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Evaluation of reference modeling for building performance assessment

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ABSTRACT

Lifecycle building performance assessment (LBPA) practices are being increasingly applied on existing buildings to ensure that performance requirements are fulfilled during building service-life. LBPA is a multi-disciplinary and information-intense process that requires computational tools for information management and decision support. We have previously developed a computational reference model (CLIP-Core) that supports various component-based LBPA practices. When CLIP-Core is considered to be used, it needs to be adapted to the specific context it addresses. We developed two such domain models, CLIP EPI-CREM and CLIP-CMU, for two existing LBPA practices. This paper addresses the evaluation of CLIP-Core and its potential in supporting various requirements. Hereto, we first discuss CLIP-Core and the two domain models. Then we present the evaluation results based on the domain models and their development processes. Finally we discuss guidelines for extending CLIP-Core and recommend technologies and alternative architectures that can increase CLIP-Core's usability.

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1. Introduction

The continuous assessment of performance of existing buildings has been brought into focus in AEC/FM due to the huge environmental impact of the existing building stock and the ever increasing user comfort requirements. Extending the building service-life and sustaining the existing stock is considered as a feasible alternative to new construction [35,44]. To this end, there is a need to ensure a building's intended performance and operation during the building service-life by practicing lifecycle building performance assessment (LBPA) through continuous inspections and measurement. We have previously developed a computational reference model named Computational support for Lifecycle Integral Performance Assessment (CLIP-Core) that supports the capturing, structuring and visualization of LBPA information [17]. CLIP-Core, as a reference model, does not address contextual variables and specific functional requirements of a particular setting. When it is being considered for practical use, it needs to be enriched representationally with local concepts and algorithms, and semantically with domain information in external ontologies. As such, CLIP-Core acts as a development accelerator by avoiding repetitive work, thereby reducing the development effort of domain-specific models.

We have previously adapted CLIP-Core to two different LBPA domains that adopt different approaches, methods and tools, EPI-CREM (Energy Performance Integration in Public Corporate Real Estate Management) and CMU FMS (Carnegie Mellon University Facilities Management Services). EPI-CREM is an EU research project that aims to embed energy-awareness to public and private real estate management processes through long-term maintenance planning. CMU FMS carries out the preventive and corrective maintenance activities of its campus buildings. CLIP-Core was extended and implemented into two domain models and software tools, CLIP EPI-CREM and CLIP-CMU respectively, and tested by its end users. These results of the model adaptation process allowed us to evaluate CLIP-Core.

This paper concerns the value of CLIP-Core as a conceptual reference model as it is operationalized through the domain model development processes. In doing so, we first briefly discuss CLIP-Core and the two domain models that adapt it, CLIP EPI-CREM and CLIP-CMU. Then we present the evaluation of CLIP-Core based on these domain models. Finally, we propose guidelines of adaptation for CLIP-Core's future use, and recommend alternative solutions that can increase its usability.

2. CLIP-Core for LBPA

2.1. LBPA and CLIP-Core

CLIP-Core is a computational model that supports LBPA, where the primary focus is an existing building's observed/measured behavior in order to maintain building's performance during its service-life. LBPA, as a semantically-rich domain, requires large amounts of information to be processed, stored and shared across various stakeholders. As LBPA practices are typically applied discretely with insufficient or no integration, building information is largely fragmented, leading to redundancy and information overlap. This poses problems regarding efficiency and effectiveness, as process actors have to spend a considerable

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amount of effort in searching, structuring, processing and translating information [14]. Without seamless information management tools, critical information is lost through ineffective documentation, posing problems for effective decision-making and leading to buildings that are often underperforming [29]. The existing off-the-shelf tools cannot wholly respond to the specific needs of a custom LBPA method due to their broad functional coverage and generic information types.

In order to tackle these problems, model-based approaches are essential for building service-life. Representations of up-to-date and accurate building information can increase the quality and performance of LBPA processes, eliminate unnecessary rework at site, and reduce inefficient use of time, resources and labor [1,38,7]. CLIP-Core concerns the development of domain models and software tools that aim to improve the efficiency and quality of existing LBPA practices by capturing, structuring and presenting LBPA information [17]. Modeling for LBPA as a loosely-defined area poses a number of challenges in clearly defining LBPA's operational domain and draw concrete requirements. Moreover, each distinct LBPA process dictates its own domain-specific knowledge, views and conceptual worlds of representations. As the granularity of the problem domain gets coarser, the solution needs to become more abstract and less complete.

Generally speaking, a model can address such ill-defined problem areas only on a conceptual level, as a reference model. Reference models address the common functions and information content on a higher level of abstraction, aiming to provide an a priori solution for the future developers to reduce the effort of developing domain-specific models. A reference model is to be reused for different but similar application areas in order to save development time and cost of proprietary domain models [2]. An efficient and correct reference model can lead to higher quality *domain models* that extend it [37]. CLIP-Core similarly provides high-level computational support for the development of fully-functional domain models supporting context-specific LBPA settings. Moreover, adaptability is a fundamental quality for CLIP-Core, facilitating its customization with little effort as compared to build-from-scratch approaches.

From a model development perspective, the increased complexity of products, shortened development cycles, and heightened user expectations of quality have created major challenges at all stages of the software life cycle [18]. This poses threats to the quality of the computational tools developed for AEC/FM as large and complex systems. Developing new models and tools for each context is a prohibitively expensive activity. Reference modeling can effectively accelerate the development process, provide a sound basis for system implementation and increase the quality of enterprise-specific domain models.

CLIP-Core is a conceptual reference model with a high level of abstraction, containing only basic concepts of LBPA. It contains data structures and algorithms for the representation, transformation and integration of LBPA information during building service-life. When considered to be used in a real LBPA setting, CLIP-Core needs to be customized functionally and representationally into a *domain model* (Fig. 1). Each domain model needs to be semantically enriched with a reference library of domain-specific objects. A library needs to be developed for each domain model by its domain actors, and codified separately from CLIP-Core.

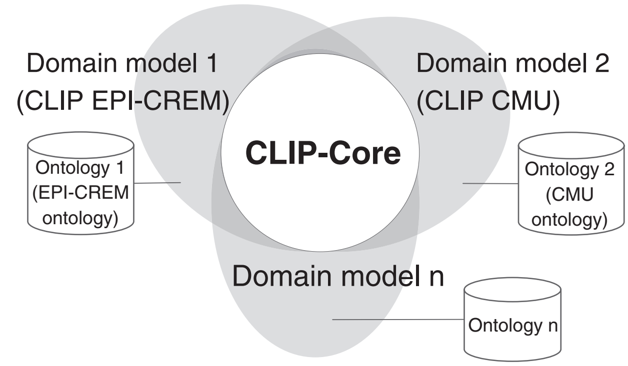

Fig. 1. CLIP-Core and its domain models.

2.1.1. LBPA and CLIP-Core requirements

For LBPA, well-informed decision-making primarily requires a building representation that reflects the as-is building condition and components (Fig. 2, R1). CLIP-Core supports component-based assessment methods in which components undergo periodic inspections and measurements throughout their service life. CLIP-Core formalizes a directed acyclic graph, named the component–topology graph, for the representation of buildings that consist of components, both hierarchically and non-hierarchically. In this graph, the nodes and edges are representationally separated as `Component` and `TopologyRelation`, together with their subtypes (Fig. 3). `Components`' descriptors are again represented with a separate object type (`PerformanceIndex`) capturing static design data that doesn't change by time, or dynamic service-life data such as inspection results. As the building undergoes changes by time, the building representation needs to correspondingly lend itself to changes by the actors through mechanisms that grant dynamic access to this representation's structural schema (Fig. 2, R2). The structural operations during the initial build-up of the component–topology graph and later modifications are supported by a set of algorithms (topology operations) in CLIP-Core.

In the build-up of an instance of a building representation, component libraries are typically used. For semantically heterogeneous areas like LBPA, the context dependency and rich-semantics of these libraries is important (Fig. 2, R3). Therefore, each LBPA domain needs to build its own library (an ontology), reflecting its own data views. Ontologies are used for the establishment of a common understanding of the information content, the reuse of this content and the separation of domain knowledge from the operational knowledge [8]. A CLIP ontology can be considered as a top-down a posteriori representation developed by the immediate stakeholders, seeking for information standardization for a specific context. A CLIP ontology specifies only the basic object types of the component–topology graph, being nodes, edges and descriptors. An ontology is physically decoupled from CLIP-Core in an XML file. As it is plugged into CLIP, the model objects are instantiated by CLIP.

During inspections, large amounts of time-based data are captured (Fig. 2, R4), which is represented in CLIP-Core by `MeasuredValue`. `MeasuredValue` registers all sources of information including manual (inspections), automated (sensors, data loggers) or calculated (using a reasoning routine that operates on available information). When many components are to be inspected at once (i.e. maintenance plans), the `AssessmentEvent` manages this dataset both representationally and visually. For visualization, CLIP-Core generates hierarchical views for planned activities, and presents a limited view to the relevant components and inspection points.

Data analysis for decision-making is the final stage of LBPA. This phase requires specific methods for each context and shows too great variance to be supported by a single model. Therefore, analysis functions need to be developed as part of domain models that extend CLIP-Core.

In short, CLIP-Core addresses functions that can be generalized such as data codification, specification and acquisition, while delegating data analysis to domain models for future development. In the following section, we discuss the development of these two domain models and software tools. In Section 4, we will comparatively evaluate CLIP-Core based on the basic requirements discussed here, which are (R1) a building representation, (R2) context-dependent, semantically-rich information content, (R3) capturing time-based data and (4) facilitating structural changes on the building representation.

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