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SUPPLEMENTARY MATERIAL TO

Semantic Agent Framework for Automated Flood Assessment Using Dynamic Knowledge Graphs

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SI.1. Agent UML Activity Diagrams

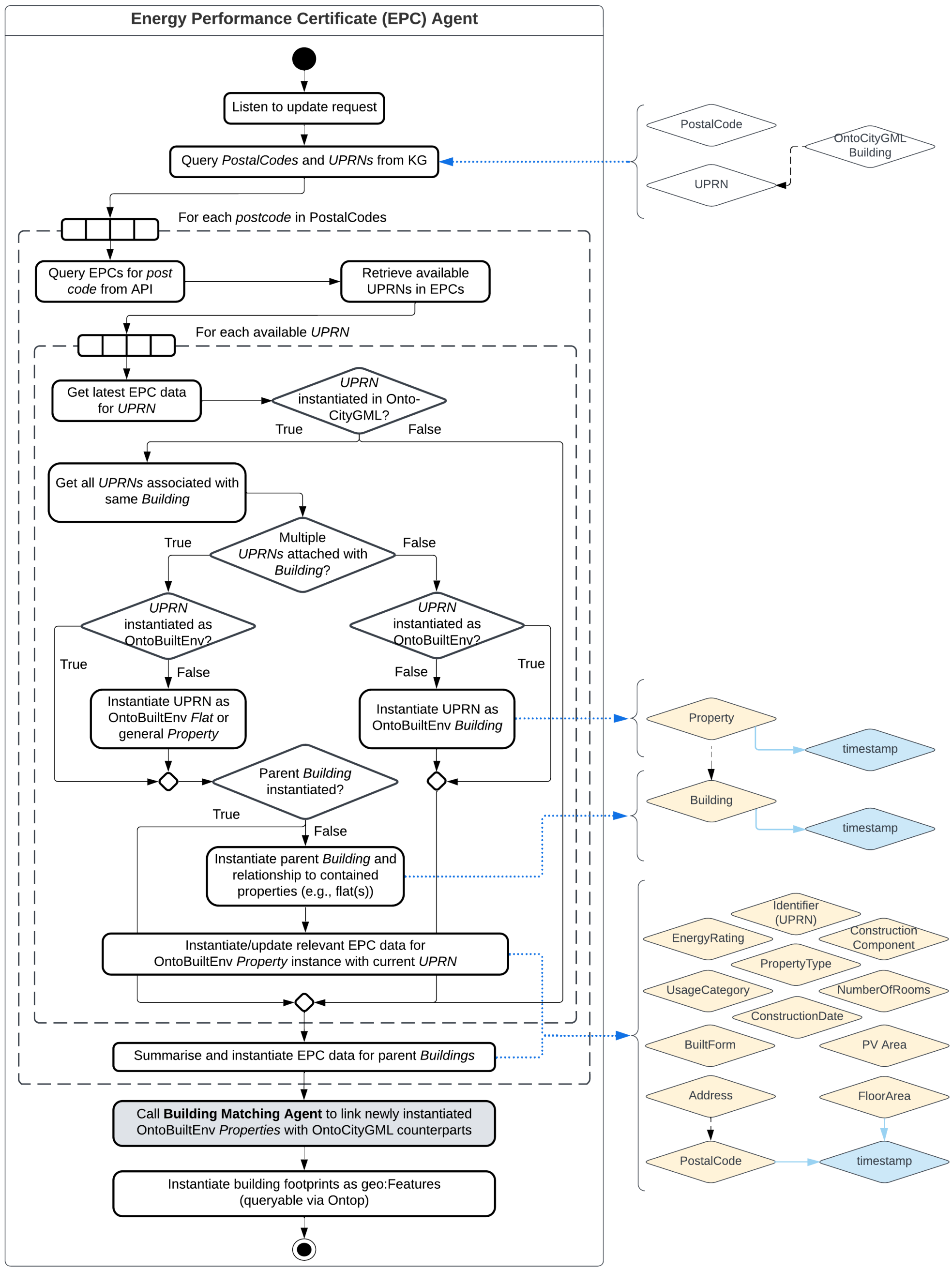


Figure SI.1. *EPC Agent. The EPC Agent continuously assimilates latest EPC data from all three EPC APIs (Department for Levelling Up, Housing & Communities, 2022) (i.e., for domestic, non-domestic, and public properties) for all OntoCityGML buildings with instantiated UPRN information (e.g., on monthly basis). For each instantiated UPRN with available EPC data, an OntoBuiltEnv* `Property` *is instantiated/updated with the respective information. In case multiple UPRNs are associated with one OntoCityGML building, a parent* `Building` *is instantiated to accommodate all associated* `Property` *instances. The Building Matching Agent is required to link corresponding building instances in OntoBuiltEnv and OntoCityGML (details in Fig. SI.2) .*

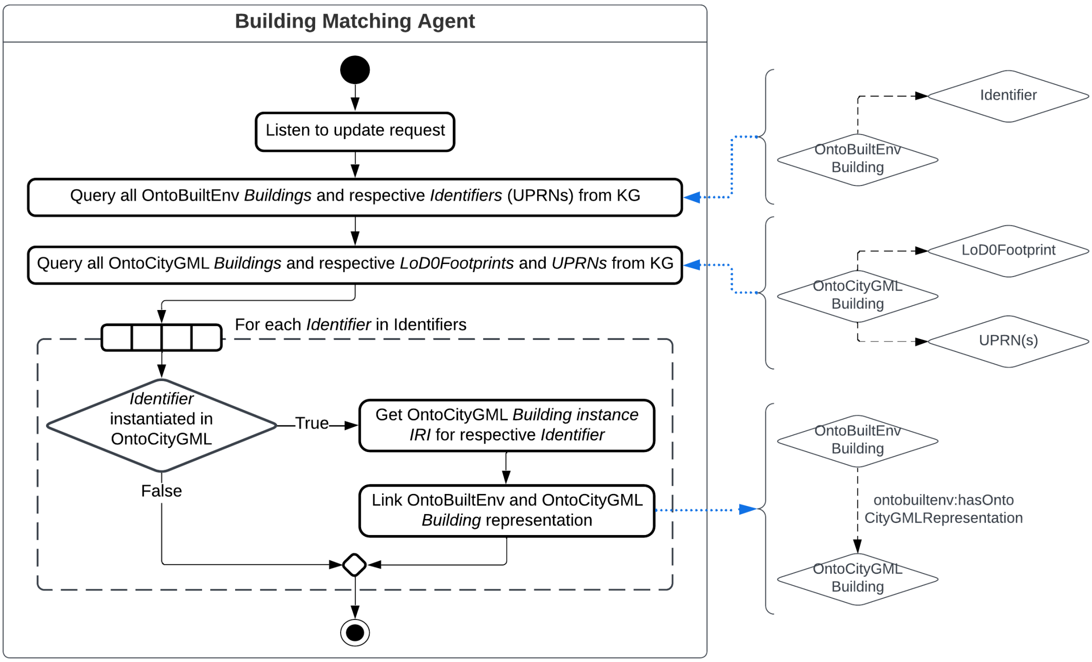


Figure SI.2. *Building Matching Agent. The Building Matching Agent is used to link a building instantiated in OntoBuiltEnv (i.e., building instances based on available EPC data) to its corresponding instance in OntoCityGML (i.e., building instances based on OS data). The link is created for buildings only (i.e., excluding flats which do not have a geospatial representation in OntoCityGML) by using UPRNs as the identifiers.*

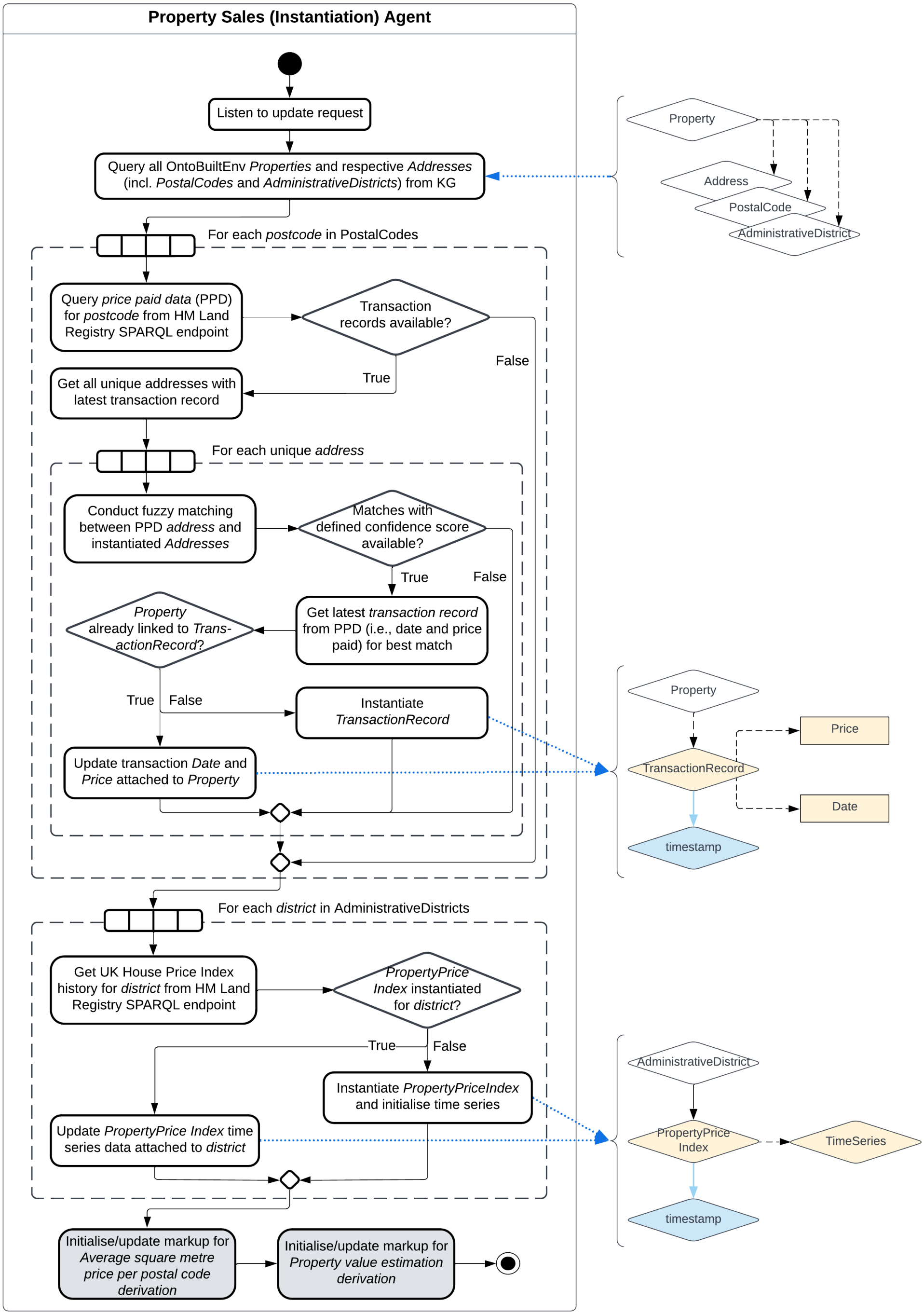


Figure SI.3. *Property Sales Agent. The Property Sales Agent queries His Majesty's Land Registry Open Data (HM Land Registry, 2022a) via its public SPARQL endpoint (HM Land Registry, 2022c) and instantiates latest available* `TransactionRecords` *for instantiated* `Properties` *as well as the* `PropertyPriceIndex` *(i.e., UKHPI). After instantiating new property sales data, the agent also instantiates the relevant derivation markups to allow for automatic assessment of the* `Average-PricePerSqm` *per postal code as well as the* `PropertyValueEstimation` *per building (for details see Figs. SI.5 and SI.7, respectively .*

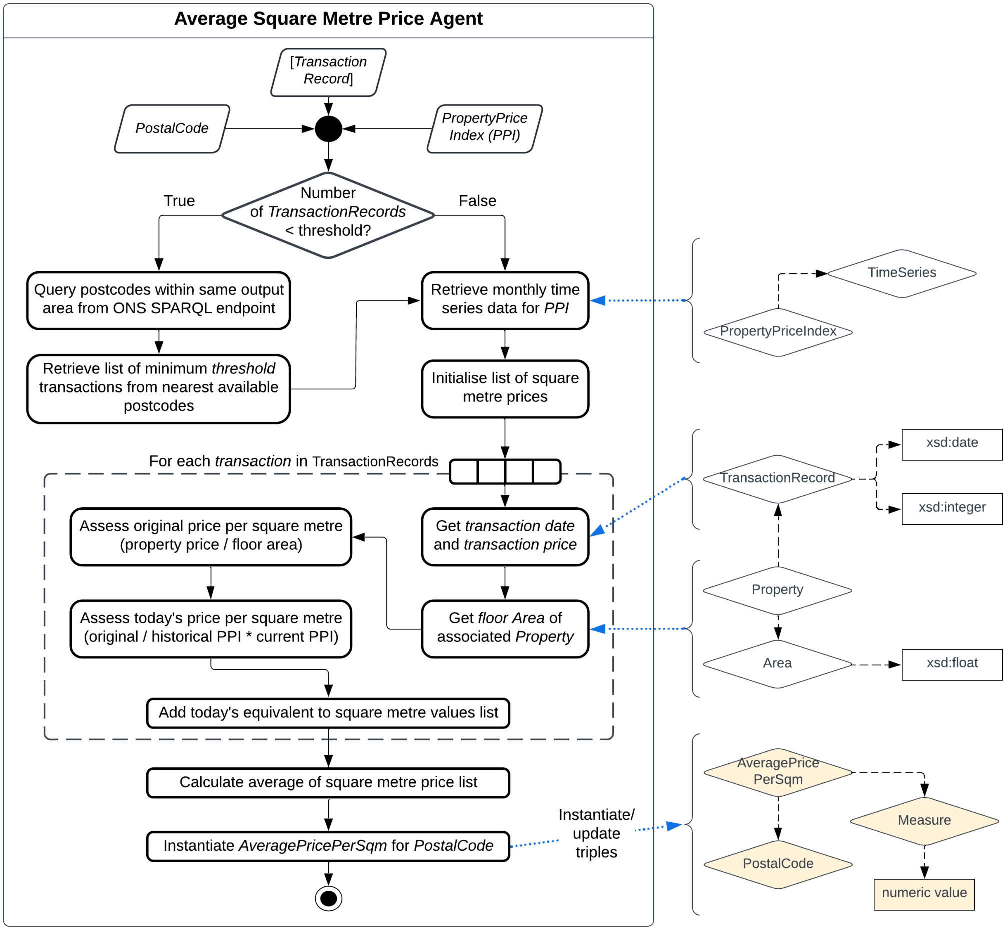


Figure SI.4. *Average Square Metre Price Agent. The Average Square Metre Price Agent calculates the current average square metre price of properties (i.e., buildings and flats) within each instantiated postal code. The required building data comprises* `FloorAreas` *(from EPC Agent) as well as previous sales* `TransactionRecords` *and the* `PropertyPriceIndex` *(from Property Sales Agent). In case of an insufficient number of instantiated* `TransactionRecords` *per* `PostalCode`*, data from surrounding postal codes are included. The agent is implemented using the derived information framework to trigger automated re-assessment once inputs become outdated. The required derivation markup is part of the Property Sales Agent and detailed in Fig. SI.5.*

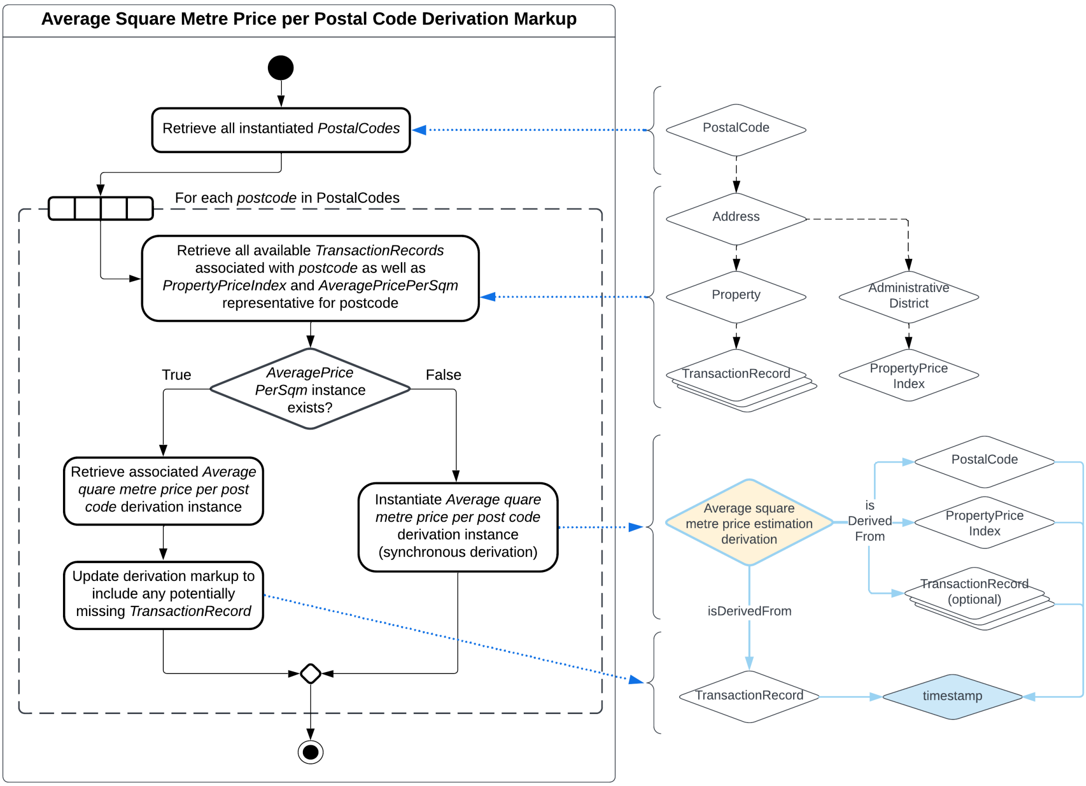


Figure SI.5. *Average Square Metre Price Derivation Markup. The derivation markup method connects all available* `TransactionRecords` *within each* `PostalCode` *with the respective* `AveragePricePerSqm` *derivation instance for that postal code: In case no derivation instance is instantiated yet, a synchronous derivation for new info is instantiated to request an initial assessment of the average price immediately. Otherwise, potentially missing* `TransactionRecords` *(i.e., newly instantiated data) are added to the existing derivation instance and a subsequent update is requested.*

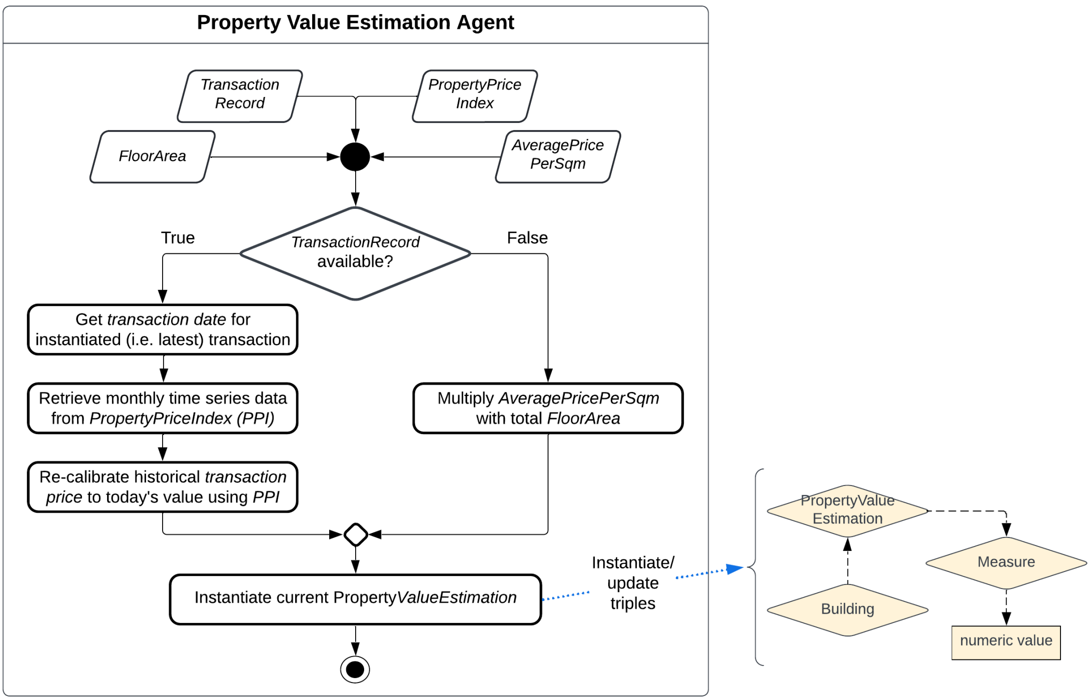


Figure SI.6. *Property Value Estimation Agent. The Property Value Estimation Agent assesses the current market value of instantiated properties. The assessment requires either 1) a previous sales* `TransactionRecord` *for the property of interest as well as the* `PropertyPriceIndex` *(both from Property Sales Agent) or, in cases where no previous sales transactions are available, 2) the* `FloorArea` *(from EPC Agent) together with the current* `AveragePricePerSqm` *for the respective* `PostalCode` *(from Average Square Metre Price Agent). The agent is implemented using the derived information framework to trigger automated re-assessment once inputs become outdated. The required derivation markup is part of the Property Sales Agent and detailed in Fig. SI.7.*

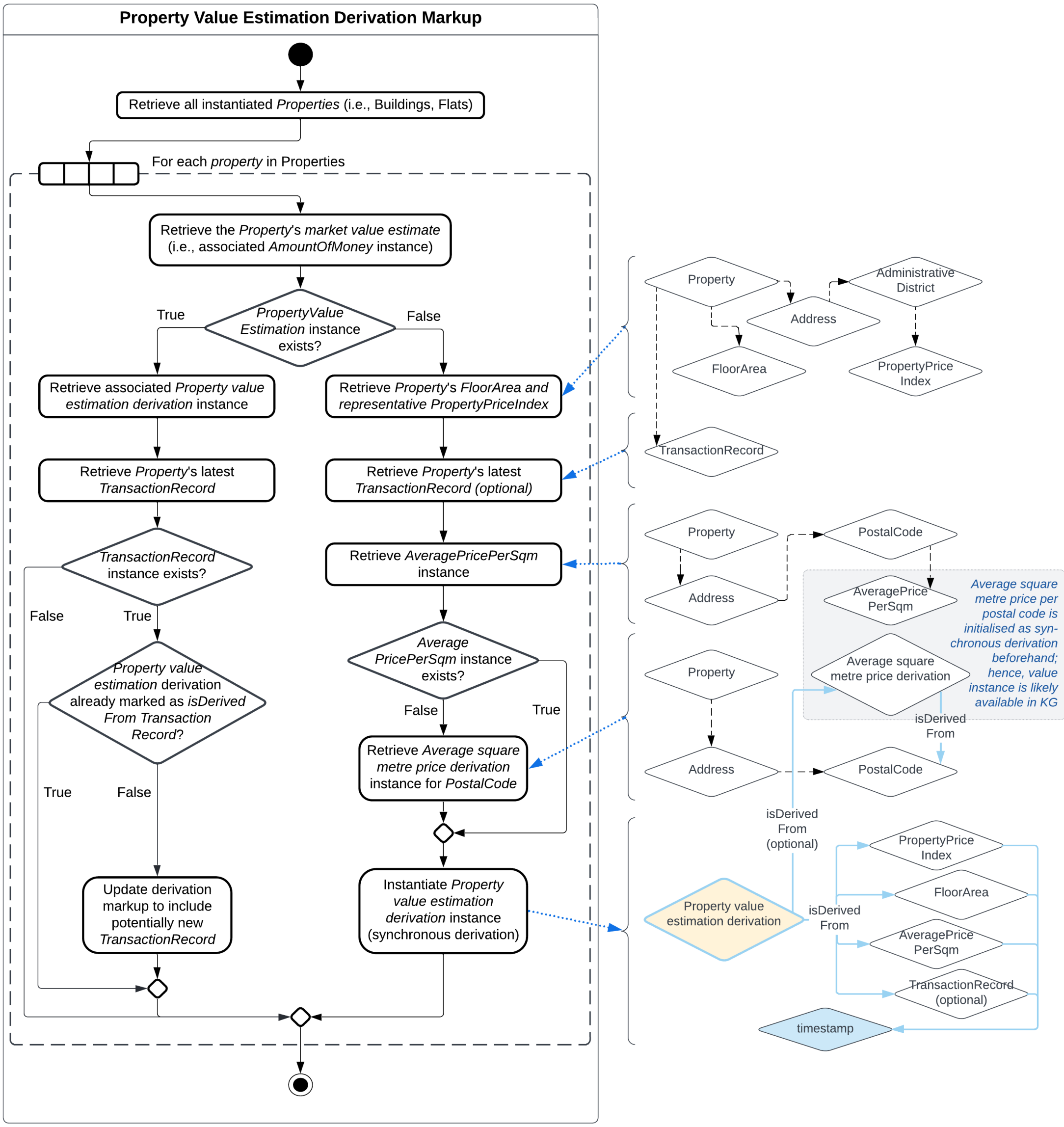


Figure SI.7. *Property Value Estimation Markup. The derivation markup method connects the* `FloorArea` *and previous* `TransactionRecord` *(if available) of a* `Property` *as well as the applicable* `AveragePricePerSqm` *(per postal code) and* `PropertyPriceIndex` *(per district) with the respective* `PropertyValueEstimation` *derivation instance for this building: In case no derivation instance is instantiated yet, a synchronous derivation for new info gets instantiated to request an initial estimation of the property value. If the* `AveragePricePerSqm` *has not been computed yet, the property value derivation gets connected to the upstream average price derivation (although this is very unlikely due to instantiation as synchronous derivation for new info). For existing derivation instances, a potentially new* `TransactionRecord` *(i.e., newly instantiated data) gets added and a subsequent update is requested.*

SI.2. Pseudocode examples

Algorithm 1: Update flood warnings/alerts in KG

```
Input: List of json objects with active flood warnings and alerts from EA API warnings_api; list of
       instantiated warnings and alerts in KG warnings_kg
Result: Newly instantiated and/or updated flood warning and alert instances in the KG

Query instantiated flood areas areas_kg from KG
areas_api ← Extract list of distinct areas associated with warnings in warnings_api
areas_new ← areas_api \ areas_kg
warnings_new ← warnings_api \ warnings_kg
warnings_outdated ← []
for w ∈ warnings_kg do
    if w ∈ warnings_api & associated timestamp from API > KG then
        warnings_outdated.append(w)

/* Instantiate new flood areas                                          */
if |areas_new| > 0 then
    Upload Ontop mapping to access PostGIS data via GeoSPARQL (if not exists yet)
    for a ∈ areas_new do
        Retrieve area details for a from EA API
        Execute SPARQL update to instantiate relevant non-geospatial details in KG
        Create GeoJSON string with relevant geo-spatial information and upload to PostGIS

/* Instantiate new flood warnings/alerts                                */
for w ∈ warnings_new do
    Execute SPARQL update to instantiate new FloodAlertOrWarning instance in KG
    Update Activity and Severity flags of associated flood area in PostGIS (to ensure visualisation)

/* Update instantiated flood warnings/alerts                            */
for w ∈ warnings_outdated do
    Extract latest details for w from warnings_api
    Execute SPARQL update to update existing FloodAlertOrWarning instance in KG
    Update Severity flag of associated flood area in PostGIS (for styling purposes)
```

Algorithm 2: Assess potential impacts of flood warning/alert

Input: IRI of `FloodAlertOrWarning` instance $warning$; list of `Building` instances $buildings$; list of corresponding `PropertyValueEstimation` instances $estimations$
Result: Count of affected buildings $bldg\_count$; total market value of buildings at risk $bldg\_value$; count of affected population pop_count

```
Query severity instance severity associated with FloodAlertOrWarning from KG
if severity == flood:InactiveFloodWarning then
    bldg_count ← 0
    bldg_value ← 0
    pop_count ← 0
else
    /* Assess building stock at risk */
    bldg_count ← length of buildings
    bldg_value ← 0
    Query numerical prices P and associated units for all estimations from KG
    for p ∈ P do
        if associated unit == om:poundSterling then
            bldg_value ← bldg_value + v
    /* Assess population at risk */
    Query flood area instance area associated with warning from KG
    Retrieve flood extend polygon for area from PostGIS
    Calculate summary statistics of raster data over clipped polygon via PostGIS as stats
    pop_count ← sum(stats)
Return bldg_count, bldg_value, pop_count
```

SI.3. SPARQL query examples

Listing 1. *SPARQL query to obtain instantiated flood warnings and alerts from KG (`optional` keyword used to include not always available triple patterns).*

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rt: <http://environment.data.gov.uk/flood-monitoring/def/core/>

SELECT ?warning_iri ?t1 ?t2 ?t3
WHERE {
  {
    ?warning_iri rdf:type rt:FloodAlertOrWarning .
    OPTIONAL { ?warning_iri rt:timeRaised ?t1 . }
    OPTIONAL { ?warning_iri rt:timeMessageChanged ?t2 . }
    OPTIONAL { ?warning_iri rt:timeSeverityChanged ?t3 . }
  }
}
```

Listing 2. *SPARQL query to obtain instantiated flood areas from KG (`optional` keyword used to include not always available triple patterns).*

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX flood: <https://www.theworldavatar.com/kg/ontoflood/>
PREFIX rt: <http://environment.data.gov.uk/flood-monitoring/def/core/>

SELECT ?area_iri ?location_iri ?warning_iri
WHERE {
  {
    ?area_iri rdf:type rt:FloodArea ;
              flood:hasLocation ?location_iri .
```

```
    OPTIONAL { ?area_iri rt:currentWarning ?warning_iri }
  }
}
```

Listing 3. *SPARQL update to instantiate new flood alert/warning in KG (<> denote placeholders for actual IRIs).*

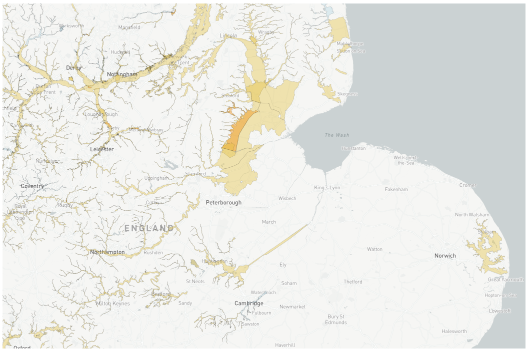
```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX envo: <http://purl.obolibrary.org/obo/ENVO_>
PREFIX flood: <https://www.theworldavatar.com/kg/ontoflood/>
PREFIX rt: <http://environment.data.gov.uk/flood-monitoring/def/core/>

INSERT DATA {
  # Object properties
  <WarningIRI> rdf:type rt:FloodAlertOrWarning .
  <WarningIRI> flood:hasSeverity <SeverityIRI> .
  <AreaIRI> rt:currentWarning <WarningIRI> .
  <WarningIRI> flood:warnsAbout <FloodEventIRI> .
  <FloodEventIRI> rdf:type envo:Flood .
  <FloodEventIRI> flood:hasLocation <LocationIRI> .
  # Data properties (only instantiated if data available)
  <WarningIRI> rdfs:label "<Label>"^^xsd:string .
  <WarningIRI> rt:message "<Message>"^^xsd:string .
  <WarningIRI> rt:timeRaised "<TimeRaised>"^^xsd:dateTime .
  <WarningIRI> rt:timeMessageChanged "<TimeMessageChanged>"^^xsd:dateTime .
  <WarningIRI> rt:timeSeverityChanged "<TimeSeverityChanged>"^^xsd:dateTime .
}
```

Listing 4. *SPARQL update to update outdated flood alert/warning information in KG (<> denote placeholders for actual IRIs).*

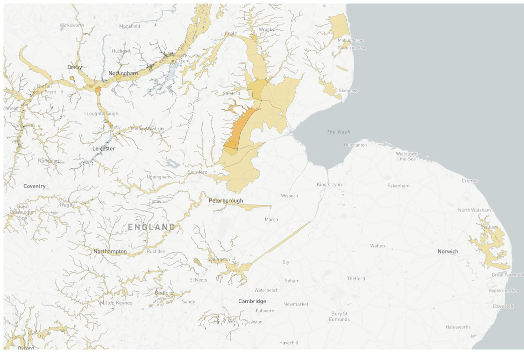
```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX flood: <https://www.theworldavatar.com/kg/ontoflood/>
PREFIX rt: <http://environment.data.gov.uk/flood-monitoring/def/core/>

DELETE {
  <WarningIRI> flood:hasSeverity ?severity_iri ;
               rdfs:label ?warning_label ;
               rt:message ?warning_message ;
               rt:timeRaised ?time_raise ;
               rt:time_message ?time_message ;
               rt:time_severity ?time_severity .
}
INSERT {
  <WarningIRI> flood:hasSeverity <SeverityIRI> .
  # Data properties (only instantiated if data available)
  <WarningIRI> rdfs:label "<Label>"^^xsd:string .
  <WarningIRI> rt:message "<Message>"^^xsd:string .
  <WarningIRI> rt:timeRaised "<TimeRaised>"^^xsd:dateTime .
  <WarningIRI> rt:timeMessageChanged "<TimeMessageChanged>"^^xsd:dateTime .
  <WarningIRI> rt:timeSeverityChanged "<TimeSeverityChanged>"^^xsd:dateTime .
}
WHERE {
  <WarningIRI> rdf:type rt:FloodAlertOrWarning ;
               flood:hasSeverity ?severity_iri .
  OPTIONAL { <WarningIRI> rdfs:label ?warning_label }
  OPTIONAL { <WarningIRI> rt:message ?warning_message }
  OPTIONAL { <WarningIRI> rt:timeRaised ?time_raise }
  OPTIONAL { <WarningIRI> rt:time_message ?time_message }
  OPTIONAL { <WarningIRI> rt:time_severity ?time_severity }
```

}

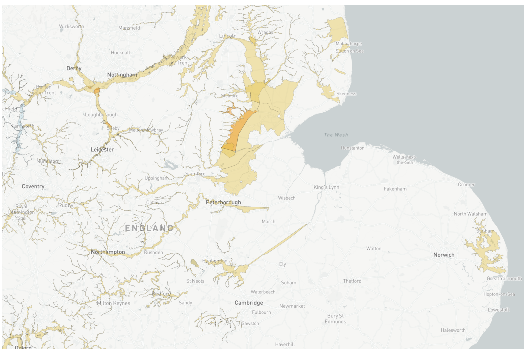
SI.4. Time Evolving Flood Warnings



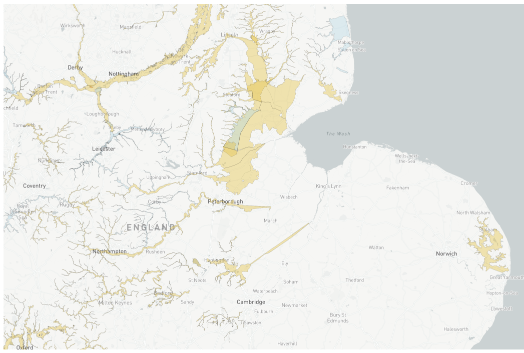
(a) Active flood alerts/warnings as of 06 Dec 2023 00:20 UTC



(b) Active flood alerts/warnings as of 07 Dec 2023 08:20 UTC



(c) Active flood alerts/warnings as of 08 Dec 2023 00:15 UTC



(d) Active flood alerts/warnings as of 09 Dec 2023 02:00 UTC

Figure SI.8. *Time evolution of flood warnings in TWA. Once deployed, the proposed framework of agents autonomously ingests and assesses newly published flood data to ensure that TWA remains current in time. Exemplarily shown are active flood alerts and warnings throughout the course of December 6-9, 2023, for East Midlands and the East of England. Orange shaded areas indicate flood warnings, yellow areas denote flood alerts, and blue shades represent soon-to-be-revoked inactive flood alerts.*

SI.5. Public Data Source Details

SI.5.1. Environmental Observations and Flood Data

The Met Office DataPoint API provides open access to both current weather observations and forecasts of future weather conditions (Met Office, 2022). The service offers predictions for around 6,000 and actual observations for approximately 140 locations throughout the UK. Forecasts cover a five-day period while observations encompass the previous 24 hours, including typical parameters such as temperature, wind speed and direction, humidity, and air pressure.

The Environment Agency provides several API endpoints with (near-real time) information related to flooding and flood risk: The Real Time flood-monitoring API (Environment Agency, 2021b) provides a listing of all current flood alerts and warnings, including relevant meta information (*e.g.*, severity, associated water bodies, and warning message), and is updated every 15 minutes. The same API also provides an endpoint for live readings of water levels and flows recorded at various measuring stations along rivers and other water bodies. Precipitation data is also integrated and provided for nearly 1000 telemetry-connected tipping bucket rain gauges. The API furnishes metadata on these stations and the diverse measurements available at each one, as well as the actual readings themselves. Beyond those (near) real-time information, the Hydrology API also provides past, and (partially) quality controlled, hydrological data about river levels, river flows, groundwater levels, precipitation, and water quality (Environment Agency, 2021a). The Flood Forecasting Centre generates a daily flood risk forecast, with more frequent updates issued when severe flooding is anticipated (Flood Forecasting Centre, 2017). The forecast assesses the likelihood of flooding for a period of five days and covers flooding from rivers, the sea, surface water and groundwater for England and Wales. Compared to immediate flood alerts and warnings, this information is associated with higher uncertainty, both with regards to areal extend and anticipated severity.

The UK Air Information Resource (UK-AIR) provides real-time air quality data for various pollutants, including nitrogen dioxide, particulate matter, and ozone. The data is collected from a network of monitoring stations located throughout the UK and publicly provisioned via a machine readable Sensor Observation Service (Department for Environment, Food & Rural Affairs, 2023). Parts of the data are enriched with meta information about reported pollutants according to the European GEMET (General Multilingual Environmental Thesaurus) vocabulary (European Environment Information and Observation Network, 2021).

SI.5.2. Building Data

The Ordnance Survey (OS) is the national mapping agency of Great Britain responsible for producing and disseminating geospatial data for government and public use (Ordnance Survey, 2022). The OS MasterMap™ is recognised as the most detailed available large-scale mapping of the UK, covering administrative boundaries, postcodes, OS identifiers, detailed digital terrain models (DTM), and building data, including the Building Height Attribute (BHA) dataset. The OS BHA data provides detailed information about the physical characteristics of the built environment, more precisely vector specifications for the base polygon, base elevation and height of individual buildings as well as other related attributes such as the number of floors and an open, officially maintained identifier, called Unique Property Reference Number (UPRN) to cross-link information across datasets. The UPRN is a unique identifier assigned to every addressable location in the UK, including residential and commercial buildings, as well as other types of buildings and structures. It provides a consistent and reliable way to identify and reference specific locations, regardless of changes in the property name or address. The BHA data is derived from a combination of remote sensing techniques such as LiDAR (Light Detection and Ranging) and aerial photography, and is processed using advanced algorithms to produce highly accurate and detailed height measurements. Although restricted redistribution and complex licensing arrangements make it not ideal for TWA, multiple relevant subsets are made accessible via Digimap (EDINA Digimap Ordnance Survey Service, 2022) for educational and research purposes. OS data is either downloaded via Digimap (*i.e.*, terrain and BHA data) or accessed via the OS Features API (*i.e.*, *UPRN Agen*t).

The Department for Levelling Up, Housing & Communities offers open Energy Performance Certificate (EPC) data (Department for Levelling Up, Housing & Communities, 2022) to increase transparency on the energy efficiency and carbon emissions of individual buildings in the UK and to provide improvement recommendations. There are three dedicated APIs for domestic, non-domestic and display (*i.e.*, mostly public buildings) certificates providing property-level information about current and potential energy efficiency, key construction characteristics (*i.e.*, number of rooms, total floor area, building type, *etc.*), high-level usage classification as well as address and location details, including UPRN. New or updated information is released every four to six months and can be directly linked to OS building information via UPRN matching.

His Majesty's Land Registry publishes several public datasets related to residential property sales on a monthly basis, and even makes them available as Linked Data via its public SPARQL endpoint (HM Land Registry, 2022c): The UK House Price Index (HM Land Registry, 2022d) captures the monthly change in the value of residential properties in England and Wales, on different levels of granularity, covering national, county, and local authority scale. The Price Paid data (HM Land Registry, 2022b) contains information about the actual transaction price and date of individual residential properties sold in England and Wales, including address, type of property, and tenure; however, without explicit UPRN information. Due to licensing constraints (*i.e.*, around OS AddressBase), open transaction data can only be linked to OS building information via (fuzzy) address matching.

SI.5.3. Population Data

The OpenPopGrid (Murdock et al., 2015) provides an open gridded population dataset for England and Wales based on the ONS 2011 Census (*i.e.*, Output Area boundaries, Postcode headcounts, ONS Postcode Directory) as well as OS OpenData (*i.e.*, VectorMap District). It aims to enhance the spatial accuracy of the ONS population dataset by utilising an asymmetric mapping technique that limits the redistribution of population to particular regions, such as residential buildings, through the use of supplementary data. Specifically, the census postcode headcounts are redistributed across a grid, which is based on the OS VectorMap District buildings dataset, which prior has been carefully screened to remove non-residential areas using unpopulated postcode centroids. It is ensured that population values remain consistent with the Census data when aggregated at the Output Area level.

SI.6. Ontology Review

SI.6.1. Sensor and Measurement Ontologies

Sensor ontologies provide a formal way to represent sensor related concepts and relationships to enable interoperability and integration among different sensor systems with non-homogeneous data acquisition and monitoring techniques:

The Semantic Sensor Network (SSN) ontology (World Wide Web Consortium, 2017) is designed to describe sensors and their observations, samples and procedures used, observed properties, and actuators. It utilises a modular architecture, based on the Sensor, Observation, Sample, and Actuator (SOSA) ontology (Janowicz et al., 2019) as its core, which allows for flexible use and covers a wide range of applications. The SOSA ontology provides a general-purpose foundation for sensor related applications with defining elementary classes and properties, while the SSN ontology incorporates more specialised and domain-specific concepts to provides a more comprehensive ontology for describing sensors and their observations in greater detail. The SSN ontology is developed and maintained by the W3C, making it widely recognised and adopted, and its well-designed modular architecture enables flexibility and ease of re-use (even individual components). While its comprehensive coverage of standardisation is one of the key advantages, some aspects of the ontology may be overly complex for certain use cases. The SOSA ontology, on the other hand, provides a lightweight, modular, and self-contained core ontology for describing basic concepts related to sensors, observations, and actuators to foster re-use by simplicity compared to other ontologies. However, one of the challenges of SOSA is its limited coverage, which may not be suitable for all sensor related applications.

The Modular Environmental Monitoring (MEMOn) ontology (Masmoudi et al., 2020a) has been developed to represents various environmental monitoring data and to support semantic interoperability between heterogeneous data collected through a variety of observation techniques and systems. It defines a set of concepts and relationships for describing environmental monitoring equipment, including sensors, mainly borrowing concepts from SSN and SOSA. MEMOn is designed based on a modular architecture, making it easy to extend and reuse its components. The ontology covers various aspects of sensor data, such as sensor metadata, observations, and the context in which they occur and provides clear guidelines for mapping sensor data to the ontology. One of the main advantages of MEMOn is its domain-specificity, which ensures accurate representation of environmental monitoring data. However, MEMOn only supports limited coverage of non-environmental sensors and may be overly specific for some applications.

The Smart Appliances REFerence (SAREF) ontology (ETSI, 2020) is a top-level ontology designed to describe smart appliances with their features and functions, including sensors and actuators. SAREF aims to provide a standardised framework for representing smart appliances and associated data and is designed in a modular fashion covering various aspects of smart appliances and systems. Compared to SSN and SOSA, SAREF has a narrower scope, focusing specifically on smart appliances rather than sensors and observations more broadly. However, SAREF can be used in conjunction with other ontologies, including SSN and SOSA, to provide a more comprehensive representation of smart systems. One strength of SAREF is its focus on consumer-facing applications, making it particularly useful for the development of smart home systems and the Internet of Things. However, its limited scope may also be seen as a weakness, as it may not provide enough coverage for more specialised or complex sensor related applications outside of the smart appliance domain.

Several approaches have been proposed to ontologically describe environmental water resources and associated sensor readings; however, the focus has mainly been to either align the heterogeneous data from various sensor web resources (*e.g.*, (Wang et al., 2018,0)) or support water quality monitoring (*e.g.*, (Xiaomin et al., 2016)) with focus on data management and query capabilities. A hydrological sensor web ontology based on the SSN ontology has been developed to align semantics and support collaboration between individual water related sensor networks and data feeds (Wang et al., 2018), primarily in response to natural disasters such as floods. It introduces hydrological domain classes and establishes relevant reasoning rules. Further SSN-based domain ontologies describing information from sensors, observation values, and reading time series for distributed water sensor networks have been proposed (Dutta and Morshed, 2013; Liu et al., 2012), partially even including data reliability assessment capabilities (Dutta and Morshed, 2013).

A semantic-enhanced modelling approach for river water quality monitoring and observation data processing has been proposed using the Observational Process Ontology (OPO) (Wang et al., 2020). The ontology describes entities related to water resource management and associated observation data. While the SSN ontology contains more comprehensive concepts of sensor metadata, OPO provides more details about observational processes and models. Furthermore, OPO also defines entities related to water quality monitoring and pollution alerting to automatically trigger potential alerts.

SI.6.2. Flood Ontologies

SWEET is a highly modular mid-level ontology suite for Earth system science and contains approximately 6000 concepts in 200 separate ontologies (Buttigieg et al., 2018). SWEET ontologies define a hierarchy of many flood risk related terms and are often referenced for a variety of environmental concepts. SWEET provides nine top-level concepts (*e.g.*, phenomena, and processes) which can be used as a foundation, and extended further to build domain-specific ontologies. Additionally, SWEET already provides several domain-specific ontologies (*e.g.*, for hydrosphere phenomena).

The Environmental Ontology (ENVO) is a FAIR-compliant domain ontology concerned with environments as encountered in ecological applications (*e.g.*, describing ecosystems, astronomical bodies, or environmental processes) (Buttigieg et al., 2016). It aims to promote interoperability of diverse datasets through the concise, controlled description of environment types across several levels of granularity. The *environmental hazard* subset contains suitable concepts to represent a flood and flooding in general, including more detailed descriptions of various kinds of flooding. Furthermore, it includes links to GEMET (European Environment Information and Observation Network, 2021) as one of the general thesauri to describe core terminology for the environment as well as additional metadata from Wikidata (Wikimedia Foundation, 2023). Links to a variety of further machine-readable thesauri (*e.g.*, AGROVOC by the Food and Agriculture Organization of the United Nations) can be retrieved via GEMET. ENVO has been published in OWL format, which fosters its re-use to represent the phenomenological nature of flood events; however, no concepts to represent social or economic damage are considered.

The Modular Environmental Monitoring Ontology also aims to support semantic interoperability in the environmental monitoring domain (Masmoudi et al., 2020b); however, most of the concepts related to floods are directly borrowed from ENVO, and only amended with further (non-semantic) annotations. A modular ontology-based framework for flood forecasting using a continuous stream of data about watersheds and sewer flow conditions has been developed by Agresta et al. (2014). A group of information-centric ontologies encompassing the flood domain are described in (Sermet and Demir, 2019), including their potential to access, analyse, and visualise flood related data with natural language queries. The proposed artificial intelligence system facilitates the generation of knowledge that supports the communication of flood data and information. An ontology for riverine flood management has been developed by Wrachien et al. (2012) to foster decision support strategies by generating a knowledge base for decision making.

The Ontology for River Flow and Flood Mitigation (ORFFM) (Mughal et al., 2021) has been developed to resolve ambiguity during flood disaster management. The key objective of this ontology is to improve collaboration between multiple stakeholders and the integrated domains of irrigation, flood management, and administration through effective coordination and explicit semantic formalisation of common concepts. ORFFM estimates the impact and damage of a flood based on the affected instances (*e.g.*, areas, assets, roads, livestock, crops, *etc.*) and the assessment of likelihood and magnitude of a flood is based on the physiographic attributes and meteorological information. Affected areas are linked to administrative spatial regions.

Khantong et al. (2020) have developed a domain ontology to enable seamless collaboration and information exchange between various stakeholders during a flood disaster response. The focus of this ontology is rather conceptualising the structure and sequence of relevant information, involved organisations and roles as well as the interplay and processes between them rather than conceptualising the data itself. To address both static and dynamic aspects of real world concepts involved in disaster response, one of the most prominent and influential upper ontologies, the Linguistic and Cognitive Engineering ontology (DOLCE), is used. DOLCE distinguishes entities into two main types, namely, `perdurants` to describe entities that happens in time and `endurants` referring to entities that exist in a timeless way.

Kollarits et al. (2009) have developed the MONITOR risk management ontology as formalised knowledge base to describe the relations between natural, social and built environments, potentially hazardous events and several risk assessment and management terms. MONITOR builds on well established top-level ontologies, such as DOLCE, for formalised definitions of general terms, *i.e.*, reusing the concepts of `endurants` and `perdurants` to represent the (non-)transient nature of concepts. `Damage` is a subclass of `impact` and the central concept for all risk related propositions. `Risk` is defined as the probability of a damage of defined extent. An `event` is a `perdurant` (*i.e.*, occurrence, happening) which can cause an impact (*i.e.*, change) and has a magnitude (also referred to as intensity) and a spatio-temporal location, which can have a certain probability. `Hazard` is an event, which causes damage, and includes both an actual event and a potential event. `Damage potential` depends on the value of objects affected by a particular event and their vulnerability. `Hazard potential` describes the (potential) impact of a hazard and depends on the probability and the magnitude of the event.

Scheuer et al. (2013) have proposed an ontology for a multi-criteria flood risk assessment domain, which builds and extends the conceptual model of risk as described by MONITOR. Furthermore, introduced concepts have been matched against their semantic counterparts in SWEET and other relevant ontologies to foster knowledge-based integration. A `flood` is a particular type of `event`, which in turn represents any potentially hazardous event. Any `event` and is characterised by its `intensity` and `recurrence interval`. Intensity is described as the combination of three different intensity parameters, namely inundation depth, duration and areal extent. To represent elements at risk of being affected by an event, *i.e.*, elements of natural, social or built environments, the concepts of `element` `at risk` is proposed. This concept encompasses infrastructure elements (*i.e.*, material and institutional infrastructure), population, and environmental components (*i.e.*, nature). The work states that material infrastructure and population are regarded the most relevant elements at risk by relevant flood risk assessment stakeholders. The `vulnerability` of an element at risk is assessed using susceptibility functions which relate given intensity parameters to an expected damage. To describe the hazard potential imposed by a particular flood event, `flood hazard maps` are introduced. Its subclasses `flood extend` and `flood depth` map link to visual representations of the areal extend and geospatial depth distribution, respectively.

SI.6.3. Building Ontologies

The Building Topology Ontology (BOT) (Rasmussen et al., 2021) is an upper ontology that aims to represent the core topological concepts of a building, including relationships between sub-components contained within a building. BOT has been established by the W3C Linked Building Data Community Group to provide a minimal ontology for describing relationships between a building's sub-components and is designed as extensible baseline ontology to be used together with domain-specific schemas for more complex, specific use cases. BOT's scope is limited to buildings and their specific topologies. While BOT covers many high-level concepts of a building such as sites, floors, zones, and rooms, it does not include representations of properties or units of measurements related to systems, equipment, and devices, such as sensors or actuators.

The RealEstateCore (REC) ontology (RealEstateCore Consortium, 2020) builds upon a broader conceptualisation of buildings, including land and real estate classes. REC is specifically designed to facilitate building control as well as the development of integrated services within smart cities. It is funded and produced by a consortium of major real estate companies in Northern Europe. REC is a modular ontology based on data schemas describing concepts and relationships relevant to a variety of building systems and also captures the control aspects of technical systems, facility maintenance, certification, and financial aspects.

The Brick Schema (Brick Schema, 2022) is an application ontology that standardises how physical, logical, and virtual assets in buildings are represented, as well as their relationships and associated telemetry, including sensors and actuators. It has been created through empirical analysis of concepts and relationships needed in real building applications and provides a formalised and extensible vocabulary for common building assets. The Brick Schema consists of three components: an RDF class hierarchy that describes the various building sub-systems and entities/equipment, a minimal and principled set of relationships for connecting these entities into a directed graph, and a method of encapsulation that allows complex components to be composed from a set of lower-level ones. Its design is focused on abstracting and simplifying some aspects of common building equipment to make queries easier for users and integrate and interoperate with other linked data models, such as BOT and REC.

The Google Digital Building ontology (Google, 2022) is an open-source project that aims to create a uniform schema and toolset for representing structured information about buildings and building-installed equipment. The ontology is inspired by and compatible with both Project Haystack (Project Haystack, 2022) and Brick Schema (Brick Schema, 2022), and is currently used by Google to manage its very large, heterogeneous building portfolio in a scalable way. The Haystack ontology is a lightweight, extensible ontology that is focused on the semantic modeling of various building systems with a simpler data model than the Brick Schema. The ontology enables applications and analyses to be easily transferable between buildings through a combination of semantically-expressive abstract modeling and an easy-to-use configuration language.

The iCity Building ontology (Katsumi, 2021) is a module of the larger Urban System Ontology. It provides a foundational vocabulary to represent building related data within the urban context, including physical building elements, systems, and their interactions. The Urban System Ontology extends this by including additional modules for representing other urban related domains, such as transportation, environment, and governance to enable interoperability between different urban systems and applications.

The Domain Analysis-Based Global Energy Ontology (DABGEO) has been proposed as global ontology for the energy domain that provides a common representation of relevant (sub-)domains captured by existing ontologies to foster interoperability across energy management applications and scenarios (Cuenca et al., 2020). The ontology (Cuenca and Larrinaga, 2019) follows a modular approach to provide a balance of abstraction (*i.e.*, to foster re-usability) and specification (*i.e.*, to foster direct usability) of energy domain data, with a focus on smart home and smart city energy management. The ontology contains a tailored sub-module for knowledge about infrastructure and buildings, containing classes, properties and axioms to represent static building features (*e.g.*, surface, material), geometrical details (rooms, floors) as well as internal and external environmental conditions (*e.g.*, room temperature). DABGEO also contains concepts to describe dynamic building behaviour, especially relevant to derive a holistic view of the energy consumption and generation performance of green buildings, self-sufficient in solar energy.

The BIMERR Building ontology (Ontology Engineering Group (OEG), 2020b) forms the core module for building topology and components data within the BIMERR Ontology Network (Ontology Engineering Group (OEG), 2020a), which connects several other domains related to the building industry and smart cities. The ontology extends the BOT ontology (Rasmussen et al., 2021), which provides the vocabulary to describe the topology of a building as well as the relationships between its main components such as zones, spaces, and construction elements. Additionally, it reuses concepts from the SAREF4Building ontology (ETSI, 2020) to represent components and systems that directly impact the energy consumption buildings and are susceptible to change in a renovation project.

SI.7. Competency Questions

OntoEMS

- What properties are typical for a reporting station?
- What quantities can be reported by a station?
- Are the reported values actual observations or forecast values?
- How many reporting stations (for a particular quantity) are in a given area?
- What is the nearest measuring station (for a particular quantity) from a geolocation?
- What is the current reading for a particular quantity at a specific station?
- Are information about reporting stations consistent across different data providers?
- What water level stations are located along the same river?
- Which water level stations are currently indicating high readings?

OntoFlood

- What types of floods exist?
- How is the risk level of a flood defined?
- What can be affected by a flood?
- What is the areal extent of a given flood or flood warning?
- How many people/buildings are affected by a particular flood/flood warning?
- What is the total damage estimate of a particular flood?
- What water body causes a particular flood alert/warning?
- Which areas are forecast to be flooded with a particular likelihood?
- Is flood risk (*i.e.*, flood warning frequency and/or intensity) increasing in a particular area?
- What is the most common flood type (in a particular area)?

OntoBuiltEnv

- What types of properties exist?
- What are typical property usages?
- What are typical construction characteristics of a property?
- What is the geospatial footprint of a given building?

- Which buildings are in the vicinity of a given location?
- How many and which buildings are located in a given postcode?
- What is the average property price in a certain area?
- What is the most frequent property usage within a certain postcode?

SI.8. Description Logic Representations of Ontologies

SI.8.1. OntoEMS

The latest version of the ontology is publicly available as OWL file on GitHub under: https://github.com/cambridge-cares/TheWorldAvatar/tree/main/JPS_Ontology/ontology/ontoems. A representation of the ontology in Description Logic is provided below:

Classes:

ReportingStation $\sqsubseteq$ geo:Feature
ReportingStation $\sqsubseteq \forall$ reports:om:Quantity
WaterLevelReportingStation $\sqsubseteq$ ReportingStation
WaterLevelReportingStation $\sqsubseteq \leq 1$ hasDownstreamStation.WaterLevelReportingStation
$\sqcap \geq 1$ hasDownstreamStation.WaterLevelReportingStation
om:Measure $\sqsubseteq \leq 1$ hasCurrentTrend.Trend $\sqcap \geq 1$ hasCurrentTrend.Trend
om:Measure $\sqsubseteq \leq 1$ hasCurrentRange.Range $\sqcap \geq 1$ hasCurrentRange.Range
om:Measure $\sqsubseteq \leq 1$ ts:hasTimeSeries.ts:TimeSeries $\sqcap$
≥ 1 ts:hasTimeSeries.ts:TimeSeries
om:Measure $\sqsubseteq \leq 1$ om:hasUnit.om:Unit $\sqcap \geq 1$ om:hasUnit.om:Unit
Forecast $\sqsubseteq \leq 1$ om:hasUnit.om:Unit $\sqcap \geq 1$ om:hasUnit.om:Unit
Forecast $\sqsubseteq \leq 1$ ts:hasTimeSeries.ts:TimeSeries $\sqcap$
≥ 1 ts:hasTimeSeries.ts:TimeSeries
AirTemperature $\sqsubseteq$ om:Temperature
AirTemperature $\equiv$ m3l:AirTemperature
AirTemperature $\equiv$ weather:AirTemperature
FeelsLikeTemperature $\sqsubseteq$ om:Temperature
DewPoint $\sqsubseteq$ om:Temperature
DewPoint $\equiv$ m3l:DewPoint
DewPoint $\equiv$ weather:DewPointTemperature
AtmosphericPressure $\sqsubseteq$ om:Pressure
AtmosphericPressure $\equiv$ m3l:AtmosphericPressure
AtmosphericPressure $\equiv$ weather:AtmosphericPressure
RelativeHumidity $\equiv$ om:RelativeHumidity
RelativeHumidity $\equiv$ m3l:RelativeHumidity
RelativeHumidity $\equiv$ weather:Humidity
Rainfall $\sqsubseteq$ om:Height
Rainfall $\sqsubseteq$ m3l:Rainfall
Rainfall $\sqsubseteq$ weather:Precipitation
SnowFall $\sqsubseteq$ om:Height
SnowFall $\sqsubseteq$ weather:Precipitation
PrecipitationProbability $\sqsubseteq$ om:Number
PrecipitationProbability $\sqsubseteq$ sio:SIO_000638
CloudCover $\sqsubseteq$ om:Number
CloudCover $\equiv$ m3l:CloudCover
UVIndex $\sqsubseteq$ om:Number
Visibility $\sqsubseteq$ om:Distance

WindSpeed $\sqsubseteq$ om:Speed
WindSpeed $\equiv$ m3l:WindSpeed
WindGust $\sqsubseteq$ om:Speed
WindGust $\sqsubseteq$ m3l:WindSpeed
WindDirection $\sqsubseteq$ om:Angle
WindDirection $\equiv$ m3l:WindDirection
AirPollutantConcentration $\sqsubseteq$ ontouom:Concentration
om:VolumeFraction $\sqsubseteq$ ontouom:Concentration
ontouom:MassOfSubstanceConcentration $\sqsubseteq$ ontouom:Concentration
CarbonMonoxideConcentration $\sqsubseteq$ AirPollutantConcentration
CarbonDioxideConcentration $\sqsubseteq$ AirPollutantConcentration
OzoneConcentration $\sqsubseteq$ AirPollutantConcentration
SulfurDioxideConcentration $\sqsubseteq$ AirPollutantConcentration
NitrogenOxidesConcentration $\sqsubseteq$ AirPollutantConcentration
NitrogenDioxideConcentration $\sqsubseteq$ NitrogenOxidesConcentration
NitrogenMonoxideConcentration $\sqsubseteq$ NitrogenOxidesConcentration
ParticulateMatterConcentration $\sqsubseteq$ AirPollutantConcentration
PM10Concentration $\sqsubseteq$ ParticulateMatterConcentration
PM2.5Concentration $\sqsubseteq$ ParticulateMatterConcentration
GlobalHorizontalIrradiance $\sqsubseteq$ om:Irradiance
GlobalHorizontalIrradiance $\sqsubseteq$ weather:SolarIrradiance
GlobalHorizontalIrradiance $\sqsubseteq$ m3l:SolarRadiation
DiffuseHorizontalIrradiance $\sqsubseteq$ om:Irradiance
DiffuseHorizontalIrradiance $\sqsubseteq$ weather:SolarIrradiance
DiffuseHorizontalIrradiance $\sqsubseteq$ m3l:SolarRadiation
DirectNormalIrradiance $\sqsubseteq$ om:Irradiance
DirectNormalIrradiance $\sqsubseteq$ weather:SolarIrradiance
DirectNormalIrradiance $\sqsubseteq$ m3l:SolarRadiation
WaterLevel $\sqsubseteq$ om:Height
WaterLevel $\sqsubseteq$ m3l:WaterLevel
WaterFlow $\sqsubseteq$ om:VolumetricFlowRate
Falling $\sqsubseteq$ Trend
Steady $\sqsubseteq$ Trend
Rising $\sqsubseteq$ Trend
UnavailableTrend $\sqsubseteq$ Trend
LowRange $\sqsubseteq$ Range
NormalRange $\sqsubseteq$ Range
HighRange $\sqsubseteq$ Range
UnavailableRange $\sqsubseteq$ Range

Object properties:
$\exists$ rt:StageScale.owl:Thing $\sqsubseteq$ WaterLevelReportingStation
$\top \sqsubseteq \forall$ rt:StageScale.owl:Thing
$\exists$ hasCurrentRange.owl:Thing $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ hasCurrentRange.Range
$\exists$ hasCurrentTrend.owl:Thing $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ hasCurrentTrend.Trend
$\exists$ hasDownstreamStation.owl:Thing $\sqsubseteq$ WaterLevelReportingStation
$\top \sqsubseteq \forall$ hasDownstreamStation.WaterLevelReportingStation
$\exists$ hasForecastedValue.owl:Thing $\sqsubseteq$ om:Quantity

$\top \sqsubseteq \forall$ hasForecastedValue.Forecast
$\exists$ ts:hasTimeSeries.owl:Thing $\sqsubseteq$ om:Measure $\sqcup$ Forecast
$\top \sqsubseteq \forall$ ts:hasTimeSeries.ts:TimeSeries
$\exists$ om:hasUnit.owl:Thing $\sqsubseteq$ Forecast
$\exists$ om:hasUnit.owl:Thing $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ om:hasUnit.om:Unit
$\exists$ om:hasValue.owl:Thing $\sqsubseteq$ om:Quantity
$\top \sqsubseteq \forall$ om:hasValue.om:Measure
$\exists$ includedIn.owl:Thing $\sqsubseteq$ DiffuseHorizontalIrradiance $\sqcup$ DirectNormalIrradiance
$\top \sqsubseteq \forall$ includedIn.GlobalHorizontalIrradiance
$\exists$ measureOf.owl:Thing $\sqsubseteq$ AirPollutantConcentration
$\top \sqsubseteq \forall$ measureOf (m3l:AirPollution $\sqcup$ weather:AirPollution)
$\exists$ reports:owl:Thing $\sqsubseteq$ ReportingStation
$\top \sqsubseteq \forall$ reports:om:Quantity

Data properties:
$\exists$ rt:catchmentName.rdfs:Literal $\sqsubseteq$ WaterLevelReportingStation
$\top \sqsubseteq \forall$ rt:catchmentName.xsd:string
$\exists$ createdOn.rdfs:Literal $\sqsubseteq$ Forecast
$\top \sqsubseteq \forall$ createdOn.xsd:dateTime
$\exists$ dataSource.rdfs:Literal $\sqsubseteq$ ReportingStation
$\top \sqsubseteq \forall$ dataSource.xsd:string
$\exists$ hasIdentifier.rdfs:Literal $\sqsubseteq$ ReportingStation
$\top \sqsubseteq \forall$ hasIdentifier.xsd:string
$\exists$ hasObservationElevation.rdfs:Literal $\sqsubseteq$ ReportingStation
$\top \sqsubseteq \forall$ hasObservationElevation.xsd:float
$\exists$ ts:hasRDB.rdfs:Literal $\sqsubseteq$ ts:TimeSeries
$\top \sqsubseteq \forall$ ts:hasRDB.xsd:string
$\exists$ ts:hasTimeUnit.rdfs:Literal $\sqsubseteq$ ts:TimeSeries
$\top \sqsubseteq \forall$ ts:hasTimeUnit.xsd:string
$\exists$ rdfs.label.rdfs:Literal $\sqsubseteq$ AirPollutantConcentration $\sqcup$ ReportingStation
$\top \sqsubseteq \forall$ rdfs.label.xsd:string
$\exists$ rt:period.rdfs:Literal $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ rt:period.xsd:string
$\exists$ rt:qualifier.rdfs:Literal $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ rt:qualifier.xsd:string
$\exists$ rt:riverName.rdfs:Literal $\sqsubseteq$ WaterLevelReportingStation
$\top \sqsubseteq \forall$ rt:riverName.xsd:string
$\exists$ om:symbol.rdfs:Literal $\sqsubseteq$ om:Unit
$\top \sqsubseteq \forall$ om:symbol.xsd:string
$\exists$ rt:typicalRangeHigh.rdfs:Literal $\sqsubseteq$ owl:Thing
$\top \sqsubseteq \forall$ rt:typicalRangeHigh.xsd:float
$\exists$ rt:typicalRangeLow.rdfs:Literal $\sqsubseteq$ owl:Thing
$\top \sqsubseteq \forall$ rt:typicalRangeLow.xsd:float
$\exists$ rt:valueType.rdfs:Literal $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ rt:valueType.xsd:string

SI.8.2. OntoFlood

The latest version of the ontology is publicly available as OWL file on GitHub under: https://github.com/cambridge-cares/TheWorldAvatar/tree/main/JPS_Ontology/ontology/ontoflood. A representation of the ontology in Description Logic is provided below:

Classes:

envo:ENVO_01000710 ⊑ soph:Event
envo:ENVO_01000710 ≡ sophhy:Flood
envo:ENVO_01000711 ⊑ envo:ENVO_01000710
envo:ENVO_01000712 ⊑ envo:ENVO_01000710
envo:ENVO_01000713 ⊑ envo:ENVO_01000710
soph:Event ⊑ ≤ 1 hasLocation.Location ⊓ ≥ 1 hasLocation.Location
soph:Event ⊑ ≤ 1 hasTimeInterval.time:Interval ⊓
    ≥ 1 hasTimeInterval.time:Interval
Impact ⊑ ≤ 1 hasMonetaryValue.om:AmountOfMoney ⊓
    ≥ 1 hasMonetaryValue.om:AmountOfMoney
ArealExtentPolygon ⊑ geo:Feature
FloodDepth ⊑ om:Depth
WaterVelocity ⊑ om:Velocity
om:Measure ⊑ ≤ 1 hasGeospatialDistribution.ArealDistribution ⊓
    ≥ 1 hasGeospatialDistribution.ArealDistribution
Building ⊑ InfrastructureComponent
ArealInfrastructure ⊑ InfrastructureComponent
Vehicle ⊑ InfrastructureComponent
NetworkInfrastructure ⊑ InfrastructureComponent
IndustrialArea ⊑ ArealInfrastructure
ResidentialArea ⊑ ArealInfrastructure
CommercialArea ⊑ ArealInfrastructure
MobilityNetwork ⊑ NetworkInfrastructure
ProvisioningNetwork ⊑ NetworkInfrastructure
envo:ENVO_01000707 ⊑ envo:ENVO_02500002
envo:ENVO_01000708 ⊑ envo:ENVO_02500002
envo:ENVO_01000709 ⊑ envo:ENVO_02500002
envo:ENVO_01000717 ⊑ envo:ENVO_02500002
envo:ENVO_01000718 ⊑ envo:ENVO_02500002
rt:FloodAlertOrWarning ⊑ ≤ 1 warnsAbout.envo:ENVO_01000710 ⊓
    ≥ 1 warnsAbout.envo:ENVO_01000710
rt:FloodAlertOrWarning ⊑ ≤ 1 hasSeverity.Severity ⊓ ≥ 1 hasSeverity.Severity
SevereFloodWarning ⊑ Severity
FloodWarning ⊑ Severity
FloodAlert ⊑ Severity
WarningNoLongerInForce ⊑ Severity
rt:FloodArea ≡ rt:FloodAlertArea
rt:FloodArea ≡ rt:FloodWarningArea
rt:FloodArea ⊑ ≤ 1 hasAlertOrWarningHistory.FloodAlertOrWarningHistory ⊓
    ≥ 1 hasAlertOrWarningHistory.FloodAlertOrWarningHistory
FloodAlertOrWarningHistory ⊑ ≤ 1 ts:hasTimeSeries.ts:TimeSeries ⊓
    ≥ 1 ts:hasTimeSeries.ts:TimeSeries
envo:ENVO_00000014 ⊑ envo:ENVO_00000063
envo:ENVO_00000016 ⊑ envo:ENVO_00000063
envo:ENVO_00000020 ⊑ envo:ENVO_00000063

envo:ENVO_00000022 $\sqsubseteq$ envo:ENVO_00000063
rt:FloodArea $\sqsubseteq \leq 1$ hasLocation.Location $\sqcap \geq 1$ hasLocation.Location
FloodForecast $\sqsubseteq \leq 1$ predicts.envo:ENVO_01000710 $\sqcap$
≥ 1 predicts.envo:ENVO_01000710
FloodForecast $\sqsubseteq \leq 1$ hasLocation.Location $\sqcap \geq 1$ hasLocation.Location
FloodForecast $\sqsubseteq \leq 1$ hasRiskLevel.RiskLevel $\sqcap \geq 1$ hasRiskLevel.RiskLevel
RiskLevel $\sqsubseteq \leq 1$ hasPotentialImpact.PotentialImpact $\sqcap$
≥ 1 hasPotentialImpact.PotentialImpact
RiskLevel $\sqsubseteq \leq 1$ hasLikelihood.Likelihood $\sqcap \geq 1$ hasLikelihood.Likelihood
SevereImpact $\sqsubseteq$ PotentialImpact
SignificantImpact $\sqsubseteq$ PotentialImpact
MinorImpact $\sqsubseteq$ PotentialImpact
MinimalImpact $\sqsubseteq$ PotentialImpact
HighLikelihood $\sqsubseteq$ Likelihood
MediumLikelihood $\sqsubseteq$ Likelihood
LowLikelihood $\sqsubseteq$ Likelihood
VeryLowLikelihood $\sqsubseteq$ Likelihood
GroundWater $\sqsubseteq$ FloodSource
RiverWater $\sqsubseteq$ FloodSource
SurfaceWater $\sqsubseteq$ FloodSource
CoastalWater $\sqsubseteq$ FloodSource

Object properties:
$\exists$ envo:RO_0002354.owl:Thing $\sqsubseteq$ envo:ENVO_01000710
$\top \sqsubseteq \forall$ envo:RO_0002354.envo:ENVO_02500002
$\exists$ affects.owl:Thing $\sqsubseteq$ envo:ENVO_01000710
$\top \sqsubseteq \forall$ affects (EnvironmentalComponent $\sqcup$ InfrastructureComponent $\sqcup$ Population)
$\exists$ attachedWaterBody.owl:Thing $\sqsubseteq$ rt:FloodArea
$\top \sqsubseteq \forall$ attachedWaterBody.envo:ENVO_00000063
$\exists$ rt:currentWarning.owl:Thing $\sqsubseteq$ rt:FloodArea
$\top \sqsubseteq \forall$ rt:currentWarning.FloodAlertOrWarning
$\exists$ hasAdministrativeDistrict.owl:Thing $\sqsubseteq$ Location
$\top \sqsubseteq \forall$ hasAdministrativeDistrict.AdministrativeDistrict
$\exists$ hasAlertOrWarningHistory.owl:Thing $\sqsubseteq$ rt:FloodArea
$\top \sqsubseteq \forall$ hasAlertOrWarningHistory.FloodAlertOrWarningHistory
$\exists$ hasArealExtent.owl:Thing $\sqsubseteq$ Location
$\top \sqsubseteq \forall$ hasArealExtent.ArealExtentPolygon
$\exists$ time:hasBeginning.owl:Thing $\sqsubseteq$ Interval
$\top \sqsubseteq \forall$ time:hasBeginning.Instant
$\exists$ time:hasEnd.owl:Thing $\sqsubseteq$ Interval
$\top \sqsubseteq \forall$ time:hasEnd.Instant
$\exists$ hasFloodSource.owl:Thing $\sqsubseteq$ FloodForecast
$\top \sqsubseteq \forall$ hasFloodSource.FloodSource
$\exists$ hasGeospatialDistribution.owl:Thing $\sqsubseteq$ Measure
$\top \sqsubseteq \forall$ hasGeospatialDistribution.ArealDistribution
$\exists$ hasIntensity.owl:Thing $\sqsubseteq$ envo:ENVO_01000710
$\top \sqsubseteq \forall$ hasIntensity.Quantity
$\exists$ hasLikelihood.owl:Thing $\sqsubseteq$ RiskLevel
$\top \sqsubseteq \forall$ hasLikelihood.Likelihood
$\exists$ hasLocation.owl:Thing $\sqsubseteq$ rt:FloodArea $\sqcup$ soph:Event $\sqcup$ FloodForecast

$\top \sqsubseteq \forall$ hasLocation.Location
$\exists$ hasMonetaryValue.owl:Thing $\sqsubseteq$ Impact
$\top \sqsubseteq \forall$ hasMonetaryValue.AmountOfMoney
$\exists$ hasPotentialImpact.owl:Thing $\sqsubseteq$ RiskLevel
$\top \sqsubseteq \forall$ hasPotentialImpact.PotentialImpact
$\exists$ hasRiskLevel.owl:Thing $\sqsubseteq$ FloodForecast
$\top \sqsubseteq \forall$ hasRiskLevel.RiskLevel
$\exists$ hasSeverity.owl:Thing $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ hasSeverity.Severity
$\exists$ hasTimeInterval.owl:Thing $\sqsubseteq$ Event
$\top \sqsubseteq \forall$ hasTimeInterval.Interval
$\exists$ ts:hasTimeSeries.owl:Thing $\sqsubseteq$ FloodAlertOrWarningHistory
$\top \sqsubseteq \forall$ ts:hasTimeSeries.TimeSeries
$\exists$ hasTotalAffectedArea.owl:Thing $\sqsubseteq$ InfrastructureComponent
$\top \sqsubseteq \forall$ hasTotalAffectedArea.Area
$\exists$ hasTotalMonetaryValue.owl:Thing $\sqsubseteq$ InfrastructureComponent
$\top \sqsubseteq \forall$ hasTotalMonetaryValue.AmountOfMoney
$\exists$ om:hasUnit.owl:Thing $\sqsubseteq$ Measure
$\top \sqsubseteq \forall$ om:hasUnit.Unit
$\exists$ om:hasValue.owl:Thing $\sqsubseteq$ om:AmountOfMoney $\sqcup$ Area
$\exists$ om:hasValue.owl:Thing $\sqsubseteq$ Quantity
$\top \sqsubseteq \forall$ om:hasValue.Measure
$\exists$ predicts.owl:Thing $\sqsubseteq$ FloodForecast
$\top \sqsubseteq \forall$ predicts.envo:ENVO_01000710
$\exists$ resultsIn.owl:Thing $\sqsubseteq$ Event
$\top \sqsubseteq \forall$ resultsIn.Impact
$\exists$ warnsAbout.owl:Thing $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ warnsAbout.envo:ENVO_01000710

Data properties:
$\exists$ hasAreaIdentifier.rdfs:Literal $\sqsubseteq$ rt:FloodArea
$\top \sqsubseteq \forall$ hasAreaIdentifier.xsd:string
$\exists$ hasClassification.rdfs:Literal $\sqsubseteq$ Impact
$\top \sqsubseteq \forall$ hasClassification.xsd:string
$\exists$ hasEffectiveDate.rdfs:Literal $\sqsubseteq$ FloodForecast
$\top \sqsubseteq \forall$ hasEffectiveDate.xsd:date
$\exists$ hasImpactLevel.rdfs:Literal $\sqsubseteq$ PotentialImpact
$\top \sqsubseteq \forall$ hasImpactLevel.xsd:integer
$\exists$ hasLikelihoodScore.rdfs:Literal $\sqsubseteq$ Likelihood
$\top \sqsubseteq \forall$ hasLikelihoodScore.xsd:integer
$\exists$ om:hasNumericalValue.rdfs:Literal $\sqsubseteq$ Measure
$\top \sqsubseteq \forall$ om:hasNumericalValue.xsd:float
$\exists$ ts:hasRDB.rdfs:Literal $\sqsubseteq$ TimeSeries
$\top \sqsubseteq \forall$ ts:hasRDB.xsd:string
$\exists$ hasSeverityLevel.rdfs:Literal $\sqsubseteq$ Severity
$\top \sqsubseteq \forall$ hasSeverityLevel.xsd:integer
$\exists$ ts:hasTimeUnit.rdfs:Literal $\sqsubseteq$ TimeSeries
$\top \sqsubseteq \forall$ ts:hasTimeUnit.xsd:string
$\exists$ hasTotalCount.rdfs:Literal $\sqsubseteq$ InfrastructureComponent $\sqcup$ Population
$\top \sqsubseteq \forall$ hasTotalCount.xsd:integer

$\exists$ hasWGS84LatitudeLongitude.rdfs:Literal $\sqsubseteq$ Location
$\top \sqsubseteq \forall$ hasWGS84LatitudeLongitude.geolit:lat-lon
$\exists$ time:hasXSDDuration.rdfs:Literal $\sqsubseteq$ Interval
$\top \sqsubseteq \forall$ time:hasXSDDuration.xsd:string
$\exists$ time:inXSDDateTimeStamp.rdfs:Literal $\sqsubseteq$ Instant
$\top \sqsubseteq \forall$ time:inXSDDateTimeStamp.xsd:string
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ Severity
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ Likelihood
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ PotentialImpact
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ rt:FloodArea
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ envo:ENVO_00000063
$\top \sqsubseteq \forall$ rdfs:label.xsd:string
$\exists$ rt:message.rdfs:Literal $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ rt:message.xsd:string
$\exists$ om:symbol.rdfs:Literal $\sqsubseteq$ Unit
$\top \sqsubseteq \forall$ om:symbol.xsd:string
$\exists$ rt:timeMessageChanged.rdfs:Literal $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ rt:timeMessageChanged.xsd:dateTime
$\exists$ rt:timeRaised.rdfs:Literal $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ rt:timeRaised.xsd:dateTime
$\exists$ rt:timeSeverityChanged.rdfs:Literal $\sqsubseteq$ FloodAlertOrWarning
$\top \sqsubseteq \forall$ rt:timeSeverityChanged.xsd:dateTime

SI.8.3. OntoBuiltEnv

The latest version of the ontology is publicly available as OWL file on GitHub under: https://github.com/cambridge-cares/TheWorldAvatar/blob/main/JPS_Ontology/ontology/ontobuiltenv/OntoBuiltEnv.owl. A representation of the ontology in Description Logic is provided below:

Classes:
Property $\sqsubseteq \top$
Flat $\sqsubseteq$ Property
dabgeo:Building $\sqsubseteq$ Property
dabgeo:Building $\sqsubseteq$ geo:Feature
dabgeo:Building $\equiv$ bot:Building
dabgeo:Building $\equiv$ bimerr:Building
dabgeo:Building $\equiv$ db:Building
dabgeo:Building $\equiv$ icity:Building
dabgeo:Building $\equiv$ ifc:IfcBuilding
dabgeo:Building $\sqsubseteq \leq 1$ hasInstalledPVArea.om:Area $\sqcap$
  ≥ 1 hasInstalledPVArea.om:Area
dabgeo:Building $\sqsubseteq \leq 1$ hasGroundElevation.om:Height $\sqcap$
  ≥ 1 hasGroundElevation.om:Height
dabgeo:Building $\sqsubseteq \leq 1$ hasTotalRoofArea.om:Area $\sqcap$
  ≥ 1 hasTotalRoofArea.om:Area
dabgeo:Building $\sqsubseteq \leq 1$ hasOntoCityGMLRepresentation.owl:Thing $\sqcap$
  ≥ 1 hasOntoCityGMLRepresentation.owl:Thing
dabgeo:Building $\sqsubseteq \leq 1$ hasPVsuitableRoofArea.om:Area $\sqcap$
  ≥ 1 hasPVsuitableRoofArea.om:Area
Property $\sqsubseteq \leq 1$ hasAddress.icontact:Address $\sqcap \geq 1$ hasAddress.icontact:Address
Property $\sqsubseteq \leq 1$ hasMarketValue.om:AmountOfMoney $\sqcap$

≥ 1 hasMarketValue.om:AmountOfMoney
Property $\sqsubseteq \leq 1$ hasPropertyType.PropertyType $\sqcap$
≥ 1 hasPropertyType.PropertyType
Property $\sqsubseteq \leq 1$ hasTotalFloorArea.om:Area $\sqcap \geq 1$ hasTotalFloorArea.om:Area
Property $\sqsubseteq \leq 1$ hasBuiltForm.BuiltForm $\sqcap \geq 1$ hasBuiltForm.BuiltForm
Property $\sqsubseteq \leq 1$ hasLatestTransactionRecord.lrppi:TransactionRecord $\sqcap$
≥ 1 hasLatestTransactionRecord.lrppi:TransactionRecord
icontact:Address $\sqsubseteq \leq 1$ hasPostalCode.PostalCode $\sqcap$
≥ 1 hasPostalCode.PostalCode
Domestic $\sqsubseteq$ PropertyUsage
Non-Domestic $\sqsubseteq$ PropertyUsage
SingleResidential $\sqsubseteq$ Domestic
MultiResidential $\sqsubseteq$ Domestic
EmergencyService $\sqsubseteq$ Non-Domestic
FireStation $\sqsubseteq$ EmergencyService
PoliceStation $\sqsubseteq$ EmergencyService
Education $\sqsubseteq$ Non-Domestic
School $\sqsubseteq$ Education
University $\sqsubseteq$ Education
MedicalCare $\sqsubseteq$ Non-Domestic
Clinic $\sqsubseteq$ MedicalCare
Hospital $\sqsubseteq$ MedicalCare
CulturalFacility $\sqsubseteq$ Non-Domestic
DrinkingEstablishment $\sqsubseteq$ Non-Domestic
EatingEstablishment $\sqsubseteq$ Non-Domestic
Hotel $\sqsubseteq$ Non-Domestic
IndustrialFacility $\sqsubseteq$ Non-Domestic
Office $\sqsubseteq$ Non-Domestic
ReligiousFacility $\sqsubseteq$ Non-Domestic
RetailEstablishment $\sqsubseteq$ Non-Domestic
SportsFacility $\sqsubseteq$ Non-Domestic
Bungalow $\sqsubseteq$ PropertyType
House $\sqsubseteq$ PropertyType
Maisonette $\sqsubseteq$ PropertyType
ParkHome $\sqsubseteq$ PropertyType
TransportFacility $\sqsubseteq$ Non-Domestic
Detached $\sqsubseteq$ BuiltForm
Semi-Detached $\sqsubseteq$ BuiltForm
Terraced $\sqsubseteq$ BuiltForm
Floor $\sqsubseteq$ ConstructionComponent
Roof $\sqsubseteq$ ConstructionComponent
Wall $\sqsubseteq$ ConstructionComponent
Window $\sqsubseteq$ ConstructionComponent
AveragePricePerSqm $\sqsubseteq$ ontouom:AmountOfMoneyPerArea
AveragePricePerSqm $\sqsubseteq \leq 1$ representativeFor.PostalCode $\sqcap$
≥ 1 representativeFor.PostalCode
PropertyPriceIndex $\sqsubseteq \leq 1$ ts:hasTimeSeries.ts:TimeSeries $\sqcap$
≥ 1 ts:hasTimeSeries.ts:TimeSeries
ontouom:pound_sterling_per_sqm $\sqsubseteq$ om:Unit

Object properties:

$\exists$ hasAddress.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasAddress.icontact:Address
$\exists$ hasAdministrativeDistrict.owl:Thing $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ hasAdministrativeDistrict.AdministrativeDistrict
$\exists$ time:hasBeginning.owl:Thing $\sqsubseteq$ time:Interval
$\top \sqsubseteq \forall$ time:hasBeginning.time:Instant
$\exists$ hasBuiltForm.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasBuiltForm.BuiltForm
$\exists$ hasConstructionComponent.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasConstructionComponent.ConstructionComponent
$\exists$ hasConstructionDate.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasConstructionDate.time:Interval
$\exists$ time:hasEnd.owl:Thing $\sqsubseteq$ time:Interval
$\top \sqsubseteq \forall$ time:hasEnd.time:Instant
$\exists$ hasGroundElevation.owl:Thing $\sqsubseteq$ dabgeo:Building
$\top \sqsubseteq \forall$ hasGroundElevation.om:Height
$\exists$ hasInstalledPVArea.owl:Thing $\sqsubseteq$ dabgeo:Building
$\top \sqsubseteq \forall$ hasInstalledPVArea.om:Area
$\exists$ hasLatestTransactionRecord.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasLatestTransactionRecord.lrppi:TransactionRecord
$\exists$ hasMarketValue.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasMarketValue.om:AmountOfMoney
$\exists$ hasOntoCityGMLRepresentation.owl:Thing $\sqsubseteq$ dabgeo:Building
$\top \sqsubseteq \forall$ hasOntoCityGMLRepresentation.owl:Thing
$\exists$ hasPVsuitableRoofArea.owl:Thing $\sqsubseteq$ dabgeo:Building
$\top \sqsubseteq \forall$ hasPVsuitableRoofArea.om:Area
$\exists$ hasPostalCode.owl:Thing $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ hasPostalCode.PostalCode
$\exists$ hasPropertyType.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasPropertyType.PropertyType
$\exists$ hasPropertyUsage.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasPropertyUsage.PropertyUsage
$\exists$ ts:hasTimeSeries.owl:Thing $\sqsubseteq$ PropertyPriceIndex
$\top \sqsubseteq \forall$ ts:hasTimeSeries.ts:TimeSeries
$\exists$ hasTotalFloorArea.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasTotalFloorArea.om:Area
$\exists$ hasTotalRoofArea.owl:Thing $\sqsubseteq$ dabgeo:Building
$\top \sqsubseteq \forall$ hasTotalRoofArea.om:Area
$\exists$ om:hasUnit.owl:Thing $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ om:hasUnit.om:Unit
$\exists$ om:hasValue.owl:Thing $\sqsubseteq$ om:AmountOfMoney $\sqcup$ om:Area $\sqcup$ om:Height $\sqcup$ AveragePricePerSqm
$\top \sqsubseteq \forall$ om:hasValue.om:Measure
$\exists$ isIn.owl:Thing $\sqsubseteq$ Flat
$\top \sqsubseteq \forall$ isIn.dabgeo:Building
$\exists$ isPresumedMatchOf.owl:Thing $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ isPresumedMatchOf.owl:Thing
$\exists$ locatedIn.owl:Thing $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ locatedIn.AdministrativeDistrict
$\exists$ representativeFor.owl:Thing $\sqsubseteq$ PropertyPriceIndex

$\top \sqsubseteq \forall$ representativeFor.PostalCode
$\exists$ representativeFor.owl:Thing $\sqsubseteq$ AveragePricePerSqm
$\top \sqsubseteq \forall$ representativeFor.AdministrativeDistrict

Data properties:
$\exists$ icontact:hasBuilding.rdfs:Literal $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ icontact:hasBuilding.xsd:string
$\exists$ hasEnergyRating.rdfs:Literal $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasEnergyRating.xsd:string
$\exists$ hasIdentifier.rdfs:Literal $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasIdentifier.xsd:string
$\exists$ hasLatestEPC.rdfs:Literal $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasLatestEPC.xsd:string
$\exists$ hasNumberOfHabitableRooms.rdfs:Literal $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasNumberOfHabitableRooms.xsd:integer
$\exists$ om:hasNumericalValue.rdfs:Literal $\sqsubseteq$ om:Measure
$\top \sqsubseteq \forall$ om:hasNumericalValue.xsd:float
$\exists$ ts:hasRDB.rdfs:Literal $\sqsubseteq$ ts:TimeSeries
$\top \sqsubseteq \forall$ ts:hasRDB.xsd:string
$\exists$ icontact:hasStreet.rdfs:Literal $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ icontact:hasStreet.xsd:string
$\exists$ icontact:hasStreetNumber.rdfs:Literal $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ icontact:hasStreetNumber.xsd:string
$\exists$ ts:hasTimeUnit.rdfs:Literal $\sqsubseteq$ ts:TimeSeries
$\top \sqsubseteq \forall$ ts:hasTimeUnit.xsd:string
$\exists$ om:hasUnitName.rdfs:Literal $\sqsubseteq$ icontact:Address
$\top \sqsubseteq \forall$ om:hasUnitName.xsd:string
$\exists$ hasUsageShare.rdfs:Literal $\sqsubseteq$ PropertyUsage
$\top \sqsubseteq \forall$ hasUsageShare.xsd:float
$\exists$ hasWGS84LatitudeLongitude.rdfs:Literal $\sqsubseteq$ Property
$\top \sqsubseteq \forall$ hasWGS84LatitudeLongitude.geolit:lat-lon
$\exists$ time:inXSDDateTimeStamp.rdfs:Literal $\sqsubseteq$ time:Instant
$\top \sqsubseteq \forall$ time:inXSDDateTimeStamp.xsd:string
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ AdministrativeDistrict
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ PropertyUsage
$\exists$ rdfs:label.rdfs:Literal $\sqsubseteq$ PostalCode
$\top \sqsubseteq \forall$ rdfs:label.xsd:string
$\exists$ lrppi:pricePaid.rdfs:Literal $\sqsubseteq$ lrppi:TransactionRecord
$\top \sqsubseteq \forall$ lrppi:pricePaid.xsd:integer
$\exists$ om:symbol.rdfs:Literal $\sqsubseteq$ om:Unit
$\top \sqsubseteq \forall$ om:symbol.xsd:string
$\exists$ lrppi:transactionDate.rdfs:Literal $\sqsubseteq$ lrppi:TransactionRecord
$\top \sqsubseteq \forall$ lrppi:transactionDate.xsd:date

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