Experimenting automatic generation of energy renovation scenarios with ontology reasoning

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Abstract
Semantic web technology has been progressively adopted in the AEC domain for its flexibility and extensibility in describing data schema, in particular the different IFC versions, coupled with the expressiveness of a generic querying language (SPARQL) to extract information from BIM models. Dynamic knowledge enrichment of model through reasoning is a third paradigm of semantic web on which more and more research has been completed in recent years to apply it to AEC practices, often through a reduced set of inference rules. In this paper, we present an experiment on using semantic web technologies, and in particular reasoning rules, to deploy an automatic generation of energy renovation scenarios to compare traditional renovation of envelopes and renewable installation with an integrated solution developed in the ENSNARE H2020 project, at a feasibility study stage. The semantic data model and the inference rules are presented and the overall strategy is discussed.

Keywords: Energy renovation, feasibility study, simplified modeling, data model, ontology, inference reasoning

1 Introduction

The use of semantic web technologies in the AEC sector has been in constantly growing in the last years: OWL formats of the IFC model (Beetz et al. 2009) (Pauwel & Terkaj, 2016) are now referenced by buildingSMART International, and the Linked Building Data group is constantly discussing the adoption and creation of new models, such as Building Topology Ontology (BOT) (Rasmussen et al., 2021). Translating IFC in a semantic web paradigm consists in describing the IFC schema as a knowledge graph called the TBox (terminological box), and a specific building as a graph of individuals in the ABox (assessment box). A BIM query language is then obtained for free with the SPARQL query language.

Sometimes dismissed, knowledge graphs offer an additional functionality with an inference rule engine (often called RBox for rule box) which allows the dynamic generation of additional knowledge in the data graph. The W3C Linked Building Data group and other academic works demonstrates how to apply such capacities to AEC projects: (Pauwels et al., 2017) compare the capacity of different rules engines to automatically reduce the distance between individuals in the ifcOwl models; (Bourreau & Oraskari, 2021) provides an automatic back and forth translation of ifcOwl models into a BOT-cored federated data model for energy renovation (Bourreau et al., 2020); (Hu et al. 2021) use inference rules to compute a building energy performance; (Mavrokapnidis et al. 2023) use inference rules to simplify the extraction of HVAC topology information. (Rasmussen 2024) discuss how inference rules can be used to dynamically modify thermal studies assessment when a change is made by the architect or modeler.

The current article presents the use of knowledge graphs technologies in an energy renovation context; more specifically, for the automatic generation of energy renovation scenarios, in particular using prefabricated façade panels integrating active systems. The renovation scenarios generated are used as the starting point of a decision support tool. Using a full linked data approach in this context is an innovation to the author's knowledge, although some researches already investigated the use of BIM models and answer set programming for generic renovation designs (Kamari et al. 2018) (Kamari et al. 2021).

The following section introduces the context of the development, in particular information on the ENSNARE active panels for energy renovation. Section 3 is dedicated to providing generic information on energy audits and renovation, formalizing it as a multi-step procedure that is mimicked by the reasoning rules developed. A presentation of the data model (i.e. the knowledge base or TBox) is provided in section 4, followed with a presentation of the inference rule set, the machinery to generate renovation scenarios in section 5. The final section is dedicated to discussing the implementation, its results, and future works.

2 Context

The current work was developed as part of the H2020 project ENSNARE which aims is two-folded: on one hand, a physical configurable façade module is developed, integrating an insulation layer but also active renewable energy systems, i.e. photovoltaic (PV), solar thermal (ST) or hybrid systems (PV+T); those modules are highly configurable in terms of the surface dedicated to active panels, and openings for windows or doors. On the other hand, a fully digitized methodology is developed to facilitate the industrialization, installation and operation of the façade modules: visual computing is used to pre-dimensions the panels (Iturralde et al., 2023a), drones are used to preprint the modules' anchoring on the façades (Iturralde et al., 2023b), and a digital twin is used to track the performance of the systems. The overall strategy aims at developing an off-site renovation solution that could be used in solving the challenge of improving the energy performance of the European building stock to reach carbon neutrality by 2050.

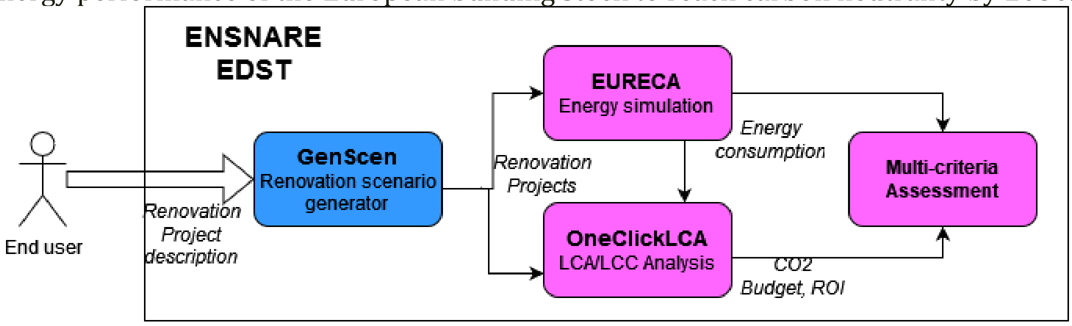


Figure 1: Schema for the ENSNARE Early Decision Support Tool

Amongst the different digital solutions developed within ENSNARE, the EDST (Early Decision Software Tool) is used at the preliminary phases of a renovation project to generate different scenarios and evaluate them, according to multiple criteria: energy consumption, carbon emission, investment and maintenance cost, and return on investment. The EDST is made of different modules: first, the GenScen tool generates different scenario; for each scenario, the energy consumption is then computed by the Eureca-based software; following it, the lifecycle carbon and costs are evaluated; finally, a multi-criteria analysis is performed to deliver a comparative study of different renovation scenarios to the end user. The overall process has the following constraints: (i) it needs to run fast, end users willing to get evaluations in less than a minute; (ii) end users may be renovation experts, with accurate information on the global energy performance of the envelope and of the installed HVAC (Heating, Ventilation, Air conditioning) systems, or may be building owners, with little expertise. In particular, no accurate information on the thermal resistance/conductivity of the walls or roofs, or solar factor for windows can be requested. Considering these constraints, no detailed energy modelling can be used, and the number of renovation scenarios generated and evaluated needs to be limited.

The work presented in this article focuses on the GenScen software (Figure 1Figure 1), which role is to quickly generate renovation scenarios based on reduced information provided by end users.

3 Energy renovation: a multi-step process

The GenScen software is built up as an intermediary expert tool that aims at generating different ENSNARE-based deep renovation scenarios considering the configuration and performance of the initial building. The GenScen process is inspired from a typical energy audit, usually performed in three consecutive steps:

1. The thermal performance of the initial envelope is evaluated, and solutions to improve it are assessed. The study focuses on improving the performance of the façade, roof and slabs. Prioritizing between a roof or façade insulation may depend on different criteria (respective insulation performance, overall roof and façade area…) that helps identifying surfaces with the highest thermal loss. Changing openings (i.e. single to double-glazed windows) is another typical renovation action. Different set of renovation actions on the envelope performance result in different estimated heating demand after renovation.
2. The second phase consists in lowering the consumption of equipment. First, heating and cooling systems are dimensioned to respond to the demands computed in phase 1. A variety of solutions can be evaluated, depending on the energy source (gas, electricity, biomass…); but the global environmental and subsequent regulatory context, through the RePower EU initiative, is strongly pushing for an electrification of the European building stock. Secondly, lowering the consumption of domestic hot water (DHW) equipment is evaluated. With a more efficient insulation, the global inside air quality of the building needs to be ensured while maintaining thermal loss as low as possible. Double flow ventilation or hygro-regulated single flow ventilations can be used as solutions.
3. Finally, the installation of renewable energy production can be assessed. Those are typically of two categories: (i) electricity production, mainly through PV panels; (ii) and thermal production through solar collectors. The energy produced can be used for self-consumption (in particular thermal energy) or can be reinjected to the electricity grid.

In an energy audit, other consumption equipment can be evaluated, such as lightings and domestic appliances. In ENSNARE, the feasibility study is limited to the points 1 to 3 above.

In a typical approach, an expert or thermal auditor would create different renovation scenarios after visiting the building and reporting on its existing state. Those scenarios are then simulated through modelling tool (EnergyPlus, Modelica, IES VE…) with building energy models, which level of details can dramatically impact the resulting accuracy and time response.

GenScen focuses on generating scenarios in terms of seconds, no accurate energy evaluations can be computed; instead, we aim at quickly evaluating scenarios based on rough hypothesis and a short list of data provided by the end user. Renovation scenarios are therefore generated based on (i) an initial assessment of the performance of the envelope; (ii) different scenarios are generated considering different envelope renovation actions; (iii) for each of these scenarios, the energy demand is estimated; (iv) Different ENSNARE configuration covering the façades with PV, ST and PV+T panels are generated to cover the energy needs of each scenario.

4 The GenScen data model

A knowledge-based decision system is made of two main modules: (i) the representation of static knowledge, a data model that represents the different concepts and relationships that describe the domain; (ii) a rule-based inference engine to generate additional key information in the decision-making process. This section presents the static part, elaborated under a graph representation, and made of three interdependent modules. The model is available online at https://models.ensnare.nobatek.com/.

4.1 The Building module

The first module (named Building) is used to represent a building, which is described, as mentioned previously, as a simplified building energy model (BEM) created with a reduced set of information provided by non-experts. Therefore, relevant information regarding the initial status of a building consists in: (i) the façades and their insulation level; (ii) identically, roof and insulation; (iv) glazed-surface and type of glazing, (iv) existing HVAC systems, type of energy and performance; (v) number of existing renewables. In addition, to design an ENSNARE renovation, one need to know the available façades and roof surface and orientation, the occupied (i.e. heated and/or cooled) surface, and the number of occupants (for an estimation of the hot water needs – number of occupants can be approximated with the number of dwellings). The resulting Building module is presented through a graph in Figure 2.

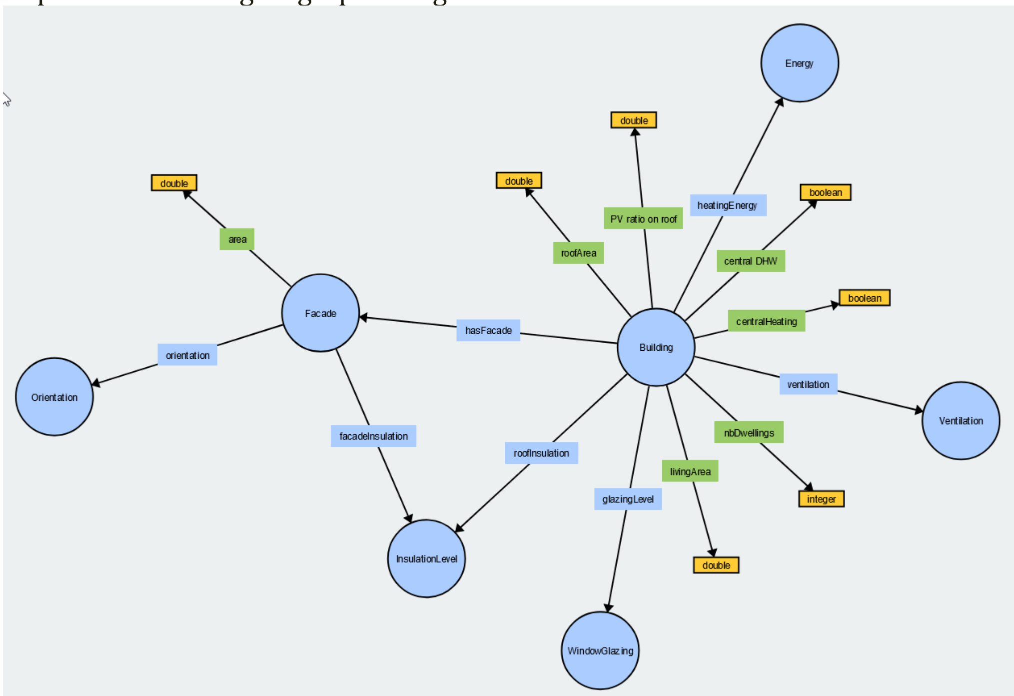


Figure 2: Graphical representation of the ENSNARE Building ontology

4.2 The renovation project module

The second module (RenoProject) describes influencing parameters of a renovation project, and generated renovation scenarios. A renovation project is considered to be based on (i) an existing building as described in the Building module; (ii) a climatic context which results from the geolocation of the building, and (iii) a set of targets expressed by the end user. To model the climatic context, each Euro region is associated with an average summer and winter solar radiance, and yearly energy demand for heating and cooling, considering three different insulation levels (low, medium and high). In the current version, insulation levels are fixed, and independent from the region. Heating and cooling demands are computed considering an archetype building (5 stories, 20 apartments) in static conditions (19°C inside and 5°C outside for heating) with 10, 20 and 30cm of glasswool insulation which leads to rounded values of 120, 70 and 40 $W/K/m^2$ heat loss coefficient respectively, where K stands for the outside/inside difference of temperature. Using the heating and cooling degree days provided by the Eurostats database, we can compute the yearly heating energy demand per region and per insulation level. A similar simplified calculation is done to compute cooling demands.

Regarding solar radiance, data are obtained from the PVGIS tool[1]: daily solar radiance between 2005 and 2020 (all data available on PVGIS) can be obtained; and average values are computed for the months ranging from June to September for summer solar radiance, and for the months ranging from November to February for winter solar radiance. Improving the accuracy of this data is discussed in conclusion of the paper.

In addition, the RenoProject module allows the modelling of resulting renovation scenarios, i.e. a list of interventions that could be performed on the building to improve its energy performance. Three type of renovation scenarios are considered: ENSNARE-based scenarios which are the main objects of the study, and focus on the insulation layer to install on the façade augmented with façade surfaces associated to renewable energy production; a baseline scenario which is a

[1] https://re.jrc.ec.europa.eu/pvg_tools/en/

typical energy renovation, with low ambitions; and an nZeB scenario as an ambitious deep renovation. Those are further discussed in section 5.

4.3 The intervention module

The final module consists in the different actions that can be performed during an energy renovation project. A renovation action is associated with a type of product, which is characterized by a set of properties. The different actions are:

- InsulateFaçade, with glasswool, either through a classic external thermal insulation of 5cm, 10cm, 15cm (for standard baseline scenarios); 20cm, 30cm or 44cm (for nZeB scenario); and ENSNARE-based insulation of 10cm, 20cm or 30cm.
- InsulateRoof only considered for baseline (15/18/22cm) and nZeB (30/45/60cm) scenarios.
- ChangeWindows consists in installing (i) double-glazed windows (for baseline and nZeB scenarios), (ii) ENSNARE double-glazed windows incorporated in ENSNARE façade modules; or (iii) ENSNARE active windows with an integrated heat exchanger.
- Heating to change heating equipment with heat pump systems, either individual (i.e. per dwelling for a collective residential building) or central. A coefficient of performance is associated.
- Ventilation: a dual flow ventilation system is considered, for an nZeB scenario; for ENSNARE scenarios, the ventilation function can be ensured by the active windows mentioned above.
- InstallPV: declined in three different actions: install PV panels on the roof, install ENSNARE PV panels or ENSNARE PV+T panels. A coefficient of performance is associated to each type of panel in terms of electricity produced based on the in-plane solar radiance, per m^2.
- InstallST: identical to InstallPV, but for the installation of Solar Thermal collectors; a thermalPerf property is associated.

Properties are reduced and simplified in the current version. Cost for installation or carbon cost will be added in future versions to filter renovation scenarios.

The installation of renewable energy systems on the façade through an ENSNARE renovation is modelled in a specific way: while it is considered that a homogenous insulation is set up on all façades of a building, one of the advantages of the ENSNARE solution is to allow the installation of multiple systems (i.e. PV, ST or PV+T). Therefore, the InstallST, InstallPV and InstallPVT actions must be associated with a façade, and with a surface (or ratio) of the same façade; this modeling is done through the Façade_Needed_Solar concept which has three subclasses/variants for PV, ST and PVT systems respectively.

5 From decision tree to rule-based reasoning

The core work consists in creating the set of inference rules that are used to generate potential renovation scenarios. This creation process can be modelled as a decision forest, i.e. a set of decision trees, i.e. a hierarchical process based on the successive evaluation of different expressions. The developed approach resides in converting a decision forest into a set of inference rules, through a flattening operation, which is detailed in this section.

Listing 1: Rules 1 – example of preliminary computations

```
[facade_vs_roof:
(?bldg bldg:roofArea ?area_roof) (?bldg bldg:hasFacade ?fcd) (?fcd bldg:area ?area_fcd)
quotient(?area_fcd, ?area_roof, ?ratio)-> (?fcd bldg:facadeRoofRatio ?ratio)]

[dhw_need:
(?bldg bldg:nbDwellings ?nb_dwellings) difference(60, 15, ?diff_temp_dhw)
product(1.163, ?diff_temp_dhw, ?energy_need_per_vol) product(?nb_dwellings, 3, ?nb_occupants)
product(?nb_occupants, 40, ?total_daily_vol)
product(?energy_need_per_vol, ?total_daily_vol, ?daily_energy_need)
-> (?bldg bldg:dhw_energy_need ?daily_energy_need)
```

The set of decision trees (rules) is divided in different groups. The first group consists of preliminary computations. Those consist in computing the ratio between the façade and roof surface (to identify the main thermal loss surfaces); to estimate the daily domestic hot water consumption which is done with the rule dhw_need in Listing 1 where ?diff_temp_dhw corresponds to the water temperature heat by the DHW equipment (in our case 60°C-15°C), 1.163 is the water volumic heat capacity; ?nb_occupants is the number of occupants (in our case, 3 occupants per dwelling), and 40 is the daily volume used by a single occupant; and to estimate the radiance on each façade of the building. Indeed, the climate characterization associated to a Euro Region is created from PVGIS data for a south orientation, and a 90° tilt angle. A loss factor needs to be applied when considering other orientations; in the current version those are East (loss factor is 0.6), West (0.6), South-East (0.75) and South-West 0.75) orientations (Khoo et al., 2013). No scenario is generated with installation of solar panels on North-oriented façades.

In parallel, the baseline and nZeB renovation scenarios are generated. As already mentioned, those scenarios are currently independent from any intermediary computation (solar potential assessment, DHW needs, heating needs…). Therefore, once a new Project is stored in the triple store, a BaselineScenario and a nZeBScenario are associated to it.

In a second step, different ENSNARE scenarios are generated, with different insulation performance on the façade, and windows changing. An example is provided in Listing 2: three different scenarios are generated for an initially low insulated building.

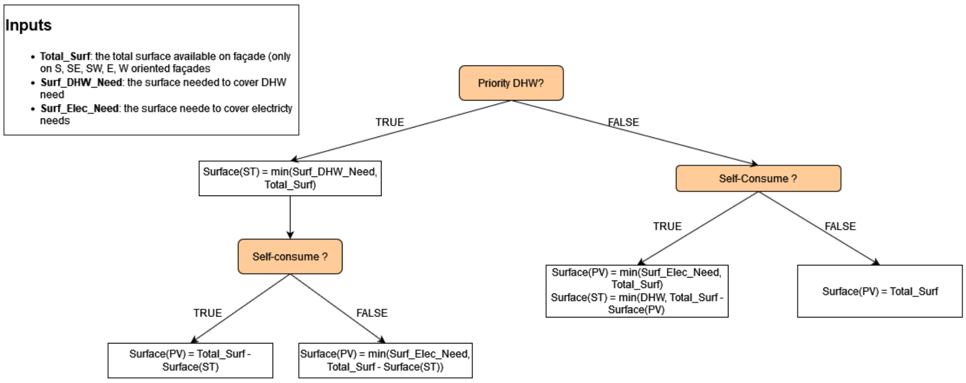
Listing 2: Step 2: generate façade renovation scenarios for ENSNARE

```
[ensnare_facade_low_insulation:
(?p rdf:type proj:Project) (?p proj:building ?bldg) (?bldg bldg:hasFacade ?fcd)
(?fcd bldg:facadeInsulation "Low") (?fcd bldg:orientation ?orientation)
regex(?orientation, '(North)(.*)')
makeTemp(?scen_high) makeTemp(?scen_medium) makeTemp(?scen_low)
-> (?scen_high proj:forProject ?p) (?scen_high rdf:type proj:EnsnareScenario_Passive_High)
(?scen_high rdfs:label "High insulation") (?scen_medium proj:forProject ?p)
(?scen_medium rdf:type proj:EnsnareScenario_Passive_Medium)
(?scen_medium rdfs:label "Medium insulation")
(?scen_low proj:forProject ?p) (?scen_low rdf:type proj:EnsnareScenario_Passive_Low)
(?scen_low rdfs:label "Low insulation")
(?scen_low proj:isMadeOf intv:ENSNARE_10cm)
(?scen_medium proj:isMadeOf intv:ENSNARE_20cm)
(?scen_high proj:isMadeOf intv:ENSNARE_30cm)
```

For each scenario, the heating and cooling and energy needs are obtained from the static knowledge. For each scenario, different ENSNARE configurations wit different PV, PV+T and ST surfaces are generated. To reduce the number of possibilities for solar panels, solar energy is assessed to be used only for DHW needs, and the electricity produced is either injected to the grid, or self-consumed for heating and cooling with a heat pump. The different strategies are further simplified and fixed:

1. Priority to electricity production and injection to the grid (no-self consumption). This strategy leads to simply install as much PV panels as possible on the buildings' south-oriented façades.
2. Priority to covering the DHW needs of the building. If some surface is still left on the building, install PV panels to produce electricity (declined in two potential sub-strategies, either for self-consumption or for the grid).
3. Priority to cover self-consumption of the produced electricity (for heating and cooling needs); if some, the rest of the facades' surface is used to install ST panels.

In strategy 2 (resp. 3), the DHW (resp. electricity) needs can be covered with either a solar thermal (resp. photovoltaic) installation, or with a hybrid photovoltaic and thermal panel; these options lead to duplicating the inference rules. In addition, the possible orientation of the building also leads to duplicating all rules to estimate the thermal and/or electrical production. The general algorithm is represented in Figure 34 as a decision tree; flattening such a tree results from formalizing each branch as an inference rule where conditional nodes (i.e. orange ones) are transformed into premises, and final noes (blank ones) as conclusions. The final version of the SWRL reasoning file is made of 80 inference rules, the more complex ones having 19 premises, and 14 conclusions. All rules can be found on Github[2].



Rule 1: Priority_DHW and Self-Consume => Surface(ST) = min(Surf_DHW_Need, Total_Surf) and Surface(PV) = Total_Surf **-** Surface(ST)

Rule 2: Priority_DHW and NOT Self-Consume => Surface(ST) = min(Surf_DHW_Need, Total_Surf) and Surface(PV) = min(Surf_Elec_Need, Total_Surf - Surface(ST))

Rule 3: NOT Priority_DHW and Self-Consume => Surface(PV) = min(Surf_Elec_Need, Total_Surf) and Surface(ST) = min(DHW, Total_Surf - Surface(PV)

Rule 4: NOT Priority_DHW and NOT Self-Consume => Surface(PV) = Total_Surf

Figure 3: Simplified schema of the transformation of the decision tree representation for renovation scenario generation into inference rules

6 Results and future work

The Jena implementation of GenScen was encapsulated in a REST API application to facilitate its interaction with other services that form the ENSNARE EDST. The service was tested and consolidated with data describing the different pilot sites provided in the ENSNARE project (6 in total). The service runs fast, generating up to 60 scenarios in few seconds, which was one of the main requirements. Nevertheless, the different strategies that are implemented often lead to duplicated renovation scenarios (i.e. scenarios with identical ENSNARE configuration); for instance, using PV panels for self-consumption or grid-connected often results in installing such panels on the overall façades, because covering heating needs with 90° tilted panels would require a large area.

In the future, the strategies could be refined in a more accurate way, to allow end users to chose the ratio of energy needs that should be covered by ENSNARE active systems for instance. Other project criteria were initially planned but not implemented, such as the available investment budget or the desired energy performance label for instance, carbon equivalent... The extensibility capacity of knowledge graphs can easily allow such improvements. Other refinements should be done, such as the more accurate computation of solar radiance with the exact coordinates of the building, which could be directly done using PVGIS API, but at the cost of time efficiency; the possibility to consider different insulation layers, or even exact thermal resistance for products. The knowledge database could also be enriched with data from different data sources, in particular open databases from regional or national initiatives such as the BDNB or ONB in France; those contain yearly energy production, current energy performance label, building dimensions or HVAC systems for instance, which could simplify the use of an EDST-like software. Finally, refining renovation projects through information update and enrichment could be done using the knowledge graph technological environment which provides a dynamic reasoning engine, that infers new knowledge at each model change.

[2] https://github.com/Nobatek/GenScen/blob/main/Jena/DecisionTree.swrl

More generally, the experiment demonstrated that implementing a decision-support tool with knowledge graphs technologies can be a complex task for different reasons. First, to our knowledge, no tool ensures the rules are correct nor syntactically, nor semantically. The framework used was Jena native inference engine, and no syntactic checker was found; semantically-speaking the soundness and completeness of the rules in solving the problem can be complex; using initial formalisms such as decision trees can help in doing so and tools based on such formalisms and transformation into inference rule sets would be valuable.

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