveness to percept upper floor

(0/4). It also shows little improvement compared with transparency solution (3/4 compared with 3/4).

  b. The visual solution that uses hue is more effective (3/4) and marginal preferable (2/4) than transparency (effective 3/4, preferable 0/4).
  c. One participant expected that the color used for adjacent property units have a certain relation with the color used for selected property unit.

- **Task 7**: Identify the official measurements of property units
  a. All the 3D models tested are effective (4/4).
  b. The annotation in the center of the lot is the most efficient (average response time: 5.25 and 6.75 compared with annotation outside the lots 11 seconds and 27.5 seconds).
  c. Adding linking line shows no improvement of efficiency (6.75 seconds compared with 5.25 seconds) when the label is placed inside the volume.
- **Task 8**: Background the condominium with its surrounding environment
  a. Features that is necessary: PC number (3/4), geometries of surrounding lots (4/4), lot number of surrounding lots (4/4), road number (3/4), 3D geometry of this building (3/4). Landmarks are evaluated not necessary (1/4)
  b. Photo-realistic may not a good idea for professional users since simple vector model is obviously preferable (4/4). All four notaries recognized the importance of the eight visual tasks in their ordinary cadaster tasks.
- **Open discussion:** All the notaries expressed great interests towards 3D visualization of cadastre. However, they want to know what is the real value gaining of 3D. Also, for design strategy, they expressed the preference towards simple non-photorealistic design rather than photo realistic design. One notary said that he still favored 2D visualization, since he believed that it is more simple.

4.1.3 Perceptual property synthesis and discussions

Synthesize perceptual properties of visual variables in 3D

The results of the preliminary evaluation and the face-to-face interview with notaries contain the suitability of visual variables and enhancement techniques for specific visual tasks. These visual tasks may involve different perceptual properties of visual variables, such as selective, associative, order, and quantitative. Synthesizing current test results to visual variables' perceptual properties may be helpful to guide the design of 3D cadastre model for other decision-making goals since their visual tasks may require certain perceptual properties as well. The allocation also enables the comparison with existing research of visual variables in 2D visualization, as many of them, like Bertin (1983) and Carpendale (2003), analyzed the suitability of visual variables by their perceptual properties.

The synthesis of visual variables' perceptual properties exhibited in our empirical tests has two steps. In the first step, we identify the perceptual property involved in each visual task or visual requirement that has previously been tested or evaluated in our experiments. Such process is based on the interpretation of the perceptual properties' definition in six different frameworks respectively. Using six different frameworks is because that it is hard to merge their claims and results inside one vocabulary system, since first their definitions implied fundamental disparities of epistemology and ontology, and second such merge may introduce discordance and mistakes, which could only be identified by extra empirical tests. Table 4.2 presents the result of the perceptual properties involved in each tested visual task and requirement. Each column in the table represent the allocation under a specific framework. In table 4.2, some of the visual tasks require only visual enhancement techniques, and the blank cell means that there is no corresponding perceptual property for this visual task in a specific framework.

In the second step, we sum up the test result of a certain visual variable in all the visual tasks that involve a same perceptual property. For example, as indicated in table 4.2, visual task 3, 4, 5, and 6 all concern Bertin's dissociative property. Thus, the test results of visual task 3, 4, 5, and 6 that concerns a same visual variable could be combined together to demonstrate the dissociative of this visual variable in the 3D visualization of condominium property units. Another example concerns task 4, which requires dissociative. For this task, the visual variable color hue is effective. Thus we evaluate color hue is dissociative in the 3D visualization. Only feasible (the preliminary evaluation), or effective results (the face-to-face interview) are concerned positive for a specific perceptual property. Marginal effectiveness is presented in the result too. In addition, if one test of a visual variable is effective while another test is marginal effective concerning a perceptual property, we evaluate that the visual variable also processes this perceptual property, but with marginal effectiveness. For example, brightness shows marginal effective in task 1 that involves selective. It also shows marginal effective and effective for two dissociative visual tasks (task 3, task 4) respectively. As a result, we conclude that brightness is selective (based on one visual task) and dissociative (based on two visual tasks), but is marginal effective. Among the preliminary evaluation and the empirical test, we evaluate that the empirical test holds more credibility than the preliminary evaluation. Thus, if there is conflicting result, the conclusion will be derived only from the empirical result.

Table 4.3 shows the results about the visual variable's perceptual properties in 3D visualization from our test result. In table 4.3, each column represents a framework of visual variables' perceptual properties. For example, for Bertin's framework in column one, the terms "dissociative" and "selective" are used. Also for MacEachren's framework in column four, "visual isolation" and "visual levels" are used. The results between different columns are not comparable, since even the same term may have different interpretations.

Table 4.2. Perceptual property involves in each tested visual task and visualization requirement according to six different frameworks respectively

Perceptual property frameworks / Visual tasks and requirements	Bertin (1983)	Green (1998)	Carpendale (2003) Halik (2012)	MacEachren (1995)	Kraak & Ormeling (2011), Slocum (2009)	Garlandini and Fabrikant, (2009)	Visual variable tested
Visual Task1: Identify the geometric limits of the property units	Selective	Selective	Selective	Visual Isolation	Nominal		Brightness, color, transparency
Visual Task2: Locate a specific property unit inside the building	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Hue, transparency,
Visual Task3: Distinguish the limits of the property units and the associated building parts	Dissociative	Selective	Associate	Visual Levels	Nominal		Texture, saturation, brightness
Visual Task4: Distinguish the private and common parts of the condo	Dissociative	Selective	Associate	Visual Levels	Nominal		Brightness, transparency, texture
Visual Task5: Associate property units with its surrounding units	Dissociative	Selective	Selective	Visual isolation	Nominal	saliency	Hue, transparency
Visual Task6: Associate building part with 2D land parcel and compare their geometric limits	Dissociative	Selective	Selective	Visual isolation	Nominal	saliency	Hue
Visual Task7: Identify the official measurements of property units	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement
Visual Task8: Background the condominium with its surrounding environment	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement	Visual enhancement

Visual requirement 1: Represent bounded and partial bounded 3D legal units	Dissociative	selective	selective	Visual isolation	Nominal	saliency	Position, orientation, size, shape, brightness, color (hue and saturation), texture
Visual requirement 2: Represent the relationship between 3D legal units and 2D land parcels	Dissociative	Selective	Selective	Visual isolation	Nominal	saliency	Same as previous requirement
Visual requirement 3: Represent the relationship of 3D legal units with corresponding physical object	Dissociative	Selective	Associative	Visual levels	Nominal		Same as previous requirement
Visual requirement 4: Represent spatial relationships among 3D legal units	Dissociative	Selective	Selective	Visual isolation	Nominal	saliency	Same as previous requirement
Visual requirement 5: Labeling the official measurements	Visual enhancement	Selective	Associative	Visual Levels	Nominal		Same as previous requirement

Table 4.3. The perceptual properties of visual variables in 3D visualization synthesized from our test and organized by different frameworks

Perceptual property / frameworks — Visual variables	Bertin (1983)	Green (1998)	Carpendale (2003) and Halik (2012)	MacEachren (1995)	Kraak and Ormeling (2011), Slocum (2009)	Garlandini and Fabrikant, (2009)
Size	Dissociative (line)	Selective(line)	Selective (line), Associative (line)	Visual isolation (line), Visual level (line)	Nominal (line)	Salient (line)
Brightness	Dissociative*, Selective*	Selective*	Selective*, Associative*	Visual isolation*, Visual level	Nominal*	Salient (only for symbol on a same plane)
Hue	Dissociative	Selective	Selective	Visual isolation	Nominal	Salient
Saturation	Dissociative	Selective	Associative	Visual level	Nominal	Salient
Orientation	Not effective	Not effective	Not effective	Not effective	Not effective	Not effective
Shape	Dissociative (with extra symbol)	Selective (with extra symbol)	Selective (with extra symbol)	Visual isolation	Nominal	Salient (with extra symbol)
Texture	Dissociative	Selective	Selective*, Associative	Visual isolation*, Visual level	Nominal	Salient (depends on specific texture)
Transparency	Dissociative	Selective*	Selective*, Associative	Visual isolation*, Visual level	Nominal	Salient*

* Marginal effective

Discussions

The preliminary evaluation and the following face-to-face interview with notaries tests assess the suitability of visual variables and the enhancement techniques in 3D cadastre visualization. With synthesis, the perceptual properties of visual variables in 3D visualization could also be derived. However, the previous research steps have limits. Firstly, the visual variable's value settings and the environment settings have not been precisely tested. All the tests are based on a few preselected visual variable's value settings and environment settings that are supposed to construct a feasible and appropriate 3D model appearance. By rejecting the test hypotheses, which are stated negatively, this research could arrive at the conclusion that a visual variable, for example, color, has good usability (effective, efficient and preferable). However, such conclusion should be interpreted with caution. It only indicates the potential of a visual variable, yet a proper value setting as well as environment settings are also critical when using a visual variable to encode information for specific user visual task. Current tests are not sufficient to evaluate which settings are feasible. Furthermore, hypothetical-deductive means empirical evidence can either deny or support hypotheses, and hypotheses shall never be proved. As a result, the visual variables that evaluated not effective or not preferable may still be effective and preferable in certain circumstances with specific value settings or environment settings.

Secondly, a video of navigation in the 3D model is used in the tests of the face-to-face interview, instead of freely interactive navigation in 3D model. Navigation is still possible in 3D model among predefined camera locations, as participants can forward and rewind the video. This approach has advantages, as it simplified the learning process of interaction and maintained a consistent navigation process between different tests, however, it is based on a premise that such method does not greatly change the effectiveness, efficiency, and preference of visual variables in 3D model compared with a free navigation scenario. Considering the time limits for each interview, and no much appearance difference has been spotted in the comparison between the video method and interactive navigational 3D visualization, this research accepted this premise and used the video method. However, it has to mention here that such premise has never been empirically proved. The interactive and navigable 3D visualization is prominent in current 3D software in a geospatial domain like Arcscene and Google Earth. Therefore, it is preferable to place further investigations of visual variables, if applicable, in similar human-computer interface, namely interactive 3D visualization that enables participants to navigate freely.

Thirdly, as an empirical evaluation method, face-to-face interview falls short of reaching a large number of participants. Inviting highly occupied notaries to participate in the interview is always very hard. The credibility of our conclusions could be further improved with more participants; since currently, only four notaries finished the interview. On the other hand, as an important part of user-centered design(Van Velsen et al., 2008), face-to-face interview enables researchers to have a direct and in-depth discussion with the end user in order to better understand its requirements and feelings, and also promotes user's participation in further design processes.

The identification of the perceptual property involved in each visual task or visual requirement is largely subjective and is based on my personal interpretation of existing literatures. This may introduce bias and may not be in accordance with other scholars' interpretation. In addition, it reflects the limits of current visual variable research: the conclusions are expressed in natural languages with examples and statements rather than in a structuralized conceptual framework.

The face-to-face interview provide a valuable opportunity for us to understand the opinion of the notary users. Moreover, the 3D models tested give the notaries a direct impression, thus may facilitate the discussion. However, their feedback may contain bias, as all the tested models are tentative. They are constructed under the purpose to test the usability of visual variables, rather than to test a final visualization solution. Even all the models are carefully constructed and the settings are meticulously tuned, it may still incapable to fully meet all the user's demands. This may contribute to the situation that one participant believes that 2D visualization is better. This also explains why in the preliminary stage evaluating the real value gaining is infeasible, since such evaluation should better be based on a well-established 3D visualization solution, rather than a tentative, experimental model. However, the participants clearly expressed their interested in the 3D model drawn similar to the visualization design in CAD, which they are currently using. They do not like photo-realistic design. Literature gives explanation, since users normally tend to attach to the habit with existing visualization design (Ware, 2008).

4.2 A comparison of visual variables' perceptual properties between 3D and 2D

To complete the results obtained from the experimentations; this final section proposes a theoretical comparison of the perceptual properties of visualization in 3D and 2D. The visual variables' perceptual properties in 3D visualization are synthesized from the results of the previous two tests, while the perceptual properties in 2D visualization are derived from literature, since we have not tested visual variable in 2D. The comparison is based on six theoretical frameworks said as best practices and discussed in chapter 2.

A. Bertin (1983)

Table 4.4 shows the Bertin's conclusion with the perceptual properties of visual variables in 3D visualization. The comparison shows that brightness is marginal dissociative and selective in 3D visualization tested for overlapping property units in condominiums, while it is fully dissociative and selective in 2D visualization. Moreover, color, shape, and texture are effective for dissociative in both 3D visualization and 2D. At the same time, size shows no much suitability difference. Bertin's conclusion did not include transparency. However, the empirical test supports that in 3D visualization, transparency is dissociative.

Table 4.4. Compare visual variables' perceptual properties in 3D with Bertin(1983)'s result in 2D

	Bertin (1983)	**Perceptual properties in our test in 3D**
Size	Dissociative, Selective	Dissociative (line)
Brightness	Dissociative, Selective	Dissociative*,Selective*
Color	Associative, Selective	Hue: Dissociative
		Saturation: Dissociative
Orientation	Associative, Selective (point and line)	Not effective
Shape	Associative	Dissociative (with extra symbol)
Texture	Associative, Selective	Dissociative
Transparency	Not applicable	Dissociative

** Marginal effective*

B. <u>Green (1998)</u>

Table 4.5 shows the Green's conclusions with the perceptual properties of visual variables in 3D visualization. All the tested visual tasks could be allocated into Green (1998)'s perceptual property of selective. The result shows that orientation is no longer selective in 3D, and brightness is less selective compared with 2D visualization.

Table 4.5. Compare 3D perceptual properties with Green (1998)'s perceptual properties of visual variables

	Green (1998)	**Perceptual properties in our test in 3D**
Size	Selective	Selective(line)
Brightness	Selective	Selective*
Hue	Selective	Selective
Saturation	Selective	Selective
Orientation	Selective	Not effective
Shape	Selective	Selective (with extra symbol)
Texture	Selective	Selective
Transparency	Not applicable	Selective*

** Marginal effect*

C. <u>Carpendale (2003) and Halik (2012)</u>

Table 4.6 shows the Carpendale and Halik's conclusions with the perceptual properties of visual variables in 3D visualization. The result shows that transparency in both Halik's conclusion and in 3D visualization is selective, but may less promising compared with the visual variable like color hue.

Table 4.6. Compare 3D perceptual properties with Carpendale (2003) and Halik (2012)'s perceptual properties of visual variables

	Carpendale (2003)	**Halik (2012): Augment reality**	**Perceptual properties in our test in 3D**
Size	Associative, Selective	Selective(good), Associative(good)	Selective (line), Associative (line)
Brightness	Associative, Selective	Selective(good), Associative(good)	Selective*, Associative*
Color	Associative, Selective	Hue: Selective(good), Associative(good)	Hue: Selective
		Saturation: Selective(good), Associative(good)	Saturation: Associative
Orientation	Associative, Selective	Selective(good), Associative(good)	Not effective
Shape	Partial Associative and selective, not suitable for a quick visual interpretation	Selective (effective), Associative(good)	Selective (with extra symbol)
Texture	Texture: Associative, Selective	Selective (good), Associative(good)	Selective*, Associative
	Grain: Associative, Selective		
	Pattern: Partial associate and selective, not suitable for a quick visual interpretation		
Transparency	Not applicable	Selective (effective), Associative(good)	Selective*, Associative

** Marginal effect*

D. <u>MacEachren (1995)</u>

Table 4.7 shows the MacEachren's conclusions with the perceptual properties of visual variables in 3D visualization. The result shows that brightness has marginal visual isolation compared with MacEachren's "good" verdict. Also, orientation does not work in 3D visualization.

Table 4.7.Compare 3D perceptual properties with MacEachren (1995)'s perceptual properties of visual variables

	MacEachren (1995)	Perceptual properties in our test in 3D
Size	Visual levels(good), Visual isolation(good)	Visual isolation (line), Visual level (line)
Brightness	Visual levels(good), Visual isolation(good)	Visual isolation*, Visual level
Hue	Visual levels*, Visual isolation (good)	Visual isolation
Saturation	Visual levels (good), Visual isolation*	Visual level
Orientation	Visual levels (poor), Visual isolation (good)	Not effective
Shape	Visual levels (poor), Visual isolation (poor)	Visual isolation
Texture	Not applicable	Visual isolation*, Visual level
Transparency	Not applicable	Visual isolation*, Visual level

** Marginal effect*

E. <u>Kraak & Ormeling (2011) and Slocum (2009)</u>

Table 4.8 compares Kraak & Ormeling and Slocum's conclusions with the perceptual properties of visual variables in the tests in 3D visualization. The result shows that, except orientation, all visual variables can represent the nominal data in 3D visualization. Saturation shows better performance in 3D visualization than in 2D visualization according to our test results. However, brightness in both 3D and 2D situation is less effective.

Table 4.8.Compare 3D perceptual properties with Kraak & Ormeling (2011) and Slocum (2009)'s perceptual properties of visual variables

	Nominal (Slocum, 2009)	Nominal (Kraak & Ormeling, 2011)	Perceptual properties of presenting Nominal data in our test in 3D
Size	Poor	Not applicable	Good (line)
Brightness	Poor	Not applicable	Marginal effect
Hue	Good	Effective	Good
Saturation	Poor	Not applicable	Good
Orientation	Good	Effective	Not effective
Shape	Good	Effective	Good
Texture	Not applicable	Not applicable	Good
Transparency	Not applicable	Not applicable	Good

** Marginal effect*

F. Garlandini and Fabrikant, (2009)

Table 4.9 shows the Garlandini and Fabrikant's conclusions with the perceptual properties of visual variables in 3D visualization. The result in 3D visualization shows that, except orientation, the difference of other visual variables can increase visual saliency. However, transparency difference is marginal effective to increase the saliency.

Table 4.9.Compare 3D perceptual properties with Garlandini and Fabrikant (2009)'s perceptual properties of visual variables

	Garlandini & Fabrikant (2009)	Saliency in our test in 3D
Size	Salient (most effective and efficient)	Salient (line)
Brightness		Salient (only for symbol on a same plane)
Color	Salient	Hue: Salient
		Saturation: Salient
Orientation	Salient (Least effective and efficient)	Not effective
Shape	Not applicable	Salient (with extra symbol)
Texture	Not applicable	Salient (depends on specific texture)
Transparency	Not applicable	Salient*

** Marginal effect*

Results

The main differences between perceptual properties of visual variable in 3D visualization and 2D visualization concluded based on previous comparison are as follows:

1. 3D visualization affects the suitability of brightness. For example, in Bertin's evaluation, brightness is dissociative and selective, however, in 3D visualization, it is marginal dissociative and selective.

2. Orientation in 2D visualization is performing, like in Carpendale's evaluation, it is associative and selective. However, in 3D visualization, it is obviously not performing.

3. Transparency is a novelty since no 2D studies reviewed the suitability of transparency as a visual variable. The Halik (2012)'s work evaluates the visual variable's perceptual properties in a domain of Augment Reality, which 3D visualization may involve. His conclusion about transparency is similar to ours: transparency is selective and associative, yet, its selectiveness is less effective compared with the visual variable of color hue.

4.3 Conclusion of the chapter

Based on the preliminary evaluation, the empirical tests in a face-to-face interview with notaries, and the previous comparisons, the general conclusions of the suitabilitys of visual variables' differences between 2D visualization and 3D visualization of condominium property units could be deduced. The conclusion is cadastre domain specific, but some of its items reflect domain independent knowledge about visual variables in general 3D visualization, as it could find supports from literature of other domains like information visualization. The following items present the conclusion of visual variables' suitability together with those of enhancement techniques.

1. The suitability of color (hue, saturation) and texture in 3D visualization shows no difference from that in 2D visualization. They are effective and preferable in the test. One participant mentioned that too much color hue is not preferable as it gives a feeling of dazzling. For texture in 3D visualization, the textures that are similar to the physical objects' surface in the real world could give participants a feeling of physical objects intuitively. Thus it may be promising in visual tasks that require viewer to discriminate the physical objects from legal ones.

2. The visual variable orientation is no longer effective in 3D visualization. The perspective view in 3D visualization will make the perception of orientation ambiguous, as it is hard to determine whether the perceived orientation differences means different orientation direction in 3D model, or just an illusion created by perspective view. Similarly, perceptually identical orientation may also in fact have different orientation direction in 3D model. Visualization designers should prevent to use orientation in their semiotics of graphics.

3. The brightness is marginal effective and not preferable in 3D visualization. This conclusion has been supported by literature in information visualization, as McNamara (2011) concluded that the brightness perception is influenced by three-dimensional shape with convincing examples. Jobst et al. (2008) concluded that the lighting, shading, atmosphere effect, surface texture, and transparency influence the perception of brightness in 3D visualization. For example, in figure 4.3, surface A appears darker than surface B. However, they have a same brightness value. This is largely due to the illusion caused by perspective perception. Visualization designers should prevent to use brightness for their semiotics of graphics.

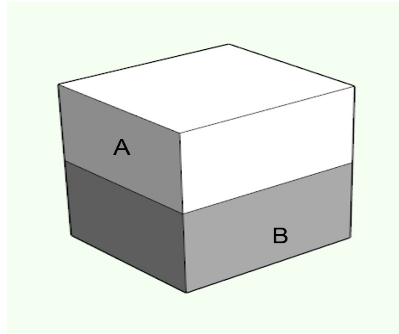


Figure 4.3. An example of how perspective view interferes the perception of brightness. In this figure, surface A appears darker than surface B. However, they have a same brightness value.

4. The usability of applying transparency for all surfaces in a 3D model in order to reduce the occlusion of highly clustered symbols is complicated: it is effective for the model with only one floor, yet no effective improvement is spotted compared with non-transparency solution. For multiple floors, when non-transparency model is not feasible, transparency is sometimes not effective and preferable. In this situation the object detaching is normally more preferable. We estimate that this may due to the interaction of transparency with other visual variables, like color. Also, it may affect user's identification of the volumetric symbols and their exact boundaries in some 3D models. Further research is needed.

5. Using transparency as a visual variable to differentiate two categories of object is effectiveness for one task it has been tested and is marginal effective for another task. However, it is less preferable solution compared with other visual variables.

6. Object detaching (detaching floors) is effective and preferable for viewer to percept the parts that remain in the central of the exploded 3D model, however, it prohibits the perception of the parts that are displaced further from the central part.

7. The labels should be placed inside or as close as possible to the symbol that it describes, as in the experiment, placing a label inside the volume symbol it related could improve the efficiency of user's perception. This conclusion is in accordance with Colin Ware (2012)'s conclusion No. 8.20 that Gestalt principles of proximity and common region could help viewers to link the text label with symbols. However, gestalt principle of connectedness does not perform for labels in the empirical tests of this research.

8. The boundary of volume symbol distracts the viewer from reading the labels. Using a different boundary color other than font color (black as we tested) may help, as in the tests it improves the effectiveness and efficiency of user to read the labeling text compared with black boundary color.

9. Using visual enhancement technique of visual highlighting to represent the spatial relationship in 3D should always preserve the relationship in all three dimensions. In our test, in order to highlight the topology relationship between a 2D land parcel and a 3D property unit, the extension of 2D surface into volume is clearly more effective and more preferable than projecting 3D object onto 2D surface. The latter method could not help user precisely locate the overlapping part in the third dimension.

The research of the suitability of visual variables and enhancement techniques is an iterative process and this chapter describes the first two rounds of evaluation. It addresses the first research objective: to evaluate the suitability of a preselected list of visual variables and visual enhancement techniques for performing unambiguous delimitation of overlapping property units in condominiums in the context of 3D visualization. It also achieves the third research objective: to compare the perceptual properties of visual variables exhibited in 3D visualization of condominium property units with those in 2D visualization. The limits of current tests in this chapter, such as no visual variable setting tested, implies the further investigations. The next chapter describes the next round of empirical test: an online questionnaire about the suitability of transparency for delimitating property units with physical counterparts.

Chapter 5 Transparency for Delimitating Property Units with Physical Counterparts

5.1 Introduction

The previous tests of visual variables and enhancement techniques in the 3D visualization of condominium property units contribute valuable results; yet, they have limitations and raises new questions as discussed in Chapter 4. The results of previous experiments with transparency in 3D visualization of condominium property units clearly showed that although transparency in certain settings may affect viewer's perception of property units geometry, using transparency as a visual variable to differentiate symbols that represent two categories of objects is effective. However, more experiments about the transparency settings are required. Furthermore, among the eight visual tasks, distinguishing the limits of property units and the associated building has specific interests: condominium property units are often demarcated by building structures like walls and ceilings, thus representing these physical objects together with artifically demarcated property unit may help viewers link the 3D model with the real world objects. This visual task has been mentioned in literature (Aien et al., 2013; Shojaei et al., 2013) or already realized in a few pilot 3D cadastre systems (Elizarova et al., 2012; Jeong et al., 2011). However, currently few works investigate how to help user unambiguously categorize and discriminate the boundaries of this two categories of objects in 3D visualization. Moreover, property units and their physical counterparts are often in a highly clustered situation in which transparency could be the relief of occlusion and at the same time be used as a visual variable.

For these reasons, this chapter present a third round of test trying to find the answer to the second research objective. This time, three levels of transparency will be tested with only one visual task, which requires the viewer not only distinguishing two categories of property units and their physical counterparts, but also unambiguously perceiving their boundaries.

5.2 Case study

Before presenting the test, the following picture (figure 5.1) shows three simple cases used to explain the possible relationships between legal and physical objects. In condominium situation, the relationship between property units' boundaries and building parts that demarcate the building space such as walls and ceilings has three possibilities: the property boundary lies along the "interior", "median" or "exterior" boundary of the building parts as shown in figure 5.1 (Aien et al., 2013). Figure 5.1 contains two property unis and a wall that separate them. There are three types of boundaries:

- Surface boundary type 1 (Simple legal boundary): A property unit's boundary artificially drawn in space with no physical correspondence (coarse dash line in black and fine dash line in blue in figure 5.1)

- Surface boundary type 2 (Simple physical boundary): A physical boundary (solid line in figure 5.1)
- Surface boundary type 3 (Legal & physical boundary): A property unit's boundary corresponding to a physical boundary (intersect part of dash lines and solid line in figure 5.1)

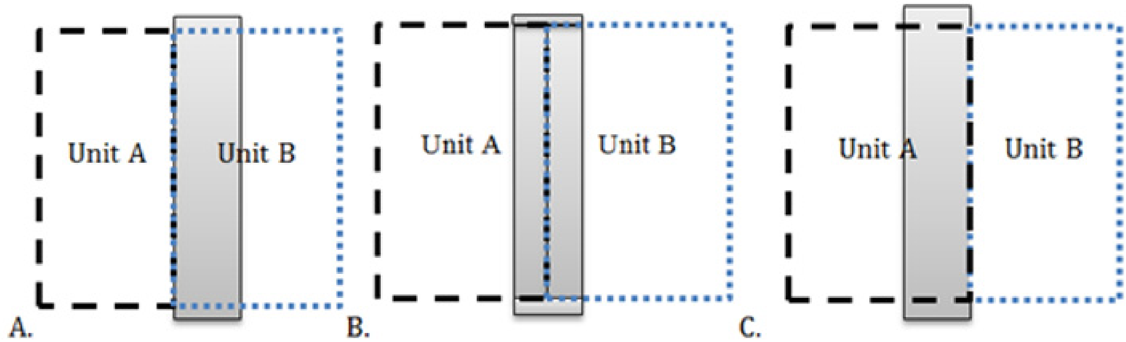


Figure 5.1.The property boundary of unit A lies along the A. interior, B. median or C. exterior boundary of the building part.

5.3 Design of the experiment

5.3.1 Methodology

The methodology used is to prebuilt 3D models involving three levels of transparency, to ask tester to manipulate those prebuilt 3D models, and to answer specific questions. In order to avoid certain limitations identified in our previous experiment, a greater number of participants are targeted. An online questionnaire is designed to show several versions of 3D cadastral models with varying level of transparency since using online questionnaire has the potential to reach more participants.

Depending on the availability of the participants and their relevance to the studied topic, three groups of participant are invited. The first group is the notarial students in Laval University since notaries are the main subject of this research and has already participated in previous tests. The second group is the students having a major in Geomatics in Laval University. Some of then are becoming land surveyors and may use cadastre data often. The third group is the scholars in IGN, France. Three groups of participants enable the comparison of test measurements between different disciplines.

The general evaluation criterion is usability, which includes effectiveness, efficiency, and preference. In this work, the effectiveness is judged by the correctness of the participants' answer to the test question, and the efficiency is judged by the response time of participants. Certitude is used instead of pure objective preference, aiming for a more visual task-centric appreciation. The test also collects four user attributes including user's discipline, user's familiarity with cadastre data, user's familiarity with 3D visualization, and if user has color perception deficiencies. Five specific questions are established in order to assess the influence of transparency settings on usability:

Question 1: Is using higher transparency on the simple physical boundary than the physical & legal boundary usable to give the unity impression of property unit it separated in a 3D cadastre model?

Question 2: Does the different settings of transparency in 3D cadastre model affect the usability to delimitating property units and their physical counterpart?

Question 3: Does the strategy of which one between the simple legal boundary and simple physical boundary uses a higher transparency influence the usability of 3D cadastre model?

Question 4: Do the settings that use very low transparency for the legal & physical boundary and the settings use no transparent for the legal & physical boundary change the usability of 3D cadastre model?

Question 5: Does user's attributes (the disciplines, the experience of cadastre, the experience of 3D, and color perception impair) influence a 3D cadastre model's usability?

For each question, null hypotheses are explicitly formulated in order to be rejected by statistical calculation of the user's responds. For example, for the question 2, three hypotheses are devised:

- Null Hypothesis 1: The correctness of participants will not be influenced by the settings of transparency in 3D models.
- Null Hypothesis 2: The certitude of participants will not be influenced by the settings of transparency in 3D models.
- Null Hypothesis 3: The response time of participants will not be influenced by the settings of transparency in 3D models.

5.3.2 Prebuilding 3D models

The 3D models used in the test are constructed based on previous evaluated case study that contains all three boundary types and two spatial relationships (interior and exterior) between legal and physical objects. The relationship that the legal boundary cut in the middle of the physical object has not been tested because it could be easily demarcated by viewer with its boundaries falling in the middle of a wall.

To eliminate the influence on the test result caused by different geometry complexity, all the 3D models share a same boundary set. Figure 5.2 demonstrates the test scenario with a boundary set that all tested 3D models share. In order to differentiate from the real tested 3D models, the 3D model in figure 5.2 uses no transparency. In Figure 5.2, the property units pointed by a red arrow is a private property, and A, B, and C are the wall parts that separate the private property unit with other property units. Each wall part could either belong to the private property unit pointed or not. For the wall part that belongs to the private property unit, the inner boundary of the wall part is boundary type 2 (simple physical boundary) and will be applied with semi-transparency. For the wall part that does not belongs to the private property unit, the inner boundary of the wall part is boundary type 3 (legal & physical boundary) and thus will be applied with lowest/no transparency.

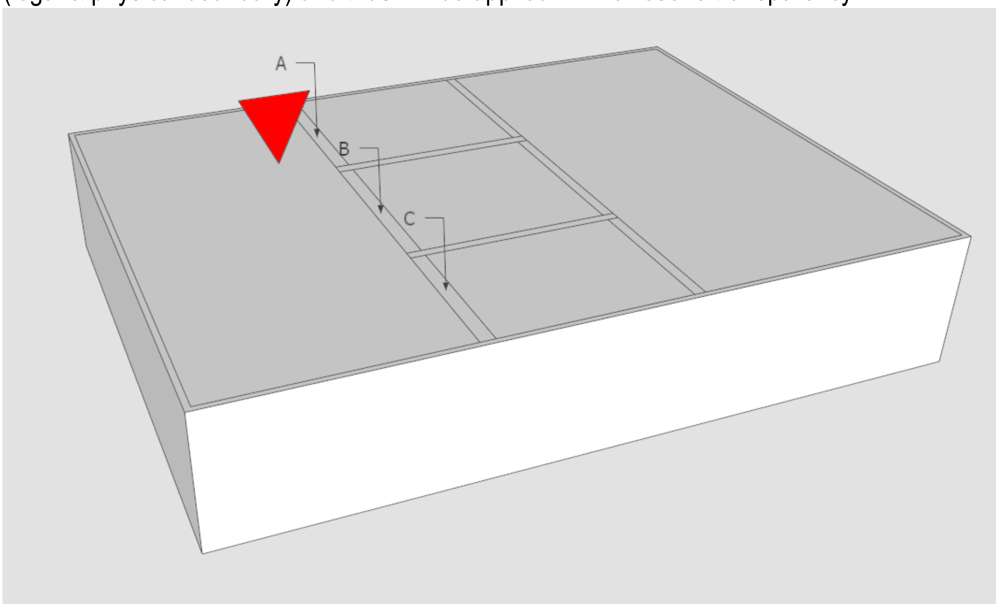


Figure 5.2. Fictional scenario used for tests, the red arrow points to a private property unit, and "A", "B", "C" point to three wall parts. Each wall part either belongs to the private property units or not

The snapshot of all the constructed models are placed in the appendix 4. The model could also be viewed online through the questionnaire website (survey.3dcadastre.com). Figure 5.3 is an example of two real 3D models tested. In each 3D cadastre model, a wall part (A, B, or C) is pointed with a green arrow, and the participant has to determine whether this part belongs to the private property unit or not. In order to eliminate the carryover effect that user can predict the answer based on the first few tests, the number (1 or 2) and placement (A, B or C) of private owned wall parts is altered among 3D models. Among six 3D models, five are constituted by three levels of transparencies, and one B/W design (black for boundaries and white for surface without transparency) is tested as reference. There are two tests for each 3D model: one (the green arrow) questions a part belongs to the private unit (Figure 5.3B) and the other questions a part that not belongs to the private unit (Figure 5.3A). The detailed transparency settings in each test are showed in Table 5.1. To limit the empirical tests, the legal & physical boundaries are always applied the lowest level of transparency or even no transparency. Using no transparency or the lowest level of transparency for legal & physical boundaries may in accordance with human's intuition of a "physical" nature as argued here, and has already proved effective in previous empirical test with two levels of transparency.

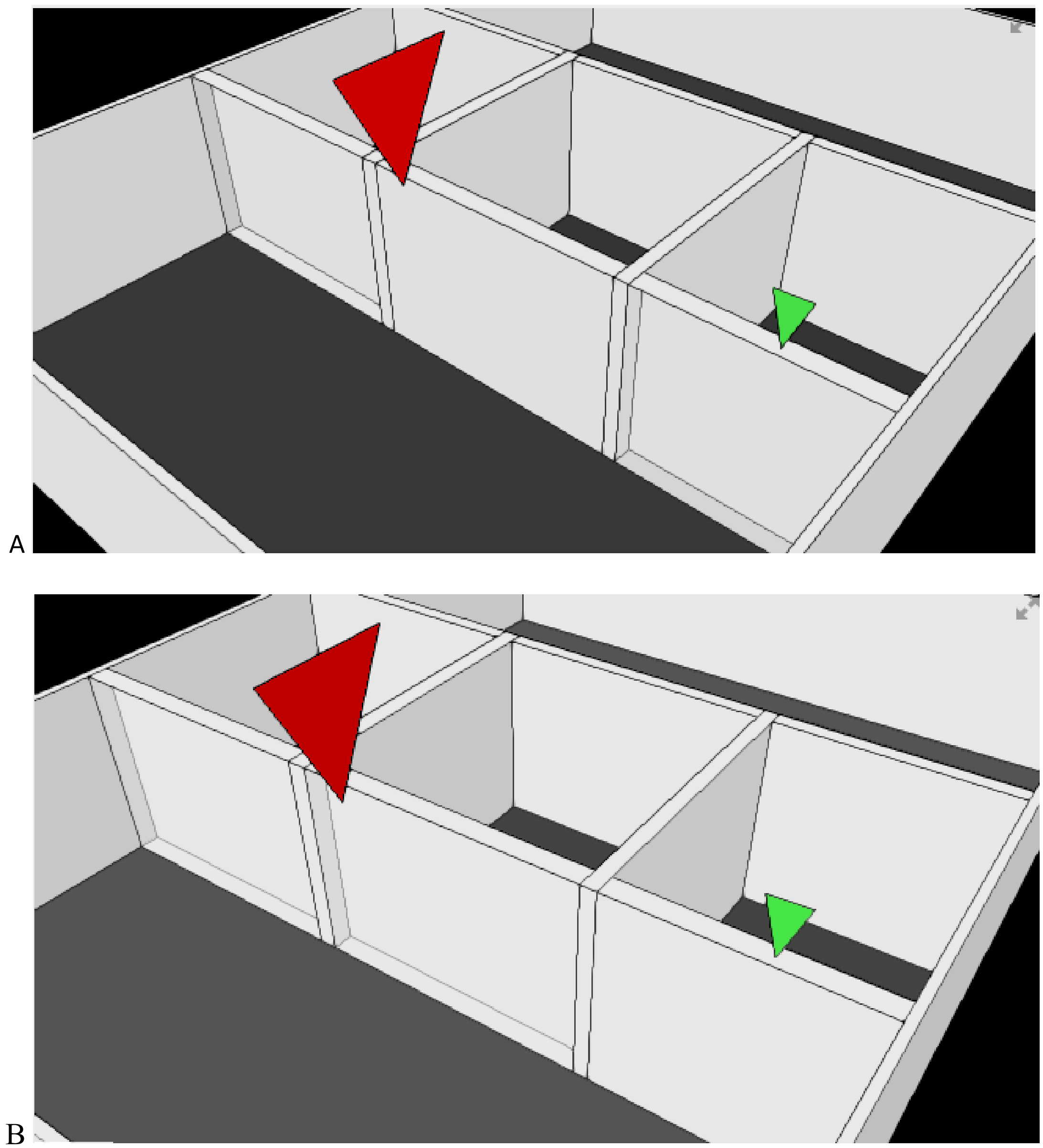


Figure 5.3. Examples of 3D models in the test, the red arrow points to a private property unit, and the green arrow points to a wall part. The participants have to decide whether this wall part belongs to the private property unit or not. A. Yes, B. No

Table 5.1.List of tested 3D models with their related Alpha values

			Alpha Values (%)	Alpha Values (%)	Alpha Values (%)
3D models	Test Number	Wall belong to Private unit (Y= Yes; N= No)	Simple legal boundary	Simple physical boundary	Legal & physical boundary
#1	1	Y	100	100	100
	2	N	100	100	100
#2	3	N	13	36	100
	4	Y	13	36	100
#3	5	Y	36	13	100
	6	N	36	13	100
#4	7	N	13	33	85
	8	Y	13	33	85
#5	9	N	60	20	100
	10	Y	60	20	100
#6	11	Y	20	60	100
	12	N	20	60	100

In Table 5.1, the transparency level is described by the alpha value, which is the weight in a weighted sum formula that used to composite foreground and background color (Stone & Bartram, 2008). Alpha value ranges from 0 (0%) to 1(100%) and could be used to represent the opacity of a feature. An alpha value of 0 (0%) means the image does not have any output and is fully transparent, and a value of 1 means the image does not let any background light pass, thus it is fully opaque (Porter, Duff 1984). In the five 3D models with transparency, the alpha value follows either geometry progression (3D model#2, 3D model#3, and 3D model#4) or arithmetic progression (3D model#5, 3D model#6). In regards to the research questions, among five 3D models with transparency, two design strategies have been used.

1. Using lower transparency for the simple legal boundary than simple physical boundary (3D model#3 3D model#5)/using higher transparency for simple legal boundary than simple physical boundary (3D model #2, 3D model #4, 3D model #6)
2. The legal & physical boundary uses non transparency (3D model #2, 3D model #3, 3D model #5, 3D model #6) / very low transparency (3D model #4)

According to literature, transparency perception is influenced by multiple factors including the surrounding brightness and color, the intersection arrangement, and the background (Cheung, 2011; D'Zmura et al., 1997; Singh & Anderson, 2002). To minimize the influence caused by the differences of these factors, other visual variables and the environment settings will be kept the same in the 3D models. For visual variables, the boundary line is always black (by RGB 255, 255, 255), the surface color is always white (by RGB 0, 0, 0), and the background color is always black (by RGB 255,255,255). This setting is to maximum the range of final output brightness. In a scenario of fully opaque background (alpha=1) with a transparency foreground feature, the alpha composting formula could be rewritten to $C_o = \alpha_a C_a + (1 - \alpha_a) C_b$ where C_a is the color of the pixel in foreground, C_b is the color of the pixel in background, and α_a is the alpha of the foreground. Based on the formula, the output brightness will be always between the foreground and the background brightness, therefore using a black background with white symbol surface is one setting that could maximum the output brightness range (color hue is not considered in the test).

5.3.3 The online questionnaire

I building the online questionnaire based on asp.net, a web application framework, and uses an SQL Server database to store test measurements automatically. The website embeds Sketchup 3D warehouse web viewer, a web 3D browser built on WebGL (a fundamental javascript API for 3D and 2D rendering in web browser), to present 3D models in the questionnaire. The 3D models are hand drawn in 3D modeling software Sketchup. The reason is first, Sketchup has all drawing functions necessary for the 3D models construction, and second, the model drawn in Sketchup could be uploaded to 3D warehouse for web browsing.

The questionnaire is presented in the form of a website running on the internet. Participants could access to the questionnaire by typing the URL "survey.3dcadastre.com" in their web browser. At the beginning of the questionnaire, the purpose, the cadastre context, the settings of transparency and the possible questions are explained. Then, the questionnaire is organized into three sections: user attributes (section A), test demo (section B) and experiments with 3D models (section C).

Section A is about the participant's attributes. Four questions are asked, and participants could choose among the pre-arranged options:

1. What is your training background? Pre-arranged options:
   a. Lawyer or Notary
   b. Pure and applied science
   c. Social and human science
   d. Medication
   e. Others (participants can specify)
2. What is the frequency of manipulating cadastre data? Pre-arranged options:
   a. Never
   b. Sometimes (less than 10 times a year)
   c. Often
3. What is the frequency of manipulating 3D visualization engine? Pre-arranged options:
   a. Never
   b. Sometimes (less than 10 times a year)
   c. Often
4. If participants have color identification deficiency? Pre-arranged options:
   a. Yes
   b. No
   c. I don't know

Section B is a demonstration section. The aim of Section B is to prepare the participants for the real tests by providing the test context and navigation practice. Firstly, as showed in Figure 5.4, with a 3D model similar to the following tests, this section explained the test context and two ownership possibilities of the wall parts in the 3D model. Next to the 3D model, literal explanations are indicated in order to help the participants. Participants are allowed to freely navigate in the 3D model to practice their navigation skills. The navigation is also provided. Then, this section explains how the transparency is employed in the 3D model to represent different boundary surfaces with two examples, and it is also a second chance that participants could familiarize themselves of the 3D navigation.

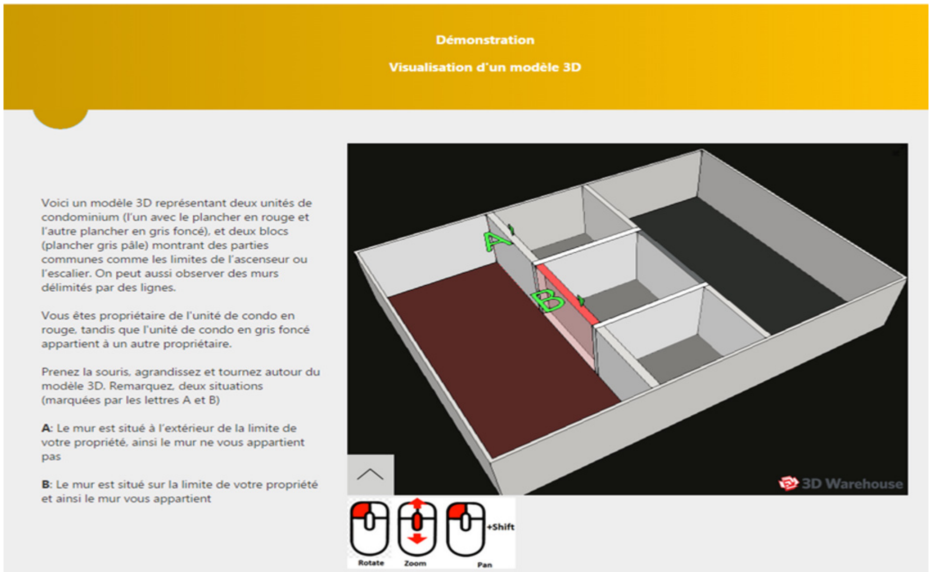


Figure 5.4. A snapshot of the interface in the demonstrative section of the online questionnaire; the left part is the description of 2 possible situations (interior and exterior); the right part is the 3D web viewer of 3D cadastre model; the lower right is the navigation aid

Section C is the real experiment with 3D models. Participants will go through all 12 tests in a randomized sequence. No rolling back is allowed. Figure 5.5 gives an example of the test interface. The left part of the figure 5.5 is the 3D model. The right part is two questions concerning viewer's effectiveness and certitude. The navigation aid is in the lower left part with the mouse movement explanation.

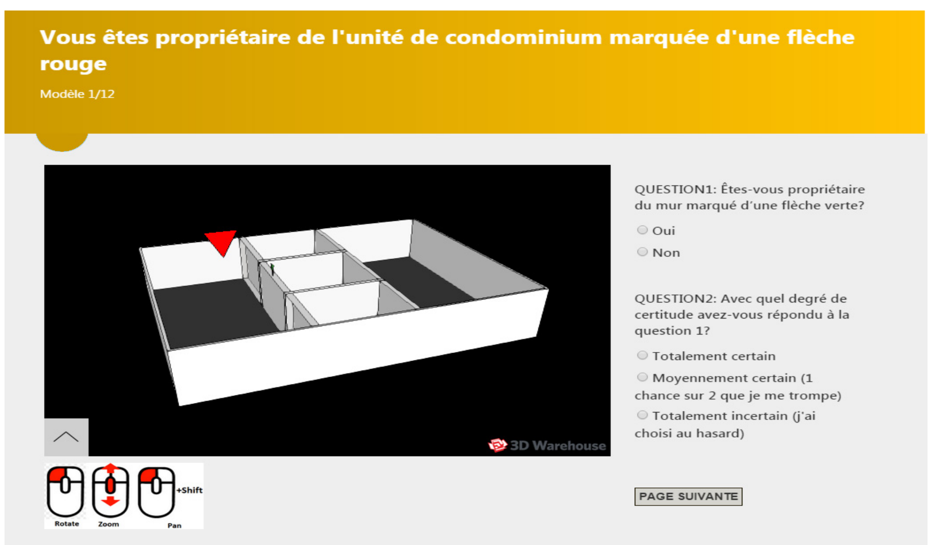


Figure 5.5. A snapshot of test interface in the online questionnaire, it contains a 3D model, two questions and a navigation aid. When the participant finished answering, it can click "Page Suivante"(the next page).

Participants are told that they are the owner of the property unit that pointed by a red arrow. The two questions in each test are:

1. Do you own the wall part that is pointed by a green arrow?
    - Possible option: Yes/No
2. What is your certainty for your answer?
    - Possible option: Totally certain/ Medium certain/ Not sure

The answer to the first question could be used to measure whether a viewer could perceive the legal status of the pointed wall part correctly. The answer to the second question could be used to measure the certitude of a viewer. Participants are allowed to freely navigate in the 3D model in order to answer the questions. The time lapse from the moment that the 3D model is fully loaded to the moment that the participant submits its choice of the two questions is registered to measure the effectiveness of user's answer.

5.4 Results and analysis

70 participants visited the questionnaire website and among them 41 finished all the tests. The complete users' responses data are uploaded online[5]. Four types of data are collected.

1. Users' attributes concerning their discipline, experience with 3D visualization, experience with the cadastre data, and if they have color perception deficiencies
2. The correctness of the response to the question concerning the ownership of the pointed wall. It is a Boolean data, which only have two possible values: false (0) and true (1).
3. The users' certitude is represented by number. It has three levels including 2 (totally certain)/ 1 (medium certain)/ 0 (not sure).
4. The response time for each test by second.

The number of participants by their discipline is shown in figure 5.6.

[5] https://docs.google.com/spreadsheets/d/1f2pB9LD1wG1K2JX9YVCo-iufVSN3qQE9QuwzEvYuiN8/pubhtml

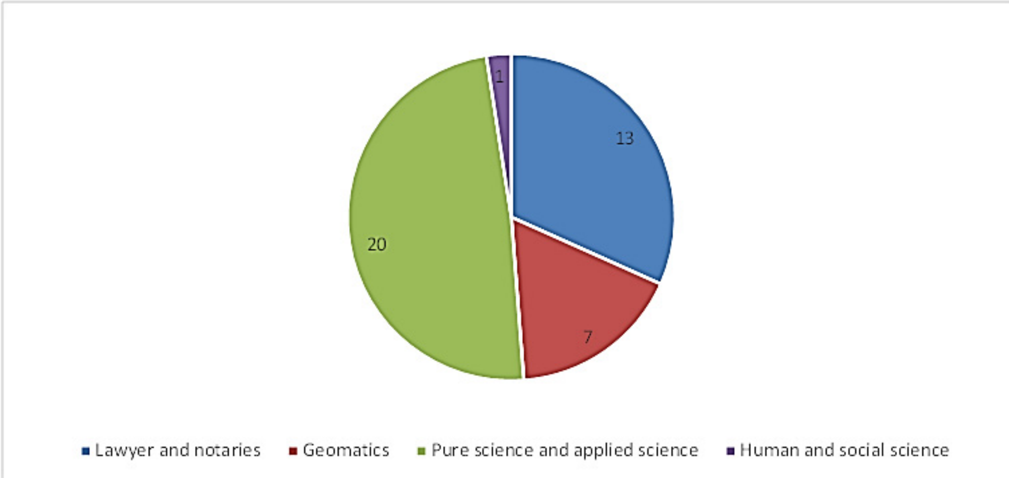


Figure 5.6. The number of participants by discipline

The data shows that for the user from different majors, their experience with cadastre varies. Figure 5.7 demonstrates that all notarial participants have dealt with cadastre data, on the other hand, some of the participants from Geomatics and Science have no experience with cadastre data.

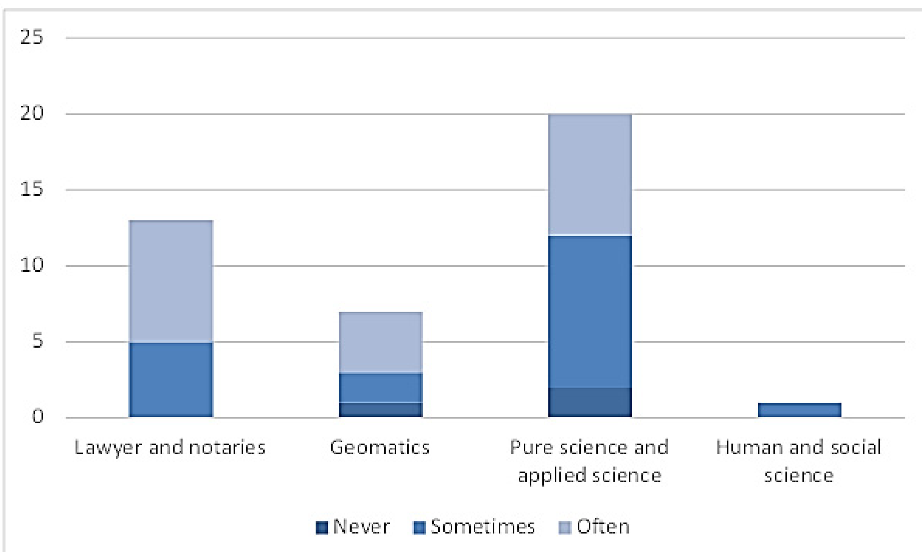


Figure 5.7. Participant's experience with cadastre data, organized by their disciplines

For participants' familiarity with 3D visualization, the data, as demonstrated in Figure 5.8, shows that most of the notarial students have never used 3D visualization.

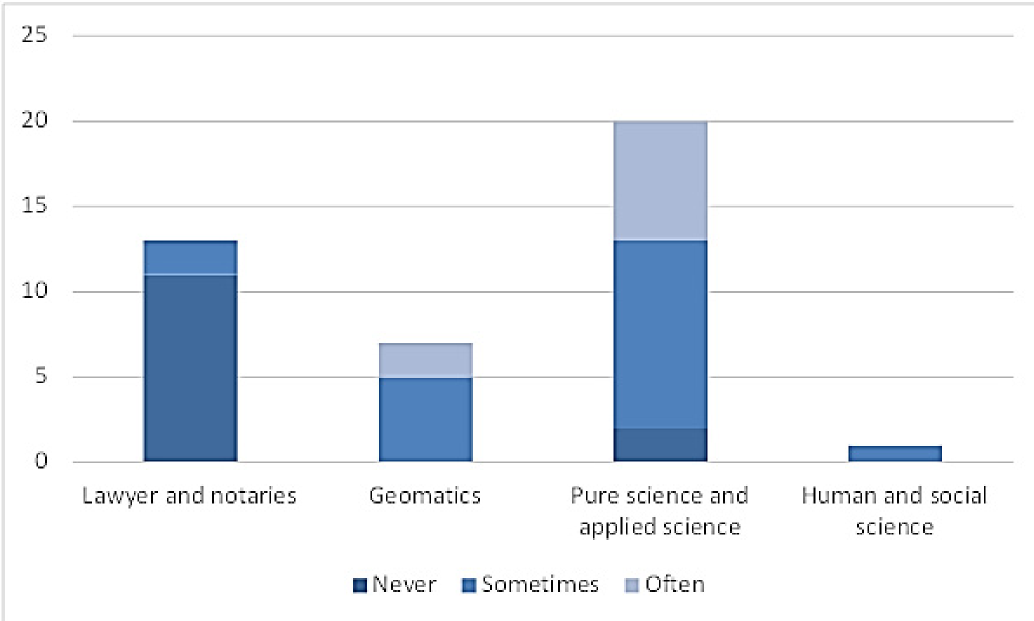


Figure 5.8. Participant's experience with 3D visualization, organized by their disciplines

For color deficiencies, only one participant has color perception deficiencies. Thus, any further analysis of its influence on user's correctness, certitude, and response time is impossible.

This section does not present the null hypothesis used for analysis. Instead, it gives statement according to the questions to give a more coherent reasoning. No statistical analysis is used to answer the general research question concerning the usefulness of transparency due to the consideration that for 3D model#1 (B/W design) the correctness is meaningless since participant's answers are largely speculative. As a result, we subjectively set a usability threshold: for effectiveness: 60% correctness, for certitude: level 1 (medium certain), and for time lapse: the respond time less than 30s. Table 5.2 shows the average correctness, certainty, and time lapse of each 3D model.

Table 5.2. Average correctness, certainty, and time elapse of the six tested 3D models

3D model	Average correctness	Average certainty	Average Time lapse (sec)
#1	55%	0.82	23
#2	63%	1.74	21
#3	67%	1.56	18
#4	60%	1.34	23
#5	65%	1.60	23
#6	63%	1.58	20

Table 5.2 demonstrates that the effectiveness and certitude of B/W model have not reach the threshold we set. With detailed data analysis, I discover that for 3D model#1 B/W, only 13.4% users have full confidence for their answer (see the original data[6]). On the other hand, with the 3D model containing three transparency levels, 61.5% users have full confidence. As the average user confidence is lower than half confidence when using non-transparency solution, it is reasonable to predict the answer is just a "guess". As a result, we concluded that 3D model#1 B/W design could not depict this situation properly. For other 3D models with three levels of transparency, the average correctness is higher than 60%, the certainty is higher than level 1 and their average responds time is 22 seconds. Therefore, the answer to the general research question is that using three levels of transparency to represent three types of boundaries is usable to help viewer demarcate the property units with its physical counterparts.

By eliminating the 3D model#1 B/W, the analysis for the five sub-questions uses three different statistical methods according to the three different data (the correctness, the certitude, and the time lapse) collected. For correctness, a logistic mix regression has been implemented with the help of lme4 package in R (Bates, Maechler, Bolker, & Walker, 2013; Hothorn, Bretz, & Westfall, 2008). For the certitude, with the help of Proc GLIMMIX of SAS[7], generalized logit link with mixed effects model has been used as we consider that the certitude data will not fulfill proportional odds assumption(Hosmer & Lemeshow, 2000; Wulff, 2007). Considering the relative small sample size, the analysis uses Laplace approximation. By log transformation, the result of response time follows normal distribution as shown in Figure 5.9. Linear mixed model has been used to analyze the result with package nlme in R (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2007). Figure 5.10 shows that there are no residual patterns. Thus the test premise of equal error variance is not violated. The original analysis results are placed in Appendix 5, 6, and 7.

[6] https://docs.google.com/spreadsheets/d/1f2pB9LD1wG1K2JX9YVCo-iufVSN3qQE9QuwzEvYuiN8/pubhtml
[7] For detailed information, see SAS/STAT® 9.2 User's Guide, available online at the address of "http://support.sas.com/documentation/cdl/en/statugglmmix/61788/PDF/default/statugglmmix.pdf"

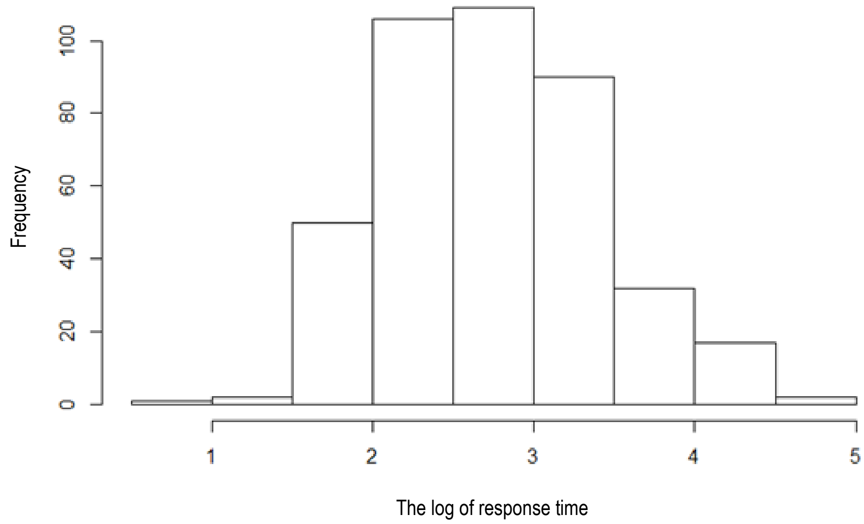


Figure 5.9. Histogram of log of the participants' response time, showing a normal distribution pattern

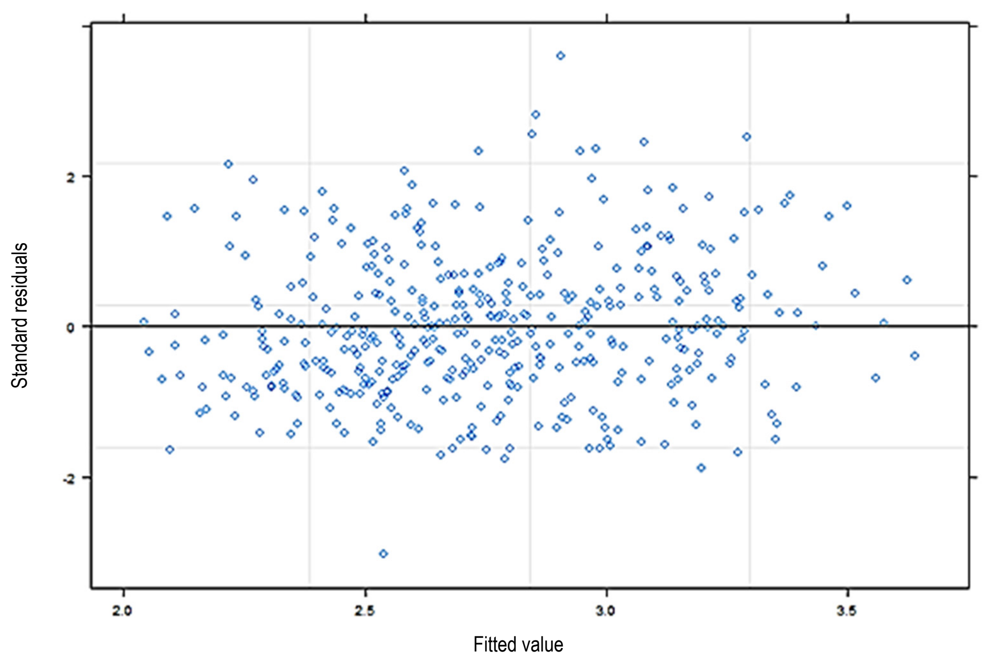


Figure 5.10. Plot of standard residuals versus fitted values, no pattern spotted

Participant's major is not regarded as a fixed effect, because the categories may contain heterogeneous sub-disciplines among which the participants' background knowledge greatly differs. For example, for the participants from Geomatics, they could be surveyor students who have plenty cadastre related knowledge, but they could also be students studying sensor network, a domain with few cadastre knowledge. The critical explanatory factors, as evaluated here, should be their experience with cadastre and experience with 3D visualization.

- **Question 1:** Is using higher transparency on the simple physical boundary than the physical & legal boundary usable (effectiveness, efficiency, and certitude) to give the unity impression of property unit it separated in a 3D cadastre model?

  The result shows that applying a physical boundary with more transparent than other physical boundaries will improve the probability for users to respond that the part belongs to them with significance (p-value: $2.36*10^{-11}<0.05$). The overall correctness is 68% (higher than 50%). The certitude level is 1,534 (2 for totally certain, 1 for medium certain). The average time spent for answering is 20.75 seconds (less than 30s). Thus, higher transparency on simple physical boundary than legal & physical boundary is effective to give viewers the impression of ownership. In addition, it is efficient and has high answering certitude.

- **Question 2:** Does 3D cadastre model with different settings of transparency affect the usability (correctness, certitude, and response time) to delimitating property units and their physical counterpart?

  For correctness, no significance has been spotted. For certitude, the result shows that the visual design of 3D visualization has significant influence on certitude (F=5.52, numDF=4, denDF=317, p-value<0.0001). Taking 3D model #6 as the comparison basis, model #2 could reduce the possibility for user to answer medium certitude compared with full certitude (Estimate= -2.56, Standard Error=0.5923, degree of freedom=317, p-value<0.0001). Model #4 could improve the possibility for user to answer medium certitude compared with full certitude (Estimate=1.1741, Standard Error=0.4942, degree of freedom=317, p-value=0.0181<0.05). Model #5 could reduce the possibility for user to answer medium certitude compared with full certitude (Estimate=-1.3376, Standard Error=0.533, degree of freedom=317, t=0.0125<0.05). Thus, the result is that the transparency settings of model #2 and model #5 could improve user's response certitude compared with the settings of model #6. In addition, the transparency settings of model #4 could reduce the user's response certitude compared with the settings of model #6. For response time, a one-factor ANOVA (Slinker & Glantz, 2008) of the linear mixed model failed to reject the null hypothesis, as no significance of the fixed effect factors has been detected. In sum, the different transparency settings will only change user's certitude, as the designs use transparency settings of model #2 and model #5 improve user's response certitude compared with the transparency settings of model #6, and the transparency settings of model #4 reduces user's response certitude.

- **Question 3:** Which one between the simple legal boundary and simple physical boundary uses a higher transparency influence the usability of 3D model?

  Contrast test between different groups of 3D models has been carried out. The result shows that the strategy using higher transparency for the simple legal boundary could decrease the response time, compared with the other strategy (estimate=0.11, p-value=0.04). No significance has been found for correctness and certitude. In sum, the answer to question 3 is that the settings that use higher transparency for the simple legal boundary than the simple physical boundary can improve the efficiency of user to delimitating the property units and their physical counterpart.

- **Question 4:** Do the settings that use very low transparency for the legal & physical boundary and the settings use no transparent for the legal & physical boundary change the usability of 3D model?

  Design strategy that uses non-transparent for the legal & physical boundary has more users that response at certitude level of very certitude (64.9% compared with 42.7%). Contrast test shows significant effect of the design strategy on user's certitude between half certain and very certain (F=26.67, numDF=2, denDF=317 p-value<0.0001). Also, the estimated effect is that with non-transparent legal & physical boundary, the possibility of very certain will increase (Estimate=2.26, degree of freedom=317, p-value<0.0001). In conclusion, the settings that use no transparency for the legal & physical boundary will increase the certitude of user to delimitating property units and their physical counterparts.

- **Question 5:** Does user's attributes (the disciplines, experience of cadastre, experience of 3D, color perception impairs) influence their effectiveness, efficient, and preference with a 3D model?

  The experience of cadastre has no significant effect on the correctness, certitude, and response time; and the user's experience of 3D visualization has no significant effect on the correctness and response time of participant. When the user's experience of 3D visualization is at the level that they never use 3D visualization, it will significantly increase the possibility of participants' certitude to be half certain from full certain, compared with the user's experience level that they use 3D visualization often (Estimate=3.09, Standard Error=1.17, numDF=2, denDF=317, p-value=0.0087<0.05). In conclusion, inexperience with 3D visualization will reduce users' certitude.

In sum, the online questionnaire successfully proved that the visual design that uses three transparency levels to represent three different boundary types in 3D visualization of condominium property units is usable for viewers to unambiguously demarcate legal and physical objects. The other conclusions include:

- Using more transparent than the legal & physical boundary on physical part's surface is performing to give the unity impression of property unit that this surface does not separate property unit.
- Different settings of transparency will influence user's response certitude.
- Design strategy that uses the highest transparency for the simple legal boundary improves the efficiency.
- Design strategy that use non-transparency for the legal and physical boundary improves the user's certitudes.
- The lack of experience in 3D visualization could reduce the user's certitude for answering visual task related query.
- No influence of user's experience of cadaste on their correctness, certitude, and response time has been spotted.

5.5 Limits and discussion

The first limit of this test is that the transparency settings are based on alpha value rather than perceptual transparency since no quantitative perceptual transparency model is available currently. Alpha value is defined from an aspect of the physical graphic attribute rather than the perceptual stimuli. Although alpha value, as the physical opacity of the feature, maybe a fundamental factor in perceptual transparency (Chan, Wu, Mak, Chen, & Qu, 2009), there are many other factors influence the viewer's judgement of perceptual transparency, like color, contrast, shadow, lighting, intersection arrangement, the background, and the occlusion (Anderson, 2003; Cheung, 2011; D'Zmura et al., 1997; Singh & Anderson, 2002).

Derived from episcotister test, Metelli's theory (Metelli et al., 1985) is widely accepted as a perceptual transparent model. However, there is obvious deviation of the prediction of Metelli's theory from the real situation。 Singh and Anderson (2002) further argued that Michelson contrast instead of simple brightness in Metelli's theory is a critical image variable to initiate percepts of transparency. Metelli's theory only concerns luminance. Jennings and Miller (1990) proposed a model that uses iso-luminance color difference to produce a feeling of transparency. These theories do not require an alpha value for a transparency perception. For example in Metelli's famous demonstration of perceptual transparency, as shown in figure 5.11, the luminance difference among the four patches undoubtedly create a perception of transparency even there is no real translucency in the two surfaces, and the perceptual transaprency, according to Metelli's theory, is (p-q)/(a-b).

In 3D visualization condition, Motoyoshi (2010), with empirical tests, proved that spatial and contrast relationship between specular highlights and non-specular shading patterns are important transparent clues in 3D visualization. He also suggested that the perceptual transparency could be divided into two independent attributes, namely, the translucency that due to sub-surface scattering and that due to the light transmittance. Chan et al. (2009) devised an automatically transparency optimization based on both Metelli (Metelli et al., 1985) and Anderson's (Anderson, Singh, & Meng, 2006) transmittance anchoring principle for improving perceptual quality of direct volume rendered images. However, to our knowledge, there is no quantitative formula to link all the perceptual cues with perceptual transparency in 3D visualization currently.

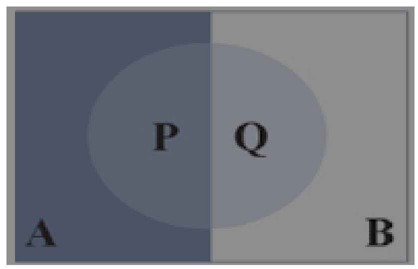


Figure 5.11. Example of bipartite background with transparent foreground coded as ABPQ regions

Transparency may also affect viewer's perception of other visual variables like color, brightness, shape and pattern (Fleming, Jakel, & Maloney, 2011; Jobst et al., 2008). However, it is yet to be examined in the tests for 3D visualization of condominium property units. Current research in perceptual science and information visualization contribute fruitful results. For example, the empirical test with notaries in a face-to-face interview showed the transparency may affect the usability of color. D'Zmura, Rinner, & Gegenfurtner (2000) also discussed the transparency's influence on color perception. Fleming et al. (2011)'s empirical test showed that the presence of transparency objects distorts the shape perception of other objects in a same scene. Jobst et al. (2008) argued that transparency will influence color, brightness and pattern perception. Current research only provides a qualitative explanation about which visual variable the transparency may influence, yet no quantitative interpretation is available. As a result, designers experience may still be critical to objectively alter all visual variables' value in order to achieve an appropriate outcome with the usage of transparency, and extra empirical tests are needed to verify the usability of the final result.

Another limit of current tests with transparency is that only simple cadastre scenario has been chosen for tests in this questionnaire concerning the limited cadastre experience of potential participants. The result with simple test case proved that the five 3D models tested are all effective. However, effectiveness difference has not yet been spotted among different transparency settings. 3D models with more complex overlapping property units should be tested in future. This is not only because supporting viewer's decision making in complex overlapping property units is one of the main reasons why 3D visualization is introduced to cadastre, but also testing with more complex case may have the potential to unveil the effectiveness difference between different transparent settings.

About the interpretation of the result, that using three transparency levels to encode boundary types is usable does not prove that it is the best visualization solution for the visual task of delimitating property units and physical counterparts. Based on the conclusions of previous empirical test with notaries, other visual variables, such as texture, saturation and hue may also be potentially applicable. Empirical tests enrich the knowledge about transparency as a visual variable in 3D model of condominium property units, whereas, a specific design choice is largely ad-hoc, as many other factors, such as building geometries, other visual requirements, and the environment settings should be well considered by designers.

Finally, the way selecting questionnaire participants is a convenience sampling. We invited those potentially available in our networks. It is a non-probabilistic sampling; thus the statistic result may only be valide to the participant group. Non-probabilistic sampling is an acceptable and commonly used sampling method in human computer interaction research, since in most research situation, researcher may not have the resource to carry out a survey of all the potential user. We estimate that the generalization of our result to the young user is appropriate, since most of the participants are student, and we have already considered two possible influential factors: their experience with 3D and with cadastre. However, the reader should be well aware of the subjectivity in the generalization from the participants to the population.

5.6 Summary

Aiming the second research objective of this dissertation, this chapter describes an online questionnaire about the usability of transparency for viewers to demarcate condominium property units with their physical counterparts. Six transparency settings have been tested, participants are allowed to freely navigate in 3D models, and 41 participants are reached. The visual task requires user not only to distinguish legal and physical object but also to unambiguously recognize their limits. The test results prove that using three levels of transparency to represent three different boundary types is usable to support the viewer in demarcating the property units in condominiums with their physical counterparts and that different transparency settings only affect the viewer’s certitude. For transparency setting strategy, using the highest transparency for simple legal boundary improves the efficiency, and using no transparency for the legal & physical boundary increases the viewer's certitude. User's profile also influences the visualization’s usability, as the test results showes that lacking 3D visualization experience may affect viewer's response certitude.

The profile of notarial students collected in this online questionnaire shows most of them did not have any experience with 3D visualization. This result is in accordance with the previous empirical study with notaries, as they have little experience neither. In current tests, which are based on a simplified case study, their inexperience only affects the answering certitude. However, the potential risk should be fully aware by visualization designers when using 3D visualization with notarial users to support their decision making in overlapping situation of condominium, and the user-centered design process may still be necessary to guarantee the usability of the final 3D visualization system of cadastre.

The test of the suitability of visual variables in the 3D visualization of condominium property units is a recursive process. The preliminary test and face-to-face interview in Chapter 4 are the first two attempts, and the online questionnaire of transparency described in this chapter is the third investigation.

Chapter 6 Conclusion and Further Research

6.1 Report on research objectives

The progress made through this research project was following three main objectives. For the first research objective (**evaluate the suitability of visual variables for delimitation of overlapping property units in condominiums in the context of 3D visualization)**, we carried out a preliminary evaluation and an empirical test in a form of face-to-face interview. The preliminary evaluation is an expert-group assessment of the feasibility of seven Bertin's visual variables (position, orientation, size, shape, value, color, and texture) and two enhancement techniques (labeling and visual highlighting). Then, the empirical test is in a form of face-to-face interview with notaries about the suitability of eight visual variables (as size, shape, brightness, saturation, hue, orientation, texture, and transparency) and three enhancement techniques (as labeling, object detaching and highlighting). Based on these experiments, the main conclusions are as follows:

- **Size**: a change in size of boundary (width) is feasible and unambiguous to descriminate two categories of objects. However, for 3D visualization of condominium property units, a 3D model should keep the surface size of the defined boundaries of property units untouched to maintain the original geometry information.

- **Shape**: for 3D visualization of condominium property units, a 3D model should keep the shape of the defined surface boundaries of property units untouched in order to maintain the original geometry information. Instead, shape as an extra symbol on a surface is promising to aid viewer distinguish different categories of property units. However, it has limits. Shape could not be used on the small surface as the shape of a small symbol is hard to be precisely perceived. Moreover, if used extensively in a 3D model, it could be a distraction for the viewer.

- **Brightness**: Brightness is not a promising choice to encode data in 3D visualisation. In the second test, It is marginal effective and not preferable. Multiple environment settings in 3D visualization, such as lighting, shading, atmosphere effect, surface texture, and transparency, may affect the perception of brightness. Visualization designer of 3D visualization of cadastre should prevent using brightness in their semiotics of graphics.

- **Saturation**: Saturation is capable to represent different categories in 3D visualization.

- **Hue**: Hue is capable to represent different categories in 3D visualization. However, too much color hues may be distracting for the viewer.

- **Orientation**: The orientation visual variable is no longer effective in 3D visualization. The perspective view in 3D visualization will make the perception of orientation ambiguous, as it is hard to determine whether the perceived orientation differences means different orientation direction in 3D model or just an illusion created by perspective view. Designers of 3D visualization of cadastre should prevent using orientation to encode underly data.

- **Texture**: Texture is capable to represent different categories in 3D visualization. One participant mentioned that the textures that are similar to the physical objects' surface in the real world may have the potential to give viewer a feeling of physical objects intuitively. Thus, we estimate they could be used to help viewer discriminate the physical objects from legal objects, yet more tests are needed.

- **Labeling**: The labels should be placed inside or as close as possible to the symbol that it describes. Using a line to connect labeling with its symbol is sometimes not effective and preferable.

- **Visual highlighting**: The visual highlighting of spatial relationship in the 3D visualization of cadastre should highlight the relationship in all three dimensions rather than project and visualize it on a 2D surface.

- **Occlusion management of object detaching**: Detaching different floors in the 3D visualization of cadastre is effective and preferable. Nonetheless, it affects the perception of the parts that are displaced further from the central part.

For the second research objective (**evaluate the suitability of transparency for delimitation of property units and their physical counterpart in 3D visualization)**, a second empirical test is carried out. The second empirical test is an online questionnaire about the usability of transparency for viewers to demarcate condominium property units with their physical counterparts. Different transparency settings are tested, and the influence of viewer's experience of cadaster and 3D visualization are investigated as well. The conclusions of the suitability of **transparency** are:

- Transparency is effective to represent two categories of the objects in 3D visualization yet affects the perception of property units' boundary. Using three levels of transparency to represent three types of boundaries (simple legal, simple physical, and legal&physical) has good usability for the users to demarcate the legal and physical boundaries unambiguously.

- Transparency settings also affects the usability. In the current tests, using the highest transparency for simple legal boundary improves the efficiency, and using no transparency for the legal & physical boundary increases the viewer's certitude. No effective difference is spotted in current tests, but as argued in Chapter 4, this may due to that the tested scenario is too simple.

- Current test show conflicting results of transparency's usability as an occlusion management technique. It is usable in a few 3D models. On the other hand in some of the tests, transparency affects the reading of other visual variables, like color. In addition, it affects user's identification of the volumetric symbols and their exact boundaries in some 3D models. Further research is needed.

For designers of 3D visualization of cadastre, using transparency has special value as it is effective for specific visual tasks, like demarcating property units and their physical counterparts, and it could be occlusion solving at the same time. However, specific attention should be paid to its interaction with other visual variables. Moreover, a careful transparency value turning up and usability tests may be preferable to guarante a usable result.

For the third objective, which is **to compare the perceptual properties of visual variables exhibited in 3D visualization of condominium property units with those in 2D visualization,** this thesis compares the visual variables' perceptual properties showed in the preliminary evaluation and two empirical test in 3D visualization with the conclusions for 2D visualization derived from literature review. The comparison used the results of the preliminary evaluation and the face-to-face interview with notaries to synthesize perceptual properties in 3D by allocating tested visual tasks and visualization requirements to the perceptual properties in six different criteria. This thesis then lines up the perceptual properties in 3D with that in 2D conclusions from six different frameworks. The detailed differences, presented in Chapter 4, are fragmentized due to the heterogeneity of the six theories. The main differences based on the previous comparison are as follows:

- 3D visualization affects the suitability of **brightness**. For example, in Bertin's evaluation, brightness is dissociative and selective, however, in 3D visualization, it is marginal dissociative and selective.

- **Orientation** in 2D visualization is associative and selective accroding to Carpendale's evaluation. However, in 3D viusalization, orientation is obviously neither associative nor selective.

- **Transparency** is associative and marginal selective. Transparency is a novelty in 3D visualization since no 2D study previously reviewed concerns the suitability and perceptual properties of transparency.

Besides the research objectives, I have reviewed some background information potentially useful for the practice of 3D cadastre visualization. The background information could be divided into two groups. The first is about general 3D geo-visualization knowledge. Based on a pipeline model, I explained the design space including graphic semiotics, visual variable, and the environment settings in 3D geo-visualization. In addition, the challenges and current solutions are listed. The second group of background information is the cadastre domain knowledge. It includes the cadastre data involved in the overlapping situation for visualization. It also includes the potential user, the possible usages, and a review of current representation designs. The background knowledge could help designers better understand the target user, the cadastre domain data, and possible design choice. Thus it may support the 3D cadastre visualization practices.

In sum, the work of this thesis has achieved all the three research objectives. It gives contribution towards the general research subject of improving the design of the 3D cadastre model. The result acquired in the research could support 3D cadastre visualization practice. However, to provide suitable graphic design based on these knowledge is still a challenge, since necessary domain knowledge and design experience are also critical.

6.2 Research significance

The contributions of this work could be summarized from practical, methodological, and theoretical aspects.

1. Contributions regarding practical aspect

The ultimate purpose of this research is to support the practice of cadastre related 3D visualization. The results of this thesis may be directly used by practitioners interested to better applied visual variables and enhancement techniques in 3D context. Other outcomes, including the first-hand information about the user's attributes and the design space, could help practitioner comprehend the targeted user and the possible design choices. By introducing cadastre user in the test, this research process may also promote the user's direct participation in the future research and the implementation of 3D cadastre visualization.

2. Contributions regarding methodological aspects

The empirical research process used in this thesis maybe anticipated as a valuable methodological attempt. According to our knowledge, little empirical research has been implemented concerning 3D visualization of cadastre and suitability of visual variables in 3D. The methodology innovation, as we use empirical test to evaluate design elements in a specific 3D geo-visualization application domain, shows promising result. In future, the knowledge of 3D geo-visualization may be acquired not only through expert analysis and reasoning, but also by empirical evidence in the test with end users. The design, implementation, and data analysis of previous test provide valuable knowledge and experience for future works, both in cadastre visualization and other application domain.

3. Contributions regarding theoretical aspect

The literature shows that there are various theories of 3D geo-visualization. The comprehensive 3D design space devised by this thesis to organize the visual variables and graphic semiotics may be assumed as a theoretical contribution to 3D geo-visualization research. It could also be used as a theoretical reference for other 3D geo-visualization investigation in future. Meanwhile, the test and the result analysis extend current understanding of semiotics of graphics from 2D to 3D and unveil the disparities and deficiencies of current visual variable based visualization theories.

6.3 Discussions

Current research could be discussed from three possible limits. The test limits are stemmed from the test settings; the methodology limits are stemmed from hypothetico-deductive methods, and the theory limits are due to the deficiencies of the current visualization theories adopted in this thesis.

First, the preliminary evaluation and the face-to-face interview with notaries have not fully considered the usability impact of different visual variable settings and environment settings of the 3D model. In current tests, visual variable value settings and environment settings in a 3D model are largely subjective with careful tune-up to eliminate infeasible result. Second, the face-to-face interview uses video to represent 3D model instead of freely interactive navigation in 3D model. Using video is based on a premise that such method does not greatly change the effectiveness, efficiency, and preference of visual variables in 3D model compared with a free navigation scenario. However, such premise has never been empirically tested. Third, only four notaries have participated in the face-to-face interview, too few to carry out a statistical result analysis. Fourth, for the third test of an online questionnaire, only a simple cadastre scenario has been tested. It may be a reason that no effectiveness difference is spotted between different transparency settings since the scenario may be too "easy" for the testers.

The general methodology of this research is the hypothetico-deductive scientific approach. The hypothesis in a hypothetico-deductive method could only be rejected or supported, but shall never be proved. As a result, the tests in this research formulate the hypotheses in a negative way to reject it by empirical evidence. For example, a hypothesis could be stated as the visual variable color that is not effective for distinguishing the private and common property units. The test result rejects this hypothesis and conclude that color is effective for distinguishing the private and common property units with one empirical clue. On the other hand, the empirical evidence may only support the hypothesis rather than prove it. Even there are plenty ineffective examples of color for distinguishing the private and common property units; it may still be effective and preferable in certain circumstances with specific value settings or environment settings. The way to formulate the hypothesis enables the formation of a positive result; however, it introduces bias: since it is also possible that an unsuitable visual variable may in chance compose a usable 3D model. Further test may be helpful to reduce the bias.

Usability has been exploited as the evaluation criterion in the second and the third test of this thesis. However, it is only one of the visualization evaluation criteria. Van Velsen, Van Der Geest, Klaassen, and Steehouder (2008) identified 44 empirical evaluation criteria. Among them, usefulness is sometimes mentioned separately or together with usability as an evaluation criterion to describe whether the adaptation of new visual design is valuable compared with existing visualization design or solutions (Bleisch, 2012; Greenberg & Buxton, 2008). It is termed "perceived usefulness" in a technology acceptance model (Davis, 1989), as the evaluation are often based on user's subjective opinions. Based on Van Velsen et al. (2008)'s classification, usefulness concerns the degree of system's adoption by the user while usability evaluates the user's actual usage of the design. Usefulness evaluation is beyond the visualization design and technical implementation and may be influenced by other social factors, such as budget, training time, and regulations. A good usability may not guarantee that a design could be well adapted by user, since there are possibilities of a visualization tool that has good usability yet is totally useless in real life (Greenberg & Buxton, 2008). Similarly, a useful visualization does not mean that it has good usability for all kind of end user. An example is the operation system Linux. It may not have a user-friendly graphical interface (in the original format) as Windows for the general public, but it has been widely adopted by professional users like system developers, especially in the web server domain. There is no usefulness evaluation of 3D visualization of cadastre currently. During the face-to-face interviews, the notaries still concerned the real value-added to use 3D visualization for their cadastre related tasks in condominiums. One participant even expressed his preference towards 2D solutions, as he is more familiar with 2D and "it is clear".

Empirical tests with intended users about the suitability of visual variables contribute valuable knowledge for 3D visualization researchers and designers of condominium overlapping property units. Nonetheless, it is still trivial to synthesize the knowledge acquired from empirical test with those from literature to a more general conclusion in order to support visualization designers' decision making. This is mainly due to the deficiencies of current visual variable based visualization theories, which have been spotted in the previous literature review as well as in the process of empirical tests of this work. First and foremost, despite some efforts have been made to extend them into 3D recent years (Häberling, Bär, & Hurni, 2008; Halik, 2012), most of the current frameworks are based on 2D visualization. Secondly, each visual variable based theories uses similar but not identical framework. Their lists of visual variables, their perceptual properties of visual variables, and their exact definition of terminologies differ. The disparities among these visual variable based theories make knowledge comparison and synthesis burdensome as can be seen previously in the comparison of perceptual property between 2D and 3D in this work.

Furthermore, current visual variable based visualization theories fail to integrate those empirically derived visual variables' knowledge from a wide spectrum of research topics. Visualization design process, as a creative activities, may always require comprehensive visualization knowledge in addition to domain-specific experience and is the intervenes of art, technologies, and cognitive science (Green, 1998; Ware, 2012). Bertin's original definition is from the point of view of a cartographer in the late 1970s without robust empirical tests. The technical advancement and research in cartography, information visualization, and cognitive science since then provide a lot of materials and may lead to a deeper understanding of visual variables. However, except Green (1998) and Jobst et al. (2008), few efforts have been made to extend current theories to accommodate the latest visualization research and knowledge from other domains. Green (1998) reviewed the perceptional issues in Bertin's theory, as the theory failed to recognize the interaction between visual variables and the disparity between physical value and perceptual stimuli. He then advocated links between Bertin's visual variable theory with those results in the domain of psychophysics, yet, he failed to point out how such links could be systematically described, as "perception is highly complex process". To establish the link, Jobst, Kyprianidis, and Döllner (2008) proposed a semiotics structure of 3D visualization of city model. Their framework, though is still very simple and elementary, contains not only visual variables but also their composition, interplay, corresponding perceptual vision variables, and psychophysical influence.

Finally, current visual variable based theories, which are normally stated in natural languages, are not a formal way of knowledge description with sufficient expressiveness, as it lacks clear structure, grammar, and restrictions. Informal expressions limit the visualization knowledge's comparison, reuse and computational reasoning (Métral, Ghoula, Silva, & Falquet, 2014; Voigt & Polowinski, 2011). Such knowledge is normally fragmentized in various documents, phrases, research findings, and prototypes (Foley, 2004), thus synthesizing them to meet specific requirement requires considerable efforts. Furthermore, Métral, Ghoula, and Falquet (2012) claimed that the pertinent visualization knowledge, which sometimes heterogeneous, may be too rich for a single designer to be fully aware of. A computerized knowledge management system, or expert system, may be helpful for researchers' research and designers' decision making. A formal schema that is capable to describe all the pertinent contents from various sources is the center of such system, as demonstrated in the research of Brandt et al (2008) for engineering process and Rhodes, Kraemer, and Reed (2006) for software visualization system, yet, currently it is still unavailable for visual variable based research.

6.4 Future research

6.4.1 Towards a 3D geo-visualization ontology

Addressing the deficiencies of current visualization theories, ontologies may have the potential to enable the construction of a formal knowledge framework for 3D geo-visualization that could be understand by both human and machine (Brodlie & Noor, 2007; Duke, Brodlie, & Duce, 2004; Duke, Brodlie, Duce, & Herman, 2005; Shu, Avis, & Rana, 2008). Ontology "*are content theories about the sorts of objects, properties of objects, and relations between objects that are possible in a specified domain of knowledge*" (Chandrasekaran, 1999). As both human and machine could understand the content that is defined in ontology, a visualization ontology may have the potential to advance the communication between human with human, machine with machine and human with machine.

Most of existing work related to visualization ontology are placed in the domain of information visualization. To our knowledge, the proposition of Top Level Visualization Ontology (TLVO) in the first visualization ontology workshop in 2004(Duke et al., 2004) marked the starting of related research. Since then, many researchers have developed their own ontology based on TLVO like Shu et al. (2008); Voigt and Polowinski (2011), Gilson, Silva, Grant, and Chen (2008), and Pérez, Risquet, and Gómez (2011). Recent years, some ontology related literatures (Gould & Chaudhry, 2012; Iosifescu-Enescu & Hurni, 2007; Métral et al., 2012a; Ruzicka, Ruzickova, & Dostal, 2013; Smith, 2010) are also spotted in the domain of cartography and geo-visualization. Smith (2010) designed a cartographic ontology for an expert system to guide the production of a well-designed map. His ontology defines the basic elements of a map, like projection, graphics, visual variable, and attribute. Visual variables' attributes have not been involved in his ontology, and the links between cartographic and cognitive science have not been mentioned. Métral et al. (2012a) created the ontology of 3D visualization techniques for computational reasoning of appropriate 3D visualization techniques to support visualization designers' decision-making. The visual variable is termed visual attributes in Métral's ontology; however, Métral's ontology did not fully develop the visual variable's perceptual properties.

There are many attempts in visualization ontology construction as previously cited, yet no existing visualization ontology fully matches to describe the design of a 3D model in geo-visualization, since they could not systematically integrate symbols, visual variables, and perceptual knowledge in a 3D context. The future research may firstly assess the feasibility to use ontology to depict the 3D model from an aspect of semiotics of graphics. Then, if there is promising result, it may design and construct comprehensive 3D geo-visualization ontology. Existing visualization frameworks shed light on the synthesis of the proposed geo-visualization ontology. The research efforts in 3D symbology encoding, like that of Haist et al. (2007); Neubauer & Zipf, (2007), and Haist et al. (2007) also provide valuable information, even their structuralized frameworks are not expressed in a form of ontology. We have already started related work and get a preliminary result, as demonstrated in figure 6.1. However, developing ontology may also be a recursive process and many works are still yet to finish.

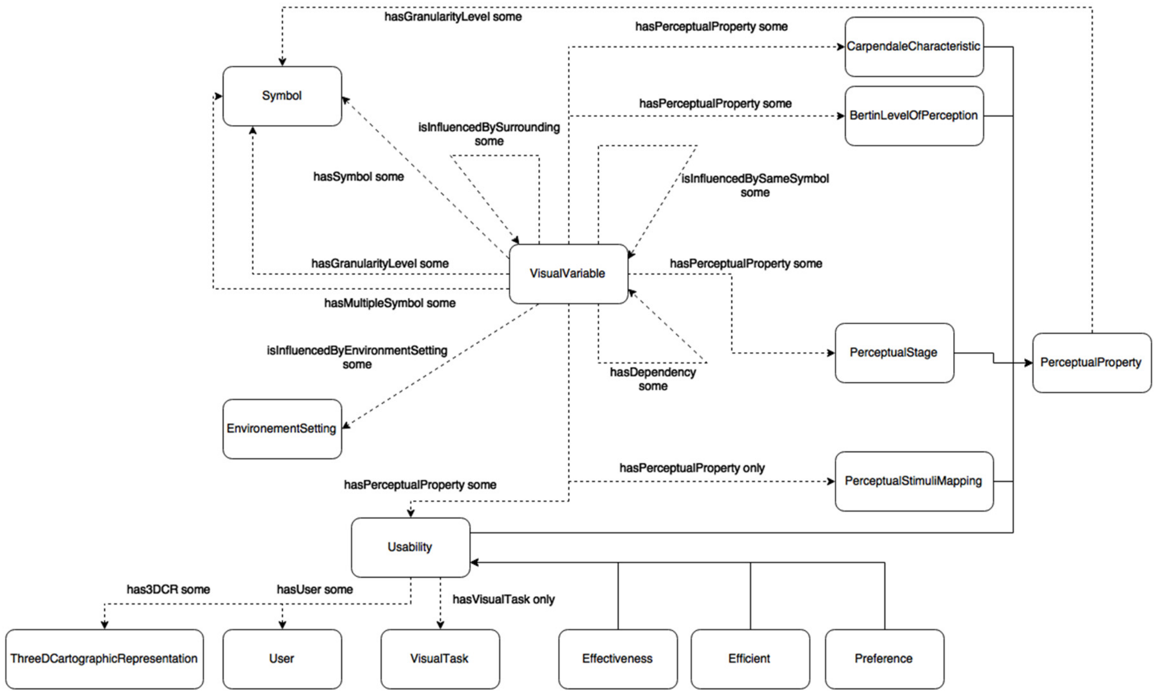


Figure 6.1. The structure of visual variable in the 3D geo-visualization ontology (sketched). The solid line represents rdfs:subClassOf, the dash line represents class property with cardinality constrains

6.4.2 Further empirical tests of visual variables in 3D geo-visualization

Online questionnaire demonstrates its capabilities to reach more participants, while at the same time, implement usability test of 3D models. Thus the future empirical tests may keep using a same testing method. However, complex situation, such as multiple floors, should in future be tested. In addition, more visual variables and visual tasks should be involved.

The future research may also test the interactions between different visual variables quantitatively. Current studies, such as those of Jobst et al. (2008) and Ware (2012) in 2D, only provide qualitative conclusions. Quantitative studies about how these visual variables interact with each other in a 3D visualization may be valuable, not only for a 3D visualization designer, but also for a potential automatic design support system if a 3D visualization ontology will be available in future. The future research should also address the environment settings' influences on visual variables quantitatively. Considering that the interactive and dynamic 3D visualization is prevailing nowadays, like those in Google Earth, investigating the human-computer-interaction actions and dynamic visualization together with visual variables may be indispensable in the future works.

The future research may be placed in cadastre domain with mainly notarial users at the beginning as an extension of current research rounds. However, in the long run, other types of users such as government officials and general public should be involved. By introducing different user groups, researchers may understand better the divergence of the user's requirements and their capability to cope with a 3D visualization medium. It also contributes to the practice of 3D cadastre visualization, since designers may need to customize the design for different user accordingly.

Finally, the research about the suitability of visual variables should in future be extended to other geo-visualization application domain. The result of each test could be largely ad-hoc as it is under a specific scenario with the intended user and their usage. However, with enough results from different domain, user, and usage, researchers could identify the common properties of a visual variable. The identified commonality is valuable since it could in turn guide the research and practice of 3D geo-visualization in a wider spectrum. However, based on the current test experience, the further investigation of the suitability of visual variables for geo-visualization could be time-consuming and may far exceed the capability of one researcher. It could be a lengthy research project with multiple researchers or even multiple research groups. Despite the length of future tests, the potential results, if structurally synthesized, as argued here, may greatly facilitate relative 3D visualization practice in cadastre or other 3D geo-visualization applications.

6.4.3 The practice of 3D visualization of cadastre

As mentioned, the ultimate purpose of this thesis is to support relative cadastre visualization practice. However, the gap between the knowledge gained in test and the visualization practice has not yet been fulfilled. How to use current knowledge of the suitability of visual variables to guide the relevant 3D cadastre visualization is a research question for future research. There are many possible solutions. First, more design principles could be devised based on the test result to educate the designers. Second, constructing automatic decision making system of visualization design may support designers' design choice. As argued before, ontology of 3D geo-visualization is the basis of this system. How to take advantage of the knowledge of the intended users and their requirements is another possible research question. Setting up principles to guide designers and constructing automatic design support system are among the possible choices. Also, giving user the right to customize the visualization to suit their own need could be another strategy but detailed usability tests are still needed.

If viewing the practice of 3D visualization of cadastre as a system implementation process, the empirical tests of visual variables' usability in this thesis are currently at an early stage. A user-centered design requires an iterative process with different phases(Wallach & Scholz, 2012). Based on the review of Mayhew (1999), Van Velsen et al (2008), and Wallach and Scholz (2012)'s discussion, generally, an iterative design process gradually increases its complexity from detailed design choice for each design dimension like color choice to comprehensive system design, and the evaluation methods in iterative design process start from interview and observation in an experimental situation with limited participants to real-life situation tests with the intended user. The future research could focus on pilot 3D visualization systems with real-life cadastre situations, and the usability should always be carefully considered and tested. Moreover, the usefulness of 3D visualization of cadastre compare with the 2D approach should be addressed with pilot systems in order to convincing the potential cadastre users of the real value gaining of 3D visualization.

3D visualization may be helpful for user to better interact with the overlapping properties in cadastre system for their decision-making goals compare with current 2D visualization. Addressing 3D visualization from the aspect of 3D model design is equally important with if not more than technical aspect. This thesis marks the beginning of the relevant research, and focus on the suitability of specific design elements (visual variables and enhancement techniques). The ultimate purpose is to get the 3D cadastre visualization “right” to facilitate cadastre related practice and contribute to the research of 3D geo-visualization, and there are still many questions yet to investigate like the interaction between different visual variables.

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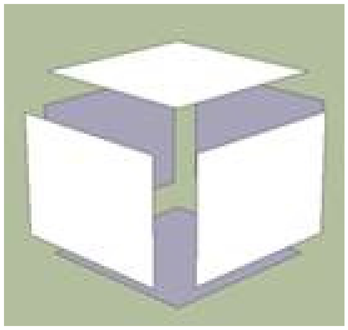
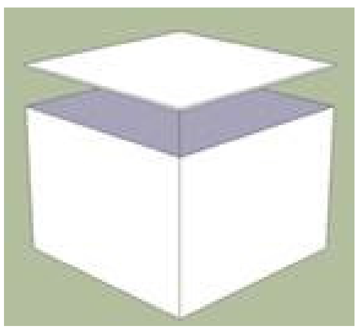
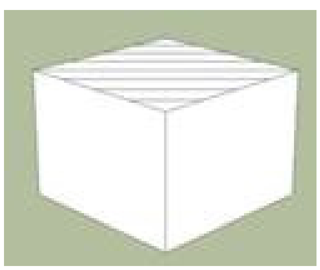
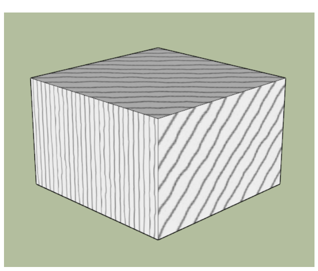
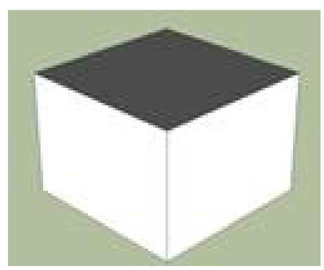
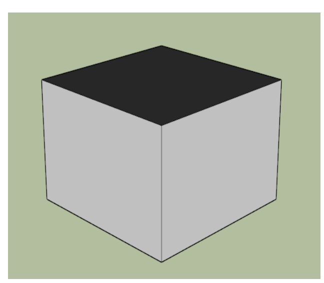
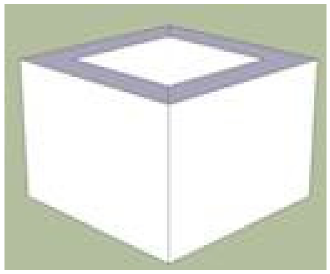
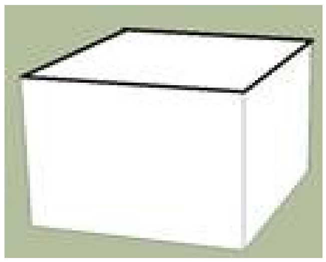
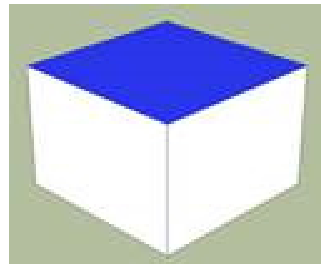
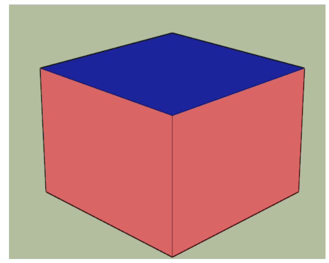
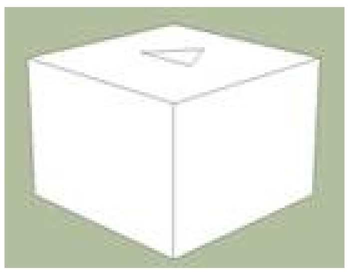
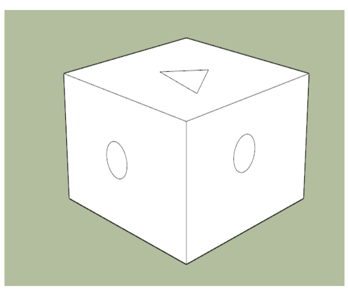
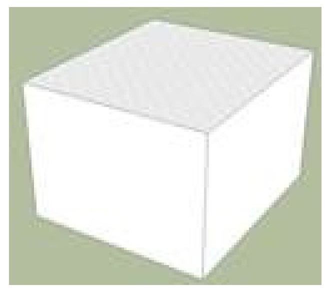
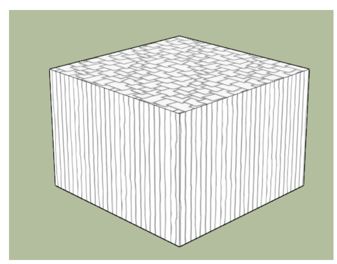
Appendix 1 Examples of the 3D models created for preliminary evaluation

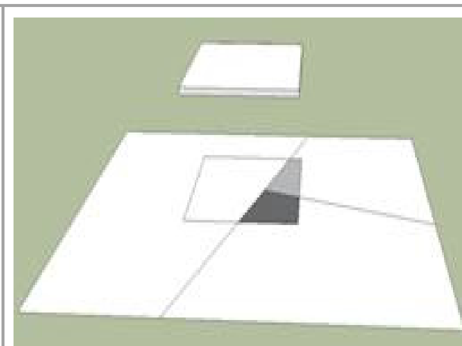
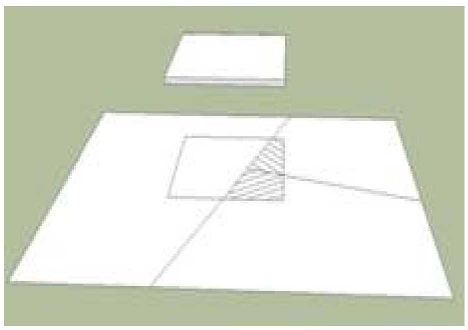
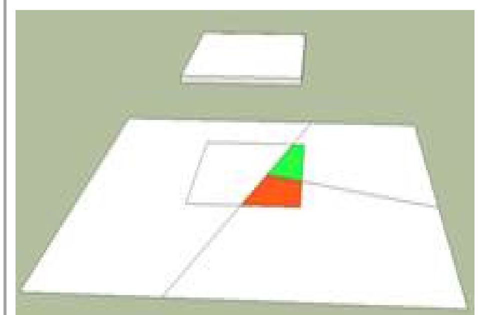
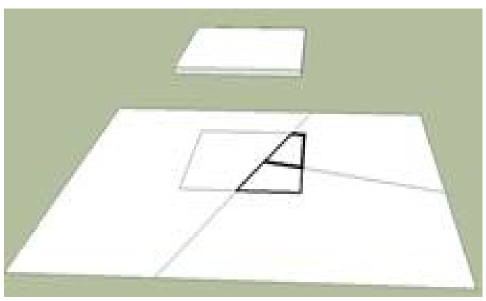
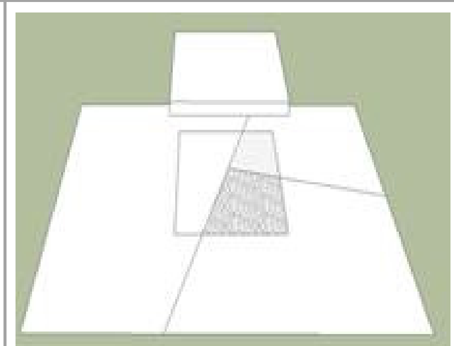
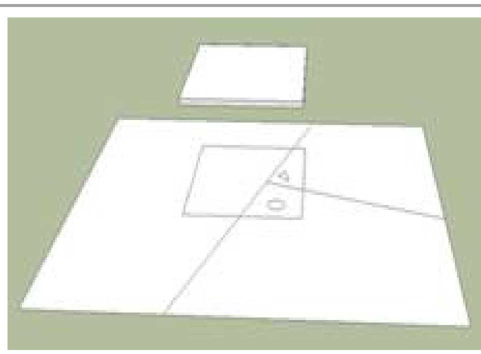
1. *Examples of test 3D models for visualization requirement 1: represent bounded and partial bounded 3D property units*

Position: Detach the unbounded surface	 		
Orientation: Change the orientation of the texture	 	Brightness: Change the brightness of the unbounded surface	 

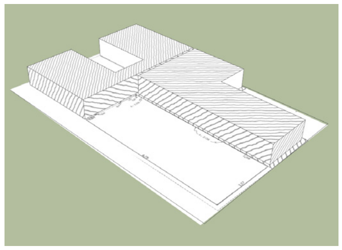
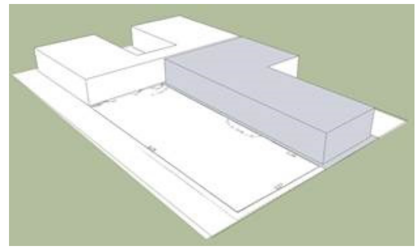
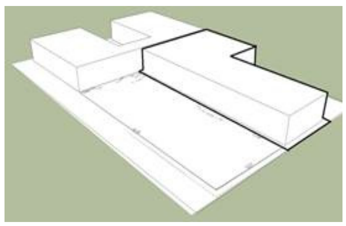
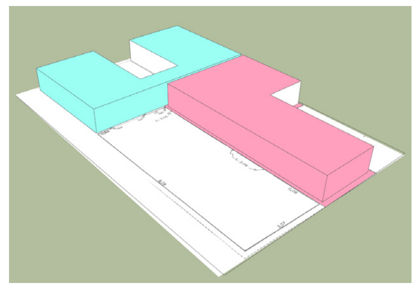
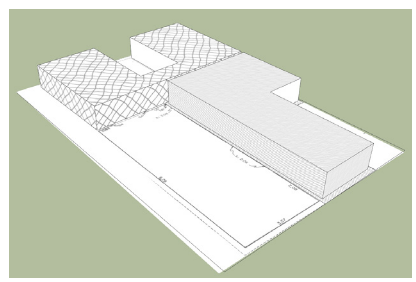
Appendix 1 Examples of the 3D models created for preliminary evaluation

Size: Change the unbounded surface’s size	 	Color: Change the unbounded surface’s color	 
Shape: Add extra shape on the unbounded surface	 	Texture: Change the texture of the unbounded surface	 

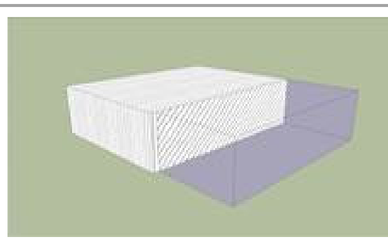
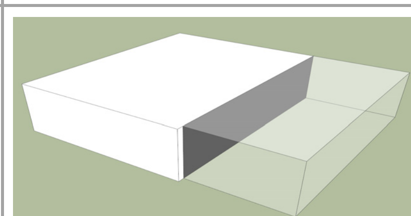
2. *Examples of test 3D models for visualization requirement 2: represent the relationship between 3D property units and 2D land parcels*

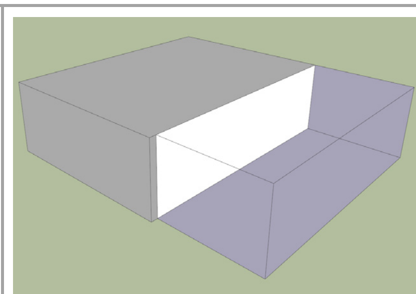
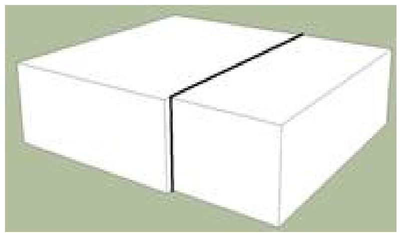
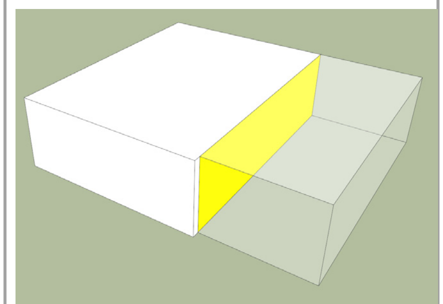
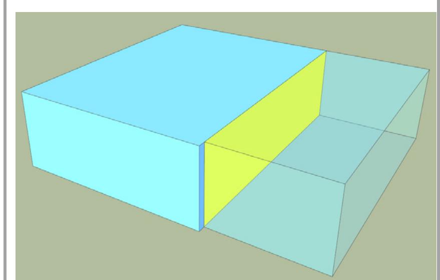
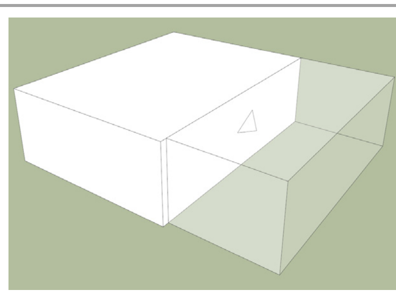
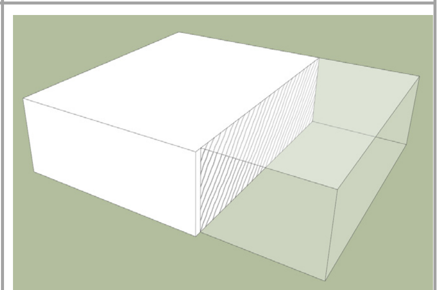
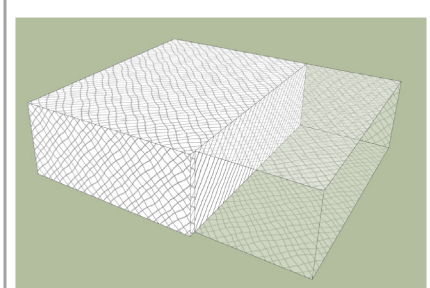
Position	Not applicable	Brightness: Use different brightness for the overlapping surfaces	
Orientation: Use different orientation for the overlapping surfaces		Color: Use different color for the overlapping surfaces	
Size: Use different size for the overlapping surfaces' boundaries		Texture: Use different texture for the overlapping surfaces	
Shape: Use different shape on the overlapping surfaces			

3. *Examples of test 3D models for visualization requirement 3: represent the spatial relationship of 3D property units with corresponding physical objects*

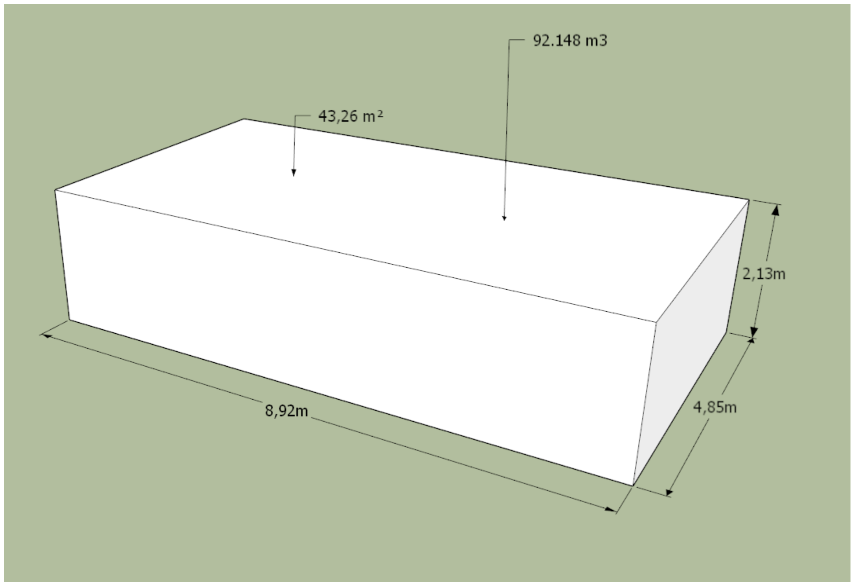
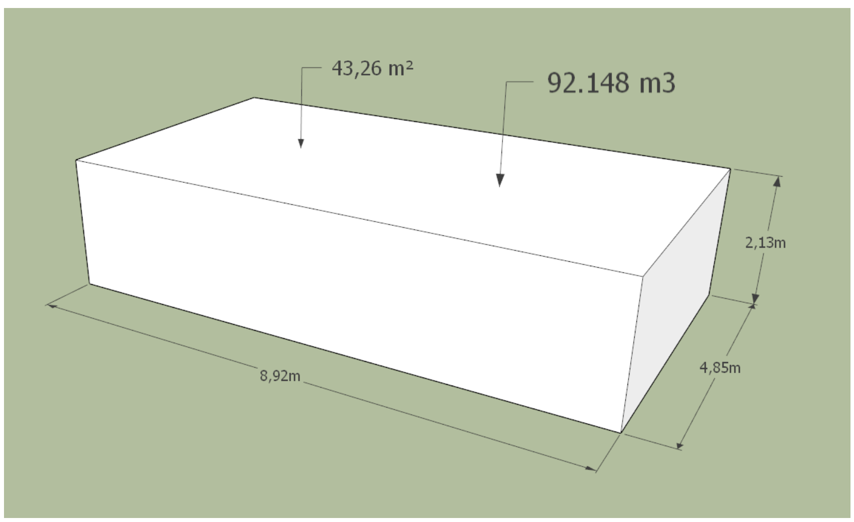
position	Not applicable		
Orientation: Use different orientation for two legal and physical object groups		Brightness: Use different brightness for two legal and physical object groups	
Size: Use different size for two legal and physical object groups		Color: Use different color for two legal and physical object groups	
shape	Not applicable	Texture: Use different texture for two legal and physical object groups	

4. *Examples of test 3D models for visualization requirement 4: represent spatial relationships (touch) among 3D property units*

position	Not applicable		
Orientation: Use different orientation for the touching surface		Brightness: Use different brightness for the touching surface	

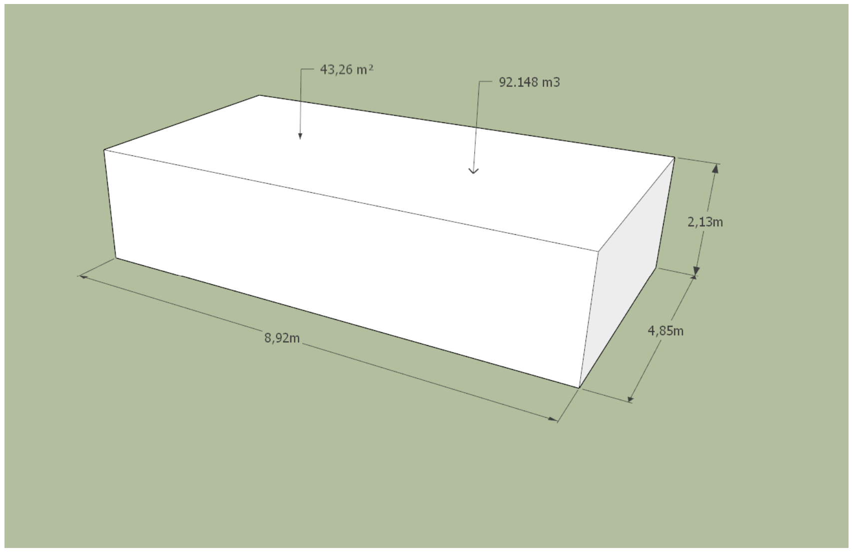
			
Size: Use different size for the touching surface		Color: Use different color for the touching surface	 
Shape: Use different shape on the touching surface		Texture: Use different texture for the touching surface	 

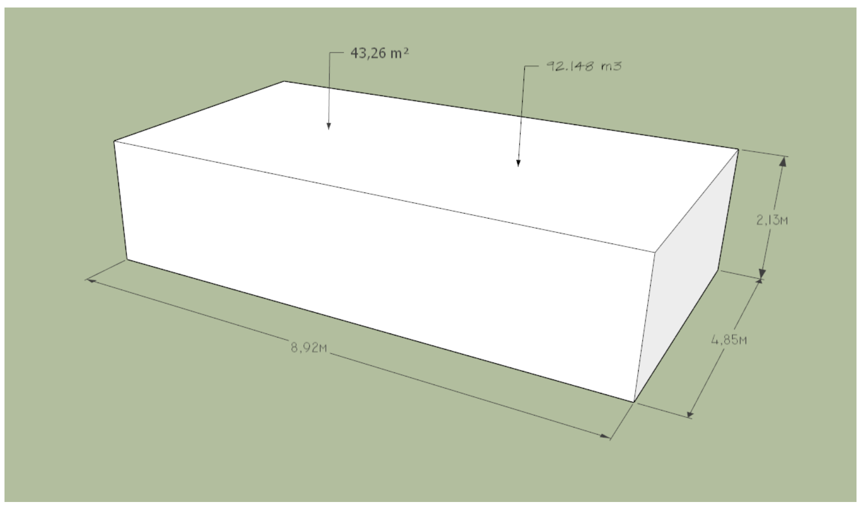
5. Examples of test 3D models for visualization requirement 5: Label with official measurements

Position: Change the distance between the label and the 3D legal unit	
orientation	Not applicable
Size: Change the font size of the label	

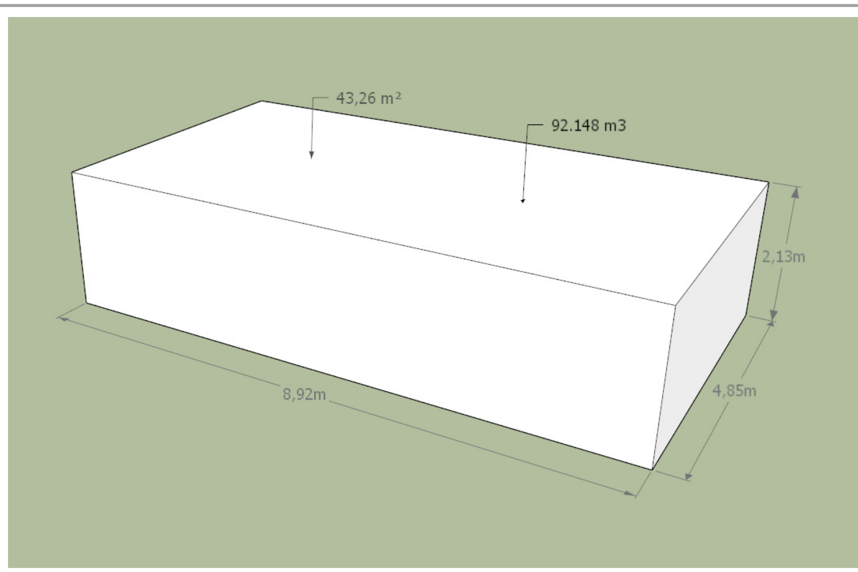
Appendix 1 Examples of the 3D models created for preliminary evaluation

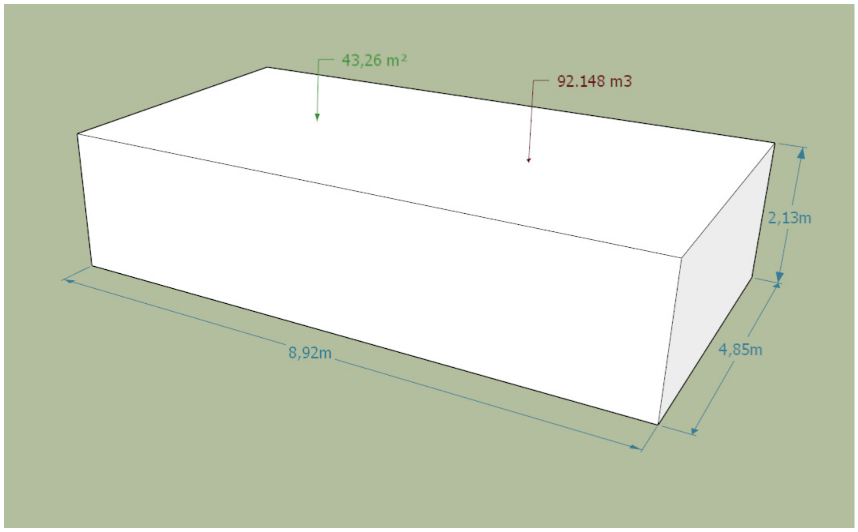
Shape: Change the font type of the label





Brightness: change the brightness of the label



Color: Change the color of the label	
texture	Not applicable

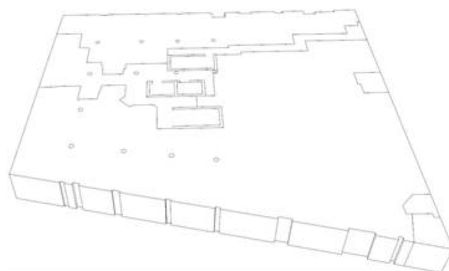
Appendix 2 List of the tested 3D models in a face-to-face interview with notaries

The tested 3D models are as follows:

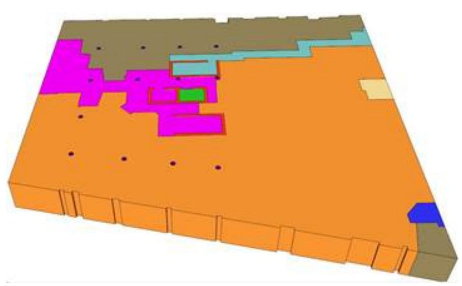
1. **Identify the geometric limits of the property units**

    - For one floor

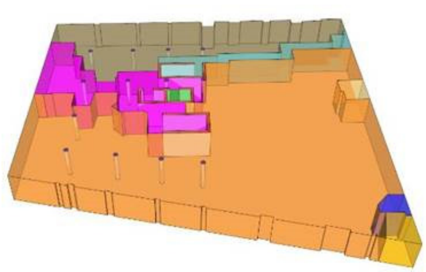
        - B&W



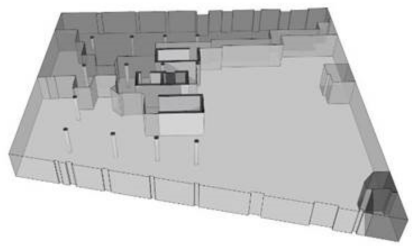
        - Hue without transparency



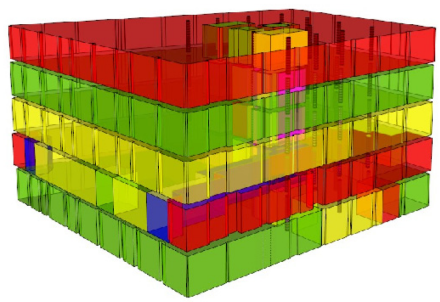
        - Hue with 40% transparency



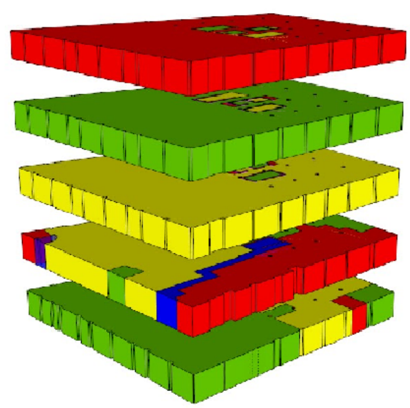
- Brightness with 40% transparency



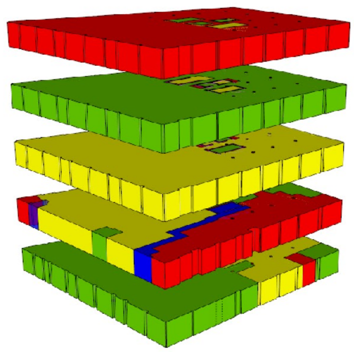
- For three floors
    - Hue with 40% transparency



- Hue with transparency, model detaching (detached floors)

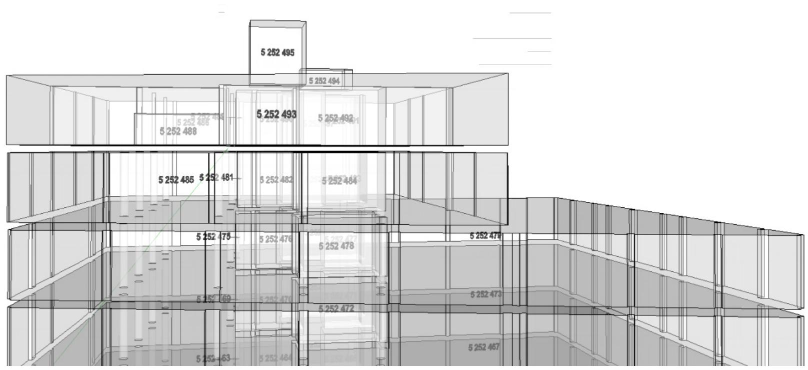


- Hue without transparency, model detaching (detached floors)

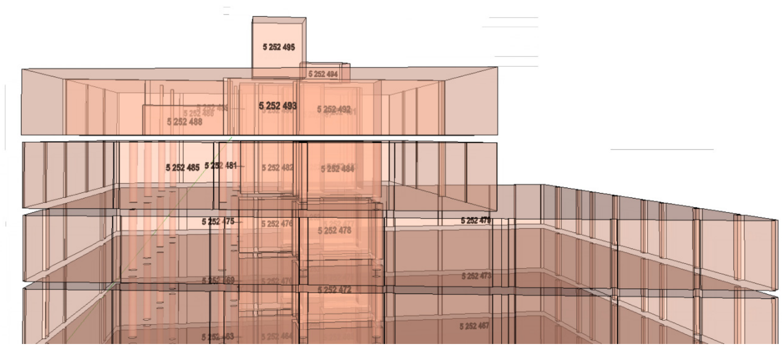


2. Locate a specific property unit inside the building

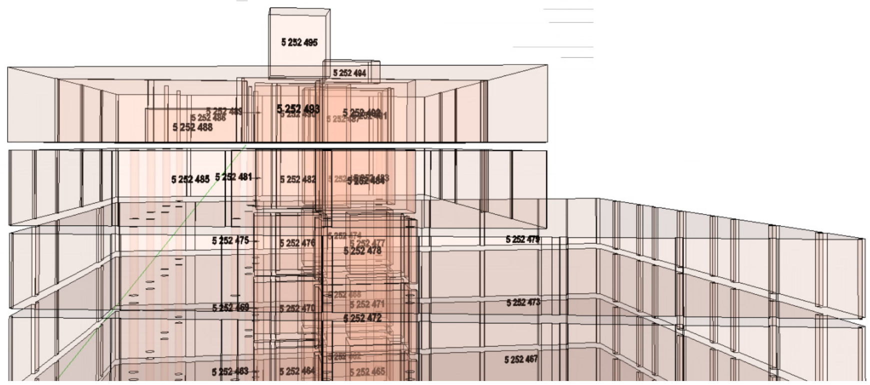
- B&W, with 70% transparency; black boundaries, black font



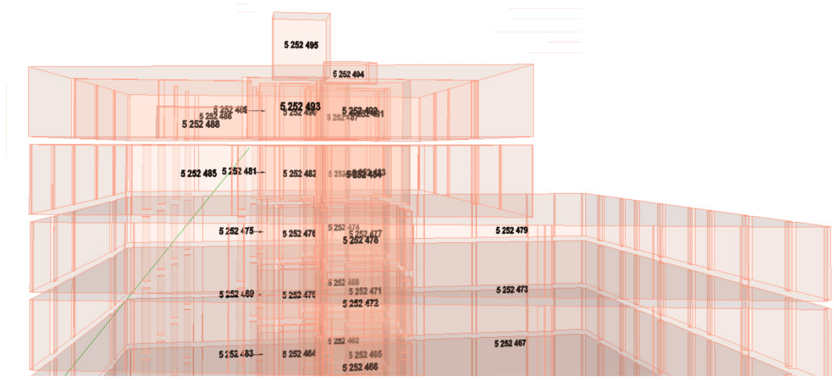
- Color for all volume (red); transparency 70 %; black boundaries; black font



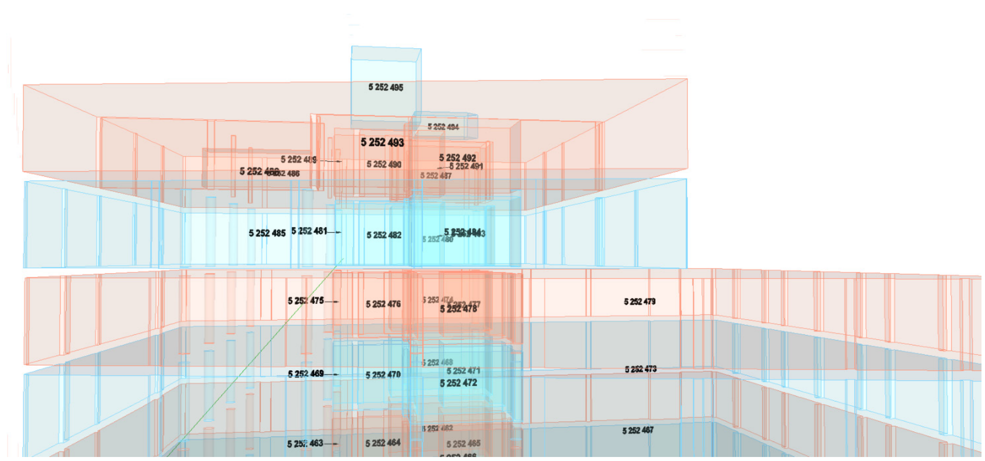
- Color for all volume (red); transparency 90%; black boundaries; black font



- Color for all volume (red); transparency 90%; pink boundaries; black font

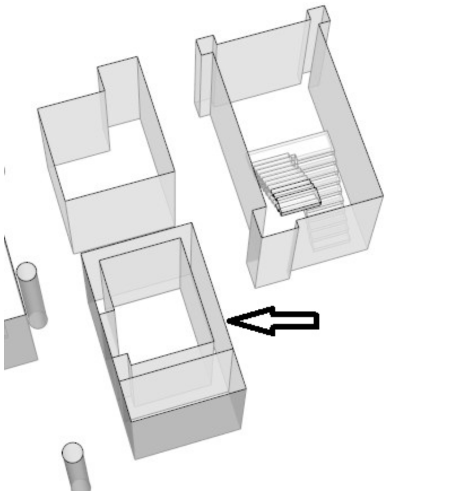


- Color by floor (from the bottom, odd floors are red and even floors are blue); transparency 90%; color boundaries (same as volume)

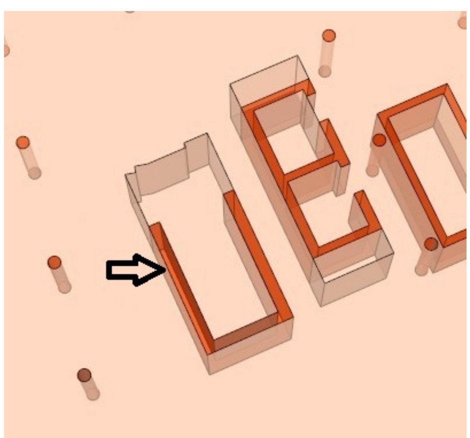


3. Distinguish the limits of the property units and the associated building parts

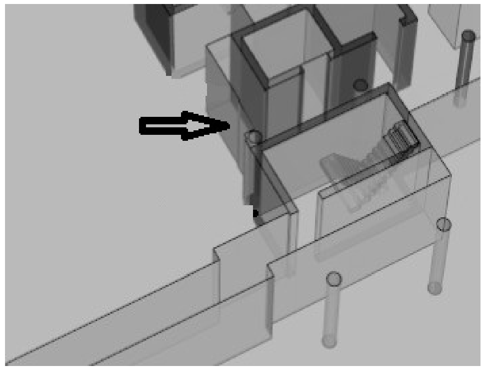
- B&W with 40% transparency



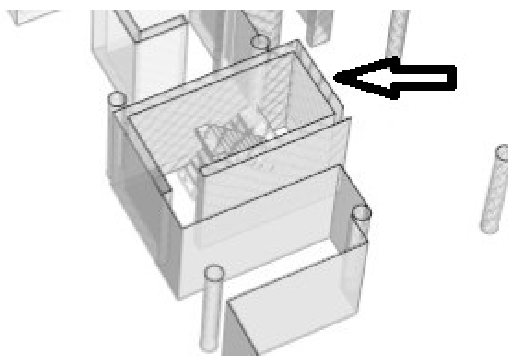
- Saturation: Higher saturation applied to lots that corresponding to both legal space and physical structures; lower saturation applied to legal space; 40% transparency



- Brightness: Lower brightness applied to lots that corresponding to both legal space and physical structures; higher brightness applied to legal space; 40% transparency



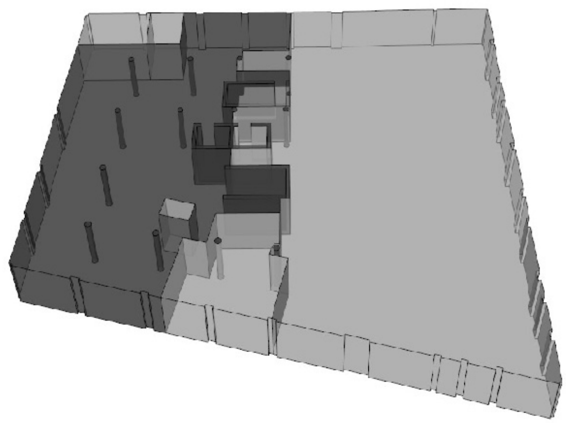
- Texture: 45 degree wavy lines applied to lots that corresponding to both legal space and physical structures; 40% transparency



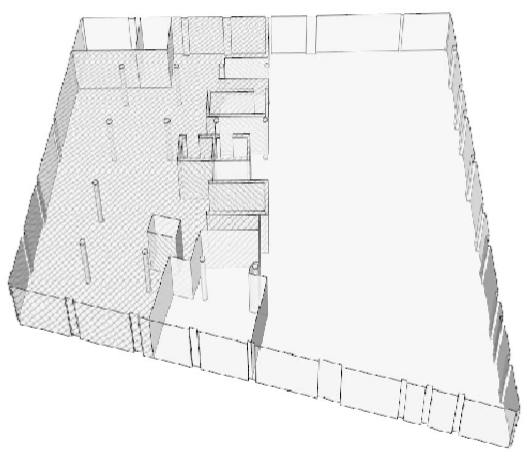
4. Distinguish the private and common parts of the condominium

- B & W is obviously ineffective， thus have not been tested.

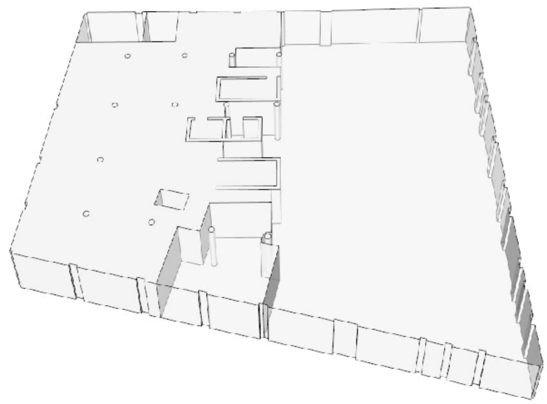
- Brightness: Lower brightness applied to common part. Higher brightness applied to private part. 40% transparency



- Texture: 45-degree wavy lines applied to common part. 40% transparency

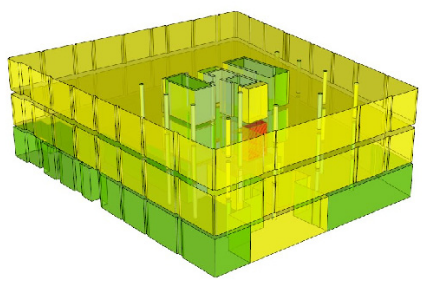


- Transparency: No transparency for common part and 40% transparency for private part

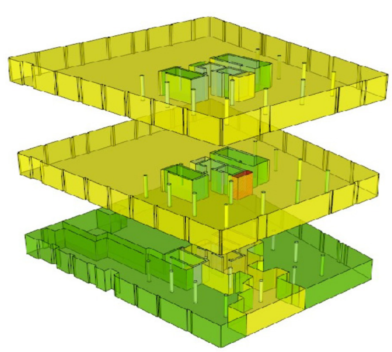


5. **Associate property units with its surrounding units**

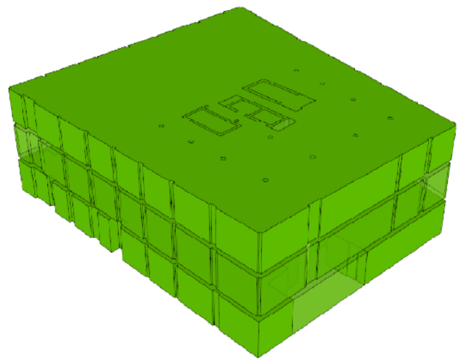
- Hue: The lots touching are applied different color from other lots (touching: yellow; non-touching: green), 40% transparency



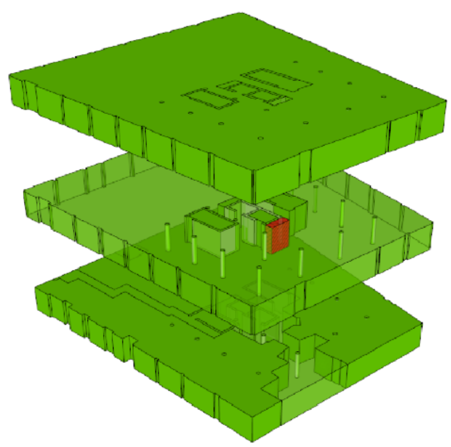
- Hue, building exploded: The lots touching are applied different color from other lots (touching: yellow; non-touching: green), 40% transparency



- Transparency: The lots touching are applied transparency, and other lots are applied non transparency



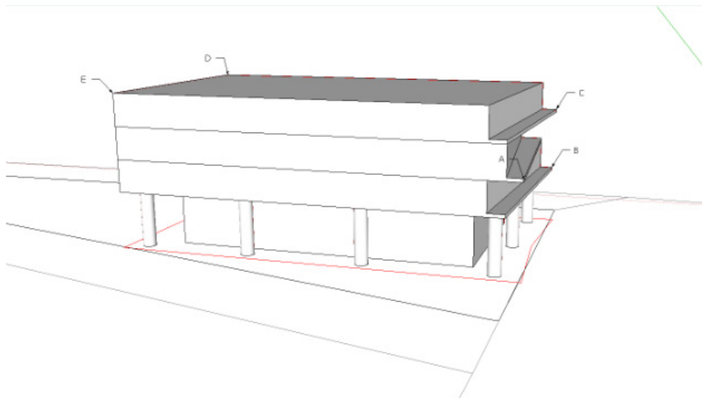
- Transparency, building exploded: The lots touching are applied transparency, and other lots are applied non transparency, floors are detached



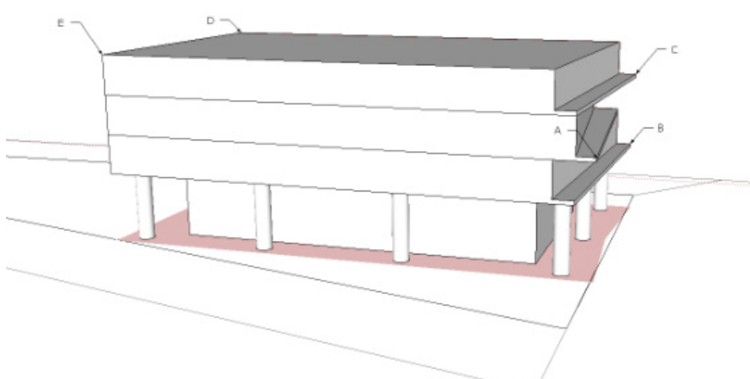
6. **Associate building part with 2D land parcel and compare their geometric limits**

- B/W: it is obviously ineffective, thus have not been tested.

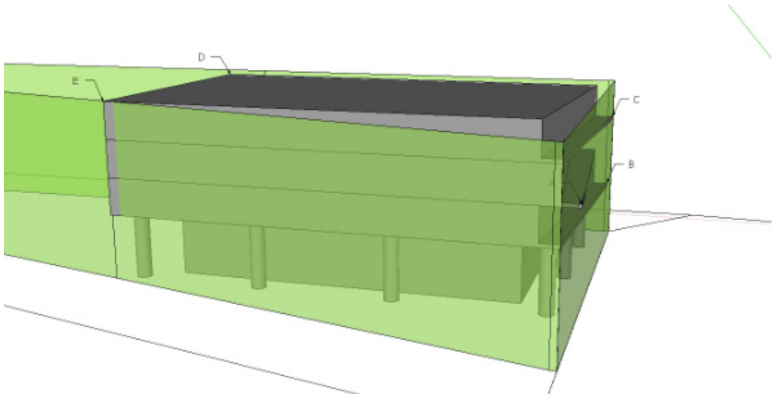
- Colored edge of footprint: The building 3D model with 2D land lots are visualized; the edges of footprint are applied different color (red) from boundaries of 2D land lots (White)



- Filled color of footprint: The building 3D model with 2D land lots are visualized; footprint of the building is presented and filled with different color (red) from other 2D land lots (white)



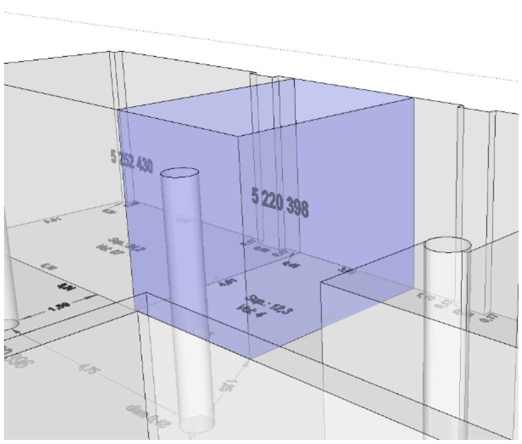
- Present vertical boundary of 2D land lots: 2D land lots boundaries are visualized as vertical faces; these faces intersect with 3D building model



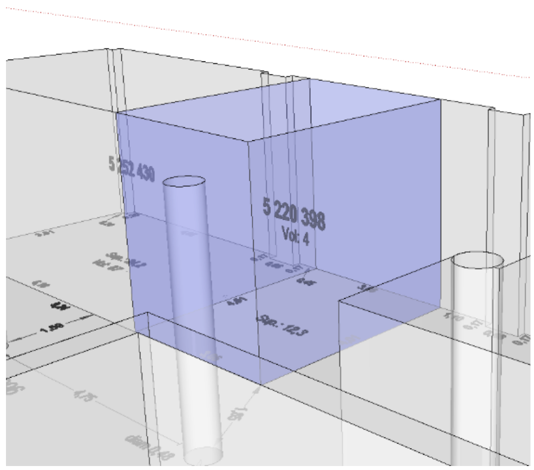
7. Identify the official measurements of property units

All the solutions are test under the situation that 40% transparency are applied to all the lots

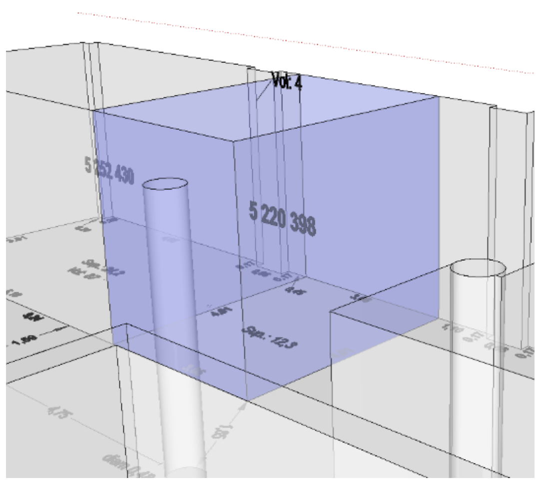
- B&W: The annotation of volume is attached to the ground surface of lots



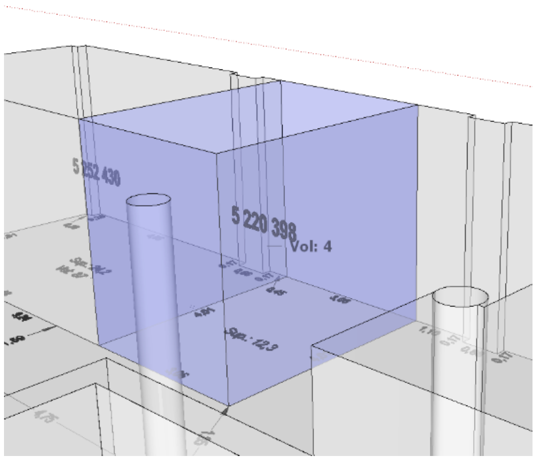
- The annotation of volume is inside the lots



- The annotation of volume is above the lots, a line links the annotation with the lots

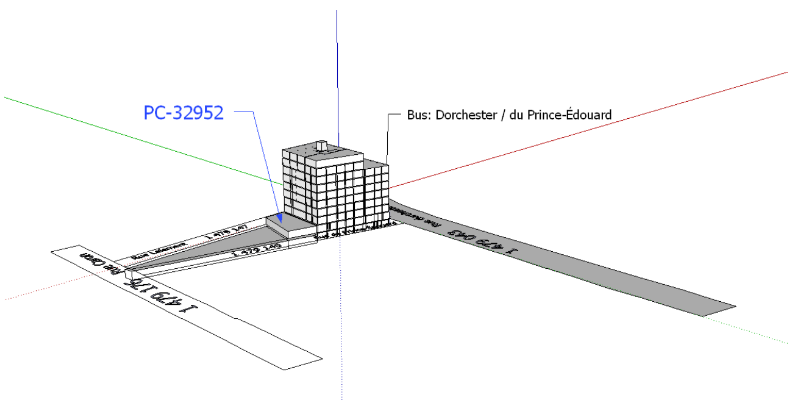


- The annotation of volume is inside the lots, a line links the annotation with the lots



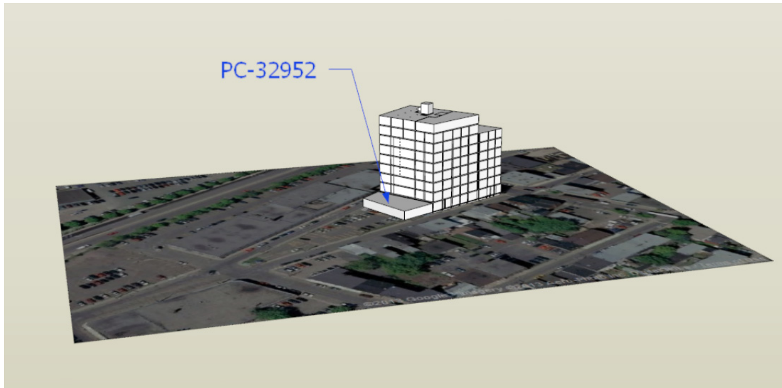
8. Background the condominium with its surrounding environment

- Vector model: Use vector map and 3D building to represent surrounding lots number, PC number, Geometry of surrounding lots, Road name and Land mark.

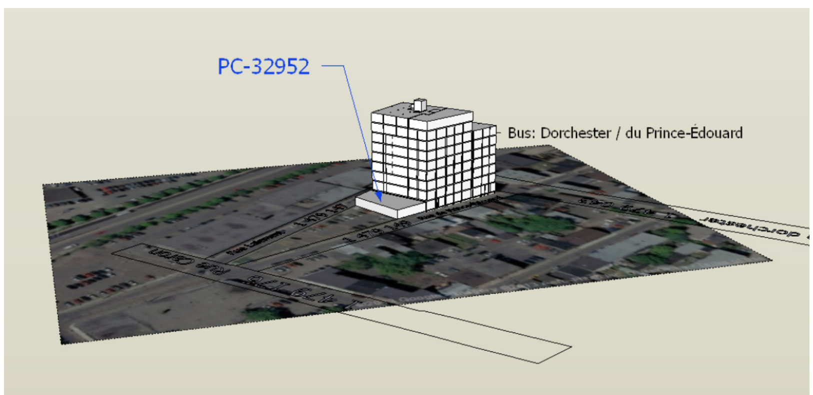


Appendix 2 List of the tested 3D models in a face-to-face interview with notaries

- Photo-realistic model: Use terrain image and 3D building to give audience a contextual understanding



- Photo-realistic model with vector map: A combination of vector map, terrain image and 3D building



Appendix 3 Test results of the face-to-face interview with notaries

Visual task 1: identify the geometric limits of the property units

For 1 floor,

1. B&W: 3/4 failed, not performing
2. Hue without transparency: 4/4 effective and 4/4 preferred
3. Hue + 40% transparency: 2/4 and 0/4 preferred
4. Brightness + 40%: 2/4 performing and 0/4 preferred

For 3 floors

5. Hue with transparency: 0/4 effective, 0/4 preferred
6. Hue with transparency, model detaching (detached floors): 1/4 effective, 2/4 preferred
7. Hue without transparency, model detaching (detached floors): 4/4 effective, 2/4 preferred

Visual task 2: locate a specific property units inside the building

1. No color, with 70% transparency, black boundaries, and black font. 4/4 effective, average response time 29.25 seconds, 3/4 preferred
2. Color for all volume (red), transparency 70 %, black boundaries, and black font. 3/4 effective, average response time 29.33 seconds, 1/4 preferred
3. Color for all volume (red); transparency 90%; black boundaries. 3/4 effective, average response time 21 seconds, 1/4 preferred

4. Color for all volume (red): transparency 90%, boundaries color is different from font. 4/4 effective, average response time 15 seconds, 1/4 preferred

5. Color by floor (from the bottom, odd floors are red and even floors are blue): transparency 90%, color boundaries (same as volume). 2/2 effective, average response time 19 seconds, 0/2 preferred

Visual task 3: distinguish the property units and the associated building

1. B&W with 40% transparency. 4/4 effective, 0/4 preferred

2. Color (Saturation): higher saturation applied to lots that corresponding to both legal space and physical structures, lower saturation applied to legal space, and 40% transparency. 3/4 effective, 3/4 preferred

3. Brightness (Value): Lower brightness applied to lots that corresponding to both legal space and physical structures, higher brightness applied to legal space, and 40% transparency. 2/4 effective, 1/4 preferred

4. Texture: 45 degree wavy lines applied to lots that corresponding to both legal space and physical structures, 40% transparency: 4/4 effective, 1/4 preferred

5. One participant indicates that there is no preference difference among these 3D model

Visual task 4, distinguish the private and common parts of the condo

1. B & W is obviously ineffective, thus have not been tested

2. Brightness: lower brightness applied to common part; higher brightness applied to private part; 40% transparency. 3/4 effective, 4/4 preferred

3. Texture: 45 degree wavy lines applied to common part; 40% transparency. 4/4 effective, 1/4 preferred

4. Transparency: no transparency for common part and 40% transparency for private part. 4/4 effective, 0/4 preferred

Visual task 5: associate property units with its surrounding units

1. model zero: 0/4 effective, preference not tested

2. Colored edge of footprint: the building 3D models with 2D land lots are visualized; the edges of footprint are applied different color (red) from boundaries of 2D land lots (White). 1/4 effective, 0/4 preference

3. Filled color of footprint: the building 3D model with 2D land lots are visualized; footprint of the building is presented and filled with different color (red) from other 2D land lots (white). 1/4 effective, 1/4 preference

4. Present vertical boundary of 2D land lots: 2D land lots boundaries are visualized as vertical faces; these faces intersect with 3D building model. 3/4 effective, 3/4 preference

Visual task 6: associate building with 2D land parcel and compare their geometric limits

1. Color (Hue): The lots touching are applied different color from other lots (touching: yellow; non-touching: green), 40% transparency.

   - Upside: 4/4 effective, 0/4 preferred

   - Horizontal: 3/4 effective, 2/4 preferred

2. Color (Hue), detached: The lots touching are applied different color from other lots (touching: yellow; non-touching: green), 40% transparency, floors are detached.

   - Upside: 0/4 effective, 3/4 preferred

   - Horizontal: 3/4 effective, 2/4 preferred

3. Transparency: The lots touching are applied transparency, and other lots are applied non-transparency.

   - Upside: 2/4 effective, 0/4 preferred

   - Horizontal: 2/4 effective, 0/4 preferred

4. Transparency, detached: The lots touching are applied transparency, and other lots are applied non transparency, floors are detached.

   Only tested with two notaries

   - Upside: 1/2 effective, 1/2 preferred
   - Horizontal: 1/2 effective, 1/2 preferred

Task 7: identify the official measurements of property units

All the solutions are test under the situation that 40% transparency are applied to all the lots

1. model zero: The annotation of volume is attached to the ground surface of lots. 4/4 effective, average response time 11 seconds, 3/4 preferred
2. The annotation of volume is in the center of the lots, just under the lots number. 4/4 effective, average response time 5.25 seconds, 3/4 preferred
3. The annotation of volume is above the lots, a line links the annotation with the lots. 4/4 effective, average time 27.5 seconds, 0/4 preferred
4. The annotation of volume is inside the lots, a line links the annotation with the lots, and the annotation is always facing the audience. 4/4 effective, average time 6.75 seconds, 2/4 preferred

Task 8: Background the condominium with its surrounding environment

1. Vector model: Use vector map and 3D building to represent surrounding lots number, PC number, Geometry of surrounding lots, Road name and Land mark.
2. Photo-realistic model: Use terrain image and 3D building to give audience a contextual understanding
3. Photo-realistic model with vector map: A combination of vector map, terrain image and 3D building

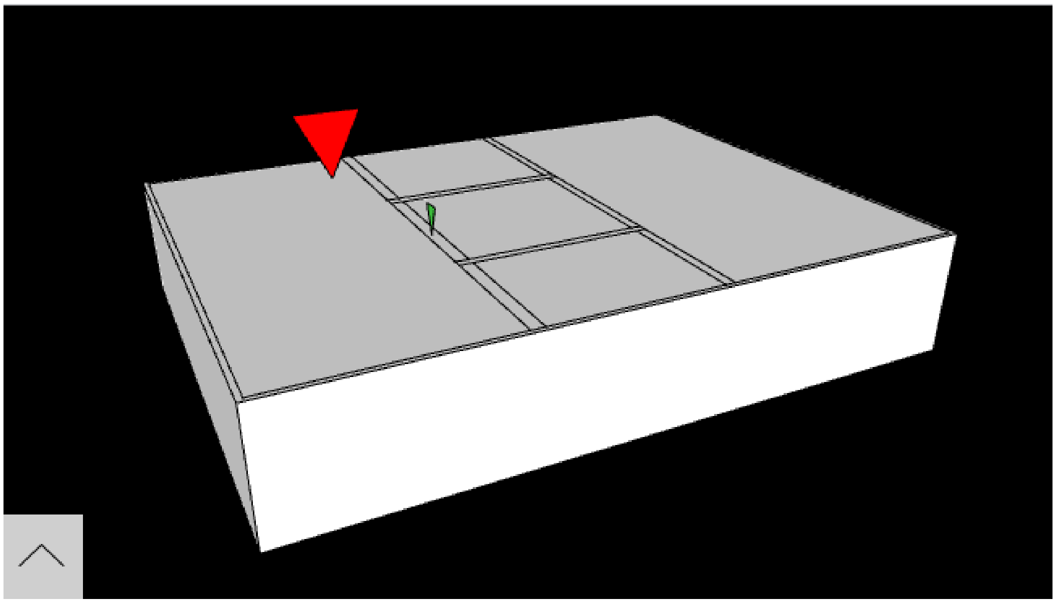
The opinion of notarial participants towards background features are as follows in the table.

Appendix 3 Test results of the face-to-face interview with notaries

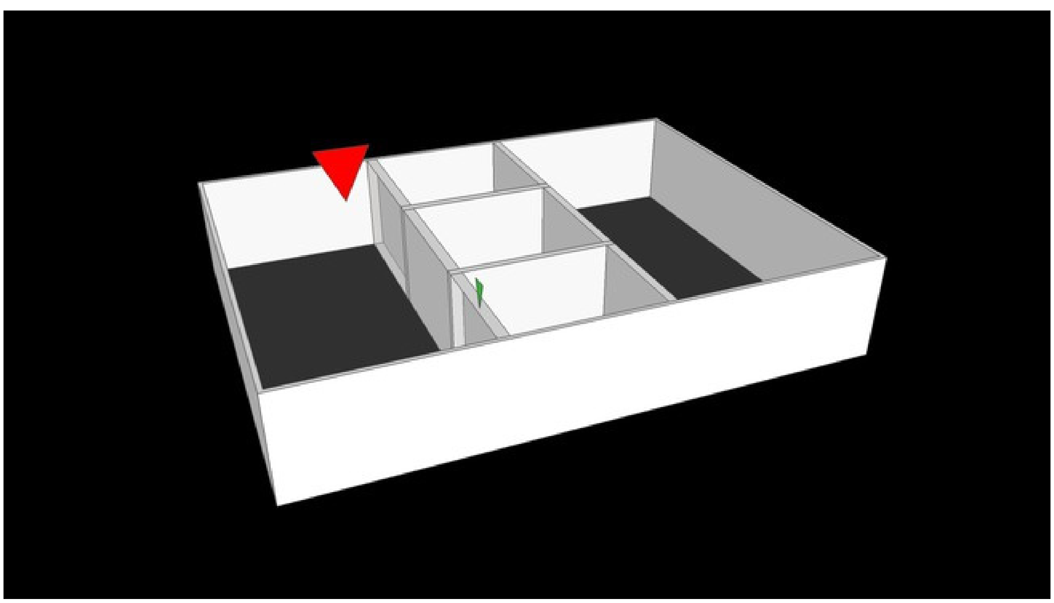
Required background features	Notary 1	Notary 2	Notary 3	Notary
Building geometries			y	y
PC numbers	y	y	n	y
The geometries of the neighbouring lots	y	y	y	y
Lot numbers of the neighbouring lots	y	y	y	y
Road name	y	y	n	y
Landmark (ex. Bus station)	n	y	n	n

Appendix 4 List of the tested 3D models in the online questionnaire

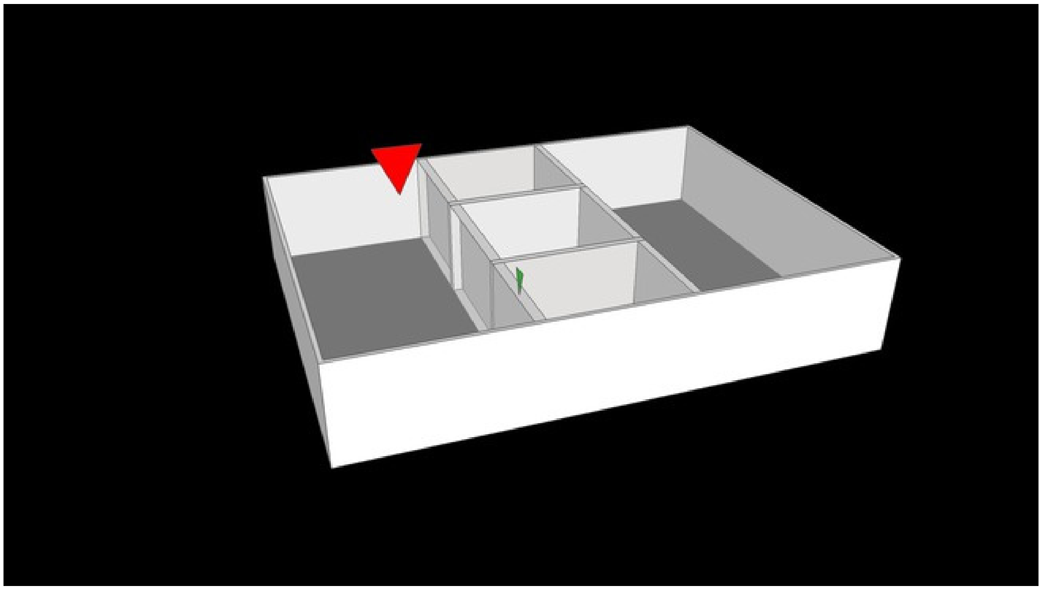
Model #1: Simple legal boundary=100% (alpha), simple physical boundary=100%; legal & physical boundary=100%



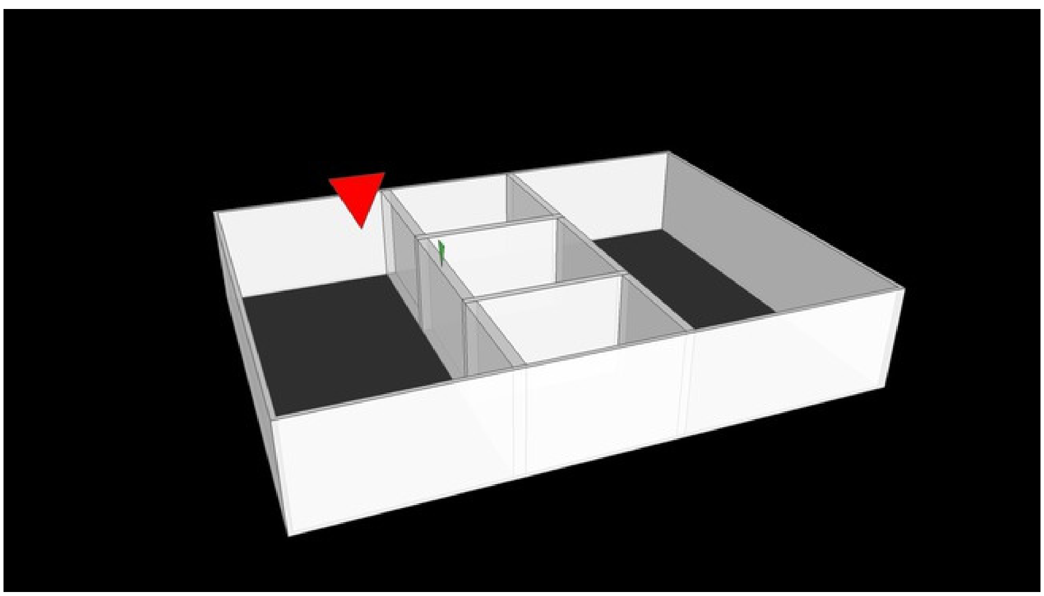
Model #2: Simple legal boundary=13% (alpha), simple physical boundary=36%; legal & physical boundary=100%



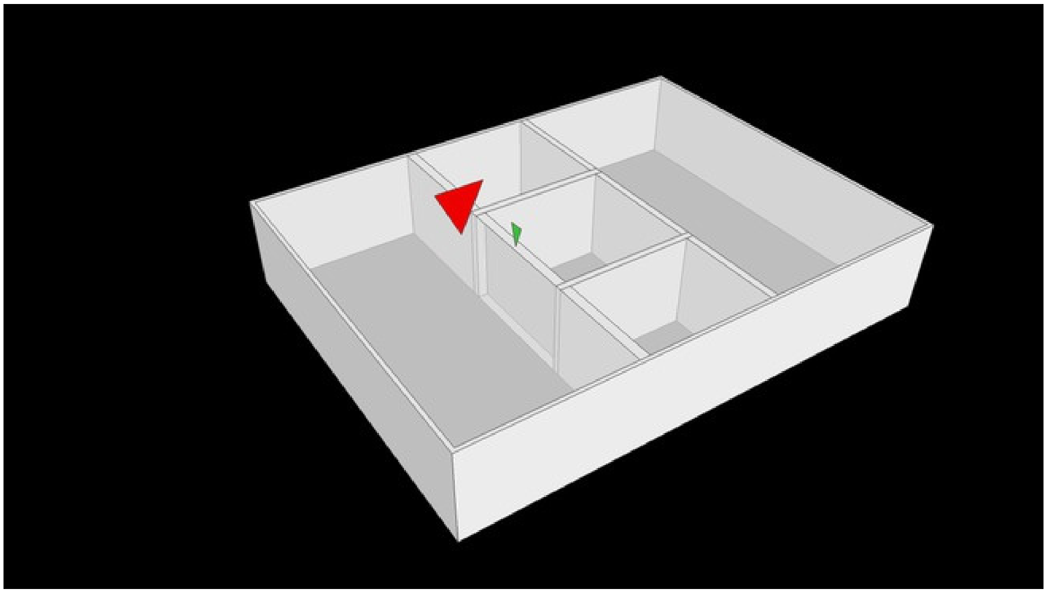
Model #3: Simple legal boundary=36% (alpha), simple physical boundary=13%; legal & physical boundary=100%



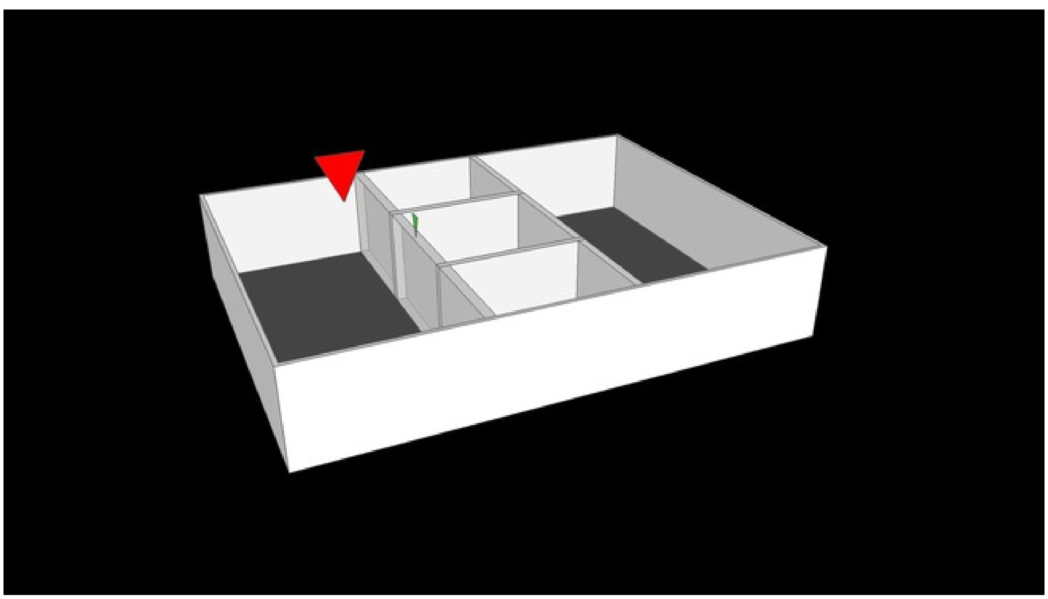
Model #4: Simple legal boundary=13% (alpha), simple physical boundary=33%; legal & physical boundary=85%



Model #5: Simple legal boundary=60% (alpha), simple physical boundary=20%; legal & physical boundary=100%



Model #6: Simple legal boundary=20% (alpha), simple physical boundary=60%; legal & physical boundary=100%



Appendix 5 Analysis of Correctness Data in the Online Questionnaire

model: logistic mixed model

Software: R, package lme4, package multcomp

Program:

```
library(lme4)
glmmres=glmer(Correctness ~ Belongs + Sol +Question2+Question3 + (1 | Ses
sionID), family=binomial(link="logit"), data=df.cad.lg)
summary(glmmres)

library(multcomp)
comp.glmmres=glht(glmmres,linfct=mcp(Sol="Dunnett"))
summary(comp.glmmres)

contrAB="StrategyAB - Y vs N" = c(1/3, -1/2, 1/3, -1/2, 1/3)
contrCD="StrategyCD - Y vs N" = c(-1/4, -1/4, 1, -1/4, -1/4)

comp.glmmresAB=glht(glmmres, linfct = mcp(Sol = contrAB))
summary(comp.glmmresAB)

comp.glmmresCD=glht(glmmres, linfct = mcp(Sol = contrCD))
summary(comp.glmmresCD)
```

Result:

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approxi
mation) ['glmerMod']
 Family: binomial  ( logit )
Formula: Correctness ~ Belongs + Sol + Question2 + Question3 + (1 | Sessi
onID)
   Data: df.cad.lg

     AIC      BIC   logLik deviance df.resid
   471.0    507.1   -226.5    453.0      400

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.7302 -0.6509  0.2961  0.5872  2.6519

Random effects:
 Groups    Name        Variance Std.Dev.
 SessionID (Intercept) 2.344    1.531
Number of obs: 409, groups:  SessionID, 41

Fixed effects:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  0.57112    0.78229   0.730    0.465
BelongsY     0.38289    0.24447   1.566    0.117
Sol3         0.39500    0.39065   1.011    0.312
Sol4        -0.22486    0.37944  -0.593    0.553
Sol5        -0.03521    0.38333  -0.092    0.927
Sol6         0.07670    0.38338   0.200    0.841
Question2   -0.25095    0.44318  -0.566    0.571
Question3    0.54605    0.37874   1.442    0.149

Correlation of Fixed Effects:
          (Intr) BlngsY Sol3   Sol4   Sol5   Sol6   Qustn2
BelongsY  -0.145
Sol3      -0.238  0.010
Sol4      -0.247 -0.006  0.491
Sol5      -0.246 -0.007  0.487  0.502
```

```
Sol6      -0.243  0.002  0.488  0.502  0.497
Question2 -0.761 -0.006 -0.003  0.002  0.002 -0.001
Question3 -0.337  0.011  0.008 -0.005  0.002  0.002 -0.107
```

```
Multiple Comparisons of Means: User-defined Contrasts


Fit: glmer(formula = Correctness ~ Belongs + Sol + Question2 + Question3 
+ 
    (1 | SessionID), data = df.cad.lg, family = binomial(link = "logit"))

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0  -0.2293     0.2502  -0.916    0.359
(Adjusted p values reported -- single-step method)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: User-defined Contrasts


Fit: glmer(formula = Correctness ~ Belongs + Sol + Question2 + Question3 
+ 
    (1 | SessionID), data = df.cad.lg, family = binomial(link = "logit"))

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0  -0.3340     0.2998  -1.114    0.265
(Adjusted p values reported -- single-step method)
```

Appendix 6 Analysis of Certitude Data in the Online Questionnaire

model: generalized logit link mixed model

Software: SAS, Proc GLIMMIX

Program:

```
proc glimmix data=myData method=laplace;

class Certitude SessionID Belongs Sol Question2 Question3 ;

model Certitude=Belongs Sol Question2 Question3/dist=multinominal link=gl
ogit solution;

random intercept/subject=SessionID group=Certitude;

contrast 'StrategyAB - Y vs N' Sol 0.3333 -0.5 0.3333 -0.5 0.3333 / e sin
gular=0.001;
contrast 'StrategyAB - Y vs N' Sol 0.3333 -0.5 0.3333 -0.5 0.3333 / e byc
at singular=0.001

contrast 'StrategyCD - Y vs N' Sol 0.25 0.25 -1 0.25 0.25 / e singular=0.
001;
contrast 'StrategyCD - Y vs N' Sol 0.25 0.25 -1 0.25 0.25 / e bycat singu
lar=0.001
run;
```

Result:

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Belongs	2	317	0.44	0.6445
Sol	8	317	5.52	<.0001
Question2	4	317	1.38	0.2414
Question3	4	317	4.01	0.0035

Solutions for Fixed Effects

Effect	Certitude	Belongs	Sol	Question2	Question3	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	0					-16.4324	130.50	72	-0.13	0.9001
Intercept	1					-2.5971	1.0441	72	-2.49	0.0152
Belongs	0	N				0.4201	0.5043	317	0.83	0.4055
Belongs	1	N				0.1925	0.3259	317	0.59	0.5551
Belongs	0	Y				0	.	.	.	.
Belongs	1	Y				0	.	.	.	.
Sol	0		2			-0.1535	0.9926	317	-0.15	0.8772
Sol	1		2			-2.5642	0.5923	317	-4.33	<.0001
Sol	0		3			1.3067	0.9312	317	1.40	0.1615
Sol	1		3			-0.4422	0.4967	317	-0.89	0.3739
Sol	0		4			1.6625	0.9605	317	1.73	0.0845
Sol	1		4			1.1741	0.4942	317	2.38	0.0181
Sol	0		5			1.4904	0.9117	317	1.63	0.1031
Sol	1		5			-1.3376	0.5326	317	-2.51	0.0125
Sol	0		6			0	.	.	.	.
Sol	1		6			0	.	.	.	.
Question2	0			0		-10.3820	194.78	317	-0.05	0.9575
Question2	1			0		3.2145	1.5625	317	2.06	0.0405

Question2	**0**	**1**		0.9702	0.8866	317	1.09	0.2747
Question2	1	**1**		0.8487	0.8862	317	0.96	0.3390
Question2	**0**	**2**		0	.	.	.	.
Question2	1	**2**		0	.	.	.	.
Question3	**0**		**0**	13.3192	130.50	317	0.10	0.9188
Question3	1		**0**	3.0910	1.1713	317	2.64	0.0087
Question3	**0**		1	11.2213	130.50	317	0.09	0.9315
Question3	1		1	0.06064	1.1210	317	0.05	0.9569
Question3	**0**		**2**	0	.	.	.	.
Question3	1		**2**	0	.	.	.	.

Contrasts

Label	Certitude	Num DF	Den DF	F Value	Pr > F
StrategyAB - Y vs N		2	317	2.70	0.0684
StrategyAB - Y vs N	**0**	1	317	2.87	0.0910
StrategyAB - Y vs N	**1**	1	317	1.55	0.2144
StrategyCD - Y vs N		2	317	13.37	<.0001
StrategyCD - Y vs N	**0**	1	317	2.34	0.1269
StrategyCD - Y vs N	**1**	1	317	26.67	<.0001

Estimates

Label	Certitude	Estimate	Standard Error	DF	t Value	Pr > |t|
StrategyAB - Y vs N	**0**	-0.8956	0.5283	317	-1.70	0.0910
StrategyAB - Y vs N	**1**	0.4266	0.3429	317	1.24	0.2144
StrategyCD - Y vs N	**0**	1.0016	0.6544	317	1.53	0.1269
StrategyCD - Y vs N	**1**	2.2601	0.4376	317	5.16	<.0001

Appendix 7 Analysis of Response Time in the Online Questionnaire

model: linear mixed model

Software: R, package nlme, package multcomp

Program:

```
library(nlme)
lmeint=lme(RespTime.Log ~ Belongs + Sol+Question2+Question3, random = ~ 1
 | SessionID, data=df.cad.lg)
summary(lmeint)
anova(lmeint)

library(multcomp)
comp.lmeint=glht(lmeint,linfct=mcp(Sol="Dunnett"))
summary(comp.lmeint)

contrAB="StrategyAB - Y vs N" = c(1/3, -1/2, 1/3, -1/2, 1/3)
comp.lmeintAB=glht(lmeint, linfct = mcp(Sol = contrAB))
summary(comp.lmeintAB)

contrCD = c(-1/4, -1/4, 1, -1/4, -1/4)
comp.lmeintCD=glht(lmeint, linfct = mcp(Sol = contrCD))
summary(comp.lmeintCD)

contrABY="StrategyAB - Y" = c( 1/3, 0, 1/3, 0, 1/3)
comp.lmeintABY=glht(lmeint, linfct = mcp(Sol = contrABY))
summary(comp.lmeintABY)

contrABN="StrategyAB - N" = c(0, -1/2, 0, -1/2, 0)
comp.lmeintABN=glht(lmeint, linfct = mcp(Sol = contrABN))
summary(comp.lmeintABN)
```

Result ():

```
Linear mixed-effects model fit by REML
 Data: df.cad.lg
       AIC      BIC    logLik
  784.3816 824.3212 -382.1908

Random effects:
 Formula: ~1 | SessionID
        (Intercept)  Residual
StdDev:    0.369604 0.5529555

Fixed effects: RespTime.Log ~ Belongs + Sol + Question2 + Question3
                 Value  Std.Error  DF   t-value p-value
(Intercept)  2.7838881 0.18232979 363 15.268422  0.0000
BelongsY     0.0658636 0.05469066 363  1.204293  0.2293
Sol3        -0.1250589 0.08635714 363 -1.448160  0.1484
Sol4         0.0155668 0.08635714 363  0.180261  0.8570
Sol5        -0.1639923 0.08664779 363 -1.892632  0.0592
Sol6        -0.1094249 0.08635714 363 -1.267121  0.2059
Question2    0.0196169 0.10280370  38  0.190819  0.8497
Question3   -0.0132403 0.08835500  38 -0.149853  0.8817
 Correlation:
          (Intr) BlngsY Sol3   Sol4   Sol5   Sol6   Qustn2
BelongsY  -0.149
Sol3      -0.237  0.000
Sol4      -0.237  0.000  0.500
Sol5      -0.238 -0.004  0.498  0.498
```

```
Sol6       -0.237  0.000  0.500  0.500  0.498
Question2 -0.759 -0.001  0.000  0.000  0.001  0.000
Question3 -0.366 -0.002  0.000  0.000  0.003  0.000 -0.089

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.03051781 -0.67547563 -0.08258593  0.53533891  3.60328909

Number of Observations: 409
Number of Groups: 41
```

Anova(lmeint)

```
            numDF denDF   F-value p-value
(Intercept)     1   363 1862.3133  <.0001
Belongs         1   363    1.4298  0.2326
Sol             4   363    1.6978  0.1499
Question2       1    38    0.0318  0.8595
Question3       1    38    0.0225  0.8817
Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: User-defined Contrasts


Fit: lme.formula(fixed = RespTime.Log ~ Belongs + Sol + Question2 +
    Question3, data = df.cad.lg, random = ~1 | SessionID)

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0  0.11324    0.05586   2.027   0.0426 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)


Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: User-defined Contrasts


Fit: lme.formula(fixed = RespTime.Log ~ Belongs + Sol + Question2 +
    Question3, data = df.cad.lg, random = ~1 | SessionID)

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0  0.11519    0.06829   1.687   0.0917 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)


Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: User-defined Contrasts


Fit: lme.formula(fixed = RespTime.Log ~ Belongs + Sol + Question2 +
    Question3, data = df.cad.lg, random = ~1 | SessionID)

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0 -0.03129    0.04986  -0.627     0.53
(Adjusted p values reported -- single-step method)


Simultaneous Tests for General Linear Hypotheses
```

```
Multiple Comparisons of Means: User-defined Contrasts


Fit: lme.formula(fixed = RespTime.Log ~ Belongs + Sol + Question2 +
    Question3, data = df.cad.lg, random = ~1 | SessionID)

Linear Hypotheses:
       Estimate Std. Error z value Pr(>|z|)
1 == 0  0.14453    0.07487    1.93   0.0536 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```