An Applicative Approach for Cadastral Processes Implementation in Multi-Dimensional Land Management Systems

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Abstract

The world's population is expected to reach 9.7 billion in 2050, 66% of them will live in urban areas, resulting in the crucial need for efficient management of the land and the urban space, namely the requirement of multi-dimensional cadastral systems. Our study aims at setting an approach for augmenting existing 2D cadastral systems to multi-dimensional ones. The full integration of the height, time and scale dimensions, including all topological aspects within the same system, will prevent the need of handling management and functional properties in segregated systems to support decision-making and multi-purpose applications, as well as providing the opportunity of sharing geo-data by diverse users. A simulation of planning a new 3D project in a complex urban environment, offering functionalities and data model for performing complex 3D analysis and editing, is presented. Our solution is the first step towards the implementation of multi-dimensional cadastral systems.

Introduction

A multi-dimensional cadastral information system is the framework for defining and understanding the spatiotemporal land management restrictions, responsibilities and rights (RRR) of, among others, land information and ownership over space and time. Nowadays, the need for such a system for effective urban planning and management is crucial, a result of population growth, urbanization complexity, and industrialization.

So far, land management systems handled realities as 2D representations, i.e., 2D land parcels (polygons). Still, complex cadastral objects include also height, representing the whole 3D 'air column' (space) above and below the 2D parcel, where the 3D 'air column' can contain a number of 3D parcels. Besides, the property's reality is dynamic, in which the land property is also represented by time and can undergo time-dependent changes that are caused either by humans (e.g., transactions, mutation plans) or by natural phenomena (e.g., coastline movements). In addition, cadastral information systems serve highly diverse users and applications, everyone with his/her specific needs and purposes, meaning that the data should be presented and queried in different Levels of Details (LODs) in order to fit for different usages (fit-for-purpose), i.e., integrating the scale dimension in the cadastral systems is a requisite.

The purpose of this paper is to describe the existing state-of-art regarding multi-dimensional land management systems, the contribution and importance of expanding land management systems from 2D to multi-dimensional, challenges and difficulties impeded into this process of creating multi-dimensional systems, the progress we achieved so far as a part of our methodology towards a multi-dimensional multi-purpose system, conclusion, and future work.

We believe that operating multi-dimensional land management system has an explicit positive effect on other fields, such as urban planning and decision-making applications that rely on land analysis, which validate this research significance.

Challenges involved in expanding 2D cadastral systems to multi-dimensional

Previous research has proven the usefulness of adding the height dimension to the 2D cadastral management system. Still, the appropriate software, data structure, functionality, systematic implementation, database, queries and guidelines for managing 3D cadastral data have not been determined as it involves a large variety of organizational, technical and legal aspects, and needs to be deeply investigated. Besides, land properties have temporal and scale-related components, which has been lately referred to in research. Questions about the need and efficiency of integrating those two elements (time and scale) in the cadastral system have been raised, and not equivocally answered.

A solution that would eliminate the need for establishing new and separated cadastral systems for storing, managing and analyzing every dimension independently is required and expected to save a lot of computational and practical complexities, as well as money, time and human resources; however, efforts are demanded for ensuring that the transfer from 2D to 3D (height extension) is uniformly and smoothly achieved, as well as making sure that there exists a proper way for defining and applying 3D topological relationships in the same system, which is very critical in the field of land management.

Adding the time dimension and scale to land management and asset registration systems is not a simple process and involves many legal, organizational and technical issues. Before the integration of time and scale, it is necessary to investigate the interaction between these three issues and determine how and to what extent a multi-dimensional cadastral can be applied legally, organizationally, and technically. It is also important to decide whether to integrate the time aspect within the three-dimensional cadastral system; which would enable efficient and integrated four-dimensional queries, shifting many parent-child relationships into generic neighboring queries; or to separate it; which is much simpler in technological implementation context and is argued to represent all available practical cases. While "for support for true 4D geometry and topology further R&D activities will be required" and "just adding one simple time dimension might not be sufficient to represent complex temporal situations and therefore the integrated 4D model alone will not be sufficient." (Van Oosterom et al., 2006).

Visualization should be investigated as an aspect of cadastral systems, as representing information on a variety of scales, while maintaining consistency, efficiency, and uniformity in the transition between different scales is challenging. In visualization, there is always the need to display the same scene from different distances, which means different scales. For that, two main approaches exist: either storing the most detailed scale and generalizing it to other scales as needed in real time or store in advance some separated databases, each of which represents a different scale. Most of the existing research related to LODs deals only with natural objects and not with man-made ones, and so are the algorithms.

Several challenges emerge in integrations LODs into cadastral systems, such as Cartographic issues (i.e. symbolized objects may cover geometric areas when switching scale; Semantic issues (i.e. semantic attributes directly affect the process in the system;

for example, when implementing generalization operator, every class should be treated properly, e.g. road should keep being connected and rectangular building remain rectangular. Which means that way of implementing generalization operator depends on the object class) and mixed scale issue, as mixed scale representation is needed for representing high detailed data close by and less detailed further away from the point of view (Van Oosterom, 2012). More challenges were mapped in LODs context for indoor cadastre (Jung et al., 2016), among them: 1) Geographical scale issues: generalization of geometric features are based on geographical scale in outdoor LODs, while geographical scale is always large-scale in indoor space; 2) Data capture methods: various methods is implemented for generating data, leading to various data types in the same model; 3) Application issues: the appropriate LOD should be determined based on the application purpose so that it would perform effectively and affordably, e.g., too detailed scale causes using huge data volume and computer resources; 4) Choosing Data types: data can be 2D/3D, vector or image data.

Data collection is another topic to be explored. The type of data, its structure, accuracy and the way in which it is collected directly affect how the dimensions are defined and induce the structure of the databases for storing, querying and representing the multi-dimensional information.

Expectations, requirements, and advantages of operating the multi-dimensional cadastral system

1. <u>Technical requirements</u>

Among the primary anticipations of the system are the management, analysis, and storage of 3D urban space and spatial engineering projects. As well as defining, modeling and modifying of 3D data, while ensuring the integrity and legitimacy of geometry, topology, and semantics.

Integrating time into cadastral systems is expected to enable effective search in four-dimensional systems, practical performance of time-based queries (archive, operations, rezoning, etc.), presentations and analysis as a function of time, the creation of time-dependent databases and change detection maps.

Different scale and LODs, are intended to answer scale-dependent queries so that end users will be able to search for spatial entities not only according to location and time parameters/considerations but also according to scale-dependent definitions. Moreover, a database at different levels of detail is a very useful tool for improving applications, especially those that support decision-making. In addition, this will enable calculating costs and effectiveness of operating applications upon different LODs and, consequently, recommend an optimal LOD. For example, Biljecki et al., (2017) refuted the assumption that finer LODs are needed for estimating shadows.

2. <u>Advantages of resources sustainability</u>

The above-described performances are needed for creating an optimal and multi-purpose geo-information system that serves for different fields such as transportation and geodesy. In urban planning, for example, adding time dimension enables historical achieving, monitoring urban changes over time and cultural heritages, detecting the past trends of urban development and studying human mobility, understanding changes of land cover and land use. These may serve for directing the upcoming urban development in a sustainable manner that will preserve natural resources for future ages. Time element will enable monitoring boundaries and ownership changes, dynamic objects in general, especially natural objects (e.g. shoreline), as well as rights and restriction that could be time-dependent, such as leases and season dependencies (grazing, gathering vegetation, hunting/fishing, etc.).

General benefits of operating 5D land management system are categorized in Table 1.

Table 1: The effects prompted by the multi-purpose land management system.

Urban Planning	Dynamic Rights and restrictions	Technical aspect	Applications
Historical achieving	Leases	Full reference to space, time and scale	**Multi-purpose applications**
Cultural heritage	Season dependencies	Integrated database	**Decision making**
Urban development trends	Natural dynamic objects	5D search	**Costs and effectiveness**
Human mobility			
Changes in land use/land cover			

Previous Research

Efforts are made to transfˋorm the existing 2D land management systems into multi-dimension ones (i.e., integration of all dimensions - space, time and scale). Several studies focused on this issue (e.g., Doner and Biyik, 2013; Seifert et al., 2017; Doulamis et al., 2015; Aien et al., 2012), still, no such system exists for a large scale management, where the aforementioned studies are limited, presenting only prototypes and pilots. One of the reasons is that the suggested methodologies for dealing with 5D require high computations and construct new systems, based on photogrammetric techniques, rather than utilizing the data in the existing 2D systems.

Van Oosterom (2012) suggested an nD approach for data modeling in five dimensions and applied the concept of previous studies in nD storage (Gray et al., 1997; Casali et al., 2003), which used nD modeling for integrating information on multiple thematic attributes rather than spatial and dimensional data. Van Oosterom (2012) adjusted this approach for managing geometric multidimensional data and created intermediate models for representing 5D models, an example for that is relating time as a third dimension, represented by axis vertical to the plane, for monitoring and recording changes of 2D land property ownership and moving objects, while planar axes x and y represent the 2D properties. According to the study, “The deep integration of time with space and scale concepts in an nD approach will fully handle changes upon position, attributes and/or extent of the objects in the unified space-time-scale continuum”.

Other research dealt with separately integrating either height, time or scale dimension. In adding height dimension context, defining the data model for storing 3D objects, validation rules, 3D topology and functionality are important aspects. Kazar et al., (2008) suggest using Oracle’s data model for storing 3D geometries (in general, not specific for 3D Cadastre). In their paper, they present different types and rules for storage, validation, and querying of 3D models. They also show that the GM_Solid representation is unsophisticated in comparison to more topological models, however qualitative enough for describing 3D geometry. In the same context, validation rules are addressed together with examples of valid and invalid geometries. It was noted that actual validation rules are domain dependent. For example, it is unclear if dangling faces (patches) or selfintersection are allowed. Currently, both Oracle and ESRI do not yet support 3D topology structure (Felus et al., 2014). In conformity with the jurisdiction of Queensland, Australia (Karki et al., 2013), a specific set of digital data validation rules in realizing a 3D cadastre is proposed, where 2D parcels are treated as infinite 3D columns containing the volume above and below ground. Processes aim to check and verify different aspects of 3D cadastre are presented, such as verifying 3D encroachments using a cadastral database, disjoint 3D rights, 3D common property, and curved surfaces.

Regarding the time dimension, 4D modeling is implemented by simple aggregation of independent 3D digital models at different time instances (Doulamis et al., 2015). Meaning that several cases in specific time points are stored, which is not appropriate for managing large-scale environments that undergo continuous changes. However, holding continuous 3D models requires high-cost and efforts. Moreover, temporal data are heterogeneous, which makes managing 4D properties even more difficult. For solving this issue, Doulamis et al., (2015) suggested a selective 4D modeling framework for the spatial-temporal land management system, based on creating change history maps. Kemec et al., (2012) researched LODs in 3D models for the purpose of managing natural disaster risks and proposed LOD hierarchy that is considered together with CityGML (City Geography Markup Language - an open standardized data model and exchange format to store digital 3D models of cities and landscapes) to improve the existing CityGML of the OGC standard (i.e., a standard that focuses on 3D urban models, which, constitute spatial visualization or analysis environment for many other application areas like cadastre, planning, traffic, etc.). LOD 1, 2 and 3 that were used previously only for outer details in CityGML, were associated with the related indoor definition and notation in the approach suggested by Kemec et al. (2012).

The scale was implemented as a separate dimension in OGC 2008, five levels of details were predefined in CityGML. This approach suffered from several problems, it did not support aggregation because it related only to individual objects and did not relate to the fact that a tree turns into a forest at lower scale for example. Besides, the interior of buildings was included as a level of detail with no unequivocal definition of it, meaning that the interior could be either an inner polygon or another whole world (Zalatanova, 2008). Other researchers, such as Kang et al., (2014), Kemec et al., (2012), Jung et al., (2016), studied indoor LODs hierarchy and the concept of LODs in 3D indoor models and suggested several LODs for presenting indoor data models. An intermediate model of 2D+scale, which is based on the tGAP concept, was suggested in the literature. The tGAP data structure was implemented for representing multi-scale data by including scale as a separate dimension with the purpose of reducing redundancy, assuring consistency, smooth zooming, and progressive transfer. For this goal, several LODs (distributed upon 1D scale dimension) for a 2D map (2D space) was stored as a 3D cube (Meijers, 2011); every map, in a specific LOD, was represented as one polyhedron. Cross sections of the resulted 3D structure produce 2D maps in different scales without gaps or overlaps. The nD approach applies to 3D+scale by integrating various scales of a 3D model in one 4D data cube. Scale dimension is perpendicular to X,Y,Z axes, which allows continuous representation city at different scales and produce 3D models at different scales by slicing the 4D cube.

Methodology and previous steps:

The practical goal of this research is to expand the existing state of two-dimensional cadastre treatment - reference to a particular surface and geometry without height information (borders without facades) - to a spatial state of five-dimensional topology. In general, cadastre management systems should offer these main operations: 1). 5D data collection and organization; 2). Visualization and navigation in the 5D environment; and, 3). 5D analysis, editing, and querying. However, for performing such operations, the technical framework needs to be determined in advance, including data structure, database, software, and hardware. So far, in this research, several stages were achieved as appears in this chapter towards implementing the 5D system.

1. Stage: Legal and Technical Aspects of CHANIT Specifications

For the sake of expanding the existing 2D management system, a summary of the CHANIT specification that defines uniform CAD format for all types of plans submitted to survey of Israel (SOI) (similar specifications exist in other national mapping and surveying authorities with minor differences) in terms of mapping the gap between the existing system and the planned one, focusing on supporting three-dimensional cadastral system database and functionality gaps in CHANIT specification were mapped.

The gap mapping process included the examination of functionalities, classes, properties, and methods. Recommendations for augmenting and promoting the existing operative 2D cadastral system to be suitable for comprehensive 3D land management are given accordingly. The gaps were categorized under the following topics: (1) Guidelines and regulations (e.g., 3D mapping and vertical datum), (2) Data structure and database (e.g. height dimension and 3D data format), (3) Data integrity and legality, i.e. spatial validations and legal terminology, (4) Quality control, error handling and accuracy assessment, (5) cadastral processes, functionality, operations and queries. These gaps were firstly mapped focusing on turning 2D cadastral systems into 3D systems. Later, shifts for turning 3D systems to 5D would be added, and would mainly include: regulations for mapping multiple timestamps in different LODs, generalization and scaling functionalities, data structure and database suitable for managing time and scale.

2. Mapping of cadastral processes and functionalities that should be integrated into the system for managing multi-dimensional land registration

Building multi-dimensional (5D) management system may enable computerized identification of objects above the surface and below the surface in given time stamp and specific LOD, and describe different spatial cadastral processes, such as land transfer, land partition, and land union. As well as processes that support discrete and continuous property changes whether they are semantic or geometric. In addition to functionalities and processes for managing fifth dimensional, e.g. zooming in/out according to the distance from the viewer or demanded LOD, generalization, and simplification.

The algorithms and practical implementation of the functions and processes among real integrated 2D and 3D, 4D or 5D data are very complicated. Besides, a lot of familiar processed into the 2D systems, such as split and search, turn to long scripts among multi-D data, especially parcels that are not simple and have to take into consideration different possible cases. Previous research is detailed in this paper, but most deal either with very simple objects and limited operations or based on separated 3D data that are mostly gathered from the point cloud and could not possibly complement the 2D system.

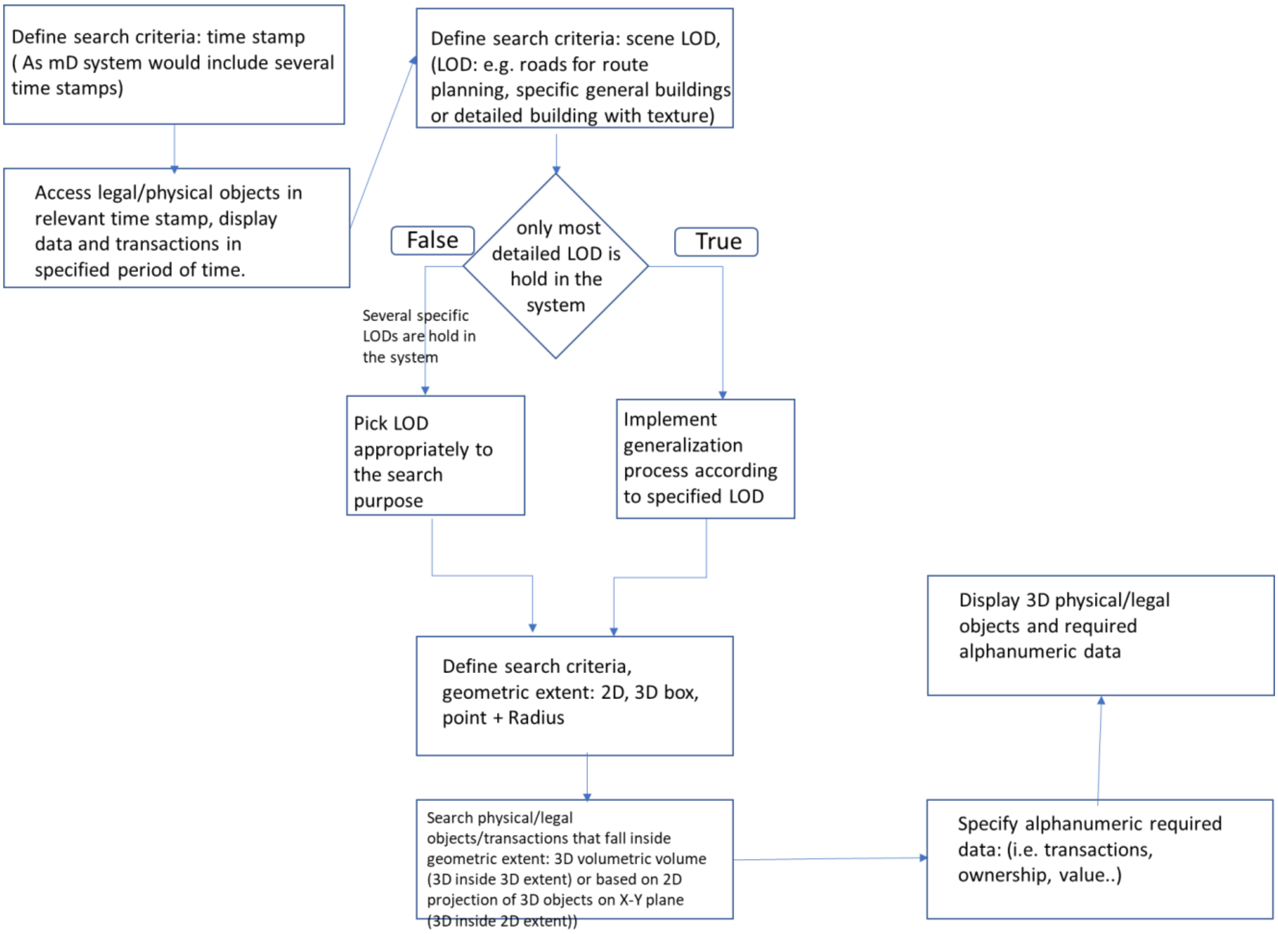

Figure 1: Illustrating a process of inserting a new volumetric spatial parcel in a multi-dimensional (5D) cadastral system.

For integrating the time element in cadastral systems, we follow two main approaches appeared in literature, which are a state-based model and an event-based model. In the state-based modeling, the states (i.e., the results) are modeled explicitly: every object gets (at least) two dates/times. While in the event-based model, transactions are modeled as separate entities within the system (with their own identity and set of attributes). When the start state is known and all events are known, it is possible to reconstruct every state in the past by traversing the whole chain of events. (Van Oosterom et al., 2006)

The process of inserting a new parcel to the 5D system is described in Figure 1 appropriately to state-based model. While in an event-based model the process would be slightly modified: in this case, it is more convenient to search geometry and LODS first, only then perform a search as a function of time, since the system needs to go through a whole chain of events when searching a specific object in the specific time stamp.

3. Data-structure, Fields, and Methods

Data structure, fields and methods that served for 2D cadastral systems, are extended to fit for 5D cadastral systems. For that, point, line and parcel classes that were used for planar cadastral data turned to 3D vertex, 3D line, 3D volumetric parcel by adding new methods and attributes and updating previous ones. Besides, more classes were created, such as 3D polygon and 3D legal object (Jaljolie et al., 2018). This data structure would be adjusted for fitting to 5D systems, by inserting time and scale related attributes. In a state-based approach, each class would be given two attributes stating start and end time of the object exists, while in event-based model event class would be created instead of adding start end dates. For describing different scales, various classes, representing 3D physical and legal objects in different LODs, would be inserted. For examples, general route and street classes will exist in a LOD needed for planning route direction, while classes describing detailed texture and structure of houses will exist in other LOD. Meaning that some object and classes would be accessible only in specific LODs and not accessible in others.

4. Insertion of a new cadastral parcel into an existing cadastral database

One of the basic cadastral processes in any cadastral system is the insertion of a new cadastral parcel into the existing cadastral database. We stimulated this process by defining a complex urban neighborhood (Figure 2), including buildings above the terrain, streets on ground and structures below terrain. The scenario used implements the process in which a city municipality is planning to construct a new subway network, which partially passes through this area. For that, planners should validate that the subway tunnels' RRR does not conflict with another 3D parcel's RRR. In case of conflicts, the problem should be resolved either by purchasing the land property rights, or by modifying the subway route, which demands, in some cases, creating, dividing and joining 3D land assets.

This scenario was implemented almost completely automatically using prototype Python scripts: the parcels' data are inputted to a GUI, and the neighborhood 3D data model was created in AutoCAD. The proposed simulation is based on a very frequent real case scenario, and the suggested solution enables cadastral analysis, fits for simple as well as for complex spatial land units, and is tailored for the specified requirement of data structure (multi-dimensional as an expansion of 2D). The prototype showed accurate and reliable results.

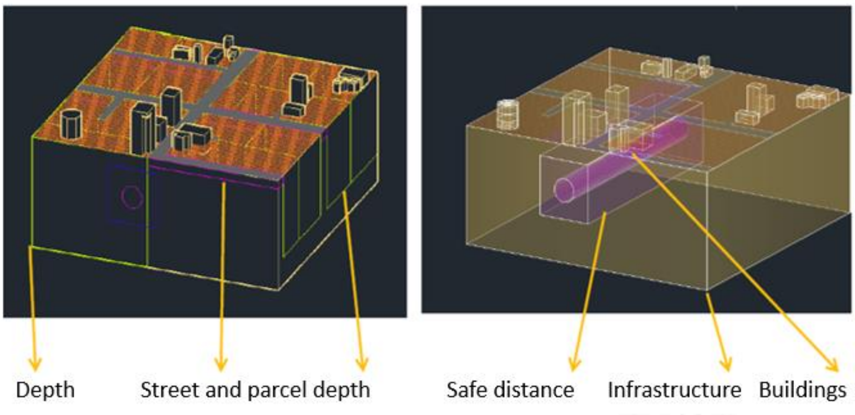

Figure 2: Insertion of the new parcel (appears in pink) below terrain in an existing neighborhood.

Conclusion and future work

Incentives for operating multi-dimensional land management are presented in this paper, all confirm the serious need of it for sustainable world. Previous research and advancements appear as well. Technical aspect, however, have not been sufficiently covered in literature leading to shortage in functioning multi-dimensional systems in different countries. 2D cadastral functionalities, databases, data structure and processes that used to properly perform till this moment tend to be much more sophisticated when expanded to fit for multi-dimensional systems, which means that extra work is required particularly for examining procedural aspect.

Trying to fill this gap, this study is planned for: 1) setting a cost and time-effective approach for expanding cadastral management systems from 2D to multi-dimensional; 2) Investigating the interaction between height, time and scale in one common system; 3) Recommendation on integrating these dimensions into one common system or keeping them separated; 4) Suggesting either storing the most detailed scale and generalizing it to other scales as needed in real time or storing a number predefined LODs; 5) Suggesting methods for collecting data as an input to the multi-dimensional cadaster system.

Significant steps toward these aims ware achieved in this research. To offer a complete conclusion, further research is required for investigating topics, such as: can temporary information be obtained from existing cadastral registration systems? is it necessary to use four-dimensional principles to implement temporal-spatial division? and if not, what measures and tests should be made for determining whether cadastral data distribution is a temporary spatial or it is some other kind of division. Since time dimension can describe many different things, a clear and uniform definition of the concept and its semantic meaning in cadastral context will effectively contribute to the implementation of adding this dimension. Next, implementing algorithms of generalization and simplification of cadastral data would be implemented, errors and distortion resulted by that would be measured.

Effects of the multi-dimensional cadastral system on other fields need to be further examined in the context of multi-purpose functionality for various end users. A multi-dimensional (5D) system should be also boosted and adjusted as a tool for ensuring sustainability in natural and human resources.

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