

An Ontology Towards BIM-based Guidance of Building Façade Maintenance

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Abstract –

To ensure public safety, major cities in the U.S. have façade ordinances that require periodic façade inspections and reporting of façade conditions. Our shadowing works show that the current inspection processes are based on inspectors' experience rather than systematic inspection guidance. Besides, façade inspectors have different preferences to group their inspection findings (e.g., grouping inspection results based on a defect type or façade component), resulting in a need to provide flexibility to inspectors to organize façade inspection results based on their preferences. Building Information Modelling (BIM), with the ability to support storage, extraction, and exchange of facility information, can help with a systematic and comprehensive inspection of façades and store and exchange the façade inspection results with the third parties. To enable model-based guidance for a comprehensive inspection of any given building and to bring flexibility to restructuring the model and inspection data based on inspector preferences, an essential step is to define information requirements and develop a generic data representation for façade inspection. We have identified a generic taxonomy of façade components, defect types, defect attributes, and the relationships among the identified elements to enable comprehensive façade inspection guidance and flexible restructuring of the inspection findings. This paper provides the details of data exchange requirements and the initial ontology for a model-based façade inspection process. The ontology builds on the Industry Foundation Classes (IFC) specification and extends it to include entities, attributes, and property sets required for model-based façade inspection. This work provides the underlying data representation requirements for supporting the reasoning mechanisms that take a model as an input, generate a comprehensive checklist for inspection, and enable grouping façade elements flexibly based on inspector preferences for inspection data storage and visualization

Keywords –

Façade Inspection, Building Information Modelling (BIM), Industry Foundation Classes (IFC), Ontology

1 Introduction

Mandatory façade inspection programs have been adopted in major cities in the U.S. to ensure public safety. However, even with the ongoing façade inspection programs, accidents caused by debris falling from façade surfaces still occur in cities [1, 2]. Aside from the reported accidents, complaints are filed by citizens on dangerous situations to city agencies. For example, more than 1,000 complaints were filed each year to the New York City agency about façade safety during the past decade [3]. These point to a necessity to improve the current façade inspection processes. With this objective in mind, we identified several challenges observed in the current façade inspection practice in earlier work [4]. These challenges included (a) a lack of systematic guidance for inspectors to check façades comprehensively, (b) a lack of mechanisms to flexibly regroup and restructure building façade data and inspection findings based on inspector preferences.

To address the identified challenges, we have been working on a model-based approach to streamline the current façade inspection practice, where customized checklists are generated for each given façade based on a generic set of information requirements, and inspection data could be stored and visualized based on flexible regrouping of the model data. Available resources (e.g., practice standards, city ordinances, façade condition glossaries, previous researchers' findings, and historical façade inspection reports) have been analyzed to identify generic categories of information requirements for a comprehensive façade inspection. Historical façade inspection reports that have been analyzed using Natural Language Processing (NLP)-based approaches have resulted in generic vocabularies for each identified information requirement category and relationships

between major concepts [5]. This paper provides the details of the formal representation of the accumulated outcomes of this broader research agenda as an ontology to support model-based inspection. First, the major concepts and their relationships to a building façade will be described. Next, additional concepts and relationships that are needed to support the two reasoning mechanisms (i.e., checklist generation and flexible regrouping) will be presented in this paper.

2 Motivating Case Study

We conducted a shadowing work with an experienced façade inspector for three inspection projects on buildings with different façade types. General findings of this work, along with analysis of historical inspection reports, have resulted in two major challenges:

Challenge 1: Lack of systematic guidance for inspectors to conduct a comprehensive inspection. During the shadowing work, we noted all the façade condition information that the inspectors collected in the inspection process and identified three major groups of information: the façade components, the defect types, and the associated defect attributes (e.g., location of the defect, associated deteriorations, affected area, etc.). Based on our follow-up interviews with the inspectors, it was clear that the inspection information they collect (e.g., defect/attributes they check) varies based on the inspectors' experiences and may lead to different inspection results for the same building. Table 1 shows an example of varying inspection results in two inspection reports done with different inspectors for the same brick masonry building. Such differences show a need for a checklist that the inspectors can follow to conduct an in-depth and comprehensive inspection regardless of their personal experience.

Table 1. Example of different façade condition information collected during inspections

Building components in building A	Inspector 1	Inspector 2
Parapets	Presence of the parapet; Material of the parapet; Location of the parapet.	Presence of the parapet; Material of the parapet; Location of the parapet; Estimation of height.
Balconies	Railings height; Structural stability.	Material of railings; Railings height; Gaps between

Brick masonry walls	Cracked brickwork; Spalled brickwork; Defective caulked coping; Cracked and spalled brickwork mortar joints; Cracked granite panels; Defective granite panel caulk joint.	railings; Structural stability. Cracked brickwork; Spalled brickwork; Defective caulked coping; Cracked and spalled brickwork mortar joints; Rusted/deteriorated lintel Out of alignment parapet wall
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Bold and Italics: Differences identified in the inspection of the same building components.

Challenge 2: Lack of mechanisms for capturing and storing inspection findings with respect to façade components. Besides the differences in what is being checked and what data is collected by the inspectors, we also identified different styles the inspectors used to record the façade conditions in historical façade inspection reports. We reviewed 40 blindly selected reports out of 2400 reports and examined how inspectors grouped the inspection findings. Initial review of the reports revealed at least three inspection data grouping styles : 1) grouping all related components and locations under the same defect type (Figure 1a.); 2) grouping all related defects under the façade component (Figure 1b); and 3) mixed grouping given grouping types 1 and 2 (Figure 1c). A flexible data representation that can regroup the building façade information and inspection findings based on the inspectors' preferences is needed.

Condition observed: Cracked/ spalled/ deteriorated/ broken/ out of alignment brickwork (a.)		
Sketch Location:	Floor:	Picture Number:
1	B	69
6	4,7-Above 7	415, 400
7	B,4	70, 416
8	6	409
North of 8	B	71
9	6-7	76,373
East of 9	1	75
10	4,5-6,6,6-7	387,377,374, 372

Masonry Openings: (b.)	
a. Window Frames	
Description: The windows are constructed of aluminum.	
Condition: The windows were observed to be in satisfactory condition during the critical examination (see photo #13).	
Classification: SAFE	
b. Window Sills	
Description: The window sills are constructed of brick masonry.	
Condition: The window sills were observed to be in satisfactory condition during the critical examination.	
Classification: SAFE	

Crazed/cracked/spalling/spalled architectural CMU along all facades and bulkheads. (c.)
 Cracked/spalling brickwork/architectural CMU mortar joints affecting approximately 20 percent of south and north façade masonry.
 Cracked/spalled brickwork/architectural CMU mortar joints and horizontal mortar joints between steel window lintels and the first course of brick/CMU above, affecting approximately 5 percent of masonry along all facades.
 Non-height-compliant parapets at the 4th floor roof.

Figure 1. Different styles of façade conditions description: (a.) grouping information based on façade defects where condition observed is the defect type (i.e., cracked brickwork in this case) and all locations/components where this defect is observed is bundled up under this defect category in the report; (b.) grouping information based on façade components, where window frames and window sills are the components that are checked where all problems/defects for the same component type are listed; (c.) general description without grouping.

Domain-specific ontology developed by the authors is able to provide a standard way to capture and exchange the façade data and its inspection data.

3 Literature Review

Ontology is defined as a conceptual model that supports knowledge reuse and sharing in a domain among different stakeholders by providing formal representation for "classes, relations, functions, and other objects" [6, 7, 8]. Ontology systems can be classified into terminological ontologies (e.g., glossary, taxonomy, and thesaurus, etc.), implementation-driven ontologies (e.g., conceptual schema, knowledge base), and formal ontologies based on the level of semantics they capture [9]. Research studies resulting in formal ontologies in civil engineering have mainly focused on domain knowledge representation for specific tasks; such as capturing and representing construction project histories [10], virtual collaboration in project design and construction modeling [11], construction and project management [12, 13], infrastructure management [14, 15], risk management [16, 17], etc. The presentation of domain knowledge for façade inspection is missing in the literature. This ontology builds on the findings of the taxonomy, mapping relationships among the essential information (i.e., façade component, defect types, and defect attributes) to support checklist generation and model restructuring for storing and exchanging inspection findings.

BIM supports information visualization, sharing, and management in different stages, from design to facility management. Several BIM-based approaches have been proposed, including bridge inspection [18], highway construction inspection [19], buildings defect and maintenance history data management [20-22], and infrastructure facilities inspection [23]. This study differentiates from earlier work by focusing on building façades and their inspection. To streamline the façade inspection practice with model-based guidance, we

developed a façade inspection ontology here to capture the façade inspection entities and relationships. This paper provides the major concepts and relationships to support model-based façade inspection.

4 Methodology and Findings

The authors develop the ontology by first performing shadowing work, investigating relevant documents to extract the main concepts and terms for façade inspection, and analyze historical façade inspection reports. The documents include 1) façade inspection regulations (e.g., [24, 25], etc.); 2) international standard practice for periodic façade inspection (e.g., [26]); 3) façade condition glossaries [27-29]; 4) Autodesk BIM library; and 5) the available façade inspection reports. Next, the authors identified the taxonomies and vocabularies for the necessary concepts to be represented. The authors also investigated the classes, attributes, and relationships that would be needed to enable automated checklist generation and flexible data regrouping. The IFC schema has been evaluated for its capability to represent the identified concepts and relationships. Findings are presented as follows:

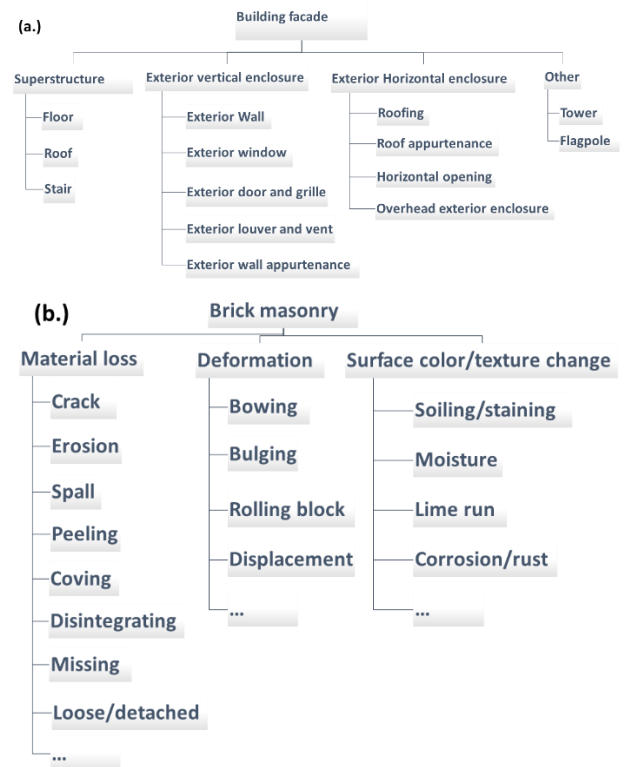


Figure 2. An overview of (a.) the identified major façade components at Level 2 and (b.) categorized defect types.

(1) **Major entities: Façade components, defect categories, and attributes.** In the shadowing work, we

identified three major information groups that were noted by inspectors: façade components on which the identified defects occur, defect types and defect attributes such as the location of defects, size of defects, patterns, and related conditions, etc. After investigating the related documents and analyzing the historical façade inspection reports [5], we combined a hierarchically organized vocabulary of façade components and decompositions, and defect types. The façade components and their hierarchy have been represented using Uniformat classification, including Level 4 elements (e.g., Level 2: Exterior Wall; Level 3: Parapet; Level 4: Unit Masonry). An overview of the major categories of façade components is presented in Figure 2a. Each category identified can be extended into a detailed level to guide inspectors through façade condition information collection.

The possible defects for different façade types are identified and grouped into three major categories based on the visual inspection evidence, namely material loss, deformation, and surface color/texture change (Figure 2b shows the subcategories for brick masonry façades). Material loss defect refers to the presence of defects where the façade material (e.g., brick unit and mortar joint on brick masonry façade) was lost. The most common defects in this category are crack, spall, surface abrasion, and missing components. Deformation refers to defects that lead to a shape change in façade components. The most common deformation defects identified are bowing, bulging, and displacement. The third category covers defects, such as water leakage, efflorescence, and corrosion, which can be identified by surface color or texture changes.

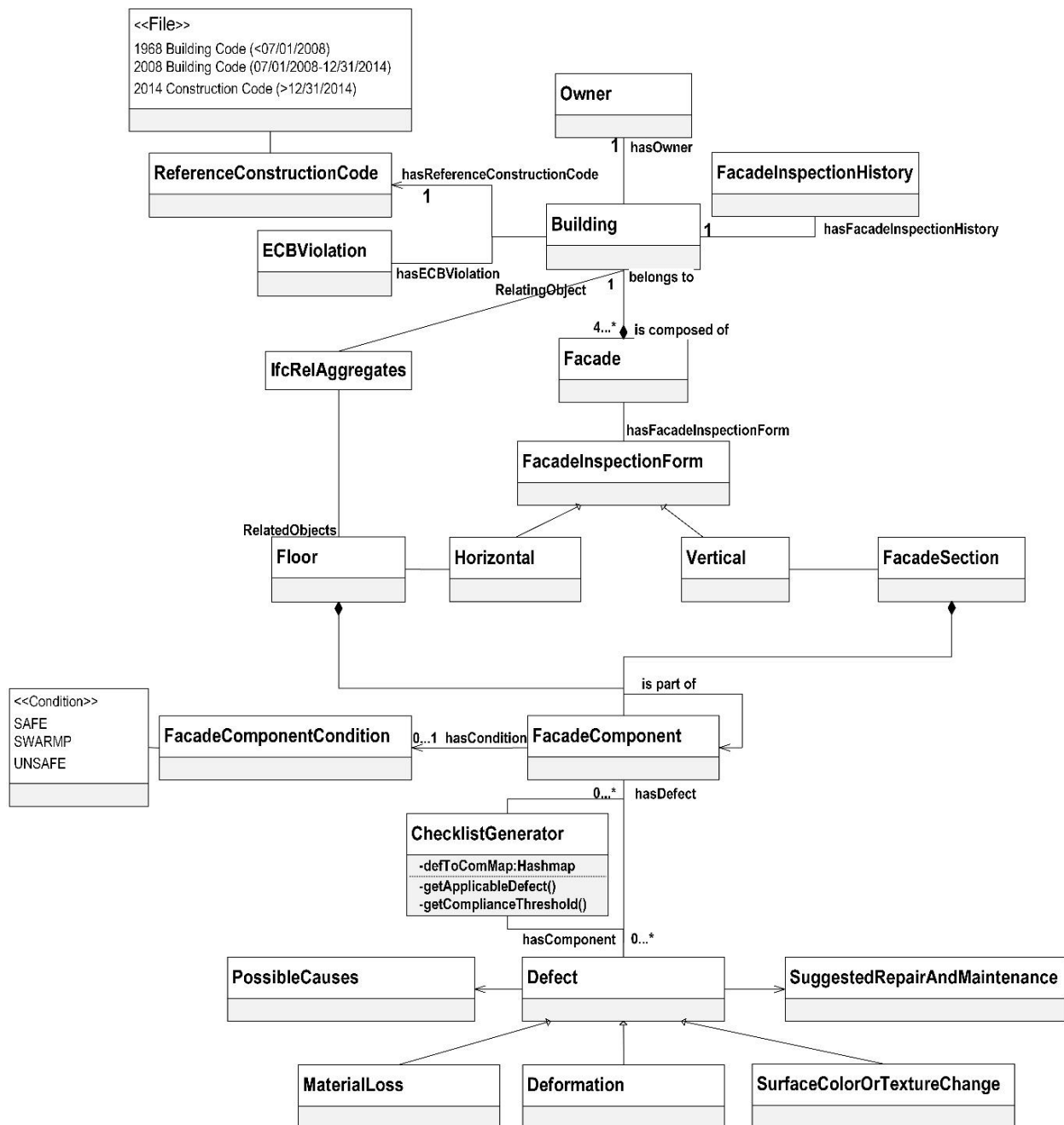


Figure 3. Part of the UML from the ontology showing the representation of façades, façade components, and defects.

Defect attributes are essential for inspectors to assess the severity of identified defects and serve as a reference value for inspectors to propose follow-up repair plans after the inspection. The authors identified several generic defect attributes together with their corresponding data types. "Location," "size," "direction," "associated façade component," "% of the affected surface on the associated component" are typically captured data in relation to defects. Another essential attribute is the presence of subsequent defects, which is

mainly applicable to deformations

The general composition and aggregation relationships between façade components have been augmented from Uniformat Classification for B. Superstructure hell. IFC schema has been utilized to represent buildings, floors, building elements, and geometrical and spatial relationships that are needed for façade inspection purposes (see Figure 3 for major concepts). Defects and associated data have been represented in relation to façade components in Figure 3.

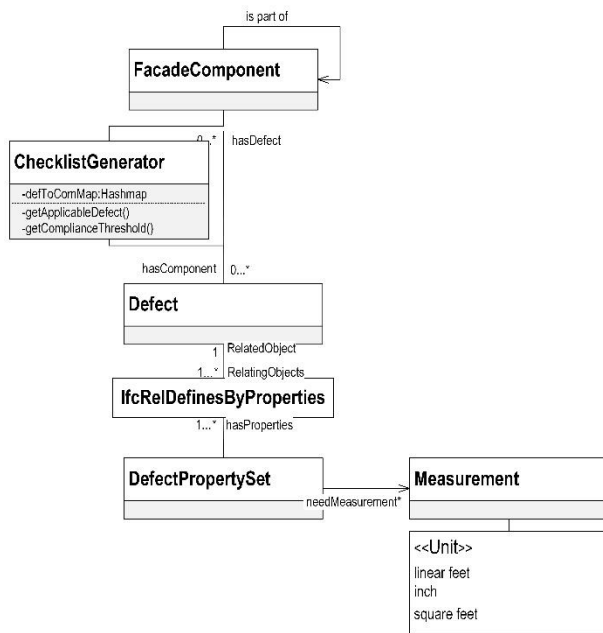


Figure 4. Part of the UML from the ontology showing major entities for checklist generation.

(2) **Necessary classes and attributes to support checklist generation and automated regrouping.** To enable the model-based customized checklist generation, we proposed a ChecklistGenerator class (Figure 4). This class is needed to identify applicable defects to a given façade component in a list of components that belong to a section or a floor of a façade and is represented as a HashMap of component type as an index and corresponding list of defects as an ArrayList. The type of a façade component defines the applicable defects to be checked by inspectors and the defect attributes to be collected in the inspection process. For this purpose, a mapping matrix has been defined and used by the checklist generator.

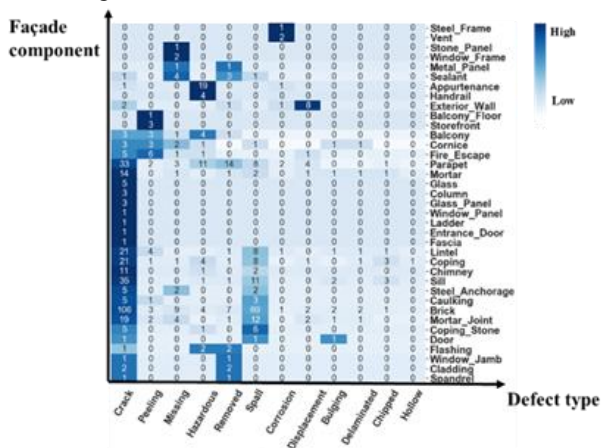


Figure 5. Mapping of façade components and defect types for stone/limestone façades.

The mapping between façade components and applicable defects (and applicable attributes) has been identified by analyzing façade inspection relevant documents and historical inspection reports (see Figure 5). This matrix contains information about the defects that are applicable to Level 4 façade components and constraints on the applicability of defects when the materials of these components are different.

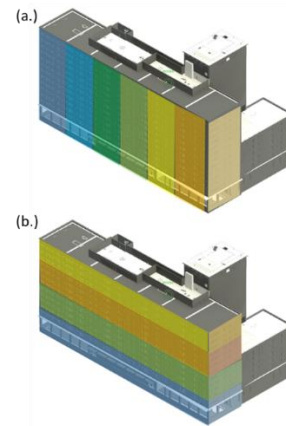


Figure 6. Examples of inspection forms for façades: (a.) vertical inspection of the façade, and (b.) horizontal inspection of the façade.

Each inspection starts with a façade direction (e.g., North, South, East, and West). Depending on whether a given direction faces a street or not, inspectors decide on the form of inspection (e.g., vertical drop-down, horizontal binoculars, and horizontal boom lift). BIM has to be divided into sections in each direction depending on the form of inspection (see Figure 6 for examples). So, sections need to be represented to understand which components fall into a section during an inspection and will be essential for regrouping information when needed.

With a BIM decomposed to a list of façade components per section, the component's material serves as a constraint, getApplicableDefect will loop through the matrix and extract the defects that need to be checked with that component and material type. getComplianceThreshold will check the related library for compliance checking, such as the height of parapets and railings. Each defect has the same generic set of attributes (i.e., description, possibleCause, referenceData, floorNumber, etc.) at the class level, and relevant defect types have a related DefectPropertySet that provides a list of defect attributes needed for façade condition assessment for that particular defect. Defect property sets have been represented using the IFC representation and relationships for attaching properties to building elements.

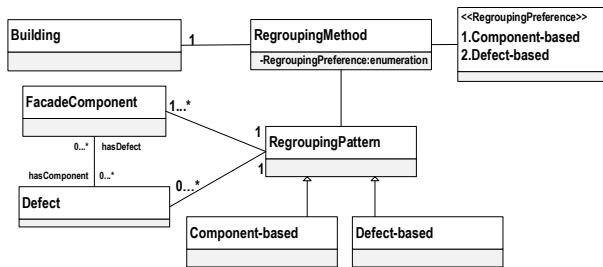


Figure 7. Part of the UML from the ontology showing high-level entities for flexible regrouping of inspection results.

Regarding the flexible regrouping of façade components to store and then retrieve using any predefined preference, the ontology includes a class called *RegroupingMethod* (see Figure 7), which has an enumeration of preferences to restructure the building elements either based on façade component hierarchies or based on the defect classification, or a mixed version of the two depending on an inspector defined tree structure. This class has a relationship with the *Building* class, as this is defined at once for all the façades of a building to be inspected. *RegroupingPattern* is a class defined in the ontology to store a preset hierarchy of façade elements based on the regrouping preferences (i.e., three types) that will speed up the regrouping for data retrieval. *RegroupingMethod* selected by an inspector to store and visualize inspection findings will have a relationship to the preset patterns stored in the *RegroupingPattern* class.

5 Conclusion

A mandatory façade inspection program is essential to avoid façade debris-related accidents and incidents, but the current façade inspection program is experience-based and needs guidance for inspectors to conduct in-depth and comprehensive inspections. With the challenges identified from the shadowing work, we envisioned a 3D model-based automated checklist generation and flexible regrouping to guide the inspectors in practice. Major classes included in the ontology are provided in this paper. These are discussed in major categories to represent façades in general (including classes such as façade components, defect categories, and defect property sets and relationships between them), to enable generation of a checklist (including classes such as generator, façade sections, façade inspection form and its subtypes, etc.) and to regroup façade elements (including classes such as regrouping patterns that are storing preset hierarchies of defects or components). This paper is an outcome of ongoing research work. Currently, we're developing a functional prototype that uses the proposed ontology as an underlying data schema to generate customized façade

inspection checklists for given buildings and enable restructuring the inspection data based on inspectors' data restructuring preferences. The generality and extensibility of the ontology will be evaluated in user and synthetic tests with the prototype. The results of this work will be published in a journal paper. The work presented in this paper lays the ground for the following research on the implementation of reasoning algorithms for comprehensive checklist generation and flexible data regrouping with BIM for façade inspection projects.

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