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Orginal Article

Developing an integrated cadastre model of land and real estate in a single setting in Ukraine: key aspects and problems

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Abstract: Many countries around the world have faced the challenge of creating 3D registrations within existing cadastral registries, which were designed to record the legal status of two-dimensional parcels. The key aspect of the 3D cadastre is the integration of 3D objects and land parcels within a single framework. This integration enables the determination of a 3D object's location relative to the surface level and specific areas on the surface. This article examines the main challenges and key aspects of developing one of the conceptual models of a 3D cadastre – an integrated model combining the 2D cadastre of land parcels with 3D real estate objects within a unified system (the so-called hybrid 3D cadastre model). The authors outline the major directions and prospects for the development of such a model. The introduction of a hybrid 3D cadastre model, as an intermediate stage in the transition to a fully developed 3D cadastre, is expected to facilitate the integration of Ukraine's existing State Land Cadastre and registration system into European and global cadastral systems.

Keywords: 3D cadastre, hybrid 3D cadastre, integrated model, land parcels, real estate objects

1. Introduction

Cadastral and registration systems play a crucial role in real estate management, taxation, mortgage lending, and the legal and informational support of the real estate market. The current state of land parcel registration and ownership rights to real estate in Ukraine, among other factors, is influenced by the level of legislative support regulating these issues. Establishing a real estate cadastre in Ukraine that meets modern requirements and international standards is a matter of great importance. Other significant challenges related to cadastre include scientific, technical, and applied issues concerning the improvement of cadastral object registration, as well as the determination of their physical and geometric parameters, geospatial position, and other relevant attributes [1]. The introduction of two-dimensional boundaries initiated the individualisation of land ownership, making the two-dimensional parcel the fundamental unit of cadastral registration.

However, the 2D cadastre is no longer capable of accurately reflecting the spatial and temporal properties of real estate objects, along with the associated rights and restrictions [2]. A possible solution to fundamental cadastral challenges, considering legal, cadastral, and technical aspects, is the development of a full 3D cadastre. Cadastral information should be fully integrated, with all data overlaid to create a unified cadastral system in three-dimensional space. One of the main challenges in combining 2D and 3D geo-objects within a single system is the vertical relationship between them, particularly the insertion of 3D geo-objects into a cadastral database containing 2D parcels. Additionally, the height coordinate serves as a control coordinate, significantly reducing the risk of overlaps and other inaccuracies in cadastral registration. The integration of a flat partition of 2D objects, such as a cadastral map, into the elevation surface will enable the representation of 2.5D surfaces of 2D objects and the visualisation of 2D maps in a 3D environment using 2.5D images [3]. Therefore, a hybrid 3D cadastre can be regarded as an intermediate stage in the development of a full 3D cadastre. The objective of this research is to examine the key aspects, challenges, and opportunities associated with the creation and implementation of an integrated hybrid 3D cadastre model as an intermediate step in the transition towards a comprehensive 3D cadastre system.

2. Literature review

The need to develop a cadastral system that complies with the current legislation and standards of the European Union arises from Ukraine's decision to adopt European economic development standards. The fundamental element of existing cadastral maps is the "parcel," which makes the cadastral map inherently two-dimensional. Consequently, if property rights extended only to the surface, the effective use of property would be impossible.

A three-dimensional cadastre is a system that registers and provides an overview of rights and restrictions not only on parcels but also on three-dimensional property units to which individuals are entitled by virtue of property rights. The current cadastral accounting of infrastructure objects results in a fragmented representation of parcels, as 3D objects are divided into parts to correlate them with surface parcels. The creation of a 3D cadastral registration can be divided into the following key stages:

- establishing 3D real estate objects within the legal framework;
- providing information on three-dimensional real estate objects, for example, through drawings included in the Land Register;
- developing regulations for the preparation and structuring of 3D information.

Many countries worldwide have encountered challenges in registering three-dimensional situations within existing cadastral systems, which were originally designed to record the legal status of two-dimensional parcels. Efforts to address these challenges in the cadastral registration of 3D real estate objects depend on each country's national legal system and the current state of its cadastral registration. Each country faces its own specific issues with 3D registration, along with distinct legal and cadastral frameworks.

In 2014, the FIG Commission 7 "Cadastre and Land Management" developed the fundamental principles and provisions of cadastral registration, considering contemporary trends such as changes in humanity's relationship with land and the impact of technology on cadastre. Although the "Cadastre 2014" statement does not explicitly mention a 3D cadastre, the report emphasises that future cadastres will no longer be based solely on or limited to two-dimensional cadastral maps [4]. The term “3D cadastre” can be interpreted in various ways, ranging from a fully developed 3D cadastre that supports three-dimensional parcels to a conventional cadastre that only stores limited information about 3D situations. There are three main concepts, with several alternatives: Full 3D Cadastre, Hybrid 3D Cadastre, and 3D Tags, which are described in detail in [3,5].

Over the past two decades, numerous events in the field of 3D cadastres have been held worldwide, including eight FIG workshops on 3D cadastres, dedicated sessions at FIG workshops and congresses, and four international surveys on 3D cadastres (conducted in 2010, 2014, 2018, and 2022) [6,7]. The results of an international workshop on 3D cadastres, organised in Delft in November 2001, contributed to further discussions at the FIG Congress in Washington, D.C., in April 2002 and at the FIG Workshops in Paris in April 2003 and Athens in May 2004, where special sessions were dedicated to 3D cadastres. Several countries have already implemented 3D cadastres, including Sweden, Norway, the Australian states of Victoria and Queensland, Canada’s provinces of New Brunswick and British Columbia, and Chinese cities such as Shenzhen [8]. An analysis of cadastral systems in leading countries, including the Netherlands, Germany, Poland, and the USA, as well as the legal frameworks governing these cadastres, reveals common global trends in cadastral system development. Certain aspects of 3D registration have also been addressed in Denmark, Norway, Sweden, Queensland (Australia), British Columbia (Canada), and Israel. However, the primary drawback of these solutions is the absence of a comprehensive approach that fully integrates legal, cadastral, and technical considerations.

A significant limitation of partial solutions for registering 3D real estate objects in cadastral systems is that 3D information is not integrated into the spatial component of the cadastral database but is instead stored only in title documents, survey plans, and ownership records. As a result, it is impossible to visualise the 3D situation of two neighbouring parcels simultaneously or to query 3D spatial data concerning the owner of a specific layer. Furthermore, the owner of a structure located above or below the surface is not necessarily the same as the owner of the corresponding land parcel [3].

In Ukraine, 3D imagery is primarily used in isolated cases to visualise objects of historical and cultural significance, as well as other fragmented elements. However, there is no cadastral system for registering land parcels, buildings, structures, and other utilities located on, above, or below the ground. Several scientific and legal acts, including the recently adopted laws of Ukraine "On Land Management" [9] and "On the State Land Cadastre" [10], are based on outdated principles of depicting land parcels within a 2D cadastre system. Moreover, buildings and structures on these parcels are recorded using data from the Bureau of Technical Inventory and Expert Evaluation (BTI), which largely fails to account for the spatial positioning of real estate objects.

One effective approach to addressing this issue is to draw on the experience of foreign countries. An analysis of conceptual models for a 3D cadastre, the legislative framework in Ukraine regarding the representation of real estate objects in 3D format, and the selection of an optimal conceptual model for a 3D cadastre is presented in [11,12]. As is well known, the cadastral system consists of two key components: a register of physical parameters (such as area and coordinates) of cadastral objects and a register of property rights associated with them [1].

Paper [13] explores the use of satellite imagery and orthophotomaps to obtain data, primarily related to an object's location (coordinates) and area. Since maps are created as orthogonal projections based on digital elevation model (DEM) data, the area measured from a map may differ from the actual physical area of a land parcel. Furthermore, it is important to consider that achieving high-accuracy DEM construction from satellite imagery is challenging due to the high altitude of satellite surveys (typically 400–600 km or more). This paper also examines three types of parcels with different topographical features – slopes, valleys, and hilly surfaces – calculating errors in area determination and their impact on value fluctuations and normative monetary valuation. According to the findings in [14,15], the accuracy of determining planned coordinates from space imagery, depending on available online resources, ranges from 3 to 15 metres. This level of inaccuracy significantly limits the potential applications of space imagery for precise area measurements.

Currently, the privatisation of land parcels, followed by the assignment of a cadastral number and the issuance of an extract from the State Land Cadastre, is typically carried out using ground-based surveying methods, including electronic total stations, GNSS, and other geodetic equipment. However, due to the challenges of using GNSS equipment in electronic warfare conditions, the most effective method for topographic surveying, solving engineering problems, and creating 3D models is the application of mobile laser scanning systems [16]. Laser scanning and digital aerial photography provide more detailed data on objects than traditional geodetic methods [17]. The primary drawback, however, is that in the absence of a GNSS signal, there is no effective long-term positioning method, and the laser scanning system lacks coordinate information [16].

Another critical issue is the integration of 3D information into survey plans. Since 3D geometry is not included in the cadastral geodatabase, it is impossible to extract a 3D representation from a 2D cadastre. Volumetric survey plans require 3D diagrams incorporating height values in the appropriate reference system. Therefore, developing an integrated terrain model of an object (hybrid 3D cadastre) necessitates the simultaneous consideration of both terrain features and 2D objects.

3. Methodology

This study is based on an analysis of the available literature on the development and implementation of conceptual models for a 3D cadastre (including relevant alternatives), specifically an integrated model combining the cadastre of land parcels and real estate objects within a single system. The accuracy of land parcel area determination when projected onto a plane, considering variations in slope angles and point elevations, was examined using current regulations and documents governing these matters. The study incorporates literature from both international (Stoter, Oosterom, Paulsson) and national (Dutchyn, Dorozhynskyi, Dubnytska) authors. Additionally, publication [23] is particularly significant, as it serves as a foundational work in the study of how slope steepness affects the accuracy of land parcel area determination.

4. Results and discussion

Parcel ownership is not restricted in the third dimension, as it is established on the parcel and extends to all areas above and below its surface. On a 2D cadastral map, it is impossible to determine the precise location of infrastructure and whether it is situated above, below, or on the ground. The current method of recording infrastructure objects in the cadastre results in a fragmented representation of parcels, as 3D objects are divided into parts to correlate them with surface parcels. Three-dimensional cadastral situations primarily concern legal, technical, and organisational aspects.

As is well known, a land parcel is the fundamental registration unit within the State Land Cadastre. This principle aligns with the legal definition of land ownership, which is determined by surface boundaries and is not explicitly limited in the vertical dimension. The main approaches to integrating 3D objects with 2D parcels when developing a hybrid 3D cadastre model can be summarised as follows:

- establishing the legal status of 3D situations;
- creating 3D real estate objects within the existing legal framework;
- selecting the optimal elevation system for integrating land parcels and real estate within a single system;
- determining the actual (physical) area of land parcels;
- defining permissible slopes and elevations of land parcel points and assessing their impact on parcel area and value;
- addressing cadastral registration issues at the legal level;
- developing software to support the operation of the hybrid 3D cadastre system.

In addition to buildings and structures, a full 3D cadastre represents land parcels as three-dimensional entities, taking terrain variations into account. When developing a hybrid 3D cadastre, it is necessary to determine the surface of the parcel, including absolute or relative heights of points, to facilitate the assessment of the height (or depth) of infrastructure and underground utilities located on the land parcels. This introduces the challenge of determining the appropriate number of height points required to accurately represent the actual surface. If the original parcel boundary is a long straight line, it will remain unchanged even in hilly terrain unless intermediate points are introduced along the boundary to reflect elevation differences. Ideally, the number and placement of height points should align with the number of contour points (boundary markers) recorded in the land inventory. For long straight boundary segments, intermediate points are typically recorded at intervals of 50–80 metres. On curved segments, new points are placed where the tangent at the previous point and the curve diverge by more than 0.25 metres [18,19].

Additionally, 2D objects sourced from topographic maps or other datasets can be incorporated as structural elements representing the digital elevation model (DEM), allowing for the integration of the DEM and 2D geodata. In this case, the structure is based on both 2D objects and height points, ensuring that additional height points are added along parcel boundaries to reflect significant elevation variations. Furthermore, land parcels must be represented in 2D with the same horizontal and vertical accuracy as the input datasets (e.g., cadastral maps). The required accuracy for land parcel area determination, as per applicable regulations, must also be maintained. A key aspect of a 3D cadastre is the integration of 3D objects with parcels within a database management system (DBMS). This integration makes it possible to determine the precise location of 3D objects relative to the surface level and corresponding parcels. One approach involves combining 2D parcel boundaries in the $z = 0$ plane (relative height system) with 3D objects that have absolute height coordinates (H). This allows for the projection of a real estate object onto a plane ($z = 0$), where parcel and real estate object boundaries with absolute height coordinates are also defined. Alternatively, land parcels can be represented in full 3D space or using a relative height system [3].

The implementation of a relative height system is feasible in certain localised cases where infrastructure, such as buildings and structures, is located in close proximity to land parcels. However, this approach is not entirely suitable in areas with significant elevation changes, where buildings and structures are situated at different levels, such as in cities and other densely populated areas. In such cases, an absolute height system should be used to determine the heights of buildings and structures relative to land parcels. When the z-coordinates of 3D geo-objects are stored relative to the surface, there is no need to expand the current database with additional z-information for 2D parcels. Instead, only the 3D situation surrounding the 3D geo-objects needs to be analysed, rather than determining the location of all 2D parcels in 3D space. In flat areas with minimal elevation variations, using relative z-coordinates provides a reasonable representation of the situation, with the surface level serving as the z = 0 reference plane. However, in most cases, defining 3D objects with absolute coordinates is the more practical solution, as absolute z-coordinates are unaffected by surface changes. In non-flat areas, determining the actual geometry of 3D objects becomes even more challenging. Therefore, using absolute z-coordinates is preferable for defining 3D objects and positioning parcels in 3D space. Assigning a single z-coordinate per parcel is insufficient, as 2D parcels in 3D space may exhibit considerable spatial dispersion in both plan and elevation, even in relatively flat terrain. Simply adding one z-coordinate per parcel does not adequately account for this complexity. Instead, creating a spatial object with a height z-coordinate, incorporating minimum and maximum values, allows for a more accurate representation of objects in both visible and underground layers, with negative height values for underground utilities [20]. By incorporating an elevation surface for parcels, it is possible to position parcels in 3D space, integrate 3D objects (defined using absolute elevation values) with the cadastral map, and scale the cadastral map in 3D using a 2.5D data representation.

Three-dimensional real estate objects do not exist independently within the land cadastre but are always linked to two-dimensional parcels. A land parcel is the fundamental cadastral unit in the State Land Cadastre, serving as the base on which real estate objects are located – on, above, or below the surface. The area of a land parcel is a crucial quantitative characteristic, and its determination is one of the standard functions within cadastral information systems [18]. The geodetic area of a land parcel refers to the area of its boundary projection onto the projection plane used in the geodetic coordinate system. This geodetic (cadastral) area is calculated based on the coordinates of boundary vertices and boundary markers [22]. In contrast, the physical area of a land parcel accounts for surface irregularities such as slopes, hills, and ravines. However, this physical area is not currently used in the State Land Cadastre [22].

A cadastral map is a two-dimensional representation that contains projections of land parcel boundaries and associated objects, drawn according to specific mathematical principles. In Ukraine, the UCS-2000 coordinate system is used for topographic, geodetic, and mapping work. This system is based on global navigation satellite observations and maintains precise, unambiguous connections with global and European coordinate systems. The reference surface in the UCS-2000 coordinate system is the Krasovsky reference ellipsoid, which has the following parameters: major axis 6,378,245 metres and a flattening ratio of 1:298.3 [29]. As a result, a cadastral map, like a cadastral plan, does not provide the actual surface area of land parcels. In mountainous regions, determining the true (real) area of land parcels is essential for setting land tax rates, rental fees, and normative monetary valuation. A fragment of the 2D cadastral map of Ukraine is presented in Fig. 1.

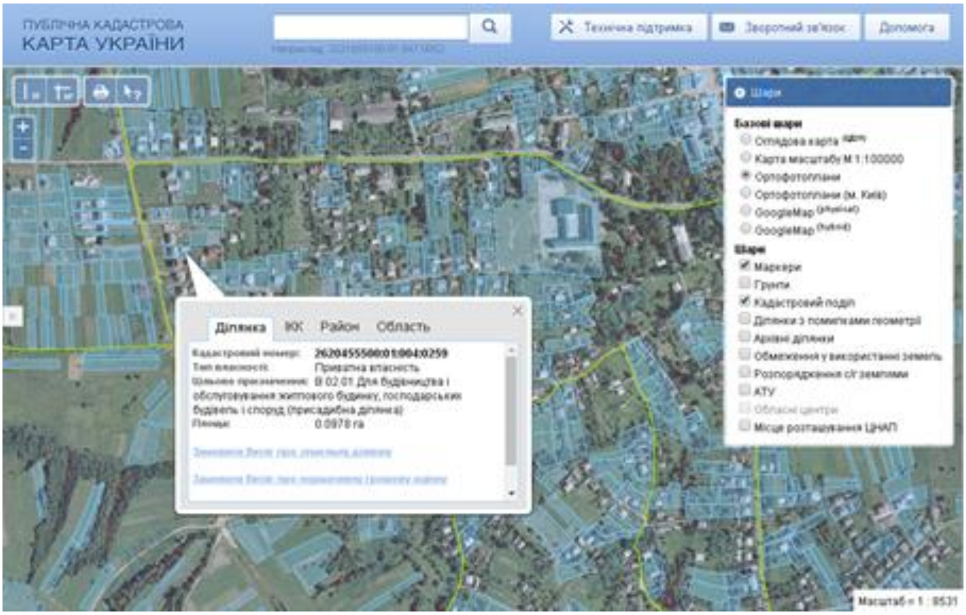

Fig. 1. Fragment of the 2D cadastral map of Ukraine. Source: own study

The accuracy of land cadastral information, which ultimately affects the precision of area determination, depends on the mean square errors in cadastral surveys, permissible errors in processing field measurements, and the digitisation of existing topographic plans and maps [23]. The area of a parcel in three dimensions can be calculated by summing the actual areas of the corresponding geometric shapes that cover the parcel in three-dimensional space. Currently, database management systems (DBMSs) do not support 3D data types and, consequently, do not include functions for calculating area in 3D. The physical surface area of a land parcel can be determined using well-established mathematical formulas, incorporating the angles of inclination to adjust the measured distance to the horizon. The required accuracy for determining land parcel areas in 2D, in accordance with applicable regulations, must be maintained.

The mean square error m_p of a land parcel's area, calculated based on the coordinates of boundary marks obtained from field measurements, can be expressed by the function [21]:

$$m_p = f(P, m_t, k, n) \tag{1}$$

where P – is the area of the land parcel, m_t – is the mean square error of the planned position of the parcel’s contour point relative to the nearest points of the state geodetic network, k – - is the coefficient representing the length of the land parcel, n – number of contour points of the land parcel (indicating the density of the survey contour).

To ensure the required accuracy in determining the area of a land parcel, the maximum allowable error for survey ground points and boundary marks relative to the nearest points of the state geodetic network in cities of republican and regional subordination should not exceed 0.1 m. The error in the relative position of adjacent boundary points should not exceed 0.1 mm on the plan scale, and the relative error in area determination should not exceed 1/1000 [18]. To evaluate the accuracy of land parcel area determination in comparison with the actual area, let us consider the simplest type of terrain – a uniform slope (Fig. 2).

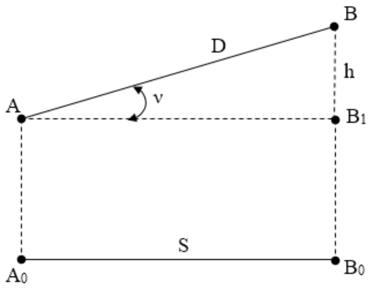

Fig. 2. Scheme of a monotonous slope. Source: own study based on [13]

For a tilted parcel (lying within the same plane), the difference *ΔP* between the real (physical) area and the geometric (cadastral) area is given by [13]:

$$\Delta P = P_{phys} - P_{cad} = D \times b - S \times b = Db(1 - \cos v) \quad (2)$$

where P_{phys} – is the physical (real) area of the land parcel, P_{cad} – is the geometric (cadastral) area of the land parcel, *D* – is the actual length of the parcel on the ground, *b* – is the width of the parcel, ν – is the angle of inclination of the parcel, S – is the horizontal projection, *h* – is the elevation difference between points A and B.

Because

$$D = S/\cos v \quad (3)$$

formula (2) is written in the form:

$$\Delta P = S/\cos v \times b - (S \times b) \quad (4)$$

In [13], in addition to slopes, more complex terrain forms such as mountain valleys and hilly landscapes are examined, along with their impact on the accuracy of area determination.

According to Fig. 1, the elevation difference h between points A and B is determined using the formula [23]:

$$h = \frac{S}{\cos v} \times \tan v \quad (5)$$

or

$$h = S \times \tan v \quad (6)$$

and angle of inclination

$$v = arc \tan \frac{h}{S} \quad (7)$$

The results of the calculations for *ΔP*, *ΔP/P*, and *h* for square parcels (S = b = 100 m) with an area of 1 ha, depending on the angles of inclination ν within a single plane, are presented in Table 1 [23].

Table 1. Accuracy of determining the area of land parcels depending on the angle of inclination. *Source*: [23]

ν°	*ΔP, m²*	*ΔP/P*	*h,m*
2.0	6.10	1/1640	3.49
2.5	9.53	1/1049	4.37
3.0	13.72	1/728	5.24
3.5	18.69	1/535	6.12
4.0	24.42	1/409	6.99
4.5	30.92	1/323	7.87
5.0	38.20	1/261	8.75
5.5	46.25	1/216	9.63
6.0	55.08	1/181	10.51
6.5	64.70	1/154	11.39
7.0	75.10	1/133	12.28

As evident from the above calculations, at inclination angles greater than 2.5°, the relative error ΔP/P exceeds the established tolerance ($\Delta P/P \leq 1/1000$) [18]. For the same inclination angles in two planes (for square-shaped parcels), the error value *ΔP* will double [23]. Thus, if $\nu \leq 2.5°$, the difference between the physical and geometric area of the land parcel can be considered negligible, i.e. $P_{phys} \approx P_{cad}$. The steepness of slopes (slope angles) can also be determined using computer models of slope steepness generated from digital elevation models (DEMs) [24]. In practical applications, slope maps created from raster DEMs, built using the SURFER software package, can be utilised to address this issue [25]. According to the current Classification of the Land Fund and other methodologies, land situated on slopes with a steepness of up to 7° is considered suitable for arable farming. Land on slopes with a steepness of 7–12° or more is typically used for perennial fodder crops [26]. Data provided in [27] indicate that in the Lviv region, substantial areas of agricultural land are located on slopes with a steepness of up to 15° or more – a total of 1,251.97 thousand hectares, including 557.2 thousand hectares with a slope of 1–7° (considered suitable for arable farming) (Table 2).

Table 2. Areas of agricultural land located on slopes. *Source:* [27]

Area of agricultural land, thousand ha				
Tilt angles				
1-2°	2-3°	3-5°	5-7°	Total, thousand ha
216. 47	127.69	119.91	93.13	557. 20

The unaccounted estimated area *ΔP* of agricultural land located on slopes with a steepness of 1–7°, based on the data in Table 1, is presented in Table 3 [23].

Table 3. Unaccounted areas of agricultural land located on slopes when projected onto a plane. *Source:* [23]

Area of agricultural land, ha				
Tilt angles				
1-2°	2-3°	3-5°	5-7°	Total, ha
74.25	121.69	292.82	512.98	1001.74

The relative error *ΔP/P* in this case is 1002/557200 = 1/556, which does not meet the regulatory requirements for the accuracy of area determination [18]. The cost equivalent of the error *ΔP* in the land parcel area can be calculated using the formula [28]:

$$\Delta C = \Delta P \times C \quad (8)$$

where *ΔC* is the deviation of the land parcel price from the probable price, and *C* is the price of the land parcel.

In this case, the relative error in the value of the land parcel will be:

$$\frac{\Delta C}{C} = \frac{\Delta P}{P} \quad (9)$$

Since the normative monetary valuation of one hectare of arable land in the Lviv region as of 1 January 2020 was UAH 21,492 [29], using formula (8), we obtain the cost error value resulting from the change in the land parcel area:

$$\Delta C \equiv 1002 \times 21492 = UAN21535thousand$$

Thus, in this case, the underestimation of the physical (real) area of agricultural land located on slopes with a steepness of 1–7° will amount to UAH 21,535 thousand.

At the same time, the normative value of the land parcel with an area of 557.2 thousand hectares will be:

$$C = 557200 \times 21492 = 11975272\ thousand\ UAN$$

and, accordingly, the relative error in the land parcel value

$$\frac{\Delta C}{C} = \frac{21535}{11975272} = \frac{1}{556},$$

which corresponds to the relative error *ΔP/P* in determining the area of the land parcel.

Almost all 3D cadastre models (full, hybrid, tagged) include the height coordinate H, which is closely related to the real (physical) area of land parcels. For example, in the Ardennes region of Belgium, cadastral maps provide the actual surface area of land parcels located on hillsides. Transferring this information onto a cadastral map, which is a projection of the terrain onto a horizontal plane, is prohibitively expensive in this case, and as a result, a digital map has not been produced in the country [3]. In Ukraine, an XML exchange file serves as an electronic document required for entering information about land plots and their owners into the State Land Cadastre and land management databases. The data in the exchange file includes information on the results and performers of land management and land valuation, topographic and geodetic works, land cadastral units, territorial zones, subjects of land relations, rights to land plots, restrictions on land use, and land plots themselves [30].

Regarding 3D cadastral registration in Ukraine, neither the Land Registry nor the XML exchange file contains data on the height coordinates of land parcel points. In the complex type of exchange file "Coordinates of polygon nodes of a cadastral unit" [31], all polyline node points are recorded with measured x, y coordinates (as land parcel boundaries are organised into a geometric structure of polylines). However, height H is not included, despite the presence of a designated field for height values in the exchange file's table structure. Thus, it is essential to modernise the legislative and regulatory framework to facilitate the development and implementation of a full 3D cadastre system in Ukraine, incorporating hybrid conceptual models as an intermediate stage.

5. Conclusions

An in-depth analysis is conducted on the establishment of the legal status of 3D situations within a unified spatial representation system for cadastral objects. A theoretical study explores the possibilities and limitations of integrating 3D objects, defined in an absolute height system, with 2D parcels by incorporating point heights and land parcel boundaries. The study substantiates the appropriate system of height references (absolute and relative) for combining land parcels and real estate objects within a single framework, depending on their location. The article examines the accuracy of land parcel area measurements based on inclination angle and its impact on changes in land parcel values. The author proposes indicative directions for developing an integrated cadastral model for land parcels and real estate objects within the existing legal framework.

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