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Masonry Unit Database Development for BIM-Masonry

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Abstract

This paper reports on the development of Masonry Unit Database (MUD), a data structure framework for storing the required data for digital representation of masonry units, as part of the BIM for Masonry initiative. As a requirement for the automation of BIM model creation, the available masonry data has to be in a standardized format; however, the current masonry models and data produced by the industry do not follow any standard. Consequently, we propose a data structure for MUD to represent the geometric and non-geometric data needed to select, specify and purchase masonry units. We argue that the main data required for MUD can be categorized into the internal attributes, including geometry, material, physical properties, color and texture required for activities such as unit specification, comparison, and selection, and the external attributes, including manufacturer, distributor and project required for business activities such as cost estimation, availability query, and unit of order verification. MUD is intended to facilitate the development of new BIM and other software applications for the masonry industry.

Keywords: Masonry, BIM, Relational Database, Product Model

Introduction

Building Information Modeling or BIM is enabling the transition from representations of buildings that contain only geometry to an information-rich environment with embedded

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semantics that describe the characteristics and functions of building systems (Eastman, Teicholz et al. 2008). As BIM software has evolved, the need to have attribute data associated with 3D geometric models has become vital to design and construction processes (Eastman 1999). As part of Building Information Modeling for Masonry (BIM-M) initiative, this research embarks on the development of Masonry Unit Database (MUD), a data structure framework for the representation and exchange of information regarding masonry units in a BIM-enabled masonry building project. The MUD is a framework for storing the required data for digital representation of masonry units, and is intended to facilitate the development of new BIM and other software applications for the masonry industry. The MUD can be compared to the database of structural steel shapes, created by the American Institute of Steel Construction (AISC) that forms the data foundation for structural steel modeling and fabrication software (AISC 2014). However, the lack of a standard system of classification across masonry industry segments as opposed to steel industry adds to the complexity of MUD development.

The first step in supporting automation for masonry BIM projects is to model information processes. Developing a masonry data model and capturing all the required information about the masonry unit, the existing data has to be represented and abstracted, which helps to reduce the complexity of the data and focus only on the required information. As Eastman asserts: “an *abstraction* of some representation is a second representation in which details of the first are purposely omitted” (Eastman 1999). Applying abstraction to data multiple times would result in an *abstraction hierarchy* that are important structures in both thinking about and organizing data for and within computers. Traversing a hierarchy from top to bottom, the single term, for example masonry unit in our case, is replaced with a set of terms that the one word characterizes, as concrete masonry unit, architectural brick, structural brick and cast stone. Every new term in the hierarchy carries attributes and relation data as well as references to even more detailed terms. At the bottom level of a hierarchy, a term is only described by a set of attributes and no reference to other terms.

Data abstraction leads to succession of data classification models such as Entity-Relationship (ER) model that links graphical information modeling with process design languages, developed by Peter Chen (Chen 1976). The power of this system is that an ER diagram is automatically translatable into a relational database schema, which is the database model for the MUD as discussed in the next sections. The ER model is a easy way to define database schema that allows definition of a common language for masonry domain experts with limited computer knowledge, and computer programmers to jointly create the masonry data model (Elmasri and Navathe 2010). Consequently, creating an abstraction hierarchy for development of a masonry unit database, the masonry domain expert knowledge has to be captured and then masonry unit data has to classified based on topological (features) and geometrical (parameters) aspects (Kalay 1989), as well as constraints that represents other product information like material properties or technology and manufacturing properties (Anderl and Mendgen 1996) in order to be represented in a ER model. In this paper, first we discuss the captured domain knowledge from masonry experts and their special data requirements from MUD, and then describe the organization of MUD and development of database schema based on this information.

Stakeholders' Data Requirements

The masonry unit database to be developed as part of this research is described generically in the literature as a building product model (Eastman 1999) or building object model (Eastman, Teicholz et al. 2008). The first step in developing a data model of this type is to determine the information needed to support a given design or construction process. Because design and construction processes are complex, with many stakeholders, we have idealized the design and construction process as consisting of 12 sub-processes so as to focus on the information needs at specific stages (Figure 1). The elucidation of data requirements from process models was first described by Eastman et al. in 2002(Eastman, Lee et al. 2002), with further examples taken from the precast concrete industry published by Sacks et al. in 2004 (Sacks, Eastman et al. 2004).

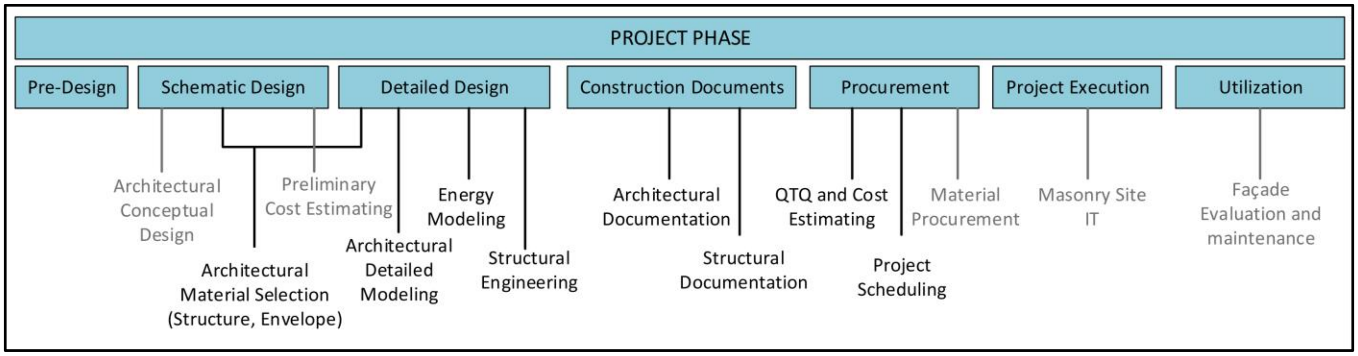


Figure 1. Masonry design and construction project timeline with project phases and proposed masonry material workflows

The content and organization of the database has been derived based on an analysis of the masonry industry from the perspective of major stakeholders in the industry, including masonry suppliers, purchasers, design professionals, contractors, and masons. Business Process Modeling Notation (BPMN) has been utilized for the representation of the masonry projects process model, which involves different stakeholders and the exchange of information among them in different stages of the project. Required data set from MUD in each of the processes and exchanges in a BIM-enabled masonry building project workflow has been described in earlier research by Gentry et al. (Gentry, Eastman et al. 2014, Witthuhn, Sharif et al. 2014). Here, the main data requirements by stakeholders is summarized:

***Masonry Manufacturer*:** The masonry manufacturer is primarily a producer of masonry units and in this role is likely to author much of the information into the MUD. The masonry supply chain is not homogeneous – in some cases the masonry manufacturer markets and sells masonry units directly to contractors, and in other cases the manufacturer sells to a supplier – who stocks and supplies the units to contractors.

Masonry Supplier: The masonry supplier is a vendor of masonry units but does not manufacture the units. Depending on the nature of the supply chain, the masonry supplier may be responsible for inputting information into the MUD.

Building Owner/Client: The building owner or client may be interested in reviewing masonry materials that complement existing building stock. Or, in residential construction, the owner/client may be directly involved in picking the masonry materials. For this stakeholder, the primary information that the stakeholder will be looking for is appearance, and the manufacturers or suppliers who may provide the price, and availability.

Architect: The architect will interact with masonry unit information in multiple stages of the design process, with the three most important being: materials selection, detailed design, and construction documents (including specification writing). The architect requires a full range of information regarding masonry units including aesthetic, geometric, physical properties, and price.

Structural Engineer: The structural engineer is primarily concerned about the geometric, physical and mechanical properties of the masonry units. In many cases, the unit properties must be considered along with the properties of allied materials (grout, reinforcement) to develop overall properties of masonry walls. The intent is to include as much unit-level property data as necessary, so that structural design can be completed with information stored in the MUD.

Energy Analyst: The energy analyst also requires geometric and physical property data – and builds thermal characteristics of masonry walls from the thermal resistivity, surface characteristics, and density of the masonry units.

***Mason Contractor*:** The mason contractor, like the architect, needs the complete range of masonry unit data depending on the phase of the project. In many cases the mason contractor may need appearance data in order to match existing units or to compare between units for product substitution. The mason contractor will also need information about coverage (that is, how many units are required per unit area of wall), price and availability to prepare cost estimates. It may be that the pricing data stored in the MUD will be valid only for preliminary pricing, and so workflows will be required that allow for cost-estimating to be updated during the QTO/Cost Estimating process.

General Contractor: The general contractor may have the same data needs as the mason contractor, but to a less detailed level. Many sophisticated GCs who practice “Virtual Design and Construction” are building high level of development (LOD) BIM models and these GCs are likely to access the geometric parts of the MUD in order to have the geometry of the masonry units.

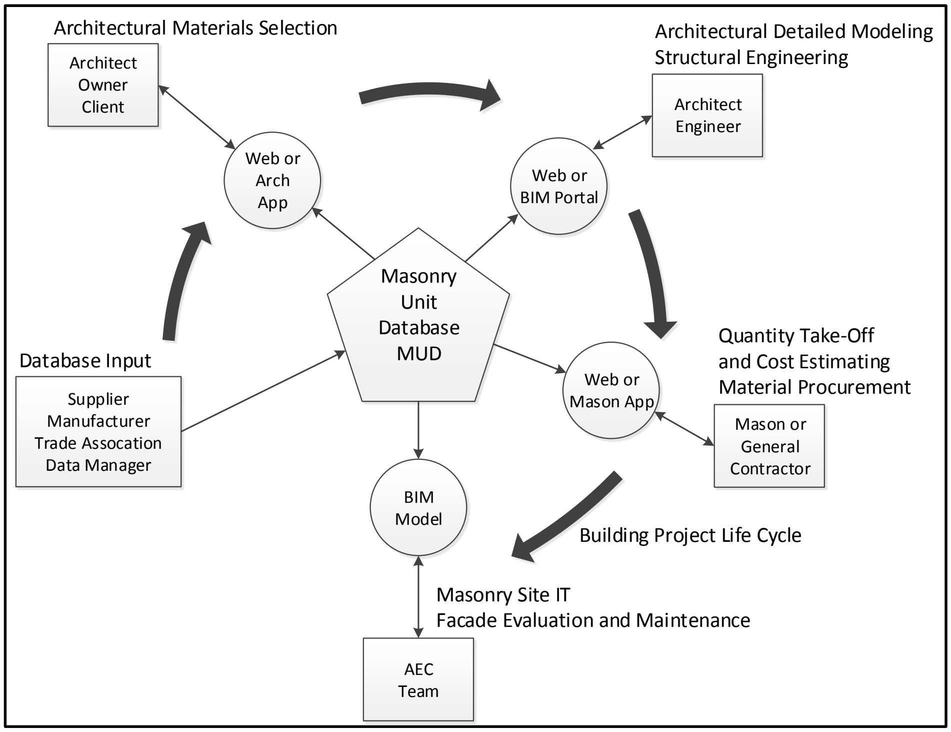


Figure 2. Stakeholder and workflow model for the MUD.

Scenarios of Use

The scenarios of use can be thought of as high-level workflows without the detail of data exchanges and data formats. There are many scenarios of use for the MUD, but four major scenarios are highlighted here

1) Material selection for aesthetics: Material selection for aesthetics involves primarily the shape, color and texture of masonry units. There are many nuances here, and in commercial construction, the selection of masonry units and associated materials (accent stone, grout, flashing) often involve the production of physical sample boards or mock-ups because digital information does not do a good job of demonstrating or promoting the “patina” that comes with masonry. In order to promote the use of the MUD for aesthetic decision making, the database will provide for storage of graphic bitmaps representing images of the finished faces of the units. The database will accommodate multiple instances of the same view, so that in an array of these randomized images will show the approximate variation across the range of units.

2) Importing geometry into BIM or CAD: In many cases, an architect (or any stakeholder attempting to create a high level of detail model) will want to insert the 3D or 2D geometry of the masonry unit into a BIM or CAD model. The database will accommodate this by providing the necessary information for parametric generation of 3D masonry units, as well as storing both 3D models and 2D drawings of the required graphic information. Common file formats for these models/drawings are DXF (AutoCad drawing exchange format), RVA (Revit), Parasolid, and SketchUp Component.

3) Wall material property determination: A structural engineer or energy analyst will need to access the MUD in order to calculate structural or thermal properties of masonry assemblies (walls). It is for this reason that the geometric properties of generic masonry units are stored as descriptors instead of as 3D solid models, and so, for example, the face shell thickness of a block can be determined directly from the database, without having to load a BIM model and query the model for that thickness. In some situations, this query will be completed through a web application that provides the information to the engineer, but it will also be easy to tie the MUD to Excel or other programs so that wall properties can be calculated automatically using third-party programs that query the MUD.

4) Determining material availability: A final scenario for the MUD is the determination of material availability. This is a typical application of databases that manage inventory, but that functionality has not been envisioned for the MUD, because at this time the MUD is not seen as a full ERP (enterprise resource planning) database for internal business processes. Nevertheless, the MUD can be a first step for a masonry customer in determining whether a given masonry unit is stocked or custom, what the minimum order quantity is likely to be, and whether it is produced within a given region of the country (which is often of interest in projects seeking a LEED rating).

Database Organization

The first step in any database design process is requirements collection, analysis and classification. The detailed data is gathered from available resources and prospective database users. In addition to data requirement specification, the functional requirements and transactions for the retrieval and update of database also have to be identified. In the next step, a conceptual schema for the database with a high-level conceptual data model has to be created (Elmasri and Navathe 2010). For MUD, we have acquired entity-relationship model (ER model) that has the ability to describe in detail the entity types, relationships, and constraints of masonry units. Conceptual schema is easier to understand and communicate with nontechnical users, as concepts do not represent implementation and storage details. Readability by nontechnical users is an important aspect that ensures the complete identification of users' data requirements and prevention of any possible requirements conflict. In addition, in conceptual schema design phase the ER model operations can be acquired to determine the high-level user queries and operations.

Here, the organization of the masonry unit database is described in detail, providing a motivation for the organization of the database, and describing the overall entity-relationship model for the database. In addition, each of the attributes to be contained in the relational database tables is described in detail.

Conceptual Schema Framework

At this level, we represent the related and required data to masonry units in an entity-relationship model (ER model), a high-level abstract method of organizing data to be later be implemented in a database application (i.e. a particular database and the associated programs that implement the database queries and updates). The ER model describes data as entities, relationships, and attributes. Entity, the basic object represented in ER model, represents a thing in the real world with an independent existence, an object with a physical or conceptual existence. Each entity is described with particular properties that are called the attributes of the entity. Any particular entity will have value for each of its attributes, which are the major part of the data stored in the database. Different types of attributes in the ER model are: simple versus composite, single- valued versus multivalued, and stored versus derived. In ER model, relationships represent references of entities types to each other. In other words, a relationship defines a set of associations among entities. In this project, we used the Enhanced ER (EER) model which is more suitable for newer applications of database technology including databases for design and manufacturing (CAD/CAM) (Elmasri and Navathe 2010).

Masonry Overall Schema

The geometric and non-geometric masonry unit data are classified and represented in an EER model. We argue that the main data required for MUD can be categorized into the internal and external data to the units (Figure 3). Internal data to the units are represented as geometry, material, physical properties, color, and texture entities. These entities, along with their associated attributes and the relationship among them are required for activities such as unit specification, comparison, and selection. The external unit data is categorized as manufacturer, supplier and project entities, which are required for business activities such as cost estimation, availability query, and unit of order verification.

The complete MUD EER model includes these entities and their associated attributes and the relationship between the entities. Relationships in this model, such MADE_BY relating UNIT entity to MANUFACTURER entity, define a set of associations that are required for the adequate functionality of the MUD. For example the MADE_BY relationship between UNIT and MANUFACTURER entity sets would be utilized in the query of specific masonry unit production locations, or contact information. The complete network of all MUD entities, attributes, and relationships is represented Figure 4.

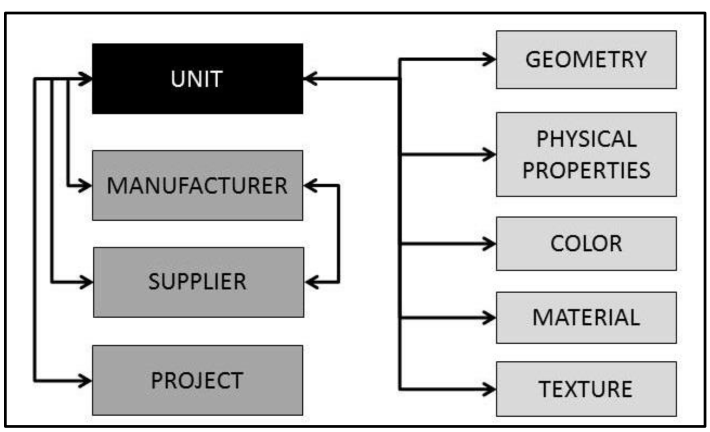


Figure 3. Main masonry unit entities to be represented in the EER model and MUD database

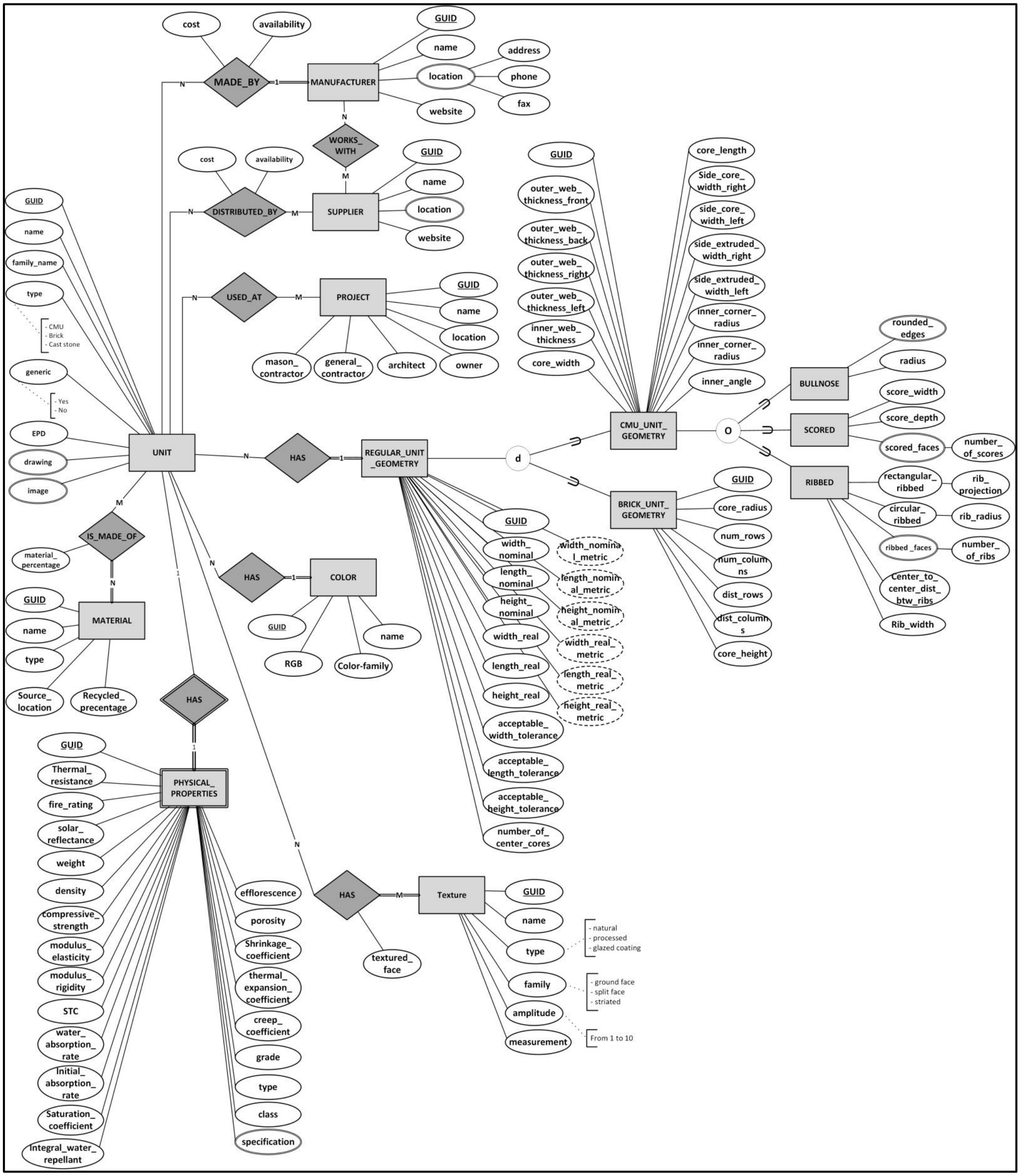


Figure 4. MUD complete EER model

Unit

The core of the MUD schema model is the UNIT entity which represents all the masonry units that is going to be represented in this database (Figure 4). There are different attributes that their values define this entity: GUID (Globally Unique ID), name, family name, type, and image and drawing. UNIT entity like all other entities in this model has a GUID attribute that is used for unique identification of each entity in the entity set. Name attribute denotes the commercial name that manufacturers specify for their masonry product. In addition, these units can have a family name that will be used for grouping of a set masonry units with similar characteristics. Type attribute at the high level classifies the masonry products and includes Concrete Masonry Unit (CMU), clay brick and cast stone masonry. The UNIT entity also stores (string) values for images or drawing file locations provided by masonry units' manufacturers.

Geometry

The most substantial entity defined in MUD is GEOMETRY, and the defined entity should be able to represent the geometry of both CMU and clay brick masonry units. The parametric geometry developed for CMU will in many instances be appropriate for structural clay units. For the development of MUD, we classify the units' geometry in three general categories: A) regular masonry unit geometry, B) special masonry unit geometry, and C) custom masonry unit geometry. The regular unit geometry is the major focus of MUD at this stage of development. The geometry attributes were developed so that a wide range of common units could be represented parametrically as regular units but also so that the database could be easily understood without the need for hundreds of parameters.

A) Regular unit geometry: the geometry of these units can be fully identified and categorized based on their parametric attributes. These units are produced by most masonry manufacturers with almost identical size and shape, although with different tolerances (Figure 5). Based on the assigned values to these attributes, each masonry unit can be identically 3D generated with the stored data in the MUD. CMU general units have parent families including stretcher, pier, corner, return corner, sash, corner sash, bond beam, conduit, lintel, open end, header, starter, and subtype groups such as bullnose, scored, ribbed (circular, rectangular). The clay bricks have two major categories of molded bricks and extruded bricks, and with parent families including thin brick, face brick, structural brick, pavers, etc. For clay units, cores and frogs can be represented as regular units.

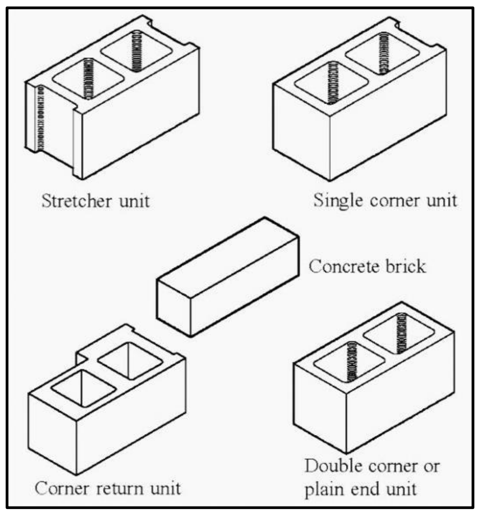


Figure 5. Typical Concrete Masonry Units that can be characterized as "regular" units.

B) Special unit geometry: these units inherits most of the attributes from the regular unit geometry, however they have some special geometric features which is unique to these units. These units are usually produced by one specific manufacturer based on their system of fabrication or particular preferences (Figure 6). Although these units can be partially represented by the parametric attributes that are defined for regular units, defining a set of parametric attributes to cover all their geometric aspects for a complete representation would be impractical, adding extensively to the complexity of the database data model. It will be up to the manufacturer whether they would like to represent their unit as a "special" unit, so that the overall shape and key features can be generated parametrically, or whether they would like to represent the unit as a custom shape.

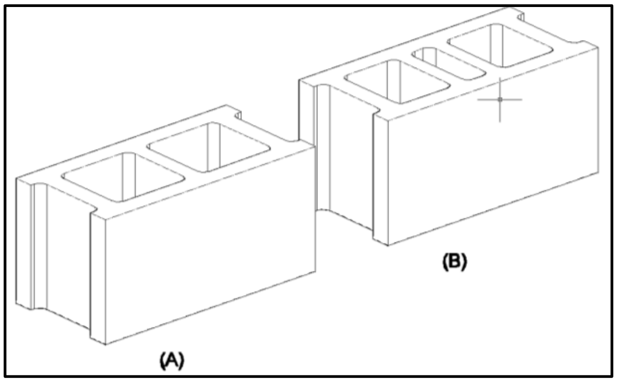


Figure 6. Masonry unit with special geometry (B) can be represented parametrically in the database as regular unit (A).

C) Custom unit geometry: these units are custom design by the request of the project architect or they are specific to a manufacturer or have such complex geometry that they cannot be represented parametrically (Figure 7). It is likely that many of the cast and cut stone units will ultimately have to be represented as custom units. They geometry is usually complex and includes almost none of the geometric attributes of the regular masonry units. Geometry of these units is one of a kind, and as a result, parameterizing their geometric features would not be practical. Consequently, these units have to be represented with B-rep (Boundary representation) or CSG (Constructive Solid Geometry) models and to be stored as string data format or 3D files in the database.

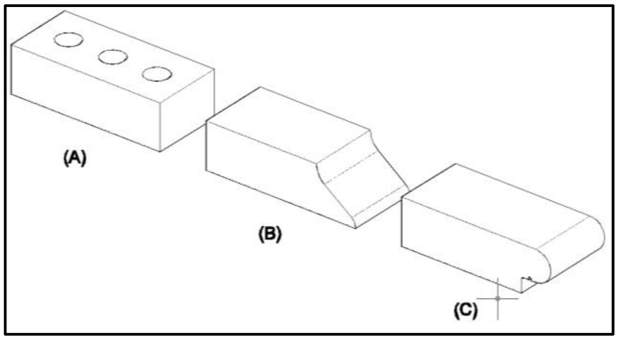
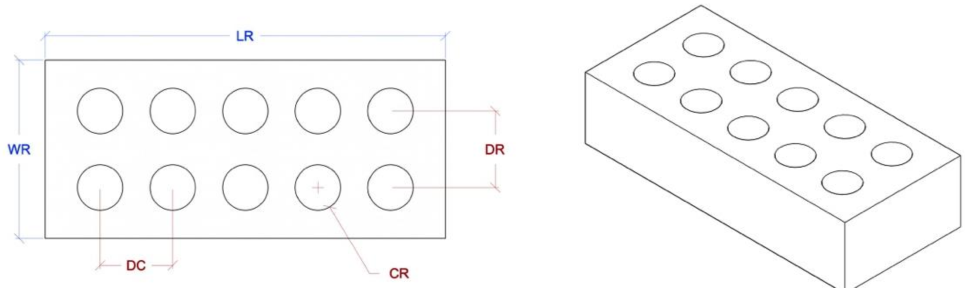


Figure 7. Custom Units (B) and (C) may be accessory units that are related to a regular unit (A).

UNIT Dimensions: Typically, CMU and clay brick units are defined with both nominal and actual dimensions. Nominal dimensions refer to unit size for planning bond patterns and modular layout with respect to door and window openings. Nominal dimensions may vary from the actual dimensions by the thickness of a mortar joint, typically 3/8 inch less than nominal dimensions but not more than 1/2 inch (9 to 12 mm). Actual dimensions refer to the real measured size of a particular unit. The actual dimensions of masonry units are usually 3/8 inch less than nominal dimensions in most masonry units, not accounting for including any adjacent or expected thickness or mortar joints, which is typical for expressions of nominal thickness. In the US, CMU have nominal face dimensions of 8 in. (20 cm) by 16 in. (40 cm), available in nominal thicknesses of 4, 6, 8, 10, and 12 in. (10, 15, 20, 25, and 30 cm). As actual dimensions are typically 3/8 in. (9) less than nominal dimensions, so that the 4 or 8 in. (102 or 203 mm) module is maintained with 3/8 in. (9.5 mm) mortar joints (Figure 8).

Parametric Geometric Attributes: For the identification of masonry both CMU and clay brick units, we have classified their geometric properties into different attributes. We anticipate that based on these defined attributes all regular geometric units can be adequately represented in the database and regenerated in BIM applications. Because the geometry can be generated parametrically, the storage of the geometry is compact and all of the units do not need to be drawn in CAD. Figure 8 illustrates these attributes for clay brick units.



CR	core radius	DC	distance between columns
NC	number of columns	DR	distance between rows
NR	number of rows	CH	core height

Figure 8. Attributes description, BRICK_UNIT_GEOMETRY entity.

Texture

The texture of a masonry unit is an indicator of its appearance, feel, and consistency of a surface. Texture can be defined as the pattern or configuration apparent in an exposed surface of a masonry unit, including roughness, streaking, striation, or departure from flatness. Because the texture is mapped to faces, it is necessary to map the faces and edges of the masonry unit. The convention for doing so is given in Figure 12. Texture applies to both clay and concrete masonry units, but the language used to describe the textures varies depends on the material type. When the database is extended to cast and cut stone, an even more extensive discussion of texture will need to be included. The intent here is to embody both the manufacturer's description of texture including adjectives like "antique", "struck", and "rolled" as well as a numerical scale so that architects can search for units with similar texture. So, for example, searching for texture amplitude of 1 will return units with absolutely flat surfaces like glazed and ground units. Searching for a texture of 10 will return units with split, slumped and highly irregular faces.

In concrete masonry, texture is closely related to the depth of the natural aggregates and the processes such as machining polish, exposing, buffing the aggregates or glazing that have been applied to the surface of a masonry unit. The attributes that we have defined for the specification of texture entity include texture type, texture family, texture amplitude, and texture measurement (Figure 4).

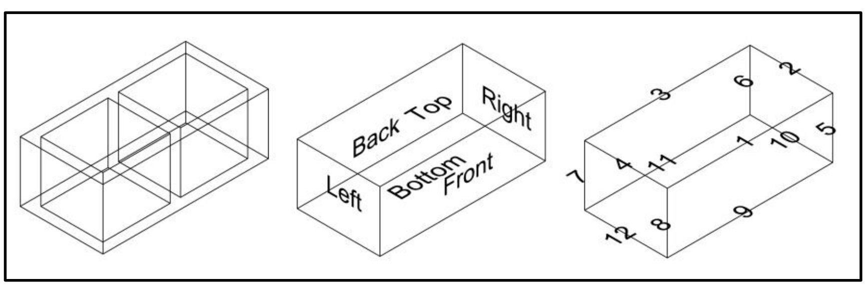


Figure 9. Naming of masonry units faces and edges.

The texture type consists of natural texture, processed texture, or glazed coating (where applicable). The texture family for CMU for example includes split-face (appearance of natural stone, rough-hewn texture with exposed aggregates), ground-face (polished surface finish produced by grinding machine), striated (random striated pattern), etc. The amplitude of the texture indicates the roughness or smoothness of the surface and is measured on the scale of 1 to 10. Measurement attributes could be represented using a quantitative assessment based on the measurement of masonry surface profiles using methods like that provided ASTM D7682, Standard Test Method for Replication and Measurement of Concrete Surface Profiles Using Replica Putty.

Color

The masonry units color is the result of color ranges in raw materials, aggregate mix, added coloring agents or glazed color in case of glazed bricks. For example the factors that influence color variations in CMU include color variation in pigments, aggregates, cements, clay, water content, degree of compaction achieved during manufacture, and for brick include kiln conditions, changes in clay materials, and atmospheric conditions such as temperature and humidity. Masonry units color variations can be standard or special order. The assigned attributes to the Color entity are RGB of the color, color name, and color family (Figure 4). The attribute color family is used to group like units together. It is also possible to add a amplitude measurement for “color uniformity”, where a brick with a large amount of color difference would have a low color uniformity.

Physical Properties

The Physical properties entity includes attributes for both mechanical properties and thermal properties of masonry units. These properties are determined based on ASTM (American Society for Testing and Materials) standards for the most part. The database represents the set of physical properties of a masonry unit that are the basis of unit selection in engineering processes. In the table below, key properties identified by the masonry industry and others identified by our research team are listed. In addition to facilitating masonry unit selection, relevant properties of units are contained in the database so that the masonry wall model database, as future part of this research, have sufficient information regarding masonry units, so that physical properties of walls, used for energy and structural analyses.

Material

Masonry units are made of combination of different raw materials created under different processes. CMU is made of a mixture of powdered Portland cement, water, sand, and gravel. Brick is made of natural clay minerals such as kaolin and shale and mixed with small amounts of additive components such as manganese and barium for production of color shades or improvement of chemical resistance. The listing of materials and their percentages is of particular interest on projects where the AEC team is pursing LEED accreditation or trying to limit the embodied energy in the building.

In MUD, each UNIT is associated with different MATERIAL entities, each of which defined with material name, type, source location and recycled percentage (post-consumer and pre-consumer content) attributes. The relationship between UNIT and MATERIAL represents the percentage of each material used in each specific entity (Figure 4).

Manufacturer

Manufacturer entity represents the information about the masonry unit manufacturers. The attributes associated with MANUFACTURER are attributes for identifying each company and includes name, location (address, phone, fax) and website. The relationship between each UNIT entity and MANUFACTURER entity is elaborated with two additional attributes, cost and availability of masonry units produced at that company.

Supplier

Masonry suppliers are the links between masonry manufacturers and the groups that are involved in the masonry selection and purchasing for any building project. The SUPPLIER entity in MUD is identified with attributes including name, location(s), and website. The relationship between this entity and UNIT entity has additional attributes, cost and availability. The attributes assigned to SUPPLIER entity and the DISTRIBUTED_BY relationship will be used for comparison and selection of masonry suppliers based on their location, the price their offer for a specific product and the stock availability. In addition, the SUPPLIER entity has an additional relationship, WORKS_WITH, which relates it to the MANUFACTURER entity.

Project

PROJECT entity represents the building projects that the masonry units have been used in. Each project entity is defined by these attributes: name of the project, owner of the project, and project location.

Conclusion

As the test case for this study, we intend to implement the database with a small selection of masonry units – in an SQL data management system such as MySQL as the backend, with an initial set of data with about 50-60 masonry units, accompanied by a simplified front end as a website for data input and query. With this test MUD, the potential for hosting the database, ant its management and access would be assessed, and the connection to software vendors' databases such as Tradesmen's, CADBLOX, Masonry Designer would be studied. This test MUD is intended to be reviewed by the current BIM-M community, and especially masonry suppliers and software providers. In addition, we recognize that the custom masonry workflow is not fully illustrated in this work at this time, as the focus has been on regular units. The feedback from the cast and cut stone communities would provide the chance to represent these materials in MUD.

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