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Local Domain Models for Land Tenure Documentation and their Interpretation into the LADM

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ABSTRACT

With an estimated 50% of global land held, used, or otherwise managed by communities, interfacing indigenous, customary, and informal land tenure systems with official land administration systems is critical to achieving universal land tenure security at a global scale. The complexity and organic nature of these tenure systems, however, makes their modelling and documentation within standard, generic land administration systems extremely difficult. This paper presents a model that loosely integrates a Local Domain Model (LDM) developed for a Maasai community in Kenya with the Land Administration Domain Model (LADM). The LDM is an ontological schema which captures local knowledge in a systematic, formal way that is directly or indirectly relevant to land administration. The integration with LADM is achieved through an ontological schema called the Adaptor Model. The concept of conditional RRR (Rights, Restrictions, Responsibilities) is introduced within the Adaptor Model to express the dynamics of social tenures. The three domain models LDM, LADM, Adaptor Model are used in the community-based land tenure recording tool SmartSkeMa. Four implementation examples demonstrate how the case-specific LDM extends the range of concepts representable in LADM in order to meet land administration needs from the local community's perspective. A panel of land administration experts found the LDM model and the functionality of the Adaptor Model to be fit-for-purpose for the Kenyan case and to be addressing an important gap in the land administration tools landscape.

1. Introduction

Modern Land Administration Systems (LAS) are structured to support the four main land administration functions: land tenure, land value, land use, and land development (Williamson, 2001). They often implement many of the processes outlined in the 1996 United Nations Economic Commission for Europe (UNECE) Land Administration Guidelines. In particular, a functioning LAS must necessarily implement "processes [for] the determination (sometimes called 'adjudication') of land rights and other attributes, surveying and describing these, their detailed documentation, and the provision of relevant information for supporting land markets" (UNECE, 1996).

The successful design, implementation, and deployment of LAS requires a clear specification of the objects that will be handled within the system and how these objects relate to each other. In terms of tenure, the general pattern involves elaborating the types and relationships between the triple of concepts: *Party* (a natural or legal entity), *RRR* (Rights, Restrictions, and Responsibilities), and *Spatial Unit* (a representation of a physical portion of space) that may exist in the system.

To this end, several models of the land administration domain have been developed by the land administration community. Examples include the Swiss DM.01 (Steudler, 2006), the FIG Core Cadastral Domain model (Lemmen and van Oosterom, 2006), the Hungarian digital base map standard, DAT (Iván et al., 2004), the Land Administration Domain Model (Lemmen et al., 2015) and its adaptation to customary land rights, the Social Tenure Domain Model – STDM (Lemmen et al., 2007). These models have been applied widely across the globe – e.g. the FIG Core Cadastral Domain model in Portugal (Hespanha et al., 2006); the STDM in Ethiopia (Lemmen and Zevenbergen, 2010), Zambia (Abanda et al., 2011) and other countries mostly across the African continent;

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and LADM, used in many countries across the world (ISO, 2012).

For the majority of the LADM implementations, land administration legislation is interpreted through LADM concepts, harmonizing already registered or registerable land information. Through these implementations, LADM follows a top-down approach, as followed by the traditional land administration systems of western countries. Latest trends in land administration encourage public participation in an attempt to cope with a series of land administration issues (high cost of land registration, land-related conflicts, social unrest due to land use transformations or corruption (Williamson, 2001)). This is not entirely new. Already, since 1998, through the 99 published Indigenous Knowledge (IK) Notes, the World Bank openly recognised the power of local participation in community problem solving. Indicatively, the sustainable use of land, based on the traditional practices is reported in the “Indigenous Knowledge and Science and Technology: Conflict, Contradiction or Concurrence?” IK Note (World Bank, 2004). Along the same perspective, modern technologies are used to develop interactive human-friendly land administration systems which can provide systematic harmonized, transparent and publicly accessible information about land resources (Enemark et al., 2015). Participatory approaches are already being used in land administration projects, as in the latest LADM implementations by Balas et al. (2017) in Mozambique and Kuria et al. (2016) in Kenya.

While all the tools listed above pay great attention to *static* aspects of the relationships between parties, RRRs, and spatial units, the *dynamic* aspects of these relations are not satisfactorily captured. In traditional agropastoral societies a plethora of social and environmental factors influence the de facto land relations at play within a community. The spatial units on which human interest is exerted are not static, but rather they are transformed through complex interactions between socio-economic and environmental factors. One indirect consequence of modeling these dynamic relations using static models is that participation of communities in the management of land tenure and land administration in general is hindered. As an example one may consider the situation with local Land Boards in Kenya where, because the traditional authorities within a community may simply be bypassed via the institution of ad hoc special land boards, an entire section of a community may have their tenure altered or even lost without having had any representation in the process (based in personal communication with a group of elders in the Maili Tisa area in Kajiado). The challenge here is that the history of tenures from within the cultural tenure system are not formally documented; they could not be, there was no model for them in the formal land administration system.

The present work continues the current trend of extending participation in land administration processes through a more comprehensive integration of local knowledge into land administration domain models. Building on the idea of the STDM, using the principles of the LADM, and taking advantage of the knowledge modeling tools offered by formal ontologies, we develop a novel, smart scheme called the Adaptor Model (AM) which helps to capture several dynamic aspects of land tenure relations. The domain model links local land domain knowledge captured in what we call Local Domain Models (LDM) to formal land administration systems domain models represented in this work by LADM. Our concrete implementation uses the Web Ontology Language (OWL) implementation of LADM (Soon, 2013a; Soon, 2013b) as the formal model and the Maasai of Southern Kenya Local Domain Model (MSKLDM) as the LDM (Karamesouti et al., 2018). An overview of the MSKLDM is given in Section 2.3 below. The present work differs from the work presented by Karamesouti et al. (2018) in that the Adaptor Model design is novel both within our research outputs and (as far as we know) within the land administration field. In addition, this paper outlines the operationalization of the idea of Adaptor Model using a concrete Web Ontology Language (OWL) implementation, complete with inference steps that produce conclusions based on user input - i.e. it is dynamic to reflect the nature of customary tenures.

The domain models presented in this work[1] are concretely implemented within the community-based land tenure recording tool, SmartSkeMa[2] (Chipofya et al., 2017). SmartSkeMa enables wider social participation in land administration processes. It is part of the its4land toolbox,[3] a set of smart, low-cost land tenure documentation tools for fit-for-purpose land registration (Koeva et al., 2017). SmartSkeMa facilitates land use and tenure documentation from a stakeholder perspective, using paper, pen and oral communication. People simply draw a sketch and communicate their land rights over the drawn objects. SmartSkeMa then automatically digitizes and geolocalizes this information making it easier to relate or integrate them with formal land administration information.

The rest of this article is structured as follows: Section 2 reviews the relevant background literature to position our research within the state-of-the-art. In Section 3 we present the Adaptor Model and give a detailed description of its implementation. Section 4 presents illustrative use cases where the Adaptor Model is applied. The results of an expert evaluation of the LDM-AM-LADM functionality within SmartSkeMa is presented in Section 5. Section 6 concludes the paper and includes an outlook on future work.

2. Background

2.1. Land Administration Challenges in Traditional African Agropastoral Communities

Traditional agropastoral communities often develop capabilities, knowledge, and codes necessary to maintain their viability under highly specialized environmental conditions with significant fluctuations in the available natural resources (Bollig and Schulte, 1999; Nyong et al., 2007). Even for contemporary societies, the management of natural resources is a core functionality of land administration systems (Brock and Tan, 2020). African countries are an indicative example of areas radically affected by the fluctuations in natural resources, which often jeopardize the viability of local populations. Most African countries are heavily dependent on land resources with a great variety of actors participating in land management processes. Understandably, land registration and monitoring are integral procedures of the land administration of contemporary governments. Although state sanctioned land registration initiatives in many African countries date back to the 20th century, rural land use registration remains a thorny issue for land administrators. Inconsistencies between the various land administration approaches at the local, national or international level, as well as the spatially and temporally dynamic character of the factors affecting the human-land relations result in controversial privatization and fencing off of large areas as well as exclusion of minority groups from the accessibility to land resources (Peters, 2013; Shipton, 1987; Unruh and Williams, 2013).

As Innes and Booher (2004) pointed out *“Planners and administrators can be out of touch with communities and local knowledge, but citizens can be out of touch with political and economic realities and long-term considerations for a community or resource”*. Although this assertion was made for the American case (and it appears to also apply to the European context, as expressed by Jones (2007)), it seems to be true in the African case as well. In Kenya for example, the weak understanding of how the traditional Maasai communities formulate their interest on natural resources often becomes the reason for serious conflicts between the Maasai and state authorities (Mwangi, 2005). Hence, a systematic account of the Maasai land tenure practices could negotiate an equilibrium between traditional tenure and the formal land administration schemata. To this process, public participation is valuable in

[1] https://smartskema.eu/data/smartskema_domain_models.zip
[2] https://smartskema.eu
[3] https://its4land.com/

terms of registering not only *objective* but also *subjective* perceptions of RRRs (Rights, Restrictions, Responsibilities). Despite some skepticism expressed about public participation (e.g. concerns about polarization, partial participation, implementation delays), wide, continuous, equal opportunity participation and systematic registration can improve information disclosure and data accuracy, and enhance clarity, which are all fundamental aspects of transparency (Moote et al., 1997).

2.2. The Web Ontology Language

The Web Ontology Language (OWL), is a suitable framework for expressing concepts and the relations between concepts in a systematic way; we give a brief introduction to OWL in Appendix A. OWL is used to formally describe *class hierarchies* (via “is-a” relations), *object properties* (the relation between the classes) and *instances* of classes (called *individuals* in OWL terminology). Our Adaptor Model is a mapping of concepts between (a) an OWL ontology for Land Domain Models (LDM) and (b) an OWL ontology for Land Administration Domain Model (LADM).

Furthermore, we use the semantic web rule language (SWRL) to model scenarios that cannot be modelled with simple OWL constructs. SWRL extends OWL with a rule-based syntax. Specifically, in Section 5 we employ SWRL rules to express conjunctions of object properties and class labels that must jointly hold on a set of instances for a third dependent object property or class label to hold.[4]

2.3. The Local Domain Models and the Maasai of Southern Kenya Local Domain Model

The Local Domain Models (LDMs) are ontological schemata for structuring case-specific information in a formal, computer-readable format. The LDMs are intended to register the various factors (i.e. social, economic, environmental) which form part of the status quo in land use. They provide the means to harmonize and align multi-source data as well as facilitating information analysis, distribution and reuse, in a highly flexible way.

The Maasai of Southern Kenya Local Domain Model (MSKLDM) is the LDM which registers concepts from the broader Kenyan Maasai system (i.e. environmental characteristics, activities, human society) (Karamesouti et al., 2018). The model is intended to capture information from the indigenous Maasai communities, communicated in a variety of modalities such as sketches, verbal communication, or through a computer software interface and supports the construction of a case-specific knowledge base. The MSKLDM was incrementally developed following the IDEF5 methodological approach (Benjamin et al., 1994). The latest version of the model consists of 280 classes (as of April 2020), which are meaningfully interrelated with *ObjectProperties*, i.e. linkages between classes and individuals of classes. The number of the *ObjectProperties* within the model was deliberately kept low in order to avoid functional conflicts between the MSKLDM and the LADM, i.e. we avoided developing linkages for functionality that is already captured within the LADM. The MSKLDM has eight high–level classes indicating the main aspects of the system, namely *SocialUnit* (social actors of the system), *EnvironmentalCharacteristic* (information about the vegetation, land and climate), *Activity* (various types of activities), *HomesteadComponent* (parts of a homestead), *Material* (various types of substances addressed in built or broader environment), *Shape* (geometric figures such as points, lines, polygons, circles), *Livestock* (domesticated or wildlife animals related to the Maasai system), *MSKDMSource* (registering metadata about the sources of information). Through a bridging mechanism, the Adaptor model links these high–level classes with the LADM relevant classes. Likewise, registered local information can be used for land administration purposes as portrayed by the LADM. In the Adaptor model discussed in the work by Karamesouti et al. (2018), the linkages have a one-to-one direct interpretation that restricts the degree of freedom and flexibility. Within the SmartSkeMa system an improved Adaptor model mechanism is established, making the system significantly more flexible as will be illustrated in Section 3.

2.4. The Land Administration Domain Model

The Land Administration Domain Model (LADM) is an international standard (ISO 19152:2012) for the development of interoperable knowledge bases, containing information about the relation between human and spatial entities (Lemmen et al., 2015). The LADM is not a specialized model that one implements directly in their system, but rather it is the basis on which a case-specific land administration model can be developed.

The number of different modalities in which the Land Administration Domain Model (LADM) has already been applied is a strong indication of the model’s flexibility and its potential to meet worldwide land administration needs (Table 1). For the majority of the case implementations the LADM is used for upgrading available land administration systems and in order to establish harmonized systems, facilitating domestic and international land administration information communication, following a top-down approach. The term *top-down* mainly refers to the interpretation of the existing legislation into standardized LADM concepts.

Particular LADM implementation cases include modelling in three dimensions (3D), capturing descriptions of unofficial land tenure and land use rights, and cases which attempt bottom–up information communication about how people actually use the land (Budisusanto et al., 2013; El-Mekawy et al., 2014; Felus et al., 2014; Janečka and Souček, 2017; Jeong et al., 2012; Kim and Heo, 2017; Kim et al., 2013; Oyetayo et al., 2015; Pouliot et al., 2013; Renzhong et al., 2011; Sengupta et al., 2013; Vandysheva et al., 2012; Zulkifli, 2014). The 3D implementations intend to describe rights above or below the earth surface and within constructions.

The interpretation of unofficial land use and land tenure rights through the LADM is performed in a variety of modes. In Malaysia, the various types of rights (i.e. qualified titles, temporary occupation licenses, customary or native land titles, reserved land) and the various modalities of spatial units (i.e. precisely demarcated, vaguely demarcated) are classified and elaborated in different levels (Zulkifli, 2014). In Indonesia customary land laws (i.e. adat law) as well as various types of restrictions (e.g. environmental restrictions) are incorporated into the LADM. These restrictions may result in topologically unstructured boundaries, a fact that was handled by the adoption of the term “Spaghetti Parcel” (Sucaya and Ary, 2009). In India, the indigenous population rights on forested land, which are already recorded by the existing legal framework, were modelled using the LADM. For the implementation in Vietnam, LADM was adjusted in order to be able to capture a particular case of customary rights. The land in Vietnam belongs to the state and citizens can only be considered land users but not landowners. However, land users can be the owners of developments above land including agricultural production (Le et al., 2012). In the Brazilian case there are official and unofficial cases of possession. Challenges were reported for the registration of certain cases of unofficial rights. Various types of restrictions (i.e. environmental restrictions, restrictions due to urban legislation, historical sites and protected areas) which were registerable on spatial units were considered, while difficulties for the incorporation of certain restrictions were reported as well (Dos Santos et al., 2013; Paixao et al., 2015). In Colombia the rights on communal lands, indigenous reserves and afro-descendant territories from abandoned lands or lands from where people were forcefully displaced, were modelled using the LADM. The rights were

[4] For a detail description of SWRL we refer the reader to the W3C submission defining SWRL at https://www.w3.org/Submission/2004/SUBM-SWRL-20040521/ (accessed 6th April 2020).

Table 1
LADM implementations around the world, categorised with respect to the modalities of their application.

LADM modality		Country
Information flow	Top - Down	Sweden, Cyprus. Poland. Czech Republic, Serbia, Croatia, Greece, Quebec, France, Turkey, Russia, Israel, Malaysia, Indonesia, India, Korea, South Korea, Vietnam, China, Brazil, Colombia, Cape Verde, Botswana, South Africa, Nigeria, Mozambique, Zimbabwe, Kenya
	Bottom - up	Malaysia, India, Colombia, Cape Verde, Botswana, Mozambique, Kenya
Functionality	Upgrade	Sweden, Cyprus. Poland. Czech Republic. Serbia, Greece, Turkey, Russia, Israel, Malaysia, Indonesia, India, Korea, South Korea, China, Colombia, Cape Verde, Botswana, Nigeria, Mozambique
	Compatibility	Cyprus. Poland. Croatia, Greece, Quebec, France, Israel, Korea, South Korea, Vietnam, Brazil, Colombia, Cape Verde, South Africa, Zimbabwe, Kenya
Dimensionality	3d	Sweden, Czech Republic, Greece, Quebec, France, Russia, Israel, Malaysia, Indonesia, India, Korea, China, Brazil, South Africa, Nigeria
Type of rights	Official	Sweden, Cyprus. Poland. Czech Republic. Serbia, Croatia, Greece, Quebec, France, Turkey, Russia, Israel, Malaysia, Indonesia, India, Korea, South Korea, China, Brazil, Colombia, Cape Verde, South Africa, Nigeria, Mozambique, Zimbabwe, Kenya
	Unofficial	Malaysia, India, Vietnam, Brazil, Colombia, Botswana, Mozambique, Kenya

modelled in different layers. The intersecting spatial units from different layers were considered as cases of restrictions (Guarín et al., 2017). In Mozambique LADM was used for a fit-for-purpose land registration by individuals. Land rights referring to unregistered occupations, which were established based on good faith and inter-community agreements, were modelled (Balas et al., 2017). In Kenya the LADM and its derivative model for unofficial land rights' registration (Social Tenure Domain Model - STDM) were adopted for the registration of spatial and non-spatial information, following the Cadastre 2014 principles and adopting the land parcel as the basic administrative unit, instead of the property, which is used by the traditional LADM (Kuria et al., 2016; Siriba et al., 2011).

2.5. The SmartSkeMa System

SmartSkeMa is a land tenure recording tool designed to support transparent community-based recording of land tenure information in rural and peri-urban areas (Chipofya et al., 2017). It accepts input in the form of scanned or photographed images of hand-drawn sketch maps and additional non-spatial attribute information entered as text and integrates this information into existing geo-referenced data.

SmartSkeMa's design responds to the gap in land information capture, left by two significant shortfalls of current land registration systems: 1. their inability to record informal and indigenous land rights (the system favors bottom-up *co-creation* of information about human relations over land) (Ho et al., 2019), and 2. their inability to automatically handle imprecise (qualitative) spatial reference information that is common in customary land tenure systems (Scott, 1998). It is composed of several components including: a specialized Local Domain Model and a visual language for sketching; a sketch recognition module for automated recognition and extraction of objects in sketch maps; and a qualitative spatial representation and alignment module for mapping sketched information onto underlying georeferenced datasets.

The key innovation in SmartSkeMa is the transformation of pictorial representations of hand-drawn sketch maps into a collection of digital objects with a clear semantic categorization and a qualitative spatial description that captures the salient relations among those objects in space. The new representation makes it possible to use land tenure data generated through low-cost community-based processes together with official data that conform to the LADM standard in a consistent way. This brings a new level of interoperability between indigenous or informal land tenure systems and official land administration systems. While SmartSkeMa has many advanced features here we only outline the main workflows to illustrate the technical environment within which our domain models are currently applied.

The SmartSkeMa tool has two main workflows (Fig. 1). Each workflow begins by loading an image of a hand-drawn map. The sketch recognition module processes the loaded image, producing a digitized version of the image in SVG format. SmartSkeMa automatically detects the feature types of drawn objects by recognizing symbols used by the sketcher as annotations of drawn objects. Fig. 2 shows how a sketch map looks after the sketch recognition step. In case the drawn objects are not detected or recognized correctly, SmartSkeMa includes a custom SVG editor that allows the user to draw, edit, or delete a drawn object. After the object recognition step the user can add non-spatial attributes to the drawn objects. Both the feature types automatically assigned by SmartSkeMa during the recognition step, and the attributes manually added by the user, are taken from concepts in the LDMs. The final step of the workflow is the sketch map alignment process by which the drawn objects are (qualitatively) geolocalized by automatically matching them to corresponding geographic map features of the base map (Chipofya et al., 2013; Chipofya et al., 2015;Chipofya et al., 2016). Once aligned, the input data can be explored in SmartSkeMa from a LADM perspective. The translation of concepts from LDMs into LADM is done in the background by the LDM-LADM-Adaptor model.

For the models presented in this paper, setting up SmartSkeMa begins with customizing an LDM and the corresponding LDM-LADM Adaptor model to capture the local social, cultural, and land related concepts. In parallel, a visual language defined by templates of symbols allowed in the sketch maps together with the LDM concepts, to which they refer, can be created. Once the LDMs and the visual language are setup, they are saved in the SmartSkeMa installation and the system is ready to be used in land documentation.

3. Connecting the LDM to the LADM

3.1. The Adaptor Model: Overview

Relating local land information to official records requires establishing connections between the LDMs and the official land information models. As already mentioned, we use LADM as a common basis for official land information models. In addition, for a tool like SmartSkeMa that is designed to be used in different cultural contexts, the connections must be made at a more abstract level. That is, rather than relating the most specific LDM concepts to LADM concepts, it is more appropriate to connect those higher level LDM concepts that are likely to be shared among several case-specific LDMs. This design choice is supported by the fact that the LADM and all official models designed on top of it are generic in that the land objects and relations they capture represent, de jure, aggregations of many different types of de facto land categories and relations. A clear example of this can be seen in the stipulations of the Community Land Act of the Republic of Kenya (2016). In that Act, community lands are set aside as lands *within* which local 'land laws' have legal standing, provided they conform to

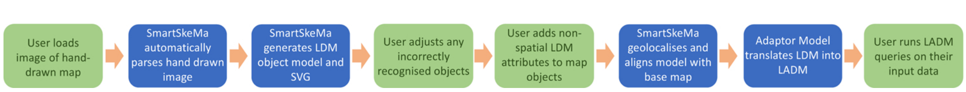

Fig. 1. SmartSkeMa workflow.

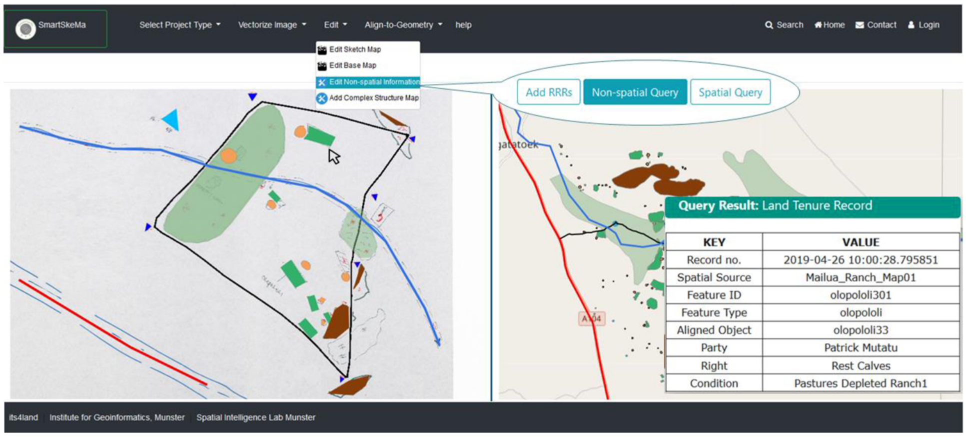

Fig. 2. SmartSkeMa in action - Information added using an LDM can be explored in terms of its LADM interpretation. The fields Party and Right (LADM concepts) above were added to the system as the LDM concepts SocialUnit and Activity - see Section 3 below.

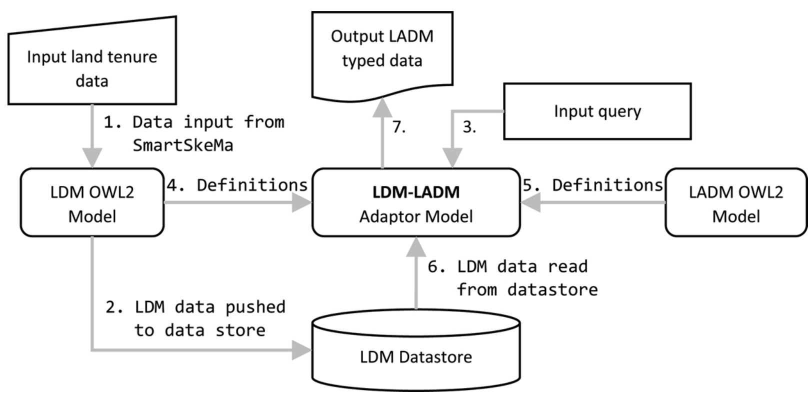

Fig. 3. The LDM-AM-LADM configuration: Inputs from SmartSkeMa's user interface are encoded as LDM facts and stored in the LDM datastore. Queries are passed into the Adaptor Model which retrieves the necessary facts and returns them in LADM format.

the country's constitution and other relevant laws. In the broader context, community lands are registered and given title just as any other category of land, but within the community land, community 'land law' applies. We quote 'land laws' to emphasize that these are not laws in the traditional sense. Within the broader legal framework, they are local rules or regulations for land governance that obtain their force of law only temporaneously through the act of community land registration.

Our approach consists of the abstraction from specialized concepts of the LDMs. This is achieved through a pruning of the LDM concept hierarchy. The result is a subset of the LDMs consisting of the 5 high-level classes: *SocialUnit*, *Activity*, *Status*, *EnvironmentalCharacteristic* and *SpatialEntity*. All LDMs with the same high-level classes can be seen as a family of LDMs and the same strategy applied here can be used to connect all such LDMs to the LADM.

The connection between LDMs and the LADM are modeled through the intermediate OWL schema we call the LDM-LADM Adaptor Model, abbreviated AM. The complete SmartSkeMa LDM-AM-LADM setup consists of three OWL files and a datastore configured as shown in Fig. 3. There are two separate configurations. The first configuration assumes LDM data and allows the user to make LADM queries to an LDM data source. The second configuration goes in the opposite direction, allowing LDM queries to be made on LADM facts. For brevity, and because the reverse direction has more intermediate steps and requires user interaction, we focus on the first configuration: from LDM to LADM. The underlying logic is the same.

The central elements of both configurations are the Adaptor Models which filter queries from one perspective to the other. The process follows the numbered steps as shown in Fig. 3. The arrows indicate the direction of information flow. First, incoming data are encoded as LDM facts by instantiating them using the LDM's classes and object properties. These data are stored in a separate datastore (step 2) which can be a simple OWL file or a more advanced system such as an RDF triple store[5] . User queries requiring a response from an LADM perspective are issued through the Adaptor Model (step 3). The Adaptor Model reads (imports) the definitions of all model elements from LDM and LADM (steps 4 and 5), reads the input data from the datastore (step 6) and uses these to generate a response containing facts labelled with LADM classes (i.e. facts that are instances of LADM classes). In the final step (7) the reinterpreted results are returned to the user.

3.2. The Adaptor Model: Technical Design

To interpret a related set of facts of an LDM into the LADM, the Adaptor Model must first be given a triple of classes of the form (*SocialUnit*, $<$ *condition* $>$, *Activity* or *Status*) connected by three object properties. The first of these object properties, *participatesIn*, connects a *SocialUnit* to an *Activity* or a *Status*. The relation *participatesIn* which has domain *SocialUnit* and range *Activity* or *Status* is a general relation in the generic LDM model which can be interpreted (read) as indicating that a particular social actor takes part in the stated *Activity* or occupies the stated *Status*. The other two object properties can be any one of the following pairs

[5] An example RDF triplestore is GraphDB (https://www.ontotext.com/products/graphdb/). See RDF technical report at https://web.archive.org/web/19980213212628/http://www13.w3.org/TR/WD-rdf-syntax/

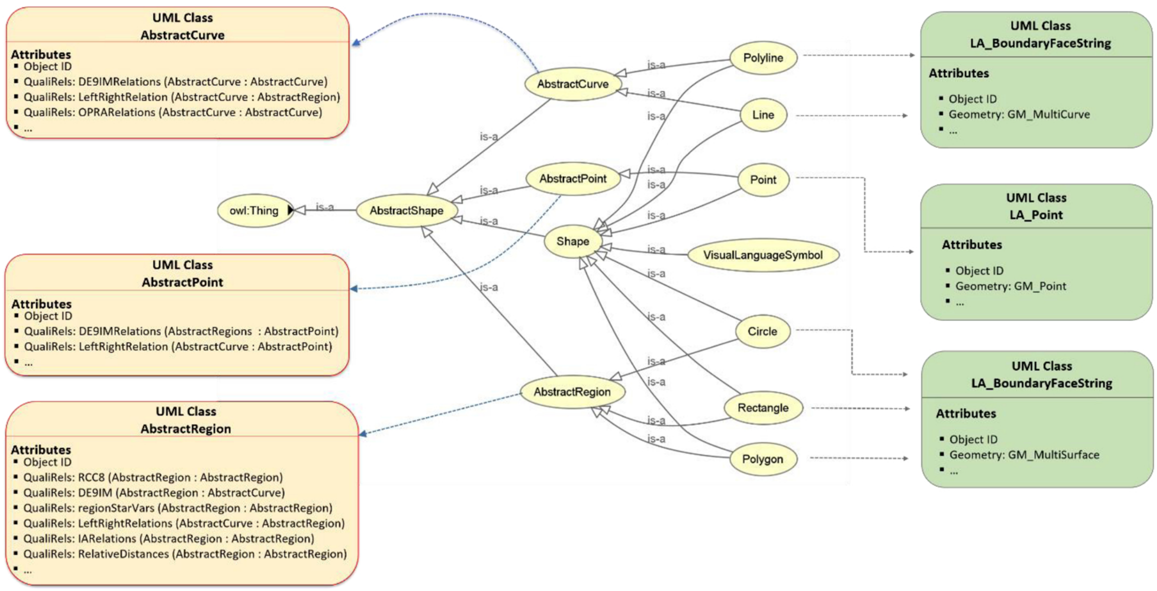

Fig. 4. Class hierarchy of the AbstractShape class and its subclasses and how they correspond to LADM geometry classes (olive green). AbstractShape and its subclasses correspond to spatial entities described using qualitative spatial relations as opposed to Cartesian or Geodetic coordinates.

i. `hasParticipationRestrictedBy` and `restrictsParticipationIn`
ii. `hasParticipationPermitedBy` and `permitsParticipationIn`
iii. `hasParticipationImposedBy` and `imposesParticipationIn`

3.2.1. From Activity or Status to RRR

The three object properties listed above enable the model to distinguish between facts that simply state that an activity occurs from those that assert that the activity is in fact a kind of RRR in LADM terms. Each of these pairs connects the *SocialUnit* to an *Activity* or a *Status* via an arbitrary object called < *condition* >. The < *condition* > "invokes" the rule that sets on the transformations as follows:

i. (`hasParticipationPermitedBy` o `permitsParticipationIn`) and `participatesIn` ⟹ `LADM::Right`
ii. (`hasParticipationRestrictedBy` o `restrictsParticipationIn`) and `participatesIn` ⟹ `LADM::Restriction`
iii. (`hasParticipationImposedBy` o`imposesParticipationIn`) and `participatesIn` ⟹ `LADM::Responsibility`

where 'o' is the OWL2 composition operator and '⟹' indicates implication. Once RRRs have been inferred, additional object properties will extend the inference to other types of objects in the model as appropriate. The first bullet can be read as saying that the object property chain *hasParticipationPermitedBy* o *permitsParticipationIn* is at the same time a kind of *hasRight* object property provided that it is also a *participatesIn* object property. Here the *hasRight* object property is defined in LADM. From the *hasRight* object property, the Adaptor Model infers that the *SocialUnit* in question is the *Party* in the LADM *hasRight* relation. The remainder of the object properties are transformed using related but slightly different patterns. In particular, to infer that the object on which the *Activity* occurs or to which a *Status* applies is a Basic Administrative Unit (*BAUnit*) in LADM, the following set of axioms are used:

i. `ConditionalRight` ≡ `isConditionalRight some Self` (`rollification of ConditionalRight`)
ii. `sConditionalRight` o `appliesAt` ⊆ `hasRightOnBAUnit`
iii. `sConditionalRight` o `occursAt` ⊆ `hasRightOnBAUnit`

The description above illustrates how the Adaptor Model infers that there exists some *Party* that has some *Right* on some *BAUnit*. Similar logic applies to LADM restrictions and responsibilities. Once the *Party*, *Right/Restriction/Responsibility*, and *BAUnit* have been established, additional reasoning steps proceed to evaluate the spatial representation of the *BAUnit*. Before we describe the reasoning applied by AM to derive LADM-typed spatial representations, it is useful to first describe how spatial concepts are modeled in the LDMs.

3.2.2. Spatial Unit, Spatial Entity, and Abstract Shape

Qualitative spatial information is a primitive information type in the SmartSkeMa model. It allows SmartSkeMa to connect imprecise knowledge given in sketch maps to standard information types used in Cadastral databases. This is achieved by introducing a spatial type called *Abstract Shape*. An Abstract Shape can be described by a concrete geometry when available or in purely qualitative terms if only relative spatial information is available. In the concrete case of the Maasai land use domain model, MSKLDM, the abstract shape is captured by the relevant class *AbstractShape*. The subclass *Shape* of the *AbstractShape* class has a geometry attribute which refers to the concrete geometry that describes the shape (e.g. Polygon, Polyline, Point, special shapes, or collections thereof). A shape is given by a set of coordinates in the Cartesian plane. Fig. 4 illustrates the relations between the geometry classes defined in MSKLDM and the corresponding classes in LADM.

Our extension of the spatial part of the LADM builds on the *SpatialUnit* class in LADM. In LADM the *SpatialUnit* class represents a generic container for the spatial component of a particular *BAUnit*. *SpatialUnit* derives its semantics from the particular LADM profile under which it is implemented. For example, in the Kenyan land administration system, using the Registry Index Maps as a reference, each polygon on the map for which there exists a reference to a record in the land register (maintained by the Land Registrar) represents an instance of *SpatialUnit* (Siriba and Mwenda, 2013; Wanyoike, 2001). *SpatialUnit* itself is not necessarily a geometry or other spatial representation but it is associated with a spatial representation such as a polygon which can have other properties – such as a topological description specifying for each boundary section the left and right side regions that it borders.

In the Adaptor model a *SpatialUnit* is associated with an *AbstractShape*. In an LDM such as MSKLDM every feature of interest is spatially defined by a *SpatialEntity* object which in turn may be described by an instance of the *AbstractShape* class. The interpretation of the class *AbstractShape* is that it is an object in Cartesian space (a point, a curve, a region, or a collection thereof). Under this interpretation, a point given by its coordinates is as good a point as one merely asserted – e.g. by the statement “the **north corner** of the boundary is at the foot of Mount Kilimanjaro”, the latter describing the point's position using qualitative spatial relations.

A spatial entity is related to its AbstractShape object through the object property *hasShape*. To infer that a Spatial Entity is a Spatial Unit the Adaptor Model applies a strategy similar to that used for *ConditionalRRR* and *BAUnit*. The following two object property chains form a cycle that determines that a Spatial Entity that represents the Spatial Aspect of a *BAUnit* must be a Spatial Unit:

i. `inverse(hasRightOnBAUnit) o appliesAt o hasSpatialAspect ⊆ hasBAUnitSpatialUnit`
ii. `inverse(hasRightOnBAUnit) o occursAt o hasSpatialAspect ⊆ hasBAUnitSpatialUnit`

3.2.3. Qualitative spatial relations

The Adaptor Model introduces a new profile of spatial unit represented by the class *QR_SpatialUnit*, a subclass of *LA_SpatialUnit*. A *QR_SpatialUnit* is a qualitatively described spatial unit defined to have an association to one or more *AbstractShape* instances. In practice, the user does not have to know of the existence of a *QR_SpatialUnit*.

The modeling of *QR_SpatialUnit* and *AbstractShape* makes it possible to:

i integrate spatial information extracted from hand-drawn sketch maps with more precise information from other sources at a compatible level of abstraction, and
ii incorporate new concepts that enrich the semantics of the identified spatial features, beyond LADM capabilities.

Within the MSKLDM these qualitative spatial relations specify the relative positions and locations of *AbstractShape* instances and are implemented as object properties with domain *AbstractShape* and range *AbstractShape*. For sketch maps the spatial relations are computed by the SmartSkeMa qualifier. For each sketched feature and each spatial aspect, a qualitative spatial relation is computed against every other applicable feature. For example, an *AbstractCurve* representing the feature River in Fig. 5 will have *LeftRight* relations with all other *AbstractShapes* in a sketch. If the *AbstractRegion* representing Boma1 in the sketch is on the left side of the river, the MSKLDM will contain an assertions of the form:

```
AbstractCurve:River  -[hasToTheLeft]->  AbstractRegion:Boma1
AbstractRegion:Boma1  -[leftOf]->  AbstractCurve:River
AbstractRegion:Boma1  -[containedIn]->  AbstractRegion:Ranch1
AbstractRegion:Ranch1 -[crosses]-> AbstractRegion:River
```

The *containedIn* relation in the example above allows the expression of containment relations between spatial features. Using the rollification design pattern (Appendix A) again the model can represent sub-BA Units and sub-Spatial Units through the *hasSubBAUnit* and *hasSubSpatialUnit* object properties. These in turn allow aggregations of BAUnits and spatial units under a single BAUnit as is often the case for multi-unit housing complexes. In the example of the Maasai communities in Kenya, that Bomas and Olopololis may be considered as sub-BA units of a family ranch. The specification of a sub-BA Unit and sub-Spatial Unit is given by the following axioms:

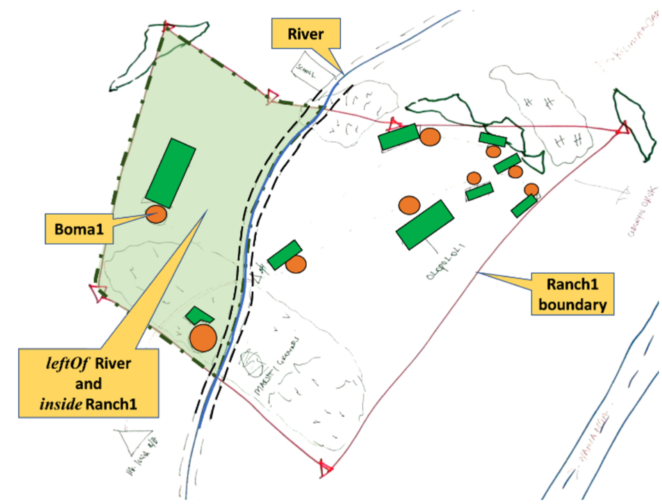

Fig. 5. Community drawn sketch map of a family ranch. The light green polygon labeled “leftOf River and inside Ranch1” represents the region satisfying the LeftRight (*leftOf* River) and the topological relation (inside Ranch1) where Boma1 is located.

i. `QRSpatialUnit ≡ isSpatialUnitWithShape some Self`
ii. `Range (isSpatialUnitWithShape (isSpatialUnitWithShape some Self))`
iii. `hasBASpatialUnit o inverse(isShapeOf) o contains o isShapeOf o hasSpatialUnitBAUnit ⊆ hasBAUnitSubBAUnit`
iv. `inverse(hasSpatialExtent) o hasBASpatialUnit o inverse(isShapeOf) o contains o isShapeOf ⊆ hasSubSpatialUnit`

The axioms above assert that if the geometries contain each other then we can infer a sub-BA Unit and a sub-Spatial Unit relation between the features concerned.

3.3. The Adaptor Model: Examples from the Maasai Of Southern Kenya Local Domain Model (MSKLDM)

In this section we illustrate the application of our Adaptor Model to examples based on data collected from field studies in a Maasai community in Kajiado, Kenya. The examples demonstrate the flexibility of the models and the power of semantic modeling for land administration applications. Each example illustrates a specific scenario that requires a reasoner to determine whether an individual (person or group of persons) can be seen to have rights as understood from an official perspective and how this determination can be altered based on local custom. All person names used in the examples are fictitious and made up. All land objects referred to in the examples are taken from the sketch map in Fig. 5.

At the end of each example we include a Description Logic query which asks the question and the corresponding response from the reasoner. These examples were executed using the HermiT[6] OWL/DL Reasoner in the Protégé OWL editor.[7]

We use a visual notation to illustrate the inference steps taken to arrive at a conclusion given a set of input data. The notation used is described in Fig. 6. Instances of classes from the domain model are represented by a rectangle with two parts. The upper part contains the class name and the lower part contains the assigned name of the instance. Class instances are connected to each other by object property instances. An object property instance is represented by a rectangular

[6] http://www.hermit-reasoner.com/
[7] https://protege.stanford.edu/

Visual Element	Description
SocialUnit / **id:** Kulesi Mutatu	Class instance. Top compartment specifies the class name and bottom part contains the instances name or ID in the model.
OP: participatesIn	Object Property instance labelled with object property name. Always connects class instances. May connect an instance to itself to indicate rollification.
●———	Connector from source class instance to object property instance.
———→	Connector from object property instance to second class instance in the relation.
- - - - - - →	Connector from premise (assumed) element to logical connector visual element.
- - - - - - ◆	Output connector from premise element(s) to inferred (implied) element.
AND	Logical connector. Labelled with the logical operation by which the inputs are combined. E.g. AND means that first input AND second input AND ... imply the elements at the ends of the output connectors.
●- - - - - -	Connector from source class to inferred object property instance (after inference).
- - - - - - →	Connector from inferred object property instance to second class instance in the relation.
OP: hasRight	Inferred Object Property instance.
1	Step number in inference of new model elements. All diagrams in the examples show only inferred object properties.

Fig. 6. Visual elements for inference diagrams used in Examples 1 to 4.

shape with rounded corners. The connector is dot shaped at the beginning and has an arrowhead at the end indicating the direction of the relation. To show inference steps where a combination of model elements (e.g. object properties) imply another element, dashed lines with arrowheads starting at the input elements join at a diamond shape. This diamond shape is labeled by the type of logical connective it represents (AND, OR, or XOR). The implied element is connected to the diamond shape by another dashed line which has a small filled diamond at its end. Where there is only one premise to an inference step, the elements can be connected directly. Inferred elements are labeled by numbers to indicate the order in which they occur.

The diagrams are intended for illustration and do not represent the precise way the reasoner draws its conclusion for the premises. They also simplify presentation by eliminating other information used by the reasoner but not required to understand the logic behind the inferences.

3.3.1. *Example 1 – Establishing pairs of facts introducing conditions*

This example illustrates how LADM rights are derived from MSKLDM concepts. Consider the relationships between two individuals, Agnes Kesho and her sister, Kulesi Mutatu. Both women live in Agnes Kesho's house, recorded in the MSKLDM as *House1*. In the MSKLDM these relationships are represented by the following set of relations:

```
(Ex.1.1) SocialUnit:AgnesKesho –[participatesIn]→ Activity:OccupationByAgnesKesho
(Ex.1.2) Activity:OccupationByAgnesKesho –[occursAt] → HumanDwelling:House1
(Ex.1.3) SocialUnit:KulesiMutatu –[participatesIn]→ Activity:OccupationByKulesiMutatu
(Ex.1.4) Activity:OccupationByKulesiMutatu –[occursAt] → HumanDwelling:House1
```

Translating these data into LADM facts entails asserting that both *AgnesKesho* and her sister have the right to occupy *House1*. But their rights of occupation are not the same. Agnes Kesho has a permanent right of occupation because it is her home. Kulesi Mutatu has the right of occupation by virtue of her relationship to Agnes Kesho. To make the translation of the input data into LADM facts the Adaptor Model looks for the triangle of (*SocialUnit*, < *condition* > , *Activity* or *Status*) instances which the user specifies by asserting the following:

```
(Ex.1.5) SocialUnit:AgnesKesho –[hasParticipationPermitedBy]→ TimeAlways:TimeAlwaysAgnesKesho
(Ex.1.6) TimeAlways:TimeAlwaysAgnesKesho –[permitsParticipationIn]→ Activity:OccupationByAgnesKesho
(Ex.1.7) SocialUnit:KulesiMutatu –[hasParticipationPermitedBy]→ Activity:OccupationByAgnesKesho
(Ex.1.8) Activity:OccupationByAgnesKesho –[permitsParticipationIn]→ Activity:OccupationByKulesiMutatu
```

The class *TimeAlways* in the MSKLDM represents time intervals that extend for the duration of any instance in the model (in this case *AgnesKesho*). The assertions above say that *timeAlways* qualifies the *participatesIn* relation between *SocialUnit* instance *AgnesKesho* and *Activity* instance *OccupationByAgnesKesho* as a relation between an LADM *Party* and an LADM *Right* as given in the model description in Section 3.1.

The corresponding interpretation for *Activity* instance *OccupationByKulesiMutatu* is qualified by Agnes Kesho's occupation of *House1*, namely, the *Activity* instance *OccupationByAgnesKesho*. The reasoner can infer from this that in LADM the instance *AgnesKesho* has type *Party* and *OccupationByAgnesKesho* has type *Right*. The reasoner infers from the domain and range specifications of *hasRightOnBAUnit* that *House1* has LADM type *BAUnit*.

Fig. 7 shows the configuration of instances and object properties in this example. If the condition had not been connected to *SocialUnit* and *Activity* in the object property chain then none of the inferences would have been made. For example, if there was no traditional stipulation that Anges Kesho's sister has the right to reside in Agnes Kesho's home, then her (the sister's) occupation of *House1* would not be interpreted as a *Right*. The condition, therefore, allows the model to distinguish between RRRs that have an official interpretation and those that do not. At the same time, the condition attaches additional information about a specific RRR which varies the situations under which the RRR holds.

Query

The following DL Query can retrieve all Parties with permanent rights, specified by the *TimeAlways* condition:

```
(Qry.1.1) hasParticipationPermitedBy some TimeAlways and hasRight some RRR
```

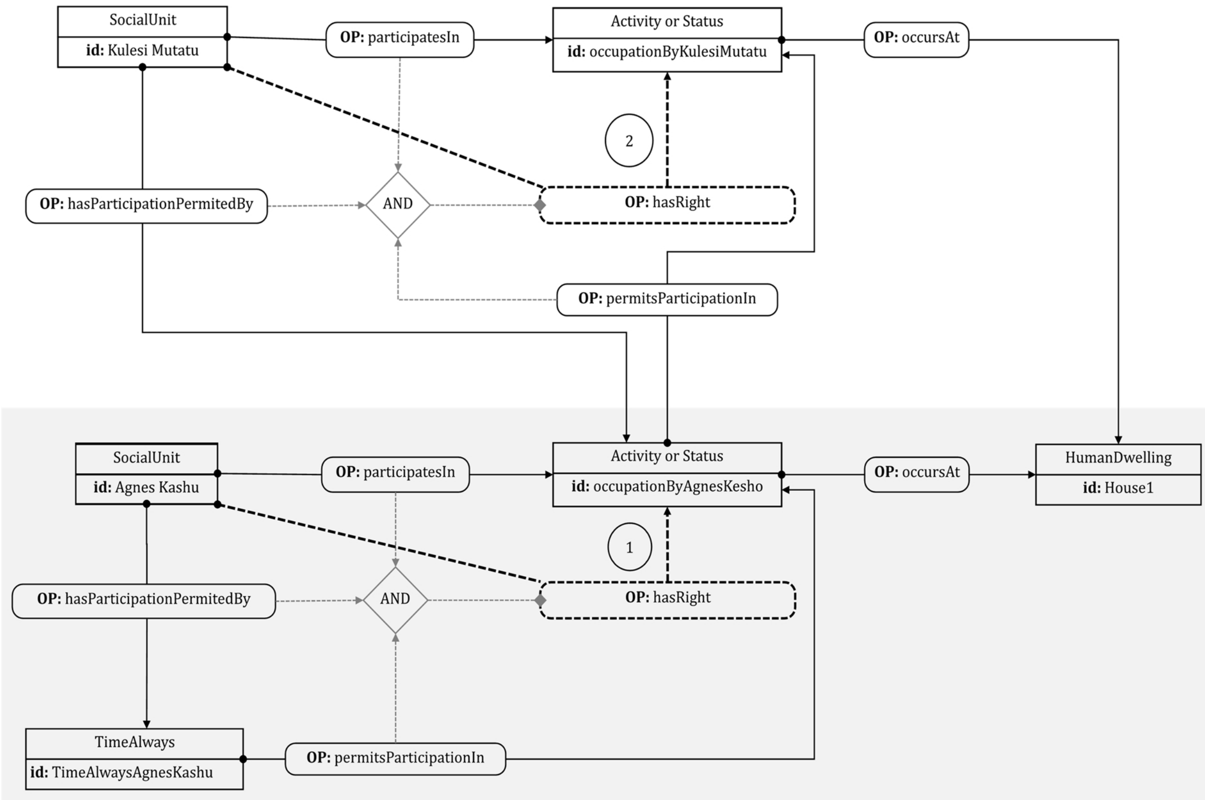

Fig. 7. Instance diagram demonstrating how LADM rights are derived from MSKLDM concepts (Example 1).

Response: Agnes Kashu

To retrieve only parties whose rights are derived from the existence of another right (or restriction or responsibility) one replaces *TimeAlways* with *Right* (or *Restriction* or *Responsibility* as the case may be):

```
(Qry.1.2) hasParticipationPermitedBy some Right and
hasRight some RRR
```

Response: Kulesi Mutatu

3.3.2. Example 2 - RRRs framed by non–spatial aspects

From our case studies we have determined that participation in a specific social group (i.e. clan, tribe), which is registered in MSKLDM as a *SocialCharacteristic*, plays an important role in human-land relations. An instance of the class *SocialUnit* with a specific ethnicity may be able to have rights on land (i.e. right to own or right to lease land) in a specific area, but the same *SocialUnit* might be barred from any right on land in another area, exclusively because of their social identity. One formalization of this example within the LADM framework is presented in (Schultz et al., 2019) (Scenario 1B). In the MSKDM this can be achieved by:

1 Using the object properties *isMemberOf* and *isNotMemberOf* to declare the membership relation between each social unit representing a person and a social unit representing a group such as a clan or family.

2 Explicitly stating the clan that has recognized claim over a region of land registered in the MSKLDM. This is achieved using the object properties *claimsExclusiveRightTo* (domain: *SocialUnit*, range: *Activity* or *Status*) and *hasJurisdictionOn* (domain: *SocialUnit*, range: *LandCharacteristic*). The following SWRL rule states that an exclusive right is validated whenever it is asserted that the social unit has jurisdiction over the land object on which the exclusive right is claimed[8] :

```
(Ex.2.1) SocialUnit(?x) ^ Activity(?y) ^
LandCharacteristic(?z) ^ hasJurisdictionOn(?x,? z) ^
claimsExclusiveRightTo(?x,? y) ^ occursAt(?y,? z) →
hasValidatedExclusiveRightTo(?x,? y)
```

3 With the potentially validated right at hand the following SWRL rule is used to infer that clan members have *participationPermitedBy* the clan and that non-family members are excluded from the activity or status in question:

```
(Ex.2.2) SocialUnit(?x) ^ SocialUnit(?y) ^ Activity
(?z) ^ isMemberOf(?x,? y) ^ hasValidatedExclusive-
RightTo(?y,? z) → hasParticipationPermitedBy(?x,? y)
(Ex.2.3) SocialUnit(?x) ^ SocialUnit(?y) ^ Activity
(?z) ^ isNotMemberOf(?x,? y) ^ hasValidated-
ExclusiveRightTo(?y,? z) → adaptorHasNoRight(?x,? z)
```

The significance of establishing the object property *hasValidatedExclusiveRightTo* is that it implicitly binds the *Activity* which is being interpreted as a right to a fixed land object on which the *Activity* (or *Status*) occurs. A claim to an exclusive right is validated only when the claiming party is recognized as having jurisdiction on the land object to which the claimed right applies. Because *hasValidatedExclusiveRightTo* ⊆ *permitsParticipationIn* combining rules Ex.2.1 and Ex.2.2 with assertion *participatesIn(?x,? z)* results directly in a *hasRight* relation as illustrated in Figs. 8 and 9.

[8] An SWRL rule has the form $\text{Predicate}_1(?\text{var}_1, ...,?\text{var}_i) \wedge ... \wedge \text{Predicate}_m(?\text{var}_j, ...,?\text{var}_k) \rightarrow \text{Predicate}_{m+1}(?\text{var}_p, ...,?\text{var}_q)$ where the '?var' terms are variables that usually occur in more than one predicate, the '^' symbol represents conjunction, and the symbol '→' represents implication. An evaluation of a rule involves finding actual individuals in the knowledge base that satisfy the predicates on the left-hand side and apply the predicate on the right-hand side.

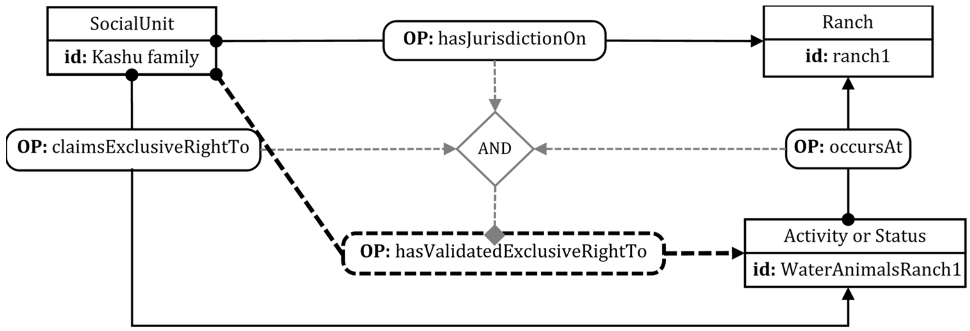

Fig. 8. Instance diagram demonstrating RRR based on non-spatial aspects (Example 2).

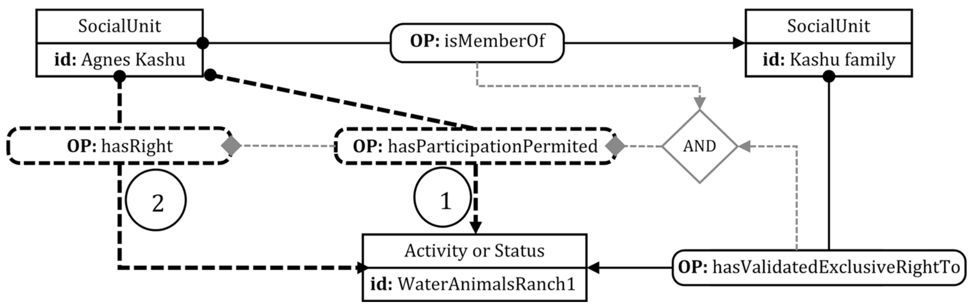

Fig. 9. Instance diagrams illustrating the case that Agnes Kashu has a right to water animals in Ranch 1 (an activity), because she is a member of the Kashu family who has exclusive access (Example 2).

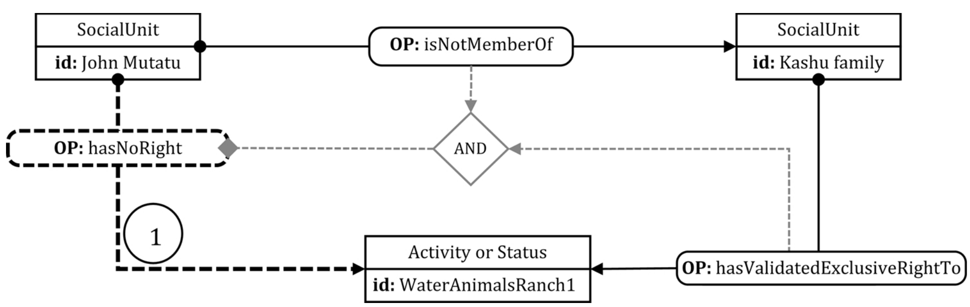

Fig. 10. Instance diagrams illustrating the case that John Mutatu does *not* have a right to water animals in Ranch 1 (an activity), because he is not a member of the Kashu family who have exclusive access (Example 2).

The instance diagram in Fig. 10 shows a concrete example where the person John Mutatu who does not belong to the Kashu family has no right to the activity *WaterAnimalsRanch1* in the ranch *ranch1* because he is not a member of the Kashu family while Agnes Kashu has that right by virtue of her belonging to the family (Fig. 9).

Query

To find all individuals that explicitly have no right on *ranch1* the following DL Query is used:

```
(Qry.2.1) hasNoRight some (occursAt some {ranch1})
```

Response: John Mutatu

or to check which activities John Mutatu 'explicitly' has no right to:

```
(Qry.2.2) Inverse(hasNoRight) some {JohnMutatu}
```

Response: WaterAnimalsRanch1

3.3.3. *Example 3 – Nested regions, Sub-spatial Units and Sub-BA Units*

Bomas and ranches are nested regions where rights on the ranch level affect rights on the boma level. Similarly, a water resource such as a borehole within a family's or a clan's land may have different rights for members of the family vs. non-members. The conditions that determine these rights could be singular or varied. As in the example above, the transitivity of rights can be expressed directly in the LDM and expressed as LADM rights through the Adaptor Model. Separating the RRRs on the container (e.g. the ranch) from the RRRs on the contained land object (e.g. a boma) is important because these rights will often be different as illustrated in this example.

In this example, *boma1* and *borehole1* are both part of the ranch *ranch1* as expressed by the assertions that the shape of the spatial extent of *ranch1* contains the corresponding shapes for *boma1* and *borehole1*. The Kashu family having jurisdiction over *ranch1*, and thus can be assumed (in the absence of contradicting information)[9] to also have

[9] This relates to the field of *defeasible* reasoning, a form of non-monotonic reasoning in which rules can take the form: by default (on authority) assume a proposition Q is True, unless we know or can deduce that it is False. Defeasible reasoning is the logical framework that many formal legal systems are based on e.g. LegalRuleML (Athan et al., 2013). In this example the assumption is that jurisdiction over the ranch is extended to the boma and borehole on the ranch. This assumption holds by default, but can be "defeated" if new information is gathered that contradicts the assumption.

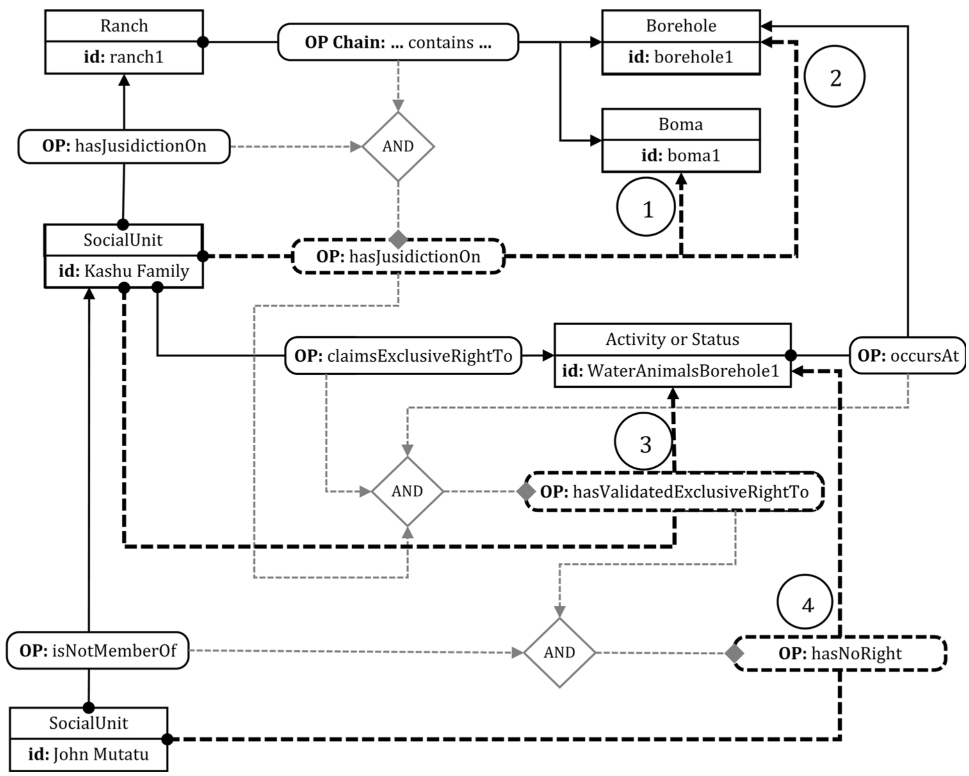

Fig. 11. Inference diagram illustrating the case that the Kashu family, by default, is assumed to have jurisdiction on boma1 and borehole1, because the Kashu family has jurisdiction on Ranch 1 which contains boma1 and borehole1 (Example 3). This assumption can be "defeated" (retracted) if new information contradicts this assumption.

jurisdiction over *boma1* and *borehole1*. In the model this is handled by adding the general rule that:

```
(Ex.3.1) hasJurisdictionOn(?x,? y) ^ hasSubBAUnit
(?y,? z) → hasJurisdictionOn(?x,? z)
```

Now consider the prior restriction that only clan members are allowed to take their animals to drink water within *ranch1*. This obviously does not hold within Maasai communities (as a rule, though there may be rare exceptions). On the other hand, it is often the case that non-clan members cannot water their animals at the clan's borehole except possibly with prior permission. Such restrictions have parallels in many cultures, justified by the understanding that the expenditure of labour is often the source of exclusivity in rights, and are exemplified in many well documented historical and contemporary examples of land tenure relations (Malinowski, 1935, chapters XI and XII; Meek, 1946, pg 19).

Extending the model with the rule above allows us to do just that. The user must state that the Kashu family claims exclusive right to activities on the *borehole1*. The resulting state of the model and inference steps taken by the system are shown in Fig. 11.

Query

John Mutatu has been automatically registered as not having the water animals right on *borehole1* but nothing is said by the model about whether he has the right over the ranch in general even though this right should hold for all natural water bodies within the ranch. The corresponding DL query is:

```
(Qry.3.1) hasRight some (AgropasturalActivity) and
hasRRR some (occursAt some {Ranch1})
```

Response: Agness Kashu

The DL query tacitly assumes that *WaterAnimalsBorehole1* has type *AgropasturalActivity* which is a subclass of *Activity*. To assert the fact that John Mutatu has a *AgropasturalActivity* right on a natural water body on the ranch, we would have to specify that he has that right for each and every natural water body item by item. The challenge here is the inability to handle default facts in OWL DL as explained in the observations section below, i.e. by default *AgropasturalActivity* on objects of type *NaturalWaterBody* contained in a *Ranch* should hold for all *SocialUnit* objects.

3.3.4. Example 4 – Staying within LADM while using LDM and the Adaptor Model

Our proposed framework allows for all entities in a particular knowledge base to be expressed directly in LADM. Thus, our framework can be used in ways that do not distort or alter standard LADM based models while allowing for the integration of more non-standard land tenure information models. For example, stating that John Mutatu has private exclusive rights to draw water for his livestock from *borehole2* located within his compound we simply assert that the *SocialUnit* 'John Mutatu' has exclusive rights to the activity *WaterAnimalsBorehole2*, that he has jurisdiction over '*borehole2*' at which this activity occurs, and that he participates in this activity (See Fig. 12). The activity *WaterAnimalsBorehole2* could be replaced by any other LADM right to yield the same result. The reasoner here uses the reflexivity of *isMemberOf* to apply the same logic as applied in Example 2.

3.4. Observations and pitfalls

Although OWL2 DL is a powerful language for expressing and reasoning over domain knowledge it is deficient in significant ways, as we describe below. Moreover, while SWRL alleviates some of these deficiencies, it is not enough to allow land domain modelers to define a generalized dynamic land tenure domain model that encompasses the entire spectrum of land tenure systems from the formalized (e.g. LADM compatible) to the unformalized (e.g. MSKLDM) or even a reasonable part of it. These deficiencies are a design tradeoff. Logical statements within Description Logics can be reasoned on efficiently while algorithms for reasoning over statements in the full first order logic cannot be guaranteed to ever complete (i.e. full first order logic is undecidable).

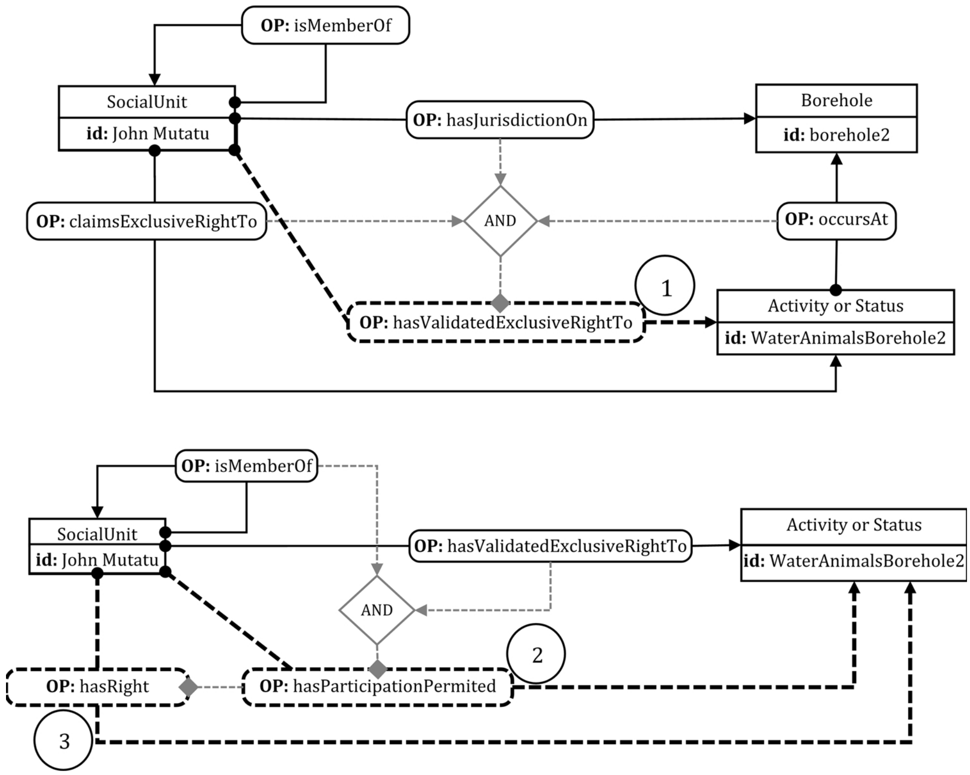

Fig. 12. Instance diagrams illustrating seamless integration of LDM concepts directly with an existing LADM model (Example 4).

One of the limitations of reasoning over DLs is that, since they are (largely) fragments of First Order Predicate Logic, the reasoning is monotonic. That is, any conclusions made before adding a new clause cannot be retracted when new knowledge has been added that contradicts the previous conclusions. E.g. Example 3 expressed a defeasible rule that, by default (on the authority of domain experts in land administration) jurisdiction of the Kashu family extended from a ranch to features contained on the ranch, namely the boma and borehole. This is not deduction (an example of a *monotonic* inference), as this assumption could later be determined to have been False in light of new information proving that some particular member of the Kashu family did not have jurisdiction over the boma or borehole.

In the example we resolved this by introducing more specific exclusive rights that apply not on the entire ranch but on specific sub-BA Units within the ranch. But this does not solve the problem entirely. It exposed the limitations brought about by the inability to express default assumptions. This is directly related to the open world assumption underlying OWL. The open world assumption implies that anything that is not explicitly stated in the model cannot be assumed to be either true or false. It is simply unknown with the information currently available. A consequence is that we must explicitly assert all positive and negative statements such as *isMemberOf* and *isNotMemberOf*. A practical example of the restrictions this imposes on modeling complex land tenure systems is the inability to express default assumptions as alluded to above. As part of our future work we are investigating an alternative query engine implementation within the logic programming paradigm Answer Set Programming, which supports default reasoning and other forms of non-monotonic reasoning.

4. Are LDMs and the Adaptor Model seen as useful in Practice? An expert evaluation

We have seen in the discussions in the preceding section that although the local domain model and adaptor model are able to represent land tenure information in a way that makes it possible to view them from the perspective of an official land administration model, some concepts and relationships were too complex to be implemented within the OWL-DL language. In addition to those challenges, it is also necessary to address the question of practical applicability.

We evaluated the practical applicability of the domain models presented in this paper for land tenure documentation and administration. This was done in the context of the SmartSkeMa system through expert evaluations. The evaluations were organized in the form of expert panels supplemented with a short questionnaire. Participants at the panels included professionals from the private sector (6) and NGOs (12) and Government departments involved in land administration (3). Three sessions were conducted altogether with 21 participants providing completed questionnaires. Questionnaires from an additional 7 participants were incomplete and therefore not included in the evaluation. In this section we report only on the results relevant to the domain models.

A session comprised two parts. First a demonstration of the main functional parts of the SmartSkeMa system was given: i) the domain model developed for one community in Kajiado was explored, and ii) the SmartSkeMa land tenure documentation workflow was demonstrated using an example sketch map from the same study site in Kajiado.

The second part comprised the expert panel discussion and completion of the questionnaire. Questions posed through the questionnaires evaluated expert impressions of the SmartSkeMa tool along 3 main dimensions: (1) ability to support conventional land tenure recording activities, (2) ability to facilitate community driven land tenure recording systems, and (3) applicability in other land administration functions. A follow-up discussion also held in plenary produced a SWOT analysis of the tool from the experts' perspectives.

The discussion panel revealed a clear division in perspective on the issue of land tenure documentation. In particular those participants who considered SmartSkeMa to be only *partly useful* focused on the

Table 2
Summary of participants' perceptions in the usefulness of SmartSkeMa for land tenure recording.

Usefulness for land tenure recording	Reasons	Comments
Partly useful	Poor geometric accuracy or poor precision	Poor accuracy or precision will lead to legal impediments. May not work in densely populated areas.
Very useful	Can be used to delimit communal land rights; physical planning; updating official maps; delimiting communal land rights; consultation and public participation; reach consensus when recording land rights; record information from community perspective.	Requires interoperability with government systems, government buy-in, and may face legal impediments.

geometric aspects of mapping land with SmartSkeMa. The most common reason given for the unfavorable assessment was that the tool might not reach legal accuracy thresholds for urban or peri-urban areas. For those who assessed the tool positively, it was the ability to capture the non-standard land rights together with the participatory nature of the tool's workflow that stood out. Table 2 shows a summary of the assessments produced in the expert panel showing clearly the division described above. While not emphasized in the discussion, some participants remarked that SmartSkeMa would not be very useful in the conventional land registration processes in urban areas (leasehold titles) where procedures are already fixed by legal and regulatory statutes (e.g. under the Land Registration Act (Kenya) of 2012).

In relation to the domain models, the most agreed upon observations among all participants were that:

1 SmartSkeMa can have a positive impact in the implementation of the Community Land Act (Kenya) of 2016 mainly due to its ability to precisely represent customary land rights.
2 The participatory nature of the application is its greatest strength.
3 There would be challenges for implementation arising from the legal regime and the lack of clarity on implementation of the Community Land Act.

In terms of facilitating community driven land tenure recording systems SmartSkeMa was considered favourably (See Fig. 13). Of the 21 participants, 18 believed that SmartSkeMa could support communities to register and govern their lands according to local customs. 16 of 21 participants thought that the tools as presented could be used with standard land administration systems at county or national level while a surprisingly lower 15 of 21 thought that CSOs, NGOs, and/or the broader civil society would be able to use the tool independently, mostly due to lack of expertise.

The results of the expert evaluation sessions gave us some targets to focus on in the near term. These include publishing a new version of the tool so that users can test it on their own data and seeking further

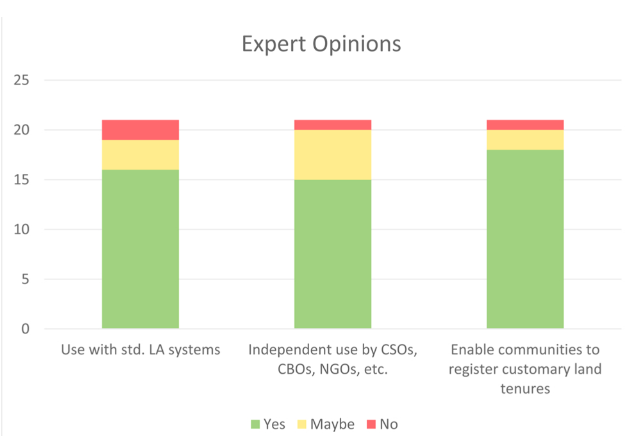

Fig. 13. Expert views on SmartSkeMa usefulness based on the inclusion of the land information domain models.

collaboration with some of the session participants to further explore how the tool can be used in their work. This is what we set out to do in 2019. One of the recommendations cited as an opportunity in Table 2 was to incorporate aerial images or orthophotos as reference surfaces for the sketching. This way sketches can be automatically digitized and more precisely georeferenced by the SmartSkeMa tool. In response we have now implemented this functionality. Since the present work does not focus on the spatial/geometric aspects of SmartSkeMa's functionalities, we direct the reader to Koeva et al. (2020) who reported that SmartSkeMa output geometries were within 1.29 m of actual cadastral boundaries for a small sample set of plots.

We will continue to add features to respond to stakeholder needs. As we go forward, we are beginning to engage stakeholders in the implementation of the *Community Land Act*. We believe that in this, Kenya will become the prime example of how good land policy can help ensure sustainable livelihoods for rural communities.

5. Conclusion

Local Domain Models are ontology-based mechanisms that enable systematic organization of indigenous knowledge.

The practical relevance of these models is made visible by the growing acknowledgement of the need to incorporate indigenous, customary, and informal forms of tenure into standard land administration systems. The Community Land Act of 2016 in Kenya and the Customary Lands Act of 2016 in Malawi are cases in point. As Alden Wily (2018) points out, these are not isolated instances. Laws attempting to recognize and/or otherwise regulate customary land laws are sprouting all across the African continent. It is no wonder that experts in the land domain in Kenya considered the concept of LDMs to be particularly relevant for the implementation of the Community Land Act.

The flexibility and adaptability of LDMs make them particularly useful for jurisdictions with a wide variety of land tenure norms. As the examples of Section 3.3 illustrate, the combination of LDMs with the Adaptor Model allows all those different tenure norms to be viewed through the singular lens of an official land administration system using the LADM standard. The LADM has been applied widely (See Table 1) and thus makes the perfect model for interfacing LDMs with official land administration information models. However, if the LDM is poorly designed it will produce undesirable results. There is therefore a need for expertise to develop the initial version of an LDM.

The focus of this paper is the Adaptor Model and how it supports different types of land tenure relations. The choice of using OWL models for the implementation of the Adaptor Model was based on the simplicity and understandability of OWL itself. However, we have also discussed some shortfalls of using the logic model within which OWL is implemented i.e. Description Logics or DL. Clearly that it is not possible to model all the scenarios that one may reasonably expect to encounter in any land tenure system. However, some of the restrictions presented by DLs such as indefeasibility can be resolved through non-monotonic reasoning. We propose a thorough study of the application of non-monotonic reasoning methods and tools such as Answer Set Programming for the modeling and implementation of land information models that incorporate a wide range of land tenure systems encompassing both the unofficial and the official realms.

While the focus of the present paper is the Adaptor Model, the focus of the broader project, of which this work forms a part, is the design, implementation, and demonstration of land information systems that are inclusive and fair by design. Through the incorporation and interpretation of the LDM information and the introduction of conditions into the LADM, full-fledged fit-for-purpose land administration tools can be realized. Another critical component of such land information systems is a hyper-decentralized and distributed information management subsystem required to implement community operated land registries. These community owned and community operated land registries are the ultimate goal of the overall project.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. A Friendly Description of the Ontology Web Language

In this section we briefly introduce basic concepts of the Ontology Web Language (OWL). OWL was developed as an extension of the RDFS (Resource Description Framework Schema) and it is formulated to describe classes, object properties (the relation between the classes) and instances of classes (called individuals in OWL terminology). The classes are the elements which store concepts describing the target domain and are hierarchically structured based primarily on an "is-a" relation. The higher classes in this hierarchy represent more general concepts, compared to those in lower hierarchical positions (Fig. A1). For example, the class "bird" is of higher level compared to the class "parrot", which in turns is a higher-level class compared to the class "Psittacoidea" (which is a parrot kind). The "is – a" relation is a class axiom which provides fundamental information about a class and its relation to other classes of the OWL schema. Other fundamental class axioms are the *equivelentClass* and the *disjointWith*, which indicate the equivalence and the disjuncture between the class individuals accordingly.

The individuals are the specific members of a class. For example, the class Parrot is a general space where one can register any object which, based on specific characteristics, is defined as a parrot. However, my parrot Alex, is one very specific object from the general class Parrot. Every specific object of *type* Parrot is an individual of the class Parrot. Object properties are the linkages between the individuals of different classes. A domain and a range can be specified for every object property, restricting the suitable individuals for each specific object property. For example, the object property "kidHasBall" may have as domain the class Kid and as range the class Ball. If Ann is an individual of the class Person, and the blueBall is an individual of the class Toys, the object property instance "Ann kidHasBall blueBall" implies that Ann is also an instance of the class Kid and blueBall is a Ball. Like the classes, the object properties also have axioms which show their relations to other object properties. These include equivalence, inverse, and composition relations. They also have cardinality constraints (how many individuals can be related by the object property) and logical characteristics such as asymmetry, symmetry, transitivity and reflexivity. In general object properties allow an owl reasoner to infer the types of objects involved and to restrict how these objects can be related.

Designing an OWL ontology that performs a translation between two other distinct ontologies requires using ontology design patterns that regularize the treatment of certain patterns in the problem domain. One pattern that is used recurrently in the adaptor model is rollification in which classes are turned into roles using an object property that relates each individual with itself. An example of rollification would be the object property isBallLovingKid which would apply to individuals of type Kid who love playing ball games. Determining that an Kid has role isBallLovingKid could then be based on several independent conditions such as that if a Kid plays with their ball more than 5 times a week then they have role isBallLovingKid. In turn role can be composed with other object properties which is what makes them a powerful for semantic modeling.

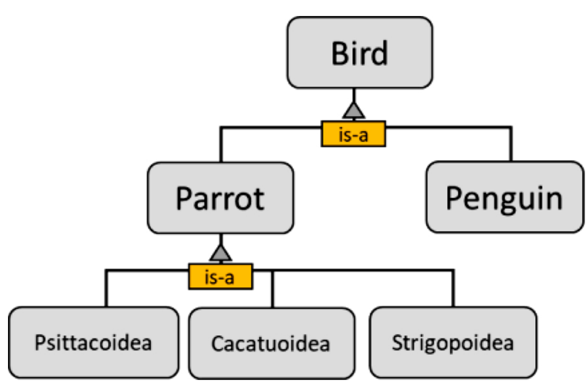

Fig. A1. Example of class hierarchical distribution in OWL.

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