MULTI-STAKEHOLDER INFORMATION REQUIREMENTS TO SUPPORT LIFE CYCLE ASSET MANAGEMENT

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Abstract

The current IT paradigm in the built environment is misaligned with sustainability policy. Previously proposed ontologies for Asset Management, such as life cycle analysis, lack complete concepts to cater to a wide stakeholder group. This paper describes a more comprehensive asset management software landscape. It details the initial development steps using the Linked Open Terms methodology including requirements gathering and ontology conceptualisation. A modular ontology landscape is proposed including top-level, domain-wide concepts and modular, application-specific concepts; a scenario suited to the particularly broad domain needs.The work fosters consensus in the domain and we propose alignment/extension with the existing RealEstateCore standard.

Background

The future of asset information management

In line with sectoral goals to reduce emissions in the built environment, various policy mechanisms exist. These include emissions target-setting, as well as a trajectory towards mandatory reporting on how efficiently assets and organisations use resources throughout their lifetime. Examples include the recent Corporate Sustainability Reporting Directive (European Commission, 2023) aimed at organisations generally, as well as the EU's ambitious Level(s) framework (European Commission, 2022) focused specifically on the built environment. Additionally, within financial markets, the value of a building is increased in investors' eyes by obtaining environmental certifications (such as LEED, BREEAM etc.) which evaluate lifetime performance around various metrics. This phenomenon reflects a shift in values where high-consumption, environmentally unfriendly assets become a business risk in a decarbonised future (Dumrose and Höck, 2023). In this context, Asset Managers (AMs) play an important role as the discipline tasked with operating and maintaining built assets, particularly throughout their in-use phase where the majority resources are consumed (Geekiyanage and Ramachandra, 2018). As a result, AMs have a significant influence on the sustainability and resulting value of buildings and infrastructure.

AMs rely on various indicators to make value-based decisions and assess the operational performance of facilities, evaluating decisions by balancing cost, risk and performance (Fang et al., 2022). This approach aligns conceptually with the Life Cycle Sustainability Assessment (LCSA) methodology which evaluates an asset through a holistic financial-social-environmental lens (Figure 1). LCSA provides a comprehensive view of an asset's resource consumption over its entire life, enabling evidence-based decision making supported by long-term value rather than solely focusing on short-term, or initial investment costs (Kehily and Underwood, 2017). This approach contrasts with the typical practice which tends to prioritise immediate investment expenses, often neglecting the broader implications of decisions over time (Grzyl et al., 2017), a tendency which, according to Collier (2018), is part of a much wider phenomenon of short-term-ism in the financialised built environment and current workings of capitalism. To conduct LCSA analysis using IT systems, AMs require structured information about facilities; however, this information is frequently unavailable due to the widely-recognised inadequacy of current information management practices (Gao and Pishdad-Bozorgi, 2019). Additionally, the software required to perform these insightful analytics is often unsuitable. Existing LCSA applications tend to be either too costly, lack the flexibility to meet specific stakeholder needs, or simply be unavailable altogether (Shaw et al., 2024). As a result, AMs currently rely on laborious, error-prone, ad-hoc analyses to support their decisions. Consequently, the potential benefits of LCSA are not being widely realised.

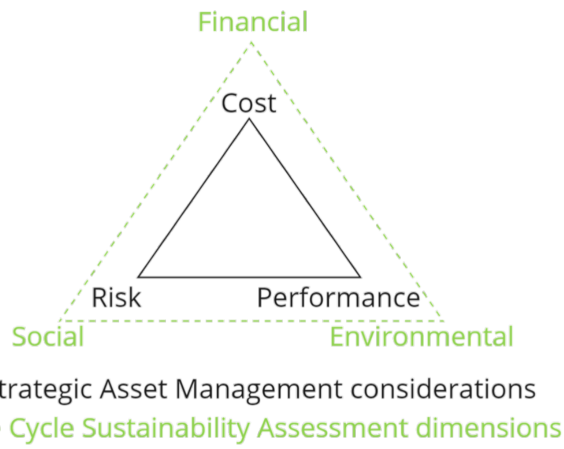

Figure 1: Conceptual overlap between AM decision-making and the holistic LCSA methodology

Ontologies can be used to organise domain knowledge in a formalised manner within IT system, facilitating information management and automation through inheritance and logical reasoning. Furthermore, ontologies can impart consensus semantic meaning to data shared over the web, referred to as Semantic Web Technology (SWT), a direction suggested by experts in the field as a necessary next step in LCSA research given the data-intensive nature of the practice (Salvado et al., 2021). A further advantage of information management using SWT is the potential for extensibility for specialised stakeholder needs. Given the expansive scope of AM activities, this is a logical requirement of a future-oriented IT landscape.

Previous efforts in AM-related ontology development

ISO 15978 (European Committee for Standardization (CEN), 2011) establishes a widely-agreed taxonomy of asset lifecycle phases. It serves as a foundational framework for much of the work in information management to support LCSA activities, involving the classification of costs and resources per phase. In accordance with the standard numerous applications and ontologies have been developed catering to various LCSA-related use cases (Lu et al., 2021), of which relevant works are now discussed.

In terms of envisioning software landscape, recent work by Sobhkhiz et al. (2021) emphasises the necessity of leveraging SWTs, enabled by ontologies, to address the substantial data handling challenges inherent in LCSA. The authors demonstrate the efficiency gains achieved over traditional relational database methods. Other studies, such as Wilde et al. (2022) and Ghose et al. (2022), focus on establishing a foundational, or top-level ontology, to support LCSA activities. These studies enable stock-level analysis, and consequently, the outcomes of these efforts do not support AMs in operational-level decision-making. In the pursuit of multi-scale analysis and aggregation, a recent work of significance is the SLiCE data model by Röck et al. (2024) which supports analysis from individual materials and parts, through building-level and up to the stock-level. Given the broad scope of AM functions, it is reasonable that achieving consensus on a universally shared ontology for the domain remains a challenge; however, the above initiatives are clearly progressing in this direction.

Another promising development are consolidation and alignment activities between standards communities. Xie et al. (2022) propose alignment between the BOT and BRICK ontologies. Their FDM ontology establishes a top-level asset information management concept for data integration in an effort towards a Digital Twin paradigm in future. Hammar et al. (2019) pioneered the development of a now widely adopted ontology tailored for asset owners, with a focus on concepts relevant to smart building applications and tenancy/leasing. Their collaborative effort, backed by a consortium of major asset owners in Sweden, aimed to establish shared domain use cases and describe these in the RealEstateCore ontology. The standard boasts a large user base and actively engages in alignment activities with other leading domain ontologies like Brick (for building automation systems) and BOT (for topological building description),

A number of efforts are of note which address specific analytical AM use cases. On the maintenance side, Katsumi et al. (2022) utilise the Ontology Requirements Specification Document (OSRD) development methodology to identify user requirements for a common AM ontology, drawing from a specific water treatment plant case study. Though focused on maintenance work orders, the study demonstrates a related ambition towards consensus that could potentially align with our own efforts at a later stage. Of particular relevance to our specific objectives of conducting multi-criteria LSCA analysis is the research by Gao et al. (2020) which proposes the LCCA Ontology, tailored for generating machine-learning-based financial life cycle cost predictions at the building level. Though publicly available, this ontology may be overly specific to its application context and not readily adaptable to the granular level of detail required for AM decision making.

Synthesis and research method

This body of research showcases a promising, future-oriented evolution toward effective asset information sharing on the web. However, none of the existing studies have comprehensively addressed multi-stakeholder needs for implementing LCSA-informed AM applications, with a particular gap in operational phase capabilities. A harmonisation of these efforts will be crucial for supporting decision-making and reporting processes in future given the broad expanse of AM activities, and it is promising to see a recognition of this in the active alignment efforts in the community. To this end, the Linked Open Terms (LOT) ontology development methodology (Poveda-Villalón et al., 2022) provides a structured approach for gathering domain requirements for a future ontology landscape. This paper describes our initial steps in this direction, following the research activities as illustrated in Figure 2.

Information requirements to support life cycle asset information management

The following information requirements derive from a combination of research activities. These include extensive reflection on the domain literature, as described in the previous section, supplementary interviews and discussions with AM practitioners and ontology developers, and from our previous practitioner-based research in AM decision-support system development (Shaw et al., 2024). In that study we developed a software prototype and reference architecture to support AMs with a number of fundamental use cases relating to financial life cycle cost analysis. The remainder of this paper builds upon this domain insight, and illustrates our perspective on future AM system requirements to support life cycle asset management more broadly, including a concept for the arrangement of top-level and modular application ontologies.

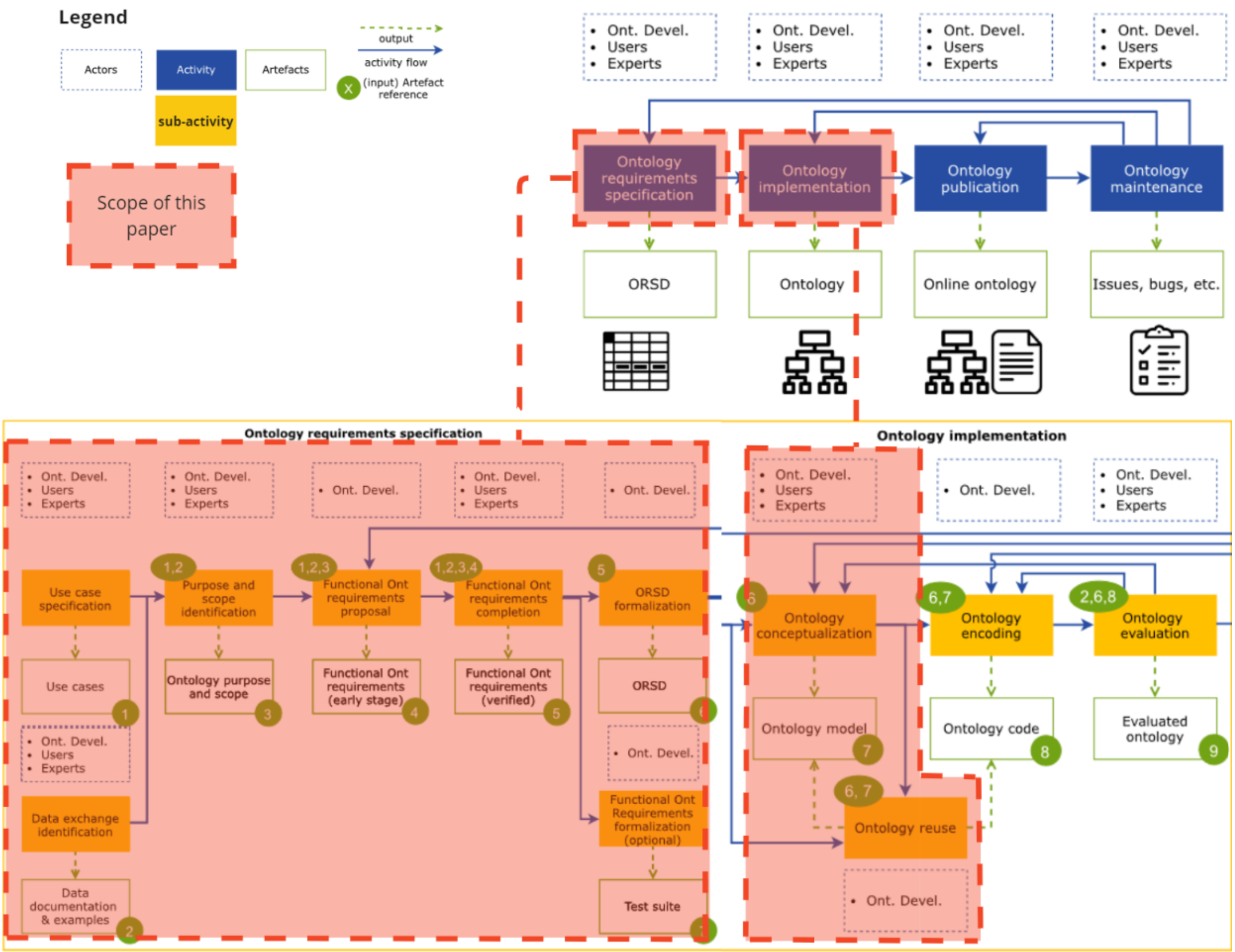

Figure 2: Paper scope - adapted from the generic LOT ontology development methodology, described by Poveda-Villalón et al. (2022)

Concept and use case specification

We envision a democratised IT landscape, and a departure from the current inflexible, proprietary software paradigm. This web-based system should be highly customisable (or *extensible*) to specific user needs, but with a foundational, shared top-level ontology which formalises domain knowledge and logic in line with international standards. Due to the data-intensive nature of the LCSA activities, a main purpose of the system is be to integrate inputs over the web, via either data warehousing or mediation, as set out by Xie et al. (2022). In this way, multiple stakeholders from diverse disciplines could make use of the structured information to suit their specialised analytics needs using additional modular, application-specific ontologies. The modularity and Microservices concepts are described by Pritoni et al. (2021) and Werbrouck et al. (2023), respectively, and our system architecture concept is presented in Figure 3. For the purposes of this study, and in line with the LOT methodology, the following use cases are suitably representative of the multi-stakeholder needs for the asset life cycle information system.

- ***Use Case 1:*** Life cycle analysis at various levels of granularity and across various indicators (ie. finance, energy, condition)
- ***Use Case 2:*** Decision-alternative analysis (or *optioneering*)
- ***Use Case 3:*** Performance gap analysis (against a baseline - supporting performance-based contracting)
- ***Use Case 4:*** Reporting in line with policy frameworks (the EU's Level(s) methodology, for example)

Non-functional requirements

- ***Purpose:*** The system architecture concept aims to define fundamental information categories for life asset management and analysis applications, offering standardised terminology and relationships to integrate information from diverse IT systems and sources.
- ***Scope:*** Both the top-level and modular application-specific ontologies are widely generalisable, ensured by their being based on international standards and remaining relatively abstract and extensible.

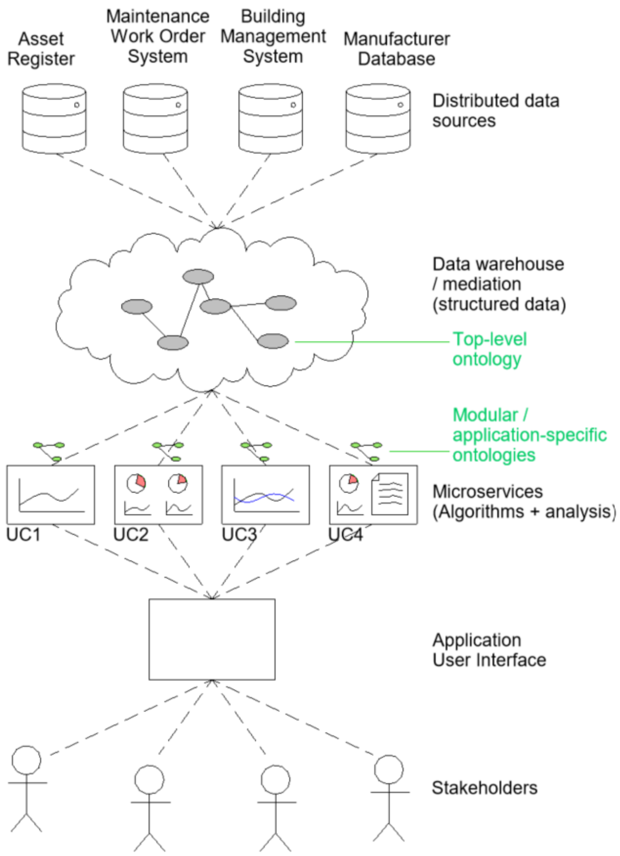

Figure 3: Concept sketch of the proposed system architecture with top-level and modular ontologies identified.

- ***Intended End-Users:*** Asset managers and owners seeking insight on decisions relating to an individual asset or a broader portfolio perspective, and to support performance contract administration. Designers comparing alternative decisions related to building, refurbishment, or maintenance projects. Regulators seeking to audit asset performance in accordance with reporting frameworks.

With the objective of supporting a variety of stakeholders, the proposed system should be ***accessible over the web*** and have an intuitive interface and functionality. Information to support LCSA is typically distributed across multiple, often unintegrated, IT systems, and is a well-established barrier to wider use. Future AM systems should therefore ***integrate information*** using standardised terminology and formalise domain knowledge through logic. Because of the wide variety of contexts to conduct LCC analysis, future systems require the flexibility to ***aggregate information*** consistently, so that assets can be looked at individually or on an aggregated basis across a portfolio, the SLiCE data model (Röck et al., 2024) providing a solid foundation for this. Again, given the wide variety of use cases, a major frustration for practitioners in the current IT landscape is being over-constrained by software. Therefore future AM systems must maintain the ***extensibility to add cost/resource items*** while maintaining a consistent top-down approach based on agreed taxonomies and classification systems. Needless to say, the systems must enable a user to ***conduct life cycle analysis*** based on standardised methodologies, namely ISO 15686-5 (International Organization for Standardization, 2017). A variety a ***'views' of the analysis*** should be possible to visualise including the temporal nature (discount to present value, future value, payback period), and visual nature (graphs, tabular). Due to the data-intensive nature of LCSA activities, an important consideration is validation and trust around the input data. Therefore, future systems need to ***demonstrate data quality*** in terms of provenance and completeness, the Shapes Constraint Language (SHACL) (W3C, 2017) providing a promising technical direction in this regard.

Functional requirements

This sub-section contains excerpts from the Ontology Requirements Specification Document (ORSD). The LOT methodology allows for the use of various requirements gathering approaches. Both Tabular and Competency Question (CQ)-based methods are use in this study. Tabular information includes a specification of Concepts, Relations and Attributes to be encoded in the semantics and logic of the ontology, as well as typical data types, units of measurement and cardinality. An excerpt is shown in Figure 4, denoting between top-level and application-specific aspects.

Since the concept has yet to be expressed in a formal ontology language, we provide informal CQs the proposed system would be expected to answer. CQs support validation during the encoding and testing activities. This list progresses from returning simple attribute values using the top-level ontology to retrieve distributed data, to increasingly complex queries requiring application-specific analytics and modular ontologies.

Top-level:

- CQ1 - What is the [Lifetime] of Asset with [AssetID]?
- CQ2 - Which Assets [List] have a [ResidualValue] > '0'?
- CQ3 - How many Assets [enumerate] have [Condition] in range[1-3]?
- CQ4 - What is the average [AnnualEnergyCost] of Assets with [AssetType]?

Application specific:

- CQ5 - What is the StudyPeriod for the AnalysisEvent [Scenario1]? ***Use Case 1***
- CQ6 - What is the [LifeCycleCost] for SUM[Assets IN AssetResister]? ***Use Case 1***
- CQ7 - What is the percentage breakdown between LifeCyclePhases for Asset [AssetID]? ***Use Case 1***
- CQ8 - Which is the most expensive year given [AnalysisEvent] and which are the Assets being renovated or replaced in that year? ***Use Case 1***
- CQ9 - Which Asset replacement option [list] has the lowest LifeCycleCost over StudyPeriod? ***Use Case 2***

Concepts

Concept	Description
Asset	A very general description of any object (example AHU), or collection of objects (building). Core concept in the ontology.
Cost	Top-level concept, subclasses include various costs (InitialCost, EnergyCost, ResidualCost)
StudyPeriod	Defines the scope of analysis in time
EconomicFactor	Top-level concept, subclasses include Discount and Inflation rates
AnalysisEvent	Specifies a particuar analysis activity

Relations

Concept	Relation	Target	Max cardinality
Asset	hasCost	Cost	1:n
Asset	hasLifetime	Lifetime	1
Asset	hasInstallationDate	InstallationDate	1
Asset	hasCondition	Condition	1
Asset	hasEnergyUse	EnergyUse	1
AnalysisEvent	hasStudyPeriod	StudyPeriod	1
AnalysisEvent	hasEconomicFactor	DiscountRate	1
AnalysisEvent	includesAsset	Asset	1:n

Application specific concepts

Attributes

Concept	Attribute	Description	Value type expected	Max cardinality	Unit
Asset	AssetID	Unique Identifier	String	1	description
Asset	AssetType	Type according to classification system	String	1	description
Asset	InstallationDate	Date of installation	Datetime	1	Datetime
Asset	InitialCost	Capital cost	Float	1	Monetary
Asset	Lifetime	Duration of usable life before requiring decommission/replacement	Int.	1	Years
Asset	ReplacementCost	Future cost of replacement (like for like)	Float	1	Monetary
Asset	RenovationCost	Cost of renovation to prolong lifetime	Float	1	Monetary
Asset	RenovationFrequencey	Number of years before renovation needed to prolong usable life	Int.	1	Years
Asset	AnnualEnergyCost	Cost of energy required to operate the asset	Float	1	Monetary
Asset	AnnualMaintenanceCost	Cost of regular maintenance operate the asset	Float	1	Monetary
Asset	ResidualValue	Positive value of asset at end of usable life (scrappage, upcycling, recycle parts)	Float	1	Monetary
Asset	Condition	Licart rating of an assets operating / quality condition (organisation spepcific, surveyed)	Int.	1	Assessed rating
Asset	AnnualEnergyUse	Sum of energy used over one year	Float	dynamic	kWh
EconomicFactor	InflationRate	Rate of annual inflation	Float	1	%
EconomicFactor	DiscountRate	Rate of discounting future value to present value	Float	1	%

Figure 4: Tabular requirements for modelling financial life cycle cost analysis, gathered per the LOT methodology. Denotes between top-level concepts and those more appropriately stored within modular application ontologies.

- CQ10 - What is the StudyPeriod which makes Option1 outweigh Option2 as the cheaper LifeCycleCost (payback period)? ***Use Case 2***
- CQ11 - What is the percentage reduction in [LifeCycleCost] over [StudyPeriod] for Asset [List] between Date1 and Date2? ***Use Case 3***
- CQ12 - What is Level(s) Indicator [6.1] for [Asset] over [StudyPeriod]? ***Use Case 4*** *- financial life cycle cost according to Level(s)*
- CQ13 - Which Level(s) Indicators [List] have value 'Null'? ***Use Case 4***

Ontology conceptualisation

A conceptualisation activity is carried out based on the above requirements. Concepts are arranged using a diagramming tool. Due to the visual nature, this activity is suitable for collaboration with experts who may not otherwise be familiar with ontology languages. In this case, input was sought from a number of AM and ontology experts via supplementary interviews, who gave input on the domain logic and hierarchical arrangement of concepts. The result of this step is an initial ontology concept diagram (Figure 5).

Potential for reuse and alignment

The LOT authors recommend carrying out an analysis of potential ontology reuse and alignment only after the conceptualisation stage. Table 1 details the considerations in this study for reuse and alignment with existing related ontologies. Based on this assessment it is determined that the RealEstateCore (REC) ontology is most promising for alignment or extension due to the many overlapping concepts, significant existing user-base and the community's active participation in alignment activities. As an exploratory step in this direction, Figure 6 identifies overlapping concepts in the REC ontology. The conclusion here is that our lifecycle information management ontology concept could potentially be achieved with a relatively light extension of the REC ontology. Further investigation will be required, however, to determine the practicality of this proposal.

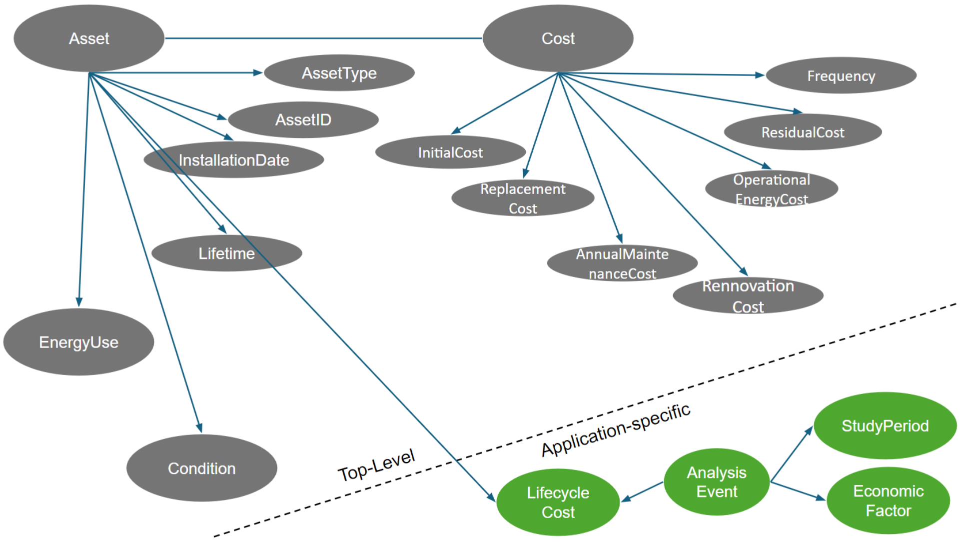

Figure 5: Initial AM Ontology concept denoting top-level and application-specific classes.

Table 1: Existing ontology reuse/extension considerations

Related ontology	Author	Suitable Concepts	Existing user base	Alignment activities	Generality
REC	(Hammar et al., 2019)	Many	Significant	Active	General
SLiCE	(Röck et al., 2024)	Some	Minimal	Active	General
FDM	(Xie et al., 2022)	Some	Unknown	Active	General
BONSAI	(Ghose et al., 2022)	Some	Unknown	Unknown	Macro-specific
LCCA	(Gao et al., 2020)	Some	Unknown	Unknown	Appl.-specific
AMO	(Katsumi et al., 2022)	Few	Under development	Unknown	case-specific

Discussion

The portrayal of the changing regulatory landscape in the built environment at the outset of this paper underscores the growing emphasis on sustainability and resource efficiency. As policy transitions towards mandatory sustainability reporting, the need for robust IT systems which are fit for purpose, becomes paramount. Life cycle analysis has emerged as a means to counteract the phenomenon of short-term-ism in decision-making by viewing impacts of decision over longer time periods. Our previous research portrays the current IT landscape as not fit for purpose to meet future information requirements, and advocates reconfiguration of future systems.

Illustrating our vision for this new software landscape, we outline a scenario whereby various stakeholders access a shared knowledge base, structured semantically around commonly agreed concepts over the web. Through specialised, modular applications, stakeholders leverage this shared knowledge base to suit their specific analytical needs. Following the LOT ontology development methodology, we describe the activities in developing an initial concept, focusing on fundamental AM use cases which serve a variety of key AM stakeholders. This involves defining the scope and use cases, gathering requirements via background research, conceptualising and verifying the ontology logic with experts, and exploring potential alignment with existing efforts. We present excerpts from the Ontology Requirements Specification Document (ORSD), including natural language Competency Questions (CQs) and tabular information, which lay the groundwork for encoding domain knowledge in a formal ontology language. The outcome is an initial conceptualisation of the AM ontology, with a recommendation for alignment with the RealEstateCore ontology, a data model which already describes multiple concepts useful for AM stakeholders and our use cases. Alignment with the RealEstate-

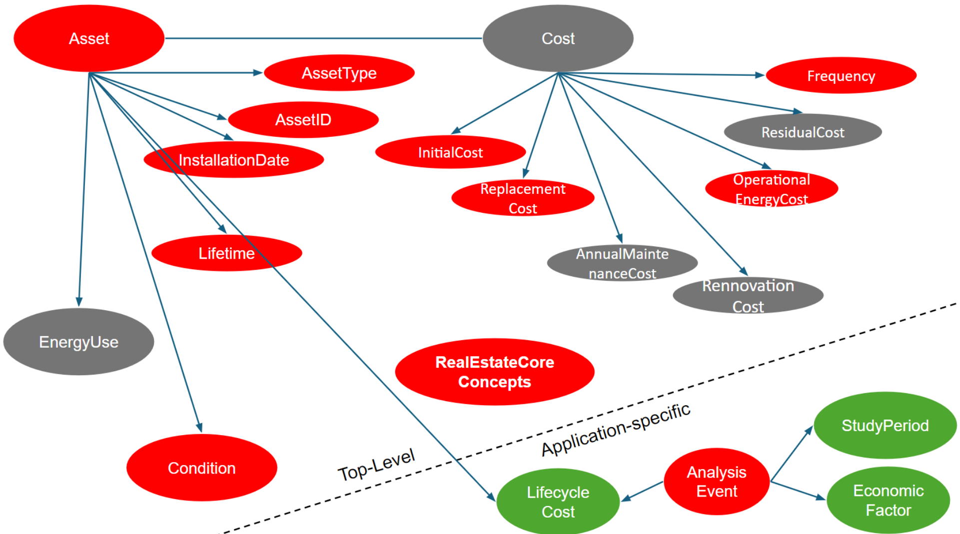

Figure 6: Ontology concept highlighting those classes already described within RealEstateCore, an indication of the extent to which REC would require extension to accommodate our research objectives.

Core ontology presents a strategic opportunity for uptake, given its existing user base and openness to alignment efforts with other ontology communities. Looking ahead, our vision for the future IT landscape aligns with the efforts of researchers in the built environment informatics domain, in particularly the activities of the Linked Building Data community (W3C, 2022).

Though this study is based upon extensive prior practitioner-based research in the AM and LCSA fields, we stop short at validating the ontology through encoding and testing in real-world scenarios, activities which remain as future work. Furthermore, though the selected use cases serve a broad selection of key stakeholders, the outcomes are nonetheless limited to describing those few applications. There are, of course, a vast range of potential uses for such a knowledge base, which is entirely the objective of the extensible and modular approach described; but with the rapidly approaching requirements of the CSRD and other sustainability reporting requirements, if we are to ensure equitable participation, it is of utmost importance to support the domain in managing their asset information particularly small-medium enterprises. Our next endeavors will focus on expanding the ontology concept to cover additional use cases and we will progress through the subsequent stages of the LOT development methodology activities to encode and validate the concept, ensuring its applicability and effectiveness in real-world scenarios.

Conclusions

This paper advocates a paradigm shift in IT systems within the built environment to align with environmental sustainability policy ambition. Proposing a web-enabled technology stack and leveraging the Linked Open Terms (LOT) methodology, we illustrate a asset management ontology landscape fit for purpose, allowing for modularity of specialised stakeholder applications ingesting shared information from a common knowledge base. With a focus on supporting fundamental Life Cycle Sustainability Assessment use cases, our research lays the groundwork for technical ontology development by gathering domain insight, outlining functional requirements and conceptualising the modular ontology landcsape. By reflecting on related research efforts, we highlight the potential for aligning with or extending existing standards such as RealEstateCore and SLiCE data models. This work contributes to fostering consensus within the domain, offering a roadmap for future research and development in enhancing asset lifecycle information management and decision-making processes.

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