

A SEMANTIC DATA MODEL FOR INTEROPERABLE EXCHANGE OF TEST TRENCH VERIFICATION DATA

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Abstract

In the Netherlands, nearly 50,000 utility strikes occurred in 2024, costing over €57 million in direct repairs. Test trenches provide centimeter-accurate verification of underground utility positions, yet this valuable data remains trapped in organizational silos, leading to repeated excavations. This paper introduces UTT (Universal Test Trench), a semantic data model extending the Dutch IMKL standard for interoperable exchange of 3D verification data. Developed using OWL/RDF with SHACL validation constraints, UTT provides a unified vocabulary for test trench observations, positions, deviations, and measurement quality. Future work includes prototype implementation and field evaluation.

Introduction

The underground infrastructure of cities contains a complex network of cables and pipes that deliver essential services, including electricity, gas, water, telecommunications, and sewerage. In the Netherlands alone, this network extends over 1.7 million kilometers. As cities pursue energy transitions and climate resilience programs, subsurface construction activity intensifies significantly. Current projections suggest that within the coming decade, one-third to half of urban roads will require reconstruction to accommodate new infrastructure systems including expanded electrical capacity, hydrogen pipelines, and enhanced drainage (COB, 2024).

This intensifying activity correlates with rising damage incidents. In 2024, the Netherlands recorded nearly 50,000 utility strikes at a rate of 137 daily occurrences, with direct repair costs exceeding €57 million (Digitale Infrastructuur, 2024). Including indirect costs such as service disruptions, project delays, and third-party damages, the true economic impact is estimated at 29 times higher (Makana et al., 2018). The root cause lies fundamentally in insufficient localization insights: the Cables and Pipelines Information Centre (KLIC) provides 2D maps based on administrative records that often deviate by over one meter horizontally and typically lack depth information entirely (Yan et al., 2019).

To mitigate this geometric uncertainty, contractors routinely excavate test trenches that expose underground utilities for direct measurement. A typical test trench is one to two meters deep and two to three meters long,

allowing surveyors to record positions with centimeter-level accuracy using total stations, GNSS/RTK receivers, or increasingly, LiDAR scanning and photogrammetry. Yet excavating these trenches is itself costly, time-consuming, and carries risk of damaging the very utilities being located, making repeated excavation at the same location inherently undesirable. Despite this, the verified data remains trapped in silos within individual organizations. Once the trench is backfilled, measurements are rarely preserved in structured formats or shared with other stakeholders who may later excavate the same location.

The Dutch Centre for Underground Construction (COB) conducted feasibility studies in 2023 and 2024 that confirmed the value proposition of a ‘test trench database’ (COB, 2023, 2024). This database should enable unified exchange of test trench data among stakeholders in the Dutch utility sector. The feasibility studies found broad stakeholder support and identified standardization of test trench data as the critical prerequisite for implementation. It was recognized that without a common data model, interoperability of data would be compromised, hampering the exchange of test trench data.

This paper addresses this standardization gap by introducing UTT (Universal Test Trench), a semantic data model that extends the Dutch IMKL standard to capture 3D test trench verification data. While 3D utility data is not yet common practice, it is rapidly becoming essential as technologies such as LiDAR and advanced surveying tools gain widespread adoption. The ambition of UTT is therefore not only to standardize current field observations but also to provide future-proof infrastructure for the next generation of high-resolution utility mapping.

The remainder of this paper is organized as follows: the literature review examines related work in infrastructure ontologies and utility data standards; the methodology section describes the ontology development approach; subsequent sections present the UTT design, validation approach, and evaluation results; finally, discussion and conclusions address practical implications and future directions.

Literature Review

Standardization and Ontologies

Standardization is critical to facilitate communication between stakeholders in fragmented industries like construction (Howard & Björk, 2008). Without shared standards, organizations develop their own digital models using different taxonomies and vocabularies for the same assets (A Ter Huurne & Olde Scholtenhuis, 2018). An ontology addresses this by providing an explicit specification of a shared conceptualization (Studer et al., 1998), encoding agreed concepts based on shared worldviews (El-Diraby & Osman, 2011). Semantic web technologies, particularly OWL and RDF, offer significant advantages over conventional relational or XML-based approaches for this purpose. Linked data principles enable distributed data integration without requiring a single centralized database, making them well-suited to multi-stakeholder environments where organizations maintain their own data stores (Berners-Lee, 2006).

Ontology in Infrastructure Engineering

Semantic web technologies have found application in infrastructure data management. In building information modeling, ifcOWL demonstrates ontology-based data integration (Pauwels & Terkaj, 2016).

For bridge infrastructure, linked data approaches support condition assessment (Hamdan & Scherer, 2020). The CityGML UtilityNetworkADE provides 3D utility representation within city models, with stronger geospatial integration than building-centric approaches (Biljecki et al., 2018 ; Kutzner et al., 2020).

Subsurface utilities remain underrepresented in semantic approaches. While above-ground infrastructure benefits from visual inspection and established BIM workflows, underground assets present unique challenges: they are invisible after installation, subject to undocumented modifications, and often predate digital documentation practices. These characteristics make semantic interoperability valuable yet technically challenging.

Utility Data Standards

Several utility data standards have emerged, each serving a particular purpose yet failing to accommodate the concepts required to comprehensively describe 3D test trench verification information.

At the European level, INSPIRE Utility Networks provides cross-border data exchange concepts for utility network topology (European Commission, 2013). CityGML's UtilityNetworkADE extends this to 3D city model integration, enabling rich geometric representation of underground networks (Kutzner et al., 2020). In the Netherlands, IMKL 3.0 provides the national standard for utility data exchange and maps to INSPIRE for European interoperability (Geonovum, 2022). However, IMKL primarily supports 2D registration and lacks concepts for verification observations or measurement uncertainty. Ter Huurne (2019) developed an OWL-based extension addressing semantic integration in utility asset management, demonstrating the feasibility of linked data approaches in this sector.

PAS 128 defines quality levels for utility detection but functions as an operational directive for survey procedures rather than a data exchange standard (BSI, 2014). International efforts like MUDDI address registry-level data but not verification observations. The gap between registered positions and actual field conditions remains outside existing standards.

While ontologies exist for building and bridge infrastructure, and data standards exist for utility network registration, no semantic model addresses the specific requirements of test trench verification data, including observed positions, deviations from registry data, measurement uncertainty, and verification provenance. UTT addresses this gap.

Methodology

The central goal of ontology development is achieving a shared conceptualization that enables meaningful data exchange between stakeholders who currently use incompatible representations. The methodology follows the Linked Open Terms (LOT) approach (Poveda-Villalón et al., 2022), a systematic framework comprising four iterative phases: requirements specification, implementation, validation, and publication. This paper covers the first three phases. LOT was selected

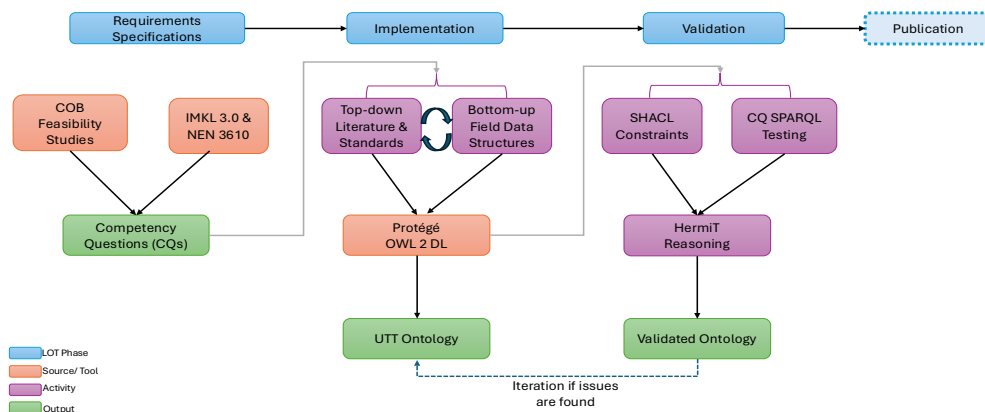


Figure 1: UTT ontology development process following the LOT methodology

because it integrates competency question formulation with standard ontology engineering practices, providing a reproducible process where requirements are formalized as testable queries against the resulting model.

Ontology Requirements Specification

Requirements were gathered through three complementary approaches. First, analysis of two COB feasibility study reports from 2023 and 2024, which collectively involved workshops with 15 organizations including utility network owners, contractors, surveying firms, and Kadaster, identified functional requirements from industry stakeholders. Second, systematic review of IMKL 3.0 documentation and NEN 3610 (the Dutch base model for geo-information) established alignment requirements with existing national standards. Third, iterative discussions with two industry partners from a utility contractor organization provided input on practical data capture workflows and current data formats in use.

The requirements specification yielded the following scope: the ontology must represent (1) the physical test trench excavation with its geometry and dimensions; (2) individual utility observations within the trench; (3) verified 3D positions with quantified accuracy; (4) deviations between observed and registered positions; (5) measurement methods and equipment; and (6) verification provenance including performer, date, and commissioning organization.

Requirements were formalized as competency questions (CQs) that the ontology must answer. CQs function as testable specifications: each translates to a SPARQL query that verifies whether the ontology captures required concepts. Table 1 lists the ten competency questions that guided development.

CQ2	What properties capture depth information for utilities?
CQ3	What measurement methods are defined in the ontology?
CQ4	What accuracy and quality properties are available?
CQ5	What properties link observations to IMKL concepts?
CQ6	What properties capture deviation between registered and observed?
CQ7	What provenance properties track verification performers?
CQ8	What supporting data file formats are defined?
CQ9	What IMKL utility types (thema) can be referenced?
CQ10	Is the trench class properly linked to spatial features?

Ontology Implementation

Implementation combined top-down and bottom-up development strategies (Noy & McGuinness, 2001). The top-down approach defined concepts derived from IMKL documentation, NEN 3610 spatial object patterns, and PROV-O provenance structures. The bottom-up approach incorporated terminology extracted from existing test trench reports, surveyor workflows, and data formats currently used in Dutch practice.

The ontology was developed using Protégé 5.5 and encoded in OWL 2 DL following ISO 19150-2 transformation rules for geographic information. This standard provides patterns for converting UML-based geographic information models to OWL, ensuring compatibility with Dutch geo-information infrastructure. SHACL (Shapes Constraint Language) shapes define validation constraints for data quality enforcement (W3C, 2012).

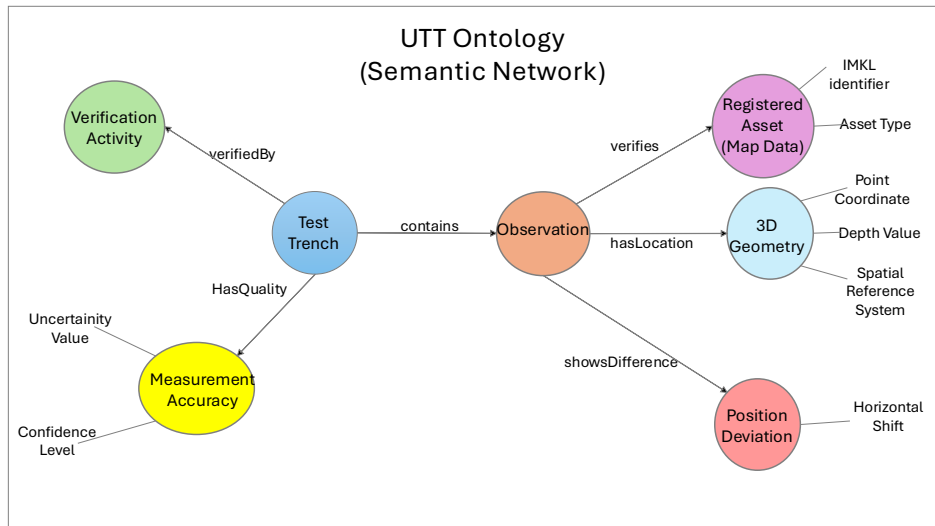


Figure 2: UTT ontology conceptual overview with core classes and relationships

Table 1: Competency questions defining ontology requirements

ID	Competency Question
CQ1	What classes represent the test trench and its observations?

The implementation reuses established ontologies following linked data best practices. GeoSPARQL provides spatial representation capabilities including geometry types and spatial relations. PROV-O (Provenance Ontology) supplies patterns for tracking data

lineage and attribution. SKOS (Simple Knowledge Organization System) structures controlled vocabularies for measurement methods and file formats.

Table 2: Namespace prefixes and URIs

Prefix	Namespace URI
utt:	https://w3id.org/utt/def/
imkl:	https://data.geostandaarden.nl/imkl/def/
geo:	http://www.opengis.net/ont/geosparql#
prov:	http://www.w3.org/ns/prov#
skos:	http://www.w3.org/2004/02/skos/core#

UTT Ontology Design

The UTT ontology comprises 13 classes, 21 object properties, and 17 datatype properties organized into seven functional modules. The complete ontology totals 378 RDF triples with an additional 275 triples in the IMKL subset and 175 triples defining SHACL validation shapes. Figure 2 presents the semantic network showing class relationships and IMKL integration points.

Test Trench and Geometry

The `utt:Proefsleuf` (Test Trench) class serves as the central container for the verification process.

Unlike standard IMKL definitions which focus on the utility network topology, UTT treats the trench as a distinct geospatial feature. A key design decision was to define this class as a subclass of `geo:Feature` (GeoSPARQL). This inheritance allows the trench to possess its own 3D geometry `utt:sleufGeometrie` (Trench Geometry), independent of the utilities contained within it.

UTT represents geometries using GeoSPARQL's `geo:hasGeometry` pattern. Trench geometries are stored as 3D Well-Known Text (WKT) polygon literals representing the excavation footprint, while observed utility positions use 3D WKT point geometries for discrete measurements or 3D linestring geometries for utility segments visible across the trench. Geometries are typed as `geo:wktLiteral` and annotated with their coordinate reference system. For Dutch geo-infrastructure integration, geometries use the Rijksdriehoek coordinate reference system (EPSG:28992) with NAP-referenced heights. This approach enables GeoSPARQL spatial queries such as `geo:sfWithin` and `geo:sfIntersects` while maintaining direct compatibility with GIS tools that consume WKT.

This structural separation is critical for spatial analysis: it allows the ontology to query which assets fall within the excavation volume, regardless of whether they were originally documented in the registry. The class creates a context for areas where utilities were expected but not found by defining the exact boundaries of the verified space.

The use of Dutch-language class identifiers and the Rijksdriehoek coordinate reference system reflects the decision to align UTT with IMKL, the mandatory national standard for utility data exchange in the Netherlands. All classes and properties carry bilingual annotations in both

Dutch and English through `rdfs:label` declarations. The coordinate reference system is specified on individual geometry literals following GeoSPARQL conventions rather than encoded as a structural constraint, permitting adaptation to other national coordinate systems at the instance level.

Observation and Registry Alignment

The `utt:Waarneming` (Observation) class bridges the gap between the physical reality and the administrative registry. While existing standards like MUDDI focus on the asset itself, UTT distinguishes the act of observing from the asset observed. This separation enables the system to handle unknown or "orphan" cables that do not exist in the KLIC registry.

To ensure interoperability, the observation class utilizes the `utt:waargenomenType` (observation) property, which is mapped directly to the `imkl:Thema` (Utility Type) code lists. This design choice ensures that a field surveyor's classification (e.g., "Low Voltage Cable") is semantically identical to the registry's classification, facilitating automatic matching. The `utt:komtOvereenMet` (matches) property explicitly links the observation to a specific `imkl:KabelOfLeiding` (Cable or Pipeline) instance using the NEN 3610 Unique Identifier (GUID). This mechanism effectively connects the physical observation to the official digital record to enable precise validation.

Position Deviation

In many existing utility models, accuracy is treated as a simple attribute. However, to support engineering decisions, UTT models deviation as a distinct class rather than a data property. This reification strategy was chosen to capture the complex vector relationship between the planned and actual location. By treating deviation as a class, the ontology can store multiple dimensions of the discrepancy specifically `utt:horizontaleAfwijking` (horizontal shift) and `utt:verticaleAfwijking` (vertical shift) along with the `utt:afwijkingRichting` (directionality). This allows for querying, such as detecting consistent depth errors in specific asset types.

Verification Provenance

The `utt:VerificatieActiviteit` (Verification Activity) class identifies the specific events and actors responsible for the data collection, ensuring traceability for the verification process (see Figure 3). Modeled as a subclass of `prov:Activity` from the W3C PROV-O standard, this class serves as the connecting node between the physical trench and the administrative data.

This module explicitly links the verification to the `utt:Landmeter` (Surveyor), defined as a subclass of `prov:Agent`, and the `utt:meetmethode` (Measurement Method). By structuring this information as semantic relationships rather than simple text strings, the ontology enables advanced data filtering based on the

acquisition source. For instance, data consumers can distinguish between measurements captured via RTK-GNSS versus those verified by a Total Station, allowing for automated reliability assessments based on the equipment's inherent precision capability.

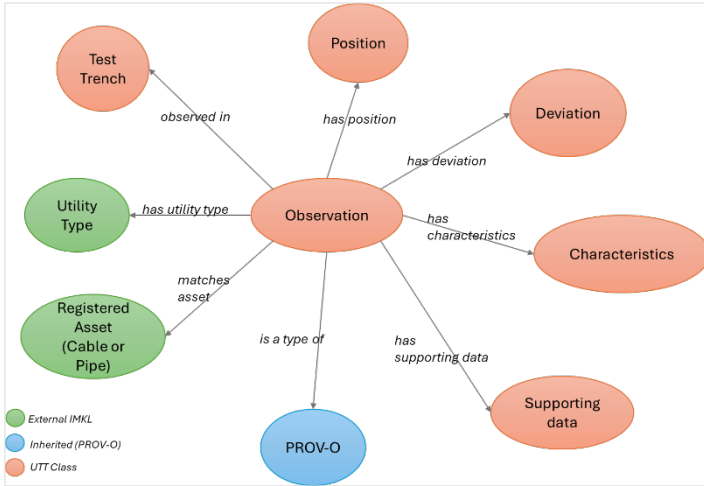


Figure 3: Observation module linking field data to IMKL

Data Validation with SHACL

The ontology includes SHACL (Shapes Constraint Language) shapes that enforce data quality rules. These shapes validate structural completeness, cardinality constraints, and value ranges.

The `utt:ProefsleufShape` (Test Trench Shape) requires each test trench to have exactly one geometry, one verification activity link, and at least one observation. Dimensional properties are constrained to reasonable ranges: trench length up to 50 meters, width up to 10 meters, and depth up to 10 meters.

The `utt:NauwkeurigheidShape` (Accuracy Shape) mandates horizontal uncertainty between 0 and 1.0 meter and vertical uncertainty between 0 and 0.5 meter. These ranges reflect typical achievable accuracies with professional surveying equipment while flagging implausible values.

Severity levels distinguish between violations (structural requirements) and warnings (recommended best practices). For example, linking an observation to a registered IMKL asset is recommended (severity: Info) but not required, acknowledging that unregistered utilities are sometimes discovered.

IMKL Integration Strategy

Integration with IMKL follows a complementary approach rather than modification of the base standard. UTT imports an OWL subset of IMKL classes transformed following ISO 19150-2 patterns. This subset includes core network classes (*Utiliteitsnet* (Utility Network), *KabelOfLeiding* (Cable or Pipeline), *Leidingelement* (Pipeline Element)), depth classes, and relevant code lists.

UTT reuses IMKL code lists for utility types (*Thema*), accuracy classifications (*NauwkeurigheidXYvalue* (Accuracy XY Value), *NauwkeurigheidDiepteValue* (Accuracy Depth Value)), depth reference points (*DiepteAangrijpingspuntValue* (Depth Reference Point Value)), and pipe materials (*PipeMaterialTypeIMKLvalue*). This reuse ensures observations can be categorized consistently with registry data and supports queries that span both data sources.

The `utt:komtOvereenMet` (Matches) property creates explicit links between UTT observations and IMKL registered assets. This enables deviation calculations and supports use cases where users need to compare verified positions against registered positions for specific utilities.

Query Capabilities & Validation

The ontology enables SPARQL queries answering the competency questions in Table 1. The following query demonstrates retrieval of observations deviating more than 50cm from registered positions:

```
PREFIX utt: <https://w3id.org/utt/def/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT ?trench ?observation ?depth ?utilityType
WHERE {
  ?trench a utt:Proefsleuf ;
          utt:heeftWaarneming ?observation .
  ?observation utt:heeftPositie ?position ;
              utt:waargenomenType ?utilityType .
  ?position utt:diepteTovMaaiveld ?depth .
  FILTER (?depth > 1.5)
}
```

Figure 4: SPARQL query for CQ3 - finding utilities deeper than threshold

This query returns all observations where utilities were found deeper than 1.5 meters below ground level, along with their utility type classification. The results enable analysis of depth distribution patterns across utility types and geographic areas. To calculate position deviations;

```
PREFIX utt: <https://w3id.org/utt/def/>

SELECT ?observation ?hDeviation ?vDeviation
WHERE {
  ?observation a utt:Waarneming ;
              utt:heeftAfwijking ?deviation .
  ?deviation utt:horizontaleAfwijking ?hDeviation ;
              utt:verticaleAfwijking ?vDeviation .
  FILTER (?hDeviation > 0.5 || ?vDeviation > 0.3)
}
```

Figure 5: SPARQL query for CQ7 - calculating position deviations

This query identifies observations where registered positions deviated significantly from field-verified positions and supports systematic accuracy analysis of registry data.

The logical consistency was verified using HermiT reasoner in Protégé 5.5 to confirm no contradictory axioms exist and there are no unsatisfiable classes. The competency question was verified by translating each CQ into a SPARQL query. All ten CQs from Table 1 were

successfully answerable using the implemented ontology to confirm functional completeness for the defined scope.

To demonstrate the representational capacity of the ontology, Figure 6 presents an RDF/Turtle serialization of a single test trench containing two utility observations.

```
@prefix utt: <https://w3id.org/utt/def/> .
@prefix imkl: <https://data.geostandaarden.nl/imkl/def/> .
@prefix geo: <http://www.opengis.net/ont/geosparql#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

utt:trench_A1 a utt:Proefsleuf ;
  utt:sleufLengte "2.5"^^xsd:decimal ;
  utt:sleufBreedte "2.0"^^xsd:decimal ;
  utt:sleufDiepte "1.8"^^xsd:decimal ;
  utt:sleufGeometrie [
    a geo:Geometry ;
    geo:asWKT "POLYGON Z((155000.0 463000.0 0.0,
      155002.5 463000.0 0.0, 155002.5 463002.0 0.0,
      155000.0 463002.0 0.0, 155000.0 463000.0
      0.0))"^^geo:wktLiteral ] ;
  utt:heeftWaarneming utt:obs_01 , utt:obs_02 ;
  utt:geverifieerdDoor utt:activiteit_01 .

utt:obs_01 a utt:Waarneming ;
  utt:waargenomenType imkl:laagspanning ;
  utt:heeftPositie [
    a utt:WaargenomenPositie ;
    utt:diepteTovMaaiveld "0.85"^^xsd:decimal ;
    utt:positieGeometrie [
      a geo:Geometry ;
      geo:asWKT "POINT Z(155001.2 463001.0
        -0.85)"^^geo:wktLiteral ] ] ;
  utt:heeftAfwijking [
    a utt:PositieAfwijking ;
    utt:horizontaleAfwijking "0.35"^^xsd:decimal ] .
```

Figure 6: RDF/Turtle serialization of a test trench instance with two utility observations

The trench instance is defined with its dimensions and a polygon geometry in three-dimensional coordinate space representing the excavation footprint, with depth captured separately. The first observation records a low-voltage electricity cable at 0.85 meters depth. The associated *PositieAfwijking* (Position Deviation) quantifies that this cable was 0.35 metres horizontally displaced from its registered position. The second observation records a telecommunications cable at 1.10 meters depth without a deviation instance, indicating an unregistered utility with no corresponding registry entry.

Discussion

This paper introduced UTT as a semantic data model addressing the absence of a standardized vocabulary for test trench verification data. Through its development, this study contributes to both the utility data modeling literature and to practice.

To the literature, UTT demonstrates that 3D field verification observations can be represented as linked data by extending existing geo-information standards. Where current standards such as IMKL, INSPIRE, and CityGML *UtilityNetworkADE* address network registration and topology (Kutzner et al., 2020 ; Geonovum, 2022) UTT introduces complementary concepts for the verification layer: what was actually found in the field, how accurately it was measured, and how it deviates from official records. The reification of position deviation as a distinct class,

rather than a simple attribute, enables systematic analysis of registry accuracy patterns, a capability absent in existing utility data models. The integration of PROV-O provenance patterns with domain-specific measurement quality further demonstrates how general-purpose semantic web vocabularies can be combined with domain standards for infrastructure applications.

For Dutch practice, UTT directly supports the national test trench database initiative identified by COB (2024) as critical for reducing repeated excavations. The alignment with IMKL code lists ensures that field observations use identical classifications to the KLIC registry, enabling automatic matching. The explicit uncertainty values in the *Nauwkeurigheid* (Accuracy) class go beyond IMKL's categorical accuracy classes, supporting risk-based excavation planning where engineers can assess whether prior observations meet their precision requirements.

More broadly, test trench excavation is common practice in utility infrastructure management internationally, and the discrepancy between registered and field-verified positions is not confined to the Netherlands. The Dutch-specific elements of the current implementation are limited to the IMKL code lists for utility type classification and the Rijksdriehoek coordinate reference system, both of which are instance-level parameters rather than structural features of the schema. Adaptation to other national contexts would involve substituting these classifications and coordinate declarations while the class hierarchy and property structure remain intact. Because IMKL maps to the European INSPIRE Utility Networks specification, UTT inherits an existing interoperability pathway across jurisdictions. The ontology thus provides a reusable semantic layer for subsurface digital twins, distinguishing as-found observations from as-registered data.

This study has several limitations. The current design focuses on point and line observations; continuous corridor surveys along extended utility routes may require additional geometric patterns. The ontology has been validated for logical consistency and competency question coverage but not yet with large-scale production datasets from multiple organizations. Future work will focus on prototype implementation of the ontology within a triple store, demonstrating data exchange between organizations, and evaluating its merit in operational utility localization practice.

Conclusions

This paper presented UTT, a semantic data model for interoperable exchange of test trench verification data in the utility infrastructure sector. The ontology extends IMKL with concepts for test trenches, field observations, position deviations, quantified accuracy, and verification provenance. SHACL shapes enforce data quality constraints appropriate to the domain.

By providing a standardized vocabulary and validation framework, UTT addresses a critical gap in the utility data

infrastructure that contributes to repeated excavations and damage incidents. The model provides a foundation for developing subsurface digital twins where verified, provenance-tracked observations complement existing registry data.

Future work will deploy the ontology within a GeoSPARQL-enabled triple store to evaluate federated querying across organizational boundaries. The data model will be validated using field datasets from utility contractor organizations to assess representational adequacy across varying trench configurations and utility types. Structured evaluation workshops with industry stakeholders will determine whether the ontology supports decision-making in excavation planning

The ontology is available under Creative Commons Attribution 4.0 license and can be accessed [here](#).

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