A Process-Driven Representation Schema for Masonry Wall Assemblies

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Abstract – The paper introduces a new approach for the representation of masonry walls in Building Information Modeling applications. The proposed representational scheme addresses the different types and levels of information required to support the design and construction of masonry walls. In particular, the paper proposes the concept of masonry wall "region", as a suitable abstraction to represent the variety of view-dependent features that characterize the life-cycle of masonry walls. At the geometric level, a masonry region works as a surrogate for the description of arbitrary aggregation relations without the cost associated with the explicit propagation of masonry units. In this way, a higher degree of semantic expressiveness can be achieved while keeping the design model flexible and agile. The concept of masonry regions motivates the formulation of a conceptual data model as foundation upon which different masonry-specific applications can be developed in the future, along with the definition of model views necessary to support masonry related data queries and exchanges. The paper outlines the theoretical background behind the concept of masonry regions and its relationship with the Industry Foundation Classes (IFC). Finally the paper introduces a proof-of-concept implementation for a masonry wall schema, and discusses the next steps in the research.

Keywords – BIM; Masonry; Representation; Levels of Development; Design Process; IFC.

1 Introduction

Building design and construction processes are being increasingly facilitated by new Building Information Modeling (BIM) technologies. At the core of these technologies there is a series of data models engineered to enable the exchange of information between different stakeholders. These data models encapsulate and codify industry standard product descriptions, enabling data exchange across software platforms and from heterogeneous stakeholder viewpoints.

In the context of a building material system such as masonry, the conceptualization of the data model should address the representation of more abstract features of assemblies beyond structural aspects such as geometry and material properties. Some of these abstract features may be performance dependent, spatiotemporal, related to cost, ownership, production status, etc. When a given stakeholder viewpoint – which includes the role of the stakeholder and the design activity in question, for example, a structural engineering performing lateral load analysis – is applied to a model, a domain-specific model view needs to be derived from the source model so to support the activity [1].

Currently, the most mature material-specific BIM data models are for structural steel – with the early standardization of steel shapes forming the basis for the steel components used in buildings today [2]. Almost a century after steel shapes were standardized, the first computational data model for structural steel was released as the "Logical Product Model" by CIMSteel [3]. Since then, material-specific models for precast concrete [4] and cast-in-place concrete [5] systems have been developed.

The Building Information Modeling for Masonry Initiative (BIM-M), organized in 2013 in North America, has developed a roadmap for establishing the requirements for masonry-specific data models, to support design, procurement and construction of masonry buildings [6]. The second phase of the roadmap, recently completed, focused on the development of data requirements for masonry units and masonry walls. In addition, the initiative has completed an extensive set of masonry-building case studies, focusing on the information needs of architects, engineers, material suppliers, and mason contractors [7].

As part of the initiative, two preliminary data models have been proposed. The first is a data model for masonry units, which is follows the functionality of databases of hot rolled steel shapes promulgated by AISC and the BSI [8]. Unlike structural steel however, the Masonry Unit Definition model or MUD is extended to include material properties, color, and texture, in addition to geometry. The second data model, called Masonry Wall Definition (MWD) aims towards a specification of masonry wall models that explicitly capture key relationships at the assembly level. As introduced earlier, it is important to point out that the complexity in the representation of masonry assemblies stems not only from the geometry of a wall and the properties of its units, but also from more abstract relationships that need to be formally described in order to provide computationally support to a variety of view-dependent tasks. In particular, one of the main challenges is the development of a flexible representation that could enable incremental levels of design information, geometric or otherwise, without the need for explicit instantiation of individual units. In this way, more informed exploration of alternatives would be facilitated by avoiding oversimplifications embedded in current representational approaches, and without the cost of excessively detailed geometric models.

The present paper focuses on the main guiding principles of the Masonry Wall Definition data model. Brief references to the Masonry Unit Definition (MUD) data model will be provided when needed. More information on the MUD model can be found on Sharif et al. [9].

2 Masonry Wall Definition model

The problem of representing masonry walls in a machine-readable format is considerably different than the representation of masonry units per se. For instance, the MUD model is internally-focused to provide comprehensive information about units, but little information about the context in which the units are applied. Masonry walls on the other hand are defined wholly by their context – the functional, engineering and aesthetic requirements dictate the geometry of the walls and the masonry is configured to fulfil these requirements. The overall geometry of a given masonry wall can be defined in terms of its start and end points, as well as its base and top reference planes. As an assembly however, a masonry wall can be characterized in several different ways simultaneously. Besides the self-evident parts such as the masonry units themselves, and other discrete accessories, a masonry wall can also be characterized by features such as openings, protrusions, niches, cut-outs, indentations, inlays, corners, etc. Furthermore, some of aspects of the assembly may be more abstract and context-dependent. For instance, a particular load-distribution pattern or a special sequence of erection entails different types of relationships. Each of these serves a specific purpose and therefore needs to have its own set of domain-specific properties and attributes.

The representation of these abstract and context-dependent features in turn requires a formal definition of modularity as well as different aggregation patterns that are relevant for masonry construction. In this way the model not only “looks” like a masonry wall, but more importantly, provides a consistent source of information regarding constructability and performance. Currently however, the representation of masonry modularity and aggregation patterns is limited to bonding and coursing. Moreover, these are typically represented in an oversimplified manner, by using a 2D pattern or “hatch” which is applied to the surfaces of wall objects to denote a masonry composition, but without explicit description of abstract and context-dependent features of the entire assembly. This limitation not only reduces the scope of automation that could be implemented otherwise, but affects the ability of teams to detect conflicts in timely manner, and ultimately, to make better design decisions.

By recognizing the importance of this problem, the goal of the Masonry Wall Definition project is to establish the nature of these assembly properties along with the best methods to represent them. For that purpose, information requirements of typical masonry workflows identified by Lee et al. [7] were used as starting point for the definition of those properties. However, the iterative and incremental nature of the design process raises a number of problems.

First, in the early stage of design, the design problem is generally ambiguous and requirements are still ill-defined [10, 11]. During this stage, several candidate building shapes and geometric relationships are explored without committing to any specific semantics of construction or materiality. As the design process moves-on, generic objects are replaced by more specific ones such as walls, doors, and windows. Once masonry is adopted as material of choice, some of these objects have to be moved, sized or deleted from the model. At this point the designer may have little interest in tracking the location of specific masonry units. All that matters is some level of coordination with an underlying modular system that is consistent with the type of masonry chosen.

As the design is refined, the issue of constructability comes into play, imposing the need for more specific information. The concept of Level of Development (LOD) in BIM was introduced to guide the amount and fidelity of information to be added to a building model as design proceeds. According to the LOD Specification [12], model elements are represented with a range of information granularity, from the most schematic representation (LOD 100), to the most detailed (LOD 500). At the early stages of design, walls are represented at LOD 100, without the need to indicate wall thicknesses and material types. At some later stage in the design process, the wall may be identified as a masonry wall, with specific masonry units, bonding patterns and reinforcement information. This may correspond to a LOD 400. At this point, the global geometry of the wall and the local geometry of masonry units have to be resolved in various situations. In particular, the way that masonry units relate to certain boundary conditions of the wall needs to be represented explicitly. This is necessary for example to calculate the number of masonry cuts, custom units or other types of components required to resolve special situations along the wall (e.g. reinforcement, barriers and insulation, etc.).

One possible method to represent such type of conditions is the explicit propagation of masonry components by means of algorithmic procedures and parametric rules [13, 14]. However, this leads to a second problem. BIM parametric applications are known to be computationally-intensive and the performance of any parametric-modeling software degrades as the number of parametric elements in the model increases, which in turn cause negative implications in the design process itself [15]. Since it is likely that a masonry building will have tens or even hundreds of thousands of masonry units, plus all relevant accessories, it is simply not efficient to model each unit, even if the procedure is automated. Furthermore, it is rather questionable that exhaustive modeling of every single unit would be actually an effective approach in supporting conventional design workflows. From a more pragmatic point of view, the aggregation of masonry units according to some functional or aesthetic criteria may provide a more cost-effective approach without losing significant precision or expressiveness.

From these observations it became evident that a different type of representational strategy was needed to model masonry walls more effectively. In particular, it became clear the need for a process-centric representation, so that the iterative and incremental nature of the design process could be not only supported but promoted. This means not only that the representation needs to be flexible enough as to support the use of different levels of information at different stages of the design process, but more importantly, to support the transition between design stages and levels of information. The need for a flexible, process-driven design representation has been discussed extensively in the past from different perspectives [16 - 18].

Within the context of the MWD project, the strategy adopted was the conceptualization of a new type of abstraction. This abstraction is intended to mediate between the monolithic representation of masonry walls and the exhaustive propagation of individual units. Such an intermediate abstraction was called in the research a masonry “region”. A masonry region is geometrically represented by a solid object that can be created by decomposition of larger solids – a wall or another region – by means conventional solid modeling operators (e.g. subtraction and intersection). From a semantic perspective however, a region describes a view-dependent aspect of feature of the wall assembly. In particular, a region denotes geometrically an arbitrary aggregation of masonry units. Such an aggregation may include components and accessories connected or functionally associated to the units. In prior work we have discussed how regions may be associated to specific stakeholders as well as with different design or evaluation tasks. Altogether, this information characterizes the context under which region definitions may be created [19].

Part of the motivation behind this formulation is that certain types of information requests between parties could be satisfied through the derivation of regions. In this regard, the conceptualization behind masonry regions is consistent with the principle of targeted interoperability within specific use case scenarios [20, 21]. In the case of masonry walls, and masonry buildings in general, the use cases in which view-dependent information may be requested typically involve analysis of some sort related to structural or energy performance evaluation, detailing, quantity take-off, construction planning, etc.

In the remaining of the paper the main principles behind the concept of masonry regions will be introduced. These principles form the basis for the Masonry Wall Definition data model under development. The requirements for the representation of regions within a wall are enumerated below. We provide specific, and somewhat limiting requirements at this time so to facilitate the implementation of an initial proof-of-concept software application.

2.1 Masonry wall regions

An example of a brick wall with region decomposition is shown in Figure 1. The regions are represented as solid partitions of the wall, each implying a specific aggregation of masonry components. As discussed before, the criterion for the aggregation is view dependent. In this case, boundary conditions for window openings and corners may be necessary for the specification of insulation and water barriers, estimation of unit types (e.g. half-units) and sequence of erection.

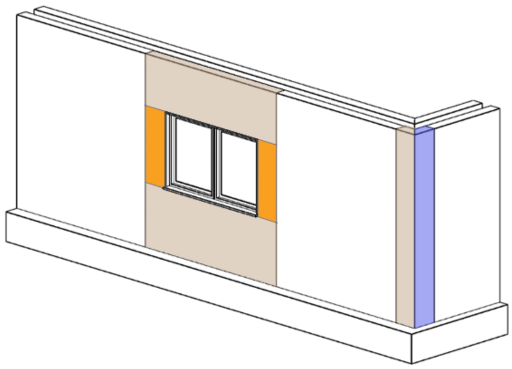

Figure 1 Decomposition of wall into regions associated to opening and corner conditions. The window opening region can be further decomposed into regions for the sill, lintel and jambs.

General definitions and rules for the decomposition of masonry regions are the following:

1. A region is the geometric representation of an arbitrary masonry wall feature. Masonry wall features may be a *bona fide* portion of the wall with a clear, identifiable shape and function (e.g. an arch, a pilaster, etc.), or a *fiat* portion of the wall defined according to some arbitrary criteria (e.g. bricks to be laid by crew per day, damaged bricks to be replaced, etc.). Masonry wall features are discussed later in section 2.3.
2. A masonry region is bound by horizontal lines of masonry courses. The first and last courses are the outermost horizontal boundaries.
3. A masonry region is bound by vertical lines in coordination with the masonry bonding pattern and head joints. Thus, a region may contain only full and half masonry units. When a wall in running bond id represented at LOD 400 or higher, the vertical boundaries are staggered lines that follow the overlapping of the bond. The first and last edges of a wall are the outermost vertical boundaries.
4. The largest possible region within a wall is the wall itself in its whole. In conjunction with the minimal region (see definition 5), the maximal region provides the basis for modular coordination for a given unit type, along with the context for which rule for boundary conditions can be established.
5. The smallest region is the size of a half unit. This is called the minimal region, representing the basic module required for dimensional coordination. In some cases, niches, recesses or other type of feature can be depicted using a minimal region representation.
6. The masonry within a given region must all be laid according to a specific bonding pattern. However, it is possible to decompose a region further into sub-regions, which can have different bonding patterns.
7. Regions may be rectangular, trapezoidal or triangular, so that gables and other forms can be represented.
8. Regions may be defined also through the thickness of the wall, to accommodate walls with multiple wythes of masonry.
9. Within a given region a set of rules can be established that control the placement of masonry-specific components, such as vertical reinforcement, bond beams, grout, wall ties, weeps, etc. A given rule set applies to a region, and if the rules change, a new subdivision is required.

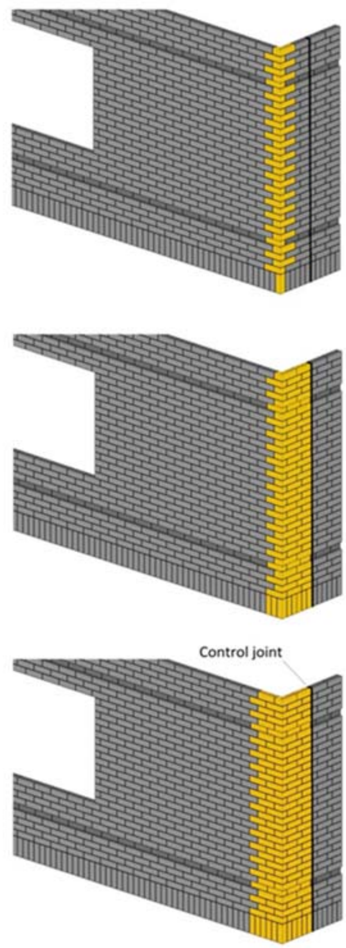

Figure 2 Possible region decompositions for L-type corner. Control joint establishes a hard boundary.

10. Parametric constraints can be associated to regions to control their placement and the geometric behavior of its boundaries, as well as individual parts within the region.
11. Parametric constrains and rules may enforce that a wall be "in-coursing" and "in-bond" in relations to its neighbors, boundary conditions, or other type of requirements. These rules may include geometric tolerance criteria to adjust the thickness of mortar joints to fit masonry units into regions where possible.
12. Masonry wall corners at L- and T- shaped intersections form their own type of region. Therefore a complex sequence of walls can all be controlled geometrically from a single "anchor point", from which the masonry pattern is established. Figure 2 shows an example of an L-type corner region.

2.2 Relationship between regions and LOD

In a design workflow certain activities can only occur if the right type of information is available in an appropriate format. In a BIM enabled workflow, the information required typically involves the exchange of only a subset of the entire model. For that reason, the concept of Levels of Development (LOD) was developed, in order to ensure that the required levels of information are present in the source model to support different design activities across different design stages.

The concept of region representation was developed to support incremental LODs as well as the existence of different LODs simultaneously in the same model. This is particularly relevant for masonry, given that in some circumstances it is necessary to model individual units and accessories explicitly (e.g. virtual mock-ups), while at the same time keeping a more generic description in other areas of the model.

At LOD 100, masonry regions are very generic. By default, only the maximal region may be defined, coinciding with the overall geometry of the wall. However, as soon as LOD 200 is required, the wall can be decomposed into more specific, view-dependent regions. For instance, the insertion of new masonry features into a wall, such as openings, corbels, pilasters, recesses or quoins, to name a few, are all associated to specific forms of region decomposition. This decomposition process is intended to be automatic, similarly to the functionality provided in some pre-cast concrete BIM applications (e.g. IDAT pre-cast module for Revit) [22].

At LOD 200, each region may have associated different masonry unit types, coursing and bonding patterns. Also, as part of this characterization, the behavior of the masonry at different region boundaries must be established in a coordinated manner. Typical examples for vertical boundaries include: "preserve running bond with adjacent regions" and "insert half bricks and establish control joint" (see Fig. 2).

At this point it is possible to generate a custom hatch (2D surface pattern) for each region on the masonry wall. These patterns can be used for manual verification that the masonry wall bonding and coursing are correct. The hatch representation is computationally lightweight – and might well be sufficient for much of the early-stage architectural design process.

The act of placing and correcting the architectural hatch on walls is not trivial. This may mean that overall building dimensions need to be adjusted, or that the size and location of doors and windows need to be changed. Or it may be that alternative masonry units will be specified to meet the overall building geometry. In some situations it may be possible to adjust the width of the head and bed joints – or allocate the dimension mismatch to vertical and horizontal control joints. Once the masonry patterning has been established, and the patterns accepted, the masonry wall can be considered to be at LOD 300. For structural masonry, LOD 350 has a specific definition as outlined in the 2015 BIM Forum Specification [12]. In the structural layer of the walls, the following elements should be included in the model: bond beam and lintels, reinforcing and embedments, and jambs sections. These are key elements included in automated clash detection and trade coordination.

Finally, the propagation of individual masonry units into the BIM model, if required, occurs at LOD 400. The region concept supports the selective placement of masonry units into the model on a region by region basis. Therefore, if certain regions require more complex detailing, then only those regions may be promoted to LOD 400. The masonry units in the MUD can be instantiated in the model and propagated either manually or algorithmically. The specification of placement rules according to local coordinate systems (Fig. 3), allows the masonry units to be merged with the hatch pattern at either the wall face or wall centreline, as appropriate.

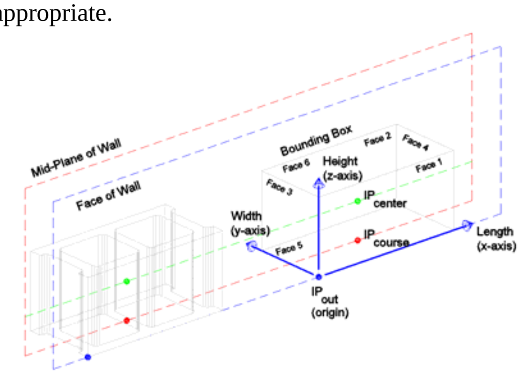

Figure 3 Insertion of masonry units into masonry walls.

The ability to specify different LODs in the same model and to explicitly propagate masonry units into specific sub-regions only when needed is a useful capability (Figure 4). Indeed, we expect that such approach would facilitate a more effective exploration and evaluation of alternatives without significant compromise in computational performance.

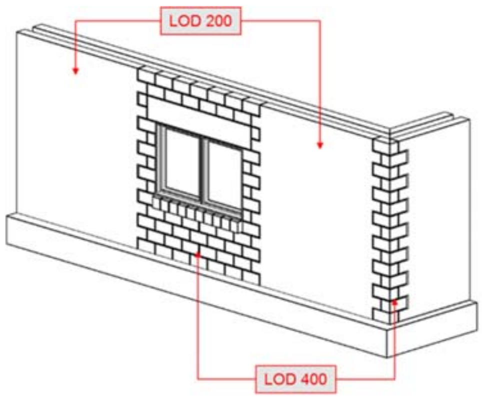

Figure 4 Different LODs assigned to masonry regions.

2.3 Masonry wall features

The implementation of masonry specific BIM applications entails first and foremost the definition of conceptual data models that capture the properties and relationships that are relevant for most use case scenarios and design workflows. As mentioned before, this need has been initially addressed by the BIM-M initiative with the development of the MUD project, which focused primarily on a conceptual model for masonry units. The next step in MUD is to include within the same conceptual framework the definition of masonry components and accessories that are most commonly used in masonry construction.

However, the computational representation of masonry walls requires more than the definition of individual masonry units, components and accessories. In fact, masonry walls need to be characterized as being composed not only of discrete, off-the-shelf collections of parts but also by a series of intermediate aggregations that result from particular arrangements of masonry units. These aggregations conform functional and aesthetic features of masonry walls, such as wythes, veneers, corbels, recesses or inlays to name a few, that that are intrinsic to masonry construction. Figure 5 provides a classification of typical masonry features identified by the research. Since different masonry features imply different combinations of components, sequences of erection, equipment and skill, they also play an important role in construction planning and cost estimation. Therefore, the semantics of masonry features was recognized as key in the specification of the masonry wall data model.

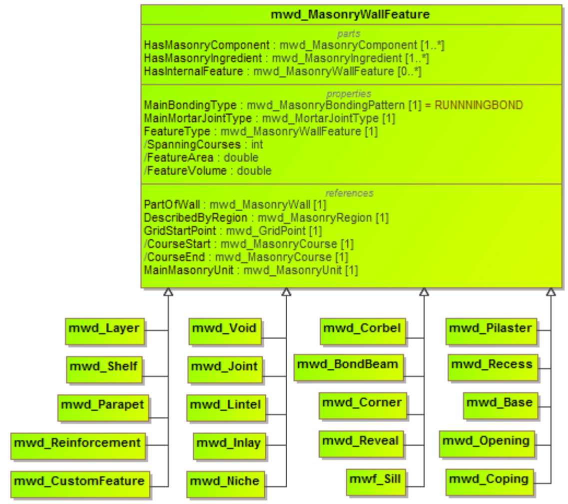

Figure 5 Schema definition for masonry wall feature types.

At the most general level, a masonry feature may be seen as being part of a wall, having a relative position, a shape, a set of internal masonry units as well as internal components and accessories, a bonding pattern and a function. Notice that a masonry feature may contain internal sub-features.

As discussed in section 2.1, regions are geometric abstractions of masonry features, similar to the notion of bounding boxes. By decoupling the representation of masonry features (i.e. the “real-world” entity of interest) from its geometric abstraction, a greater degree of modelling flexibility is provided. In particular, regions play a dual role as both place holders for further addition of geometric detail, as well as implicit form of aggregation of masonry components. This approach is intended to facilitate not only the transition from lower to higher LODS, but also the inverse, from higher to lower LODs. Such a representational capability is considered relevant to support more effective design iterations, by making it easier to designers to go back to a previous stage and explore alternatives.

3 Proof of concept schema

The conceptual data model developed for masonry walls was preliminarily implemented as a XML Schema and imported into SketchUp as a proof-of-concept. The proposed semantics for masonry walls, masonry wall features and masonry regions were formalized using IFC 2x4 definitions as main reference framework [23] This approach aims towards future compatibility with the IFC standard, and the reusability of existing definitions related to walls in general. For example, the semantics of *IfcWallElementedCase* was found to be more appropriate for the description of masonry walls, especially in situation where Levels of Development need to be higher than LOD 100. As a consequence, masonry walls can be treated explicitly as assemblies, while the allowable set of element parts (i.e. *IfcBuildingElementPart*) can be extended and customized further to meet the information requirements of masonry-specific workflows. This provision also facilitated the characterization of masonry wall features as subtype of *IfcBuildingElementPart*, thus keeping the consistency of relations established at different levels of the assembly hierarchy.

Finally, *IfcBuildingElementProxy* provides the basic framework for the semantic characterization of masonry regions. In particular, this is an IFC construct intended to serve as spatial place holders for future allocation of functions and exchange of undefined geometries. As such it can have associations to different placement objects, shape representations and material definitions, as well as spatial containment, element compositions and property sets. This is precisely the goal behind the conceptualization of masonry regions, which may be created during early design stages without a precise meaning or associated function. The process of region generation, by geometric decomposition of larger solid objects is also consistent with the exploratory nature of conceptual design which is arguably top-down.

Within the envisioned software functionality, a region can be assigned a LOD value, the type of masonry wall feature the region denotes (i.e. *isAbstractionOf* relation), along with other inherited and specialized properties (Figure 6).

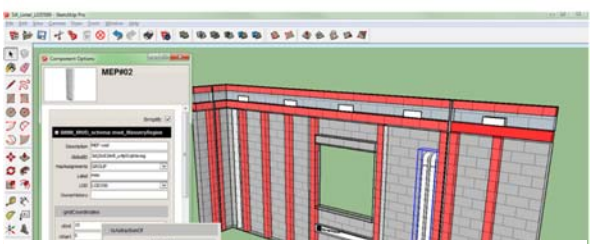

Figure 6 Masonry cavity wall modeled in SketchUp at LOD 350. Regions are created by top-down decomposition and assigned to predefined feature types by means of the "*isAbstractionOf*" relation. In this example the region represents CMU blocks in the back-up wall containing MEP ductwork.

4 Summary and Conclusions

The semantics of masonry construction and particularly of masonry walls are largely missing from current BIM applications. In order to provide better computational support, BIM applications need to go beyond representational approaches that oversimplify the complexity involved in masonry assemblies. Instead, a more sophisticated approach is needed, where information requirements that are unique to masonry workflows can be more effectively satisfied. To do so, the representation of masonry walls needs to be approached from process-centric perspective, with the goal of allowing incremental levels of design information without compromising computational performance nor the ability of designers to explore alternatives. These conditions imply the need for a more expressive representation to cover multiple stakeholders' perspectives. At the same time the representation has to be flexible, so that different Levels of Development (LOD) may co-exist in the same wall model.

This paper outlines the underlying philosophy for a compact but extensible representation of masonry walls intended to address these issues. At the core of this representation lies the concept of masonry region, which is a geometric abstraction for wall features that are meaningful from a domain-specific perspective. Since masonry wall features denote particular aggregations of masonry units, a region serves as geometric proxy for such aggregation. In this way different levels of geometric detail may be added selectively to different features of the wall, independently from their non-geometric aspects.

The paper introduces the early stage of development for a proof-of-concept implementation of a schema for masonry wall using IFC as conceptual framework. The proof-of-concept was encoded as XML Schema and imported into SketchUp for preliminary evaluation. This consisted in a number of masonry cavity wall models that were built at different LODs in order to compare modelling efforts against information content. While the evaluation is still preliminary the exercise provided some valuable insights. For instance, the use of regions facilitated the addition of geometric detail up to LOD 500 (i.e. units and accessories) at selected locations of a masonry wall while keeping overall modularity. This was seen a more efficient way of adding resolution where needed, while keeping the model workable. Similarly, geometric detail could be deleted from specific regions, while keeping semantic consistency with the overall assembly. This is an important functionality because the ability to transition back and forth between LODs may potentially facilitate the exploration of design alternatives, especially in the context of masonry construction.

Future work will focus on further refinement of the proposed masonry wall schema. This will involve development of prototypes, systematic testing and validation. For this purpose collaboration with both the masonry and software industries is critical.

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