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Land Evaluation Configuration using Answer Set Programming

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Abstract. In the realm of Land Evaluation (LE) inter-disciplinary and transdisciplinary knowledge exchange is critical for land use preservation. Geographic Information Systems (GIS) are powerful tools for real-world Knowledge Representation (KR), facilitating inter- and trans-disciplinary communication. In such knowledge exchange contexts, heterogeneity, ambiguity, abstraction are only indicative issues, underscoring the necessity for a rigorous commitment to broader transparency in KR. Answer Set Programming (ASP), a declarative, human-readable, logic-based formalism, could serve this objective and facilitate productive, case-relevant dialogues. Similarly to the fundamental GIS knowledge organization structures, ASP formalizes knowledge as entities and relations between them. In current work, leveraging Rossiter's theoretical framework for LE, and employing ASP, we aim for greater transparency in the epistemological and ontological assumptions underpinning the complex LE problem. ASP-based system configuration is used to formalize the LE Problem Instance as Components (C) with Properties (P) and Values (V). Fact-type specifications in predicate format materialize relations between problem components. Over 40 concepts, corresponding to distinct domains, 30 mereological relations and relational requirements between components, and 60 requirements on component properties have been described. We showcase the Problem Instance formalization of the non-spatial, single-area LE, based on Land Characteristics (LC), model type. The clear separation between domain knowledge (Problem Instance) and high-level theories (Problem Encoding) enables the consistent LE problem formalization using the ASP-based system configuration paradigm. A declarative Problem Instance formalization provides insight into the problem's nature and assumptions. Modular knowledge formalization using ASP, among others, enhances flexibility, scalability, and adaptability, given new knowledge becomes available.

Keywords. declarative knowledge representation, logic programming, transparency, model semantics, problem instance

1 Introduction

Land evaluation is crucial for averting the implications of improper land use, including environmental degradation, social unrest, and financial crisis (Ariti et al., 2015; Lambin et al., 2001). Acknowledging land's pivotal role in providing goods and services, its responsible utilization in the present and future is imperative. Historically, land evaluation was predominantly approached from an agricultural soil capability perspective (Bouma, 1989; FAO, 1976). Nowadays, ensuring a comprehensive understanding of factors influencing land suitability and sustainability necessitates transdisciplinary collaboration, considering the natural, social, and economic aspect of the problem (Bouma et al., 2019). Information and knowledge computerization advances have significantly contributed to the complex Land Evaluation problem consideration, by enormously increasing the efficacy and the accuracy in land use recording and status analysis (Aburas et al., 2019; Basse et al., 2014; Chaves et al., 2020; Liu et al., 2020; Naboureh et al., 2017; Noszczyk, 2018; Shi et al., 2020). Nonetheless, challenges persist in achieving transparent and interpretable problem consideration, impending productive inter- and transdisciplinary dialogue (Law et al., 2019; von Eschenbach, 2021).

Geographic Information Systems (GIS) are powerful and popular tools for analyzing complex, real-world problems by integrating a wide variety of data types, elaboration techniques, and visualization tools, facilitating inter – and transdisciplinary research. Knowledge in GIS is captured, analyzed, and represented as finite objects, along with approximations of finite properties and relations. When exploiting the GIS as modeling frameworks, it's imperative to acknowledge that their representation types lack unambiguous interpretation (Goodchild, 2010; Karamesouti et al., 2023). Abstraction and discretization are pivotal processes in GIS, since infinite entities cannot be captured, represented, or analyzed, due to the inherently limited GIS capabilities. Abstraction involves the selective retention of relevant (according to the modeler's perception) representation types, pertinent to the study of the target phenomenon, while discarding the non-relevant ones. Discretization, on the other hand, entails the representation of potentially infinite and continuous sets of individuals with a finite set of discrete symbols, thereby enabling the study of computationally complex systems with finite computational resources (Bittner and Frank, 1999). Understandably, these processes are not devoid of conventions. In the GIS environment, further conventions are necessary, during multi-source data integration and analysis (Oppenheimer, 1998; Goodchild et al., 2012; Buccella and Cechich, 2007). These conventions aid modelers in addressing data-related incompatibilities, such as structural, syntactic, or semantic heterogeneity (George, 2005), as well as inconsistencies arising in problem consideration, human-driven data interpretation and communication, commonly referred to as ambiguity (Brugnach and Ingram, 2012).

The community of Artificial Intelligence (AI) has proposed the Declarative Logic Programming (DLP) as a response to these challenges (McCarthy, 1958; Lloyd, 1994). In DLPs knowledge is formalized in high-level programming language as logical rules and facts, in very modular structures. These characteristics offer significant advantages in knowledge representation, in terms of transparency, flexibility, and scalability (Zaniolo, 1991; Calimeri et al., 2018). Answer Set Programming (ASP) is among the most popular paradigms of declarative problem solving (Schaub and Woltran, 2018) with numerous applications in knowledge representation and reasoning (Erdem et al., 2016; Nogueira et al., 2001; Alviano et al., 2020; Brewka et al., 2011; Leone and Ricca, 2015).

Current work intends to lay the groundwork for enhanced transparency in problem consideration, focusing on the Land Evaluation Problem, a well-known spatio-temporal problem, predominantly exploiting GIS techniques for knowledge representation and analysis. The specifications and definitions from David G. Rossiter's theoretical framework for Land Evaluation (Rossiter, 1996) are used as the background knowledge shaping the epistemological and ontological dimensions of the described problem. This background knowledge is formalized as system Components (C), with Properties (P) and Values (V), and relations between them, following the ASP-based configuration formalization proposed in Mishra (2021). The building blocks of the Configuration formalization are structured in two main problem categories, the Problem Instance and the Problem Encoding. At this stage, the aim is to i. recognize the fundamental system components of the general Framework for Land Evaluation, from human-readable textural definitions and ii. formally represent these components and the relations between them in ASP according to the configuration theory. Moreover, in this work we draw some preliminary conclusions and discuss future directions.

2 Answer Set Programming and the Configuration formalization

ASP is a Declarative Knowledge Representation approach with First-Order Logic Programming syntax and highly modular structure, which separates the logic form the control (Gebser et al., 2022). The ASP workflow consists of three distinct sections namely Modeling, Grounding and Solving (Figure 1). The building blocks of the Modeling section are facts and rules which establish the Ontological and Epistemological background of the problem. The Problem Instance and the Problem Encoding are subsections of the Modeling section, encoding concrete realizations and domain-independent theories of a problem, accordingly.

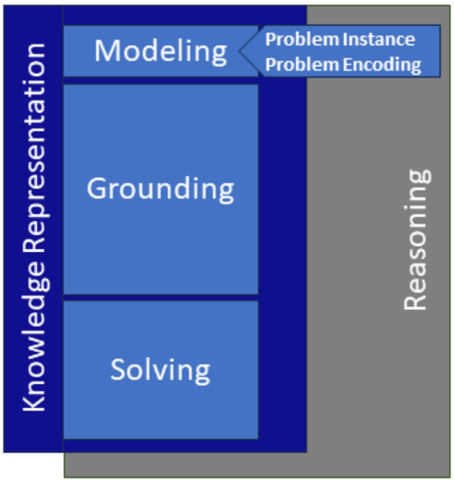
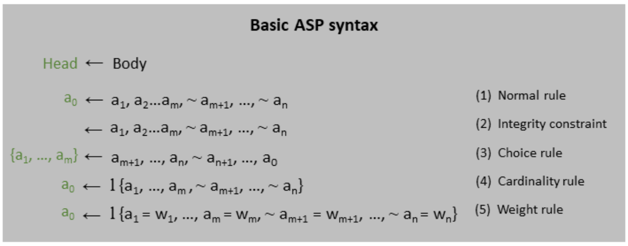


Figure 1. The ASP workflow

Compared to the traditional imperative programming structure, the declarative programs are not dedicated algorithms for computing solutions, but rather they represent the problem based on clearly described premises. The main ASP formalism is an inference relation (rule) between a body and a head, where the body captures the premises and the head the conclusion (Figure 2).



Basic ASP syntax

Head ← Body

$a_0 \leftarrow a_1, a_2 \ldots a_m, \sim a_{m+1}, \ldots, \sim a_n$ (1) Normal rule

$\leftarrow a_1, a_2 \ldots a_m, \sim a_{m+1}, \ldots, \sim a_n$ (2) Integrity constraint

$\{a_1, \ldots, a_m\} \leftarrow a_{m+1}, \ldots, a_n, \sim a_{n+1}, \ldots, a_0$ (3) Choice rule

$a_0 \leftarrow 1\{a_1, \ldots, a_m, \sim a_{m+1}, \ldots, \sim a_n\}$ (4) Cardinality rule

$a_0 \leftarrow 1\{a_1 = w_1, \ldots, a_m = w_m, \sim a_{m+1} = w_{m+1}, \ldots, \sim a_n = w_n\}$ (5) Weight rule

Figure 2. Basic ASP syntax (Gebser et al., 2022)

The arrow ← expresses the implication and the $\sim$ indicates the default negation (or negation as failure), a central concept of ASP, referring to the absence of information. The reading of this expression is: *as long as the atoms $a_1, a_2 \ldots a_m$ are true (there is proof for their existence), and there is no information about the existence*

Table 1. Theoretical Framework of Land Evaluation. Definitions in (Rossiter, 1996)

Name	Definitions
Land Evaluation	The process of assessment of land performance.
Land	An area of the earth's surface and it's relevant characteristics (geology, plants, animals, etc).
Land Utilization Type	A specific land-use system with specified management methods in a defined setting.
Land Mapping Unit	A specific area of land that can be delineated on a map and whose Land Characteristics can be determined.
Land Characteristic	A simple attribute of the land that can be directly measured or estimated.
Land Use Requirement	A condition of the land necessary for successful and sustained implementation of a specific Land Utilization Type.
Land Quality	The ability of the land to fulfill specific requirements for a LUT.
Severity Level	A ranking or classification of the LQ.
Land Suitability	The fitness of a given Land Mapping Unit for a Land Utilization Type.
Yield	The amount of an output produced on a given area.

of the $a_{n+1}, \ldots, a_n$ atoms (or there is no proof for their existence), then the atom a_0 must be true. This expression is the basis for other fundamental language constructs of ASP such as the choice rules, cardinality rules, weight rules and constraint rules (Gebser et al., 2022)

According to the ASP-based formalization in Mishra (2021), a configuration problem can be defined as a set of components with properties, a set of domains for each component property, and a set of constraints. The representation is implemented in two distinct modules, the Problem Instance and the Problem Encoding. The Problem Instance is a domain-dependent formalization, consisting of predicates capturing the epistemological background of the problem. The epistemological background refers to the underlying knowledge, beliefs, assumptions and knowledge structures adopted during a formalization process. The domain of the components (C) and the component properties (P) is specified in the formalization by respective properties (P) and property values (V). The Problem Encoding is a domain-independent formalization structured based on the Generate-and-Test approach (Lifschitz, 2008). A Generate part of the formalization creates the solution candidates, while a Test part eliminates the candidates which violate constraints or requirements.

3 The Land Evaluation problem based on the Configuration formalization

The formalization of real-world problems is a particularly challenging task, primarily due to the ambiguities inherent in natural language (Denecker et al., 2009; Wasow et al., 2005). Using the principles of the Configuration problem formalization and maintaining the basic theory described in the Problem Encoding by Mishra (2021), we aim for establishing a suitable Problem Instance for the Land Evaluation problem.

The Land Evaluation problem incorporates many domains with interacting and interdependent components. In this section we aim to describe fundamental domains of the Land Evaluation problem. For this purpose, an unambiguous problem description and formalization based on specific vocabulary is required. The problem description receives input from the Theoretical Framework of Land evaluation (Rossiter, 1996). The captured problem components and domains emerge primarily from 2 different levels of information i. the definitions in the Land Evaluation Framework (Table 1), and ii. the fundamental characteristics of the distinct land evaluation models (Table 2). A third level of information refers to auxiliary characterizations, addressed in the same document, which assign contextual information to the concepts and domains identified in the two previous cases.

Table 2. Theoretical Framework of Land Evaluation. Characteristics in (Rossiter, 1996)

LE model characteristics
1. Spatial vs. non-spatial analysis
2. Static vs. dynamic concept of the resource base and/or land suitability
3. Evaluation based on Land Qualities or not
4. Suitability expressed by physical constraints to land use, yields, or economic value
5. Homogeneous vs. Compound Land Utilization Type
6. Spatial scale & minimum decision area (continuous: small to large scale)
7. Single-area vs. multi-area suitability

From the text-based specifications of the problem we derive in predicate format over 40 concepts, corresponding to distinct domains, more than 30 mereological relations and relational requirements between components, and more than 60 requirements on component properties. These predicates are domain-specific in terms of the general land evaluation domain, but they are domain-independent in terms of the particular type of the land evaluation model. This means that these predicates can support knowledge representation for any land evaluation model type, among these defined in Rossiter (1996) Theoretical framework. In the next section we showcase the Problem Instance of one of the model types, the Non-spatial models of single-area land suitability, based on static resource base, static land suitability, using as Land Characteristic the Land Index.

4 The Land Evaluation problem formalization – Case example

In this section we showcase the formal representation of the Problem Instance of Non-spatial models of single-area land suitability, based on static resource base, static land suitability, using as Land Characteristic the Land Index.

Non-spatial land evaluation is suitable for a general overview about land suitability. Non-spatial approaches rely mainly on qualitative and quantitative data of the biophysical system without necessarily incorporating synergies between the spatial entities or other context-specific information. In other words, the described or analyzed components are viewed as series of distinct units (Burrough et al., 2015). In non-spatial land evaluation approaches, soil survey data, historical land use data, and climate data are typically used in analyses, without explicit consideration of spatial synergies. Compared to spatial approaches, the non-spatial land evaluation is not resource-demanding and can provide a broader overview of land suitability across larger regions.

Five main domains frame the areas that need to be formalized. These domains are 1. Static Land Suitability Evaluation, 2. Land Characteristic, 3. Time, 4. Static Resource Base, 5. Static, non-spatial, single-area Land suitability. For the Problem Instance we specify the different domains and their mereology, along with the properties, the requirements and the incompatibilities between components, properties and domains. The predicates were picked out from the general pool of formalizations specified according to the definitions and the criteria of the Theoretical framework for Land Evaluation (Rossiter, 1996).

In this section the problem instance becomes domain-specific for Non-spatial models of single-area land suitability, based on static resource base, static land suitability, using as Land Characteristic the Land Index. Listling 1 describes the Problem Instance of the Static Land Suitability Evaluation Domain.

Listing 1. The formalization of the Static Land Suitability Evaluation Domain

```
domain(land ,type ,LandType).
domain(landEvaluation ,type ,LET).

partOf(land ,landMappingUnit ,mandatory).
partOf(landEvaluation ,landPerformance ,
     mandatory).
partOf(landEvaluation ,luBenefit ,mandatory)
.
partOf(landEvaluation ,luConstraint ,
     mandatory).
partOf(landEvaluation ,degradation ,
     mandatory).

mandatory_property(land ,type).
mandatory_property(land , biosphere).
mandatory_property(land , atmosphere).
mandatory_property(land , soil).
mandatory_property(land , geology).
mandatory_property(land , hydrology).
mandatory_property(land , flora).
mandatory_property(land , fauna).
mandatory_property(land , humanActivity).
mandatory_property(land ,
     impactOfHumanActivity).
mandatory_property(landEvaluation ,type).

require_com_com(landUtilizationType ,land).
require_com_com(landQuality ,land).
require_com_com(landUtilizationType ,land).
require_com_com(yield ,land).
require_com_com(landEvaluation ,
     landPerformance).
require_com_com(landEvaluation ,
     landSuitability).
require_com_com(landEvaluation ,time).
```

The predicate $domain(C,P,V)$ expresses that some value V can be assigned to the property P of the component C. The predicate $partOf(C1,C2,V)$ expresses the mereological relation between different components, which can receive the value either mandatory or optional. The predicate $mandatory\_property(C,P)$ expresses the required properties of particular components. Based on the configuration formalization by Mishra (2021), the property type is a mandatory property for all components. The predicate $require\_com\_com(landUtilizationType, land)$ expresses the requirement that the existence of the component $landUtilizationType$ requires the existence of the component $land$. The Problem Instance for the rest of the domains is described in Listings 2 to 5.

Listing 2. The formalization of the Land Characteristic Domain

```
domain(landCharacteristic ,type ,lcharType).

partOf(resourceBase ,landCharacteristic ,
     mandatory).

mandatory_property(landCharacteristic ,type
     ).
mandatory_property(landCharacteristic ,
     value).
mandatory_property(landCharacteristic ,
     units).

require_com_com(landMappingUnit ,
     landCharacteristic).
require_com_com(landCharacteristic ,
     landQuality).
```

Listing 3. The formalization of the Time Domain

```
domain(time ,type ,timeType1).
mandatory_property(time ,type).
property_val(timeType1 ,type , static).
```

The Time Domain description is of particular interest since it reaches till the level of property value description. The predicate $property\_val(timeType1, type, static)$

denotes that the value $static$ is the pre-defined value for the $timeType1$ type of the component type.

Listing 4. The formalization of the Static Resource Base Domain

```
domain(resourceBase ,type ,ResourceBaseType)
    .
mandatory_property(resourceBase ,type).
partOf(resourceBase ,landCharacteristic ,
    mandatory).
require_com_com(resourceBase ,time).
require_com_com(landMappingUnit ,
    resourceBase).
```

Listing 5. The formalization of the Static non-spatial single-area Land Suitability Domain

```
domain(landSuitability ,type ,LASUTYPE).
mandatory_property(landSuitability ,type).
mandatory_property(landSuitability ,value).

require_com_com(landSuitability ,
    landMappingUnit).
require_com_com(landSuitability ,
    landUtilizationType).
require_com_com(landSuitability ,time).
```

For the formalization of the specific Problem Instance were used six concepts, seven mereological relations, fourteen relational requirements between components, eighteen requirements on component properties and one property value.

5 Discussion

Adopting a formal configuration theory, we identified the fundamental building blocks of the land evaluation problem, enclosed in the definitions and specifications of Rossiter's theoretical framework for Land Evaluation. With this work, we aim to record system components along with properties, values, and relations between them, according to the specifications of the particular formal theory. The elaboration was performed at the same level of abstraction with the definitions and the specifications of the theoretical framework for Land Evaluation. From this identification process both geographic and non-geographic components emerged. As of the current elaboration phase, these components remain identified solely at the conceptual level and they are not yet linked to any formal theories pertaining to spatio-temporal domains. (Bittner and Frank, 1999). In a following step, context-relevant parametrization of the identified building blocks of the Land Evaluation problem could provide insights into the epistemological assumptions underpinning Rossiter's general Framework for Land Evaluation. The exploitation of declarative formalization in the Land Evaluation problem representation, provides not only the formal underpinning for representing this knowledge in a structured and unambiguous manner, but also offers wide accessibility to the fundamental problem consideration assumptions. This lays the ground for a productive inter- and transdisciplinary dialogue, as declarative logic programming uses human-readable, natural language as the input and output medium for the human – computer communication.

The use of declarative logic programming in combination with GIS is not new. It has been used for GIS tool development (Kainz, 2010), as well as in various problems requiring non-monotonic reasoning capabilities (Benferhat et al., 2010; Osorio and Zepeda, 2003; Zepeda and Sol-Martinez, 2007).

The relevance of formalizing the land evaluation problem using the configuration paradigm lies in the implementation of the particular paradigm across various configuration types. Irrespective of the configuration type, key tasks of the configuration process include i. specification of the system components, ii. recognition of interdependencies between components and iii. recognition of system users along with their requirements. (Junker, 2006; Haselböck and Stumptner, 1993), Understandably, the configuration paradigm has the capacity to unveil the epistemological and ontological underpinnings of the represented system.

The modular formalization of ASP knowledge representation schemas, and the clear separation between domain knowledge (Problem Instance) and high-level theories (Problem Encoding) enables the consistent Land Evaluation Problem formalization using the Configuration paradigm. Additional notable benefits of modular knowledge formalization include enhanced flexibility, scalability and adaptability, given new knowledge becomes available. Despite these advantages, unambiguous formal representation of real-world problems is not a trivial task. The challenges in establishing unambiguous Problem Instance for complex, real-world problems have already been acknowledged by the Logic Programming community (Denecker et al., 2009). Consequently, addressing ambiguity issues in the Land Evaluation Problem Instance specification becomes imperative. Another recognized challenge pertains to the ontological aspects of problem specification. While methods for formally representing ontological relations exist, ongoing challenges persist in their maintenance (Delgrande et al., 2023). To this direction alternative ASP-based formalizations of the configuration problem are being explored (Rühling et al., 2023).

6 Conclusion

In this work-in-progress we used ASP and the Configuration paradigm to formalize the Land Evaluation Problem Instance as Components (C) with Properties (P) and Values (V). Over 220 fact-type specifications in predicate format translated text-formatted definitions and land evaluation model types, from David G. Rossiter's theoretical framework, into computer and human-readable instances. The sufficiency and the unambiguity of the formalizations need further examination. Our initial focus has been on the formal description of the Problem Instance for non-spatial, single-area Land Evaluation approach, based on Land Characteristics. In this case, all required predicates were picked out from the general pool of formalizations without the need for additional predicates. However, this is the simplest case and cannot assure the completeness of our initial pool. To ascertain sufficiency and unambiguity of existing formalizations, it is imperative to represent more land evaluation model types, particularly those with more dynamic aspects. Additionally, the sufficiency of Mishra's Configuration theory concerning the requirements of the Land Evaluation problem will be explored. Finally, the semantic integration of the identified geometric concepts with relevant formal theories from the geographic space will be performed.

7 Credit authorship contribution statement

Karamesouti Mina: Conceptualization, Methodology, Formal analysis, Writing original draft & revision.

Tignon Etienne: Formal analysis, Methodology, Writing original draft & revision.

8 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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