 doi:10.20944/preprints202210.0192.v1

Article

IndShaker: A Knowledge-based Approach to Enhance Multi-perspective System Dynamics Analysis

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Abstract: Decision making as a result of system dynamics analysis requires, in practice, a straightforward and systematic modelling capability as well as a high-level of customisation and flexibility to adapt to situations and environments that may vary very much from each other. While in general terms a completely generic approach could be not as effective as ad-hoc solutions, the proper application of modern technology may facilitate agile strategies as a result of a smart combination of qualitative and quantitative aspects. In order to address such a complexity, we propose a knowledge-based approach that integrates the systematic computation of heterogeneous criteria with open semantics. The holistic understanding of the framework is described by a reference architecture and the proof-of-concept prototype developed can support high-level system analysis, as well as it suitable within a number of applications contexts - i.e. as a research/educational tool, communication framework, gamification and participatory modelling. Additionally, the knowledge-based philosophy, developed upon Semantic Web technology, increases the capability in terms of holistic knowledge building and re-use via interoperability. Last but not least, the framework is designed to constantly evolve in the next future, for instance by incorporating more advanced AI-powered features.

Keywords: Knowledge-based Systems; Ontology; Knowledge Engineering; MCDA.

1. Introduction

Decision making as a result of system dynamics analysis requires, in practice, a straightforward and systematic modelling capability as well as a high-level of customisation and flexibility to adapt to situations and environments that may vary very much from each other. The requirements from different environments and the objective relevance of situation-specific aspects intrinsically suggest an ad-hoc approach, eventually support by some method, such as the very popular Multi-Criteria Decision Analysis (MCDA).

While, in general terms, a completely generic approach could be not as effective as ad-hoc solutions, a proper adoption of modern technology may facilitate agile strategies as the result of a smart combination of qualitative and quantitative aspects. In order to address such a complexity, we propose a knowledge-based approach [1] that integrates the systematic computation of heterogeneous criteria with open semantics [2]. The underlying idea is to adopt rich semantics to provide the highest level of flexibility and adaptability to practical cases. In order to achieve such a goal, we distinguish between functional and informative (user-level) semantics. While the former class aims to align computations and system modelling, the latter wants to properly structure, integrate and present the semantics that are relevant in order to correctly understand and interpret data frameworks, in the attempt to minimise bias and uncertainty.

The holistic understanding of the framework is described by a reference architecture and the proof-of-concept prototype developed - i.e. *IndShaker* - can support high-level system analysis, as well as it is suitable within a number of applications contexts - e.g. as a research/educational tool, communication framework, gamification [3][4] and participatory modelling [5] .

Additionally, the knowledge-based philosophy, developed upon Semantic Web technology, increases the holistic capability in terms of knowledge building [6] and re-use [7] via interoperability [8]. Last but not least, the framework is designed to constantly evolve in the next future, for instance by incorporating more advanced AI-powered features.

Previous work

IndShaker implements a computational method previously proposed[9]. Such a method has been applied, among others, to model and analyse a case study on Sustainable Global Development [10], as well as it has been further discussed in terms of bias and uncertainty management [11]. Additionally, the knowledge-base underpinning the tool proposed in this paper is linked to existing vocabularies (see Section 4). As extensively addressed throughout the paper, this contribution deals with a much more comprehensive analysis framework based on the enrichment of original models and underpinned by a formally specified knowledge-based approach.

Structure of the paper

The paper follows with a brief discussion of background concepts, while its core part is composed of three main sections that provide respectively an overview of the system (Section 3), a presentation of the knowledge-based approach (Section 4) and a discussion of potential applications (Section 5).

2. Background concepts

Because of the intrinsically multi-disciplinarity, the potential value provided by *IndShaker* should be understood in context. The proposed system assumes the following underlying concepts:

- *Multi-criteria Analysis*. The target system intrinsically addresses scenarios that require more than one criterion to perform a reasonable analysis. Typical examples are, among others, situations characterised by complexity [12], wickedness [13], as well as soft systems [14]. MCDA is a classic and consolidated approach [15] that has evolved in the context of different application domains [16].
- *Evidence-based approach*. The analysis strategy assumes measurable input (indicators) to establish an evidence-based approach to decision making [17].
- *Multi-perspective interpretation*. Interpretation is another key factor for the target analysis as any complex scenario is somehow likely to be understood and perceived in a different way by different individuals or stakeholders. It affects above all the decision making process (e.g. [18]).
- *Heterogeneity*. The information adopted to model a system that presents a certain complexity is very lickely to present a certain heterogeneity. That is normally requested whenever the target analysis aims to reflect or consider ultiple aspects. Properly dealing with heterogeneity (e.g. [19]) becomes a critical factor to create a focused analysis framework and avoid entropic or excessively biased environments.
- *Quantitative/qualitative metrics*. Qualitative (e.g. [20]) and quantitative (e.g. [21]) methods are available for decision making. The analysis framework is based in concept on quantitative measures. However, such a quantitative approach is integrated with qualitative aspects to enforce more contextual analysis.
- *Adaptive mechanisms*. Adaptive decision making [22] is a well-known need for a generic approach as frameworks need to adapt somehow to specific situations and contexts. The proposed solution adopts an adaptive algorithm that systematically tunes computational parameters to limit bias that may come from strong numerical differences in heterogeneous environments. A transparent view of tuning parameter contributes to avoid a "black-box" approach.
- *Dynamic analysis model*. In order to assure a model of analysis that takes into account the evolution of a given system, the framework works assuming an observation interval $[t_0, t_n]$ and looks at the evolution of the system from t_0.

 doi:10.20944/preprints202210.0192.v1

- *Semantics associated with data*. The analysis is performed by combining numerical indicators that are semantically enriched (e.g.[23]) to describe contextual and situation-specific interpretations. In the approach proposed, semantics are understood at different levels and, in general terms, may be dynamically specified or extended to reflect the analysis context.
- *Uncertainty management via transparency*. Uncertainty is somehow an intrinsic factor in system analysis and decision making. It evidently applies also to MCDA [24][25]. In the context of the proposed framework, uncertainty is mostly related to the relevance associated with the different criteria and to the adaptive mechanisms, as well as to missing data. The metrics provided to estimate uncertainty contribute to a more transparent analysis environment on one side and, on the other side, may be used as a driver factor to select input data in case of multiple available choices.

3. Framework Overview

As previously introduced, *IndShaker* aims to the analysis of systems characterized by a certain complexity which are modelled and analysed by combining different indicators and criteria associated with multiple potential interpretations. This section provides an overview by describing a reference architecture against the current implementation.

3.1. Reference Architecture

The Reference Architecture is depicted in Figure 1. Intuitively, it reflects the key underlying concept which assumes a systematic, yet customizable, computational framework integrated with high-level semantics to support domain-specific analysis. More concretely, in terms of software architecture, the user application distinguishes between the computational tool itself (*IndShaker*) and the *Semantic Engine* which provides an abstracted functional layer for the interpretation and management of semantics.

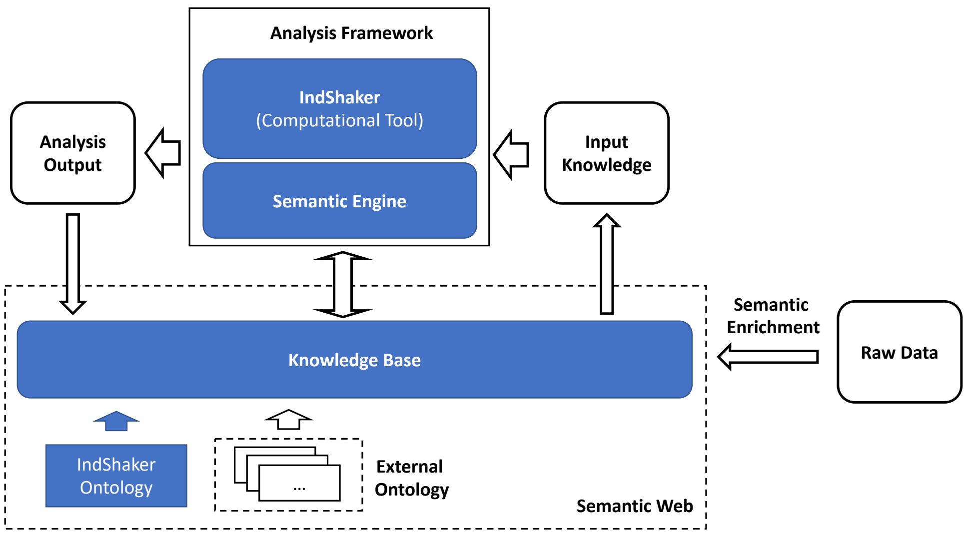

Figure 1. Reference Architecture.

Such a philosophy intrinsically relies on a *knowledge-base* and, therefore, on the capability to establish formal semantics by adopting rich data models. Semantic Web Technology [26] provides a consolidated data infrastructure upon standard Web technology to enable Linked Data [27] via interoperability.

As discussed in detail later on in the paper, the proposed architectural model is composed of 3 different layers in terms of semantics: (i) an internal ontology supports core computational functionalities and related semantics, (ii) a number of linked external vocabularies allows further capabilities, while, in general terms, (iii) additional customised

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semantics may be linked as per common ontological approach [28]. Establishing and maintaining such a kind of knowledge environment on a large scale is definitely a challange [29], while an application-specific focused approach like proposed in this paper can be considered like effective and relatively easier to adopt in practice.

At a functional level, the key assumption is, on one hand, the capability of a knowledge-based tool to interact in a way completely transparent to final users with complex semantics and, on the other hand, the existence of agile features to integrate external data to the knowledge-base. According to this philosophy, the computational tool works on semantic data at an input and output level both, meaning input data-sets are provided in an ontological format as well as the output is provided according to a formal ontological model to be automatically part of the knowledge-base. That is a key aspect in terms of knowledge building and re-usability as existing case studies can be analysed, compared and eventually modified to define new ones.

3.2. *IndShaker V1.0*

This section addresses the current development of the tool against the reference architecture. *IndShaker* is an integrated component which implements the computational tool and the semantic engine as previously defined. The emphasis is on the description of the open-source package and of the key features looking at user interfaces. Additionally, the limitations of the version 1.0 are briefly discussed.

3.2.1. Open-source package

A simplified view of the open-source software package is represented in Figure 2. The core software module is composed of five different packages. The package *app* implements the underlying algorithms and, both with *infoPanel* the GUI. The I/O is managed by the functionalities provided by *IOcontrollers*, while the package *model* provides data structures. Last but not least, *ontology* includes functionalities related to semantics and the management of the different ontological frameworks.

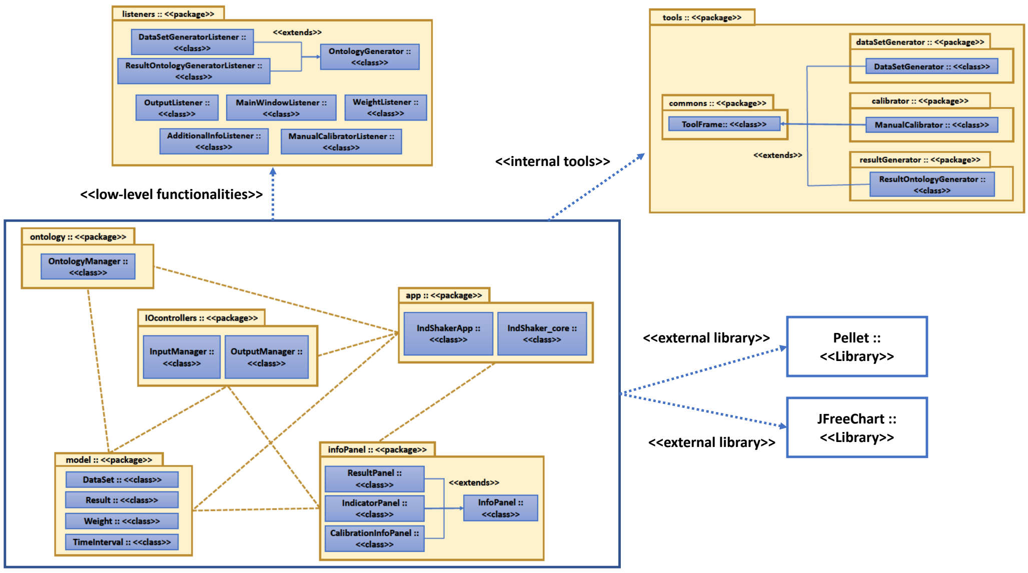

Figure 2. Open-source software package.

The core module relies on low-level functionalities implemented by the module *listeners* to support user interactions. Additionally, a number of supporting tools (e.g. to generate semantically enriched datasets from raw data) are provided by the package *tools*.

The current implementation adopts two external software libraries: Pellet [30] as an OWL reasoner and *JFreeChart*[1] for the visual representation of computations.

3.2.2. GUI

In order to provide an overview of the current implementation from a user perspective, we look at glance at the user interface, whose *main panel* is proposed in Figure 3.

Figure 3. GUI - Main panel.

As shown, it includes three different sets of components for (i) the management of the input knowledge and of the knowledge-base, (ii) advanced settings and (iii) input overview. The first set of functionalities aims to import the input datasets and to check/manage the associated semantics. Advanced settings are related to weights, calibration and the management of weights in terms of resources for decision making (e.g. establishing constraints). Finally, the last component provides a concise overview of the current input.

Figure 4 shows the *output panel*, which intuitively allows users to visualize the output of a computation and eventually to export such results into an ontological format.

Additionally, the platform includes a number of internal tools to support most common users operations. Currently, the *DataSet Generator* supports an easy conversion of raw data into an ontological format recognised by the computational component, while the *Calibrator* enables expert users to calibrate manually the computational tool and, eventually, to set-up more complex analysis (e.g. multi-system). A third tool, the *KG-Visualizer* is under development and aims to visualize the computational process, including both input and output, as a knowledge graph [31] underpinned by formal ontologies.

3.2.3. Current limitations

The implementation previously discussed is understood as a relatively mature research prototype. On one side, it supports an evolving proof of concept that allows the refining of existing functionalities and the design of further features as a response to different applications (see Section 5). On the other side, such an implementation may be used in practice as a working framework whenever a "standard" level of customisation is required.

Current limitations may be understood at different levels. More concretely, most limitations concern the user interfaces. It reflects an intrinsic difficulty to generalise needs and requirements from different kind of users across the various application domains. Such

[1] JFreeChart - https://www.jfree.org/jfreechart/index.html. Accessed: 2-Jul-2021.

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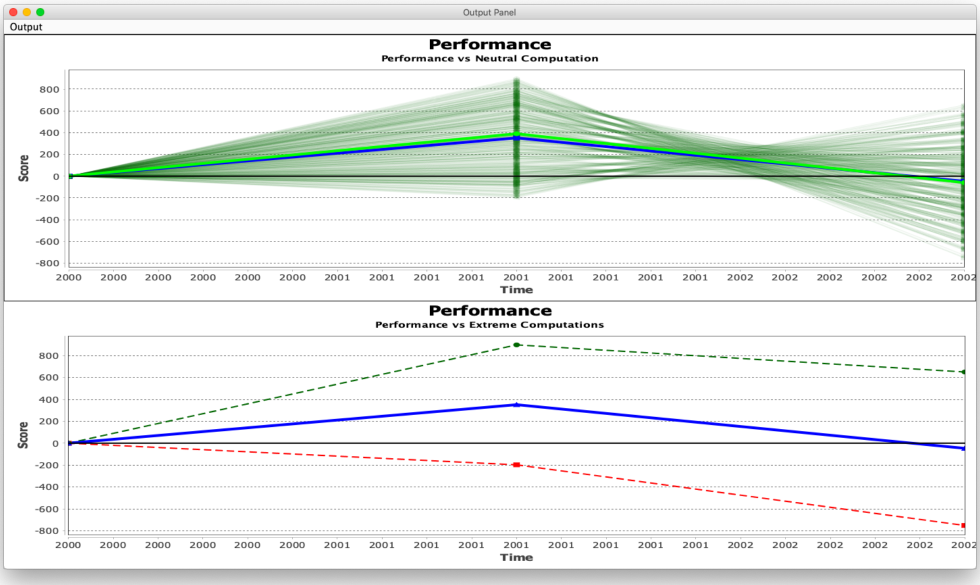

Figure 4. GUI - Output

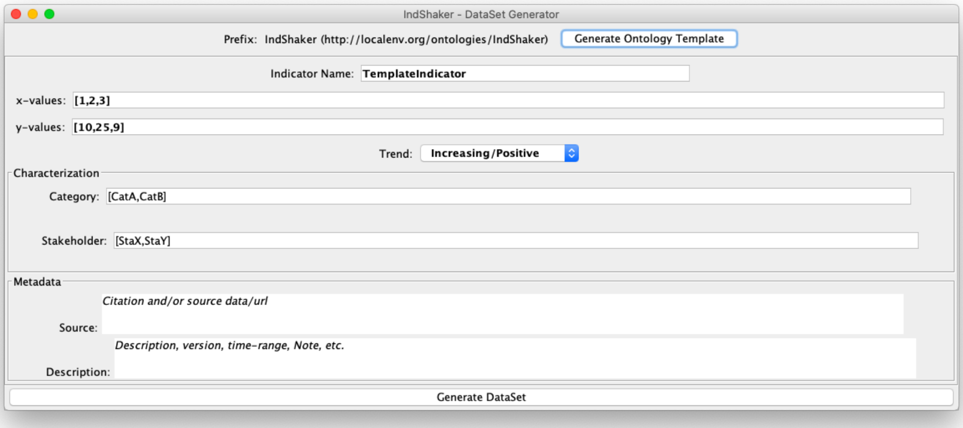

Figure 5. GUI - DataSet Generator

limitations also affect the semantic engine as the potentiality of the ontological framework provided is just partially exploited.

At a functional level, the software misses at the moment the capability to automatically adapt to imperfect data - i.e. missed data or wrong data alignment - as well as typical functionalities, such as the capability to provide projections on hypothetical future values based on previously computed trends.

Last but not least, the current version doesn't distinguish between expert users, who are expected to have a technical background, and non-expert users, that need to use the tool at a very abstracted level. The former class of user can find the customization level allowed by the GUI like very limited, while the latter may find some settings too complicated. We expect researchers to approach the framework in a completely different way, as it is supposed they need the maximum possible level of customization that requires the capability to extend or modify both the semantics and the computational engine.

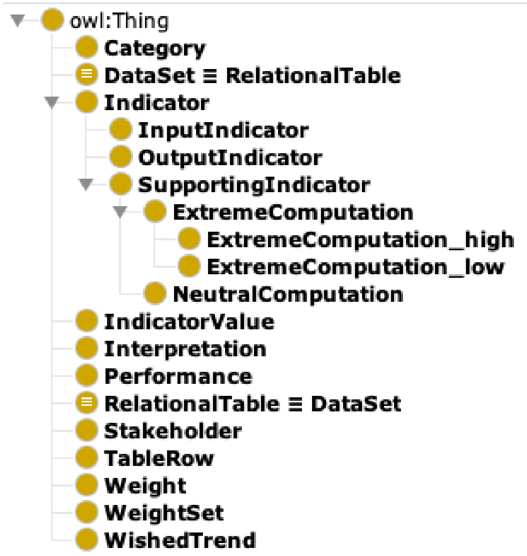

Figure 6. Main classes in Protege [36]

4. A knowledge-based approach

As briefly explained in the introductory part of the paper, the added value characterizing the current version of the framework, at a both a conceptual and a practical level, is provided by the knowledge-based approach. In this section, the ontological structure that underpins computations and user-level application is analysed in detail. First the ontology itself is described by providing, as usual, a concise overview of the main concepts and the relationships existing among them. Then, an example of formal specification focusing on input and output knowledge is proposed.

4.1. Ontological support: an overview

The OWL2 implementation of the ontological support currently provided is presented in Figure **??**, while linked external vocabularies are reported in Table 1. Main classes are proposed in Figure 6, object properties in Figure 7 and attributes/annotations in Figure 8.

Ontology	Prefix	Scope	Reference
VirtualTable	VT	Data Integration purpose	[32]
FN-Indicator	IND	Specification of composed indicators	[33]
PERSWADE-CORE	PERSWADE	Project/Case Study description	[34]
EM-Ontology	EM	Stakeholder specification	[35]

Table 1. Linked external ontologies.

The current approach assumes each building block - i.e. input indicators and computation outputs - described as a stand-alone dataset. Those building blocks are semantically linked. For instance, a computation result is associated with the input datasets considered, both with the weight-set and the configuration parameters adopted in the computation. Additionally, building blocks may be semantically enriched to also incorporate user-level semantics.

A comprehensive fine-grained description of the ontology is out of the scope of this paper. However, in order to provide an overview of the formal specifications underpinning main building blocks, the next sub-sections address the ontological specification of the input and the output knowledge respectively.

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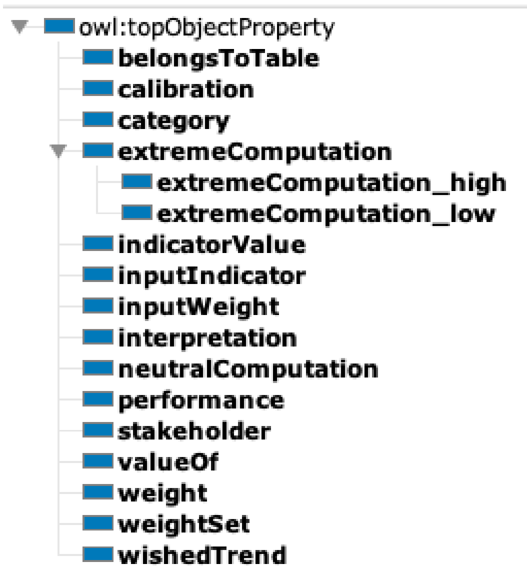

Figure 7. Main object properties in Protege [36]

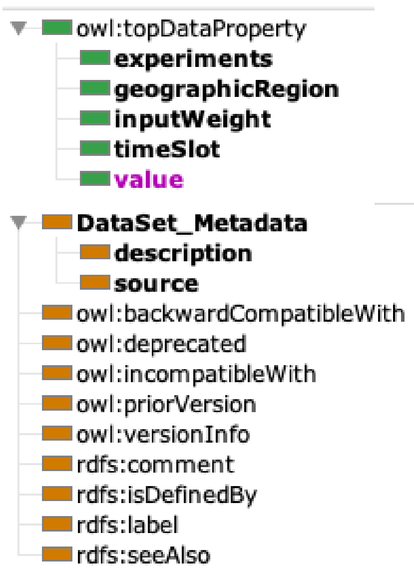

Figure 8. Attributes & Annotations in Protege [36]

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4.2. From Indicators to Input Knowledge

One of the primary goals of the ontology is to describe the input knowledge resulting from the integration of raw data with semantics, including also customized enrichments. It is the application of one of the key principles underlying the framework, which assumes the whole analysis process performed from customised knowledge that is dynamically defined to understand raw data in context.

By adopting such a rich vocabulary, an input indicator can be specified according to the data structure proposed in Figure 9.

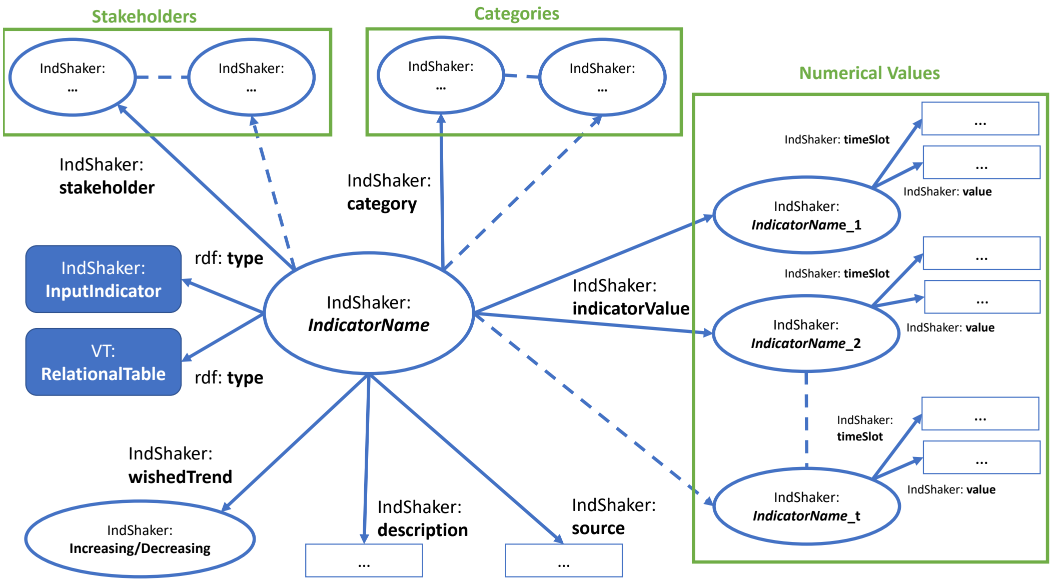

Figure 9. Specification of an input indicator.

The core specification assumes each indicator defined as the integrated description of numerical values with related semantics. The latter includes functional semantics (e.g. the wished trend), typical metadata (e.g. description and source) and other characterizations, such as associated categories and stakeholders.

Additional ad-hoc semantics may be specified and integrated with the main schema though the typical mechanisms provided by the current Semantic Web technology.

4.3. Describing Target Knowledge

A simplified view of the ontological structure adopted to describe an output is proposed in Figure 4. Such a representation is conceptually more complex and articulated than the semantics associated with inputs.

An output is still considered an indicator but it is associated with the more fine-grained concept of *OutputIndicator* as per proposed ontology. In the current version, the semantic structure includes a link to the input, including indicators both with the weight-set and the calibration details used for computations. A qualitative description of the output is reported through the properties *performance* and *interpretation*, while the numerical result of the main computation is integrated with a number of supporting indicators - i.e. neutral computation and extreme computations.

The data structure also includes a number of annotations, typically generic descriptive metadata associated with the output and more specific information, such as about the method adopted to define weights. Annotations are provided in an natural language but maybe automatically processed and eventually validated by users to provide further formally specified semantics according to PERSWADE-CORE [34].

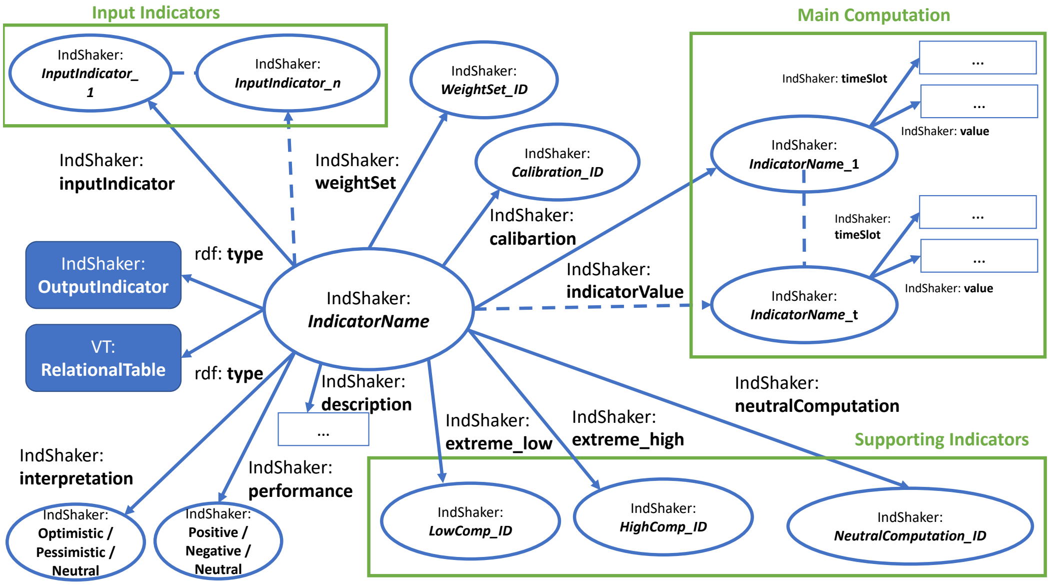

Figure 10. Ontological structure describing the output.

5. Applications

As previously discussed, the framework has been designed according to a completely generic philosophy, which can be particularised and customised to meet requirements and needs within specific environments through the specification of semantics. Moreover, the open-source approach may provide a further level of customisation assuming very specific requirements that advise some ad-hoc development or, more likely, an extension or a variant of the functionalities currently offered.

In general terms, a number of potential applications have been identified as follows:

- *Decision Making/System Analysis*. It's the most generic possible understanding of the framework. Decision making is performed as a systematic analysis of system dynamics, which result by the combination of independent indicators. Such an approach becomes valuable and practical in presence of a significant heterogeneity, as well as it allows the specification of ad-hoc semantics to enforce transparency and, in the limit of the possible, to minimise bias.
- *Communication Framework*. The current focus, that includes both quantitative and qualitative aspects, can potentially contribute to enhance the proper communication of a given result, assessment or analysis. For instance, storytelling [37] may be empowered by adopting an effective visualization based on numerical indicators and trends integrated with user-level semantics .
- *Gamification*. Similarly, the framework can underpin gamification strategies [4] at multiple levels in different context to achieve different goals. Some of the features already available, such as the possibility to define constraints for weights, are intrinsically suitable to gamification.
- *Research Tool*. The current application in the field of Sustainable Global Development previously mentioned is a clear example of use of the framework as a research tool. Indeed, the framework is expected to facilitate system modelling though indicators and semantics and to support the formulation of research questions related to the target system assessment.
- *Educational purpose*. Intuitively, applications within the education domain follow the same mainstream and underlying principles of research, as case studies can be modelled from available data and analysis/assessment can be performed accordingly. A gamified approach to learning [38] could be a further added value.
- *Stakeholders Analysis in Complex Environments*. Stakeholders analysis [39] may become challenging in complex environments where unpredictable behaviours can potentially

meet contrasting interests and resulting trade-offs. Upon data availability, *IndShaker* may integrate a quantitative dimension of analysis with qualitative ones (e.g. [35]).
- *Participatory Modelling*. Decision making and knowledge building processes that require or involve multiple stakeholders [5] can be supported by providing a knowledge-based resource to process heterogeneous data in context.

6. Conclusions and Future Work

IndShaker models a generic system as a combination of heterogeneous indicators. By analysing the resulting dynamics in context through the specification of ad-hoc semantics, the framework provides an extensive support to complex analysis. The knowledge-based approach enables a self-contained, yet open, environment that aims at knowledge building, analysis and re-use via interoperability. While the underlying ontological framework developed upon Semantic Web technology establishes an extensible semantic environment, as well as a high level of abstraction to address users without a technological background, the open source software package provides a more consistent level of customization for expert users.

Within the broad area of system analysis and decision making, a number of applications have been potentially identified and includes, among others, communication & story-telling, academic purpose including research and teaching, complex system analysis and participatory modelling.

The current implementation focuses on core functionalities and presents the limitations typical of research prototypes. Future works aims at a further development, including also AI-powered features currently object of research.

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