AN AGENDA FOR AEC PDES RESEARCH

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1 Introduction

Since the development of computer-aided drafting, data exchange between CAD systems has been cumbersome to the industry. According to James Turner of the Architecture and Planning Research Laboratory at the University of Michigan:

> "the most significant challenge facing developers of Computer-Aided Design (CAD) systems in the future is. . . in providing mechanisms for the exchange of project data--the complete interdisciplinary integration of design information between dissimilar CAD systems; and between CAD systems and application programs." [Turner90]

The consistent, integrated transfer of information is especially necessary in Architecture, Engineering, and Construction (AEC) industries because all participants involved in the building process need a unified, complete database that can supply all necessary design and construction information and that can be continually updated through a computer network. However, there is no such standardization of data exchange because different AEC firms, contractors, and subcontractors that make up any building process use differing analysis, design, and other software packages. This process results in a number of incompatible files that cannot be interchanged between companies and systems for an integrated work effort.

Integrated information transfer among all those involved in building projects would result in the following advantages:

- **Greater efficiency**. Time would be saved in automated data transfer between systems.
- **Lower costs**. Because of the manhour savings of automated data transfer, project data entry and transfer costs are much lower than they would otherwise be. Additional money is saved by enabling easier implementation of program design improvements and enhancements.

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- **Safer construction**. Since there is less room for error in design transfer automation, there is less chance for inconsistencies that could lead to unsafe construction.
- **Improved Communication**. Communication is essential to good building performance and integrated data exchange makes the communication between members of the AEC community more effective.
- **Better performance.** Because of the above mentioned advantages, the entire design process performs more economically.

The AEC industry must become more actively involved in research to obtain the above stated advantages and thus to maintain competitiveness in the international building market where work is currently being done regarding data standardization.

This paper will show that the AEC industries have lagged behind in contributing to the effort to develop data exchange standards. By evaluating the current state of the art relating to modeling in the AEC industries, we hope to stress the urgent need for the United States to become further involved in developing an AEC building model.

Major sections of this paper include 1) what the United States has done in regard to contributing to the international effort underway in developing data exchange standards, 2) an evaluation of the three existing AEC models, and 3) a summary of possible research directions associated with the development of an AEC building model.

2 Overview of Efforts to Develop Data Exchange Specifications

In September 1979 the United States began to address the problems associated with exchange of information between different CAD systems by forming the Initial Graphics Exchange Specification (IGES) to specify a data format for CAD system translators. These translators (also known as pre-processors and post-processors) convert a vendor's proprietary internal file formats into the neutral IGES format. From this format, the data may be re-processed into another vendor's database format - thereby making CAD systems more flexible and allowing different members of a project team to pass geometric data between each other. This process facilitates design improvements and increases the efficiency and cost savings of the design process. IGES, however, focused entirely on geometric data, ignoring other important engineering data such as material properties, design information, and performance data.

In the mid-1980's, research on STEP began. The International Standards Organization (ISO) document "STEP Part 1: overview and fundamental principles" defines STEP in the following way:

> "The Standard for the Exchange of Product Model Data (STEP) is a neutral mechanism capable of completely representing product data throughout the life cycle of a product. The completeness of this representation makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving. There is an undeniable need to transfer product data in computer-readable form from one site to another. These sites may have one of many relationships between them (contractor and subcontractor, customer and supplier); the information invariably needs to iterate between the sites, retaining both data completeness and functionality, until it is ultimately archived." [IPO91]

STEP is similar to, but broader in scope than IGES. Whereas IGES evolved to facilitate the exchange of geometric data, STEP attempts to establish a standard for all parts of the product design process. STEP is especially important because it is an international effort which would allow data transfer between countries.

Product Data Exchange using STEP (PDES) is currently being developed as the United States' input into the STEP movement. PDES has been under development since July, 1984. The IGES/PDES Organization (IPO) Steering Committee in March 1990 defined PDES as:

> "...the U.S. organizational activity that supports the development and implementation of STEP. It will act to ensure that the requirements of U.S. industry are incorporated into STEP. It will provide U.S. industry with a methodology for the implementation of STEP standards." [IPO91]

PDES has already been incorporated into the design systems of several United States industries. Whereas IGES focuses on basic graphic and geometric data (e.g., points, lines, and arcs), PDES focuses on accurate descriptions of relevant object properties (e.g., stairwells are not simply groups of lines, arcs, and polygons, but a series of beams, plates, and slabs and their connectivity with the associated engineering properties). PDES is not expected to replace IGES, however. IGES is effective with the exchange of two-dimensional graphic data, whereas PDES is much more comprehensive, allowing the exchange of design objects, specifications, attributes, and other nongraphic data [Warthen88].

3 Overview of PDES Research in the AEC Industries

Presently three AEC/PDES models have been developed: the Building Systems Model developed by James Turner of the University of Michigan, which includes structural, spatial, and enclosure characteristics [Turner90]; the Reference Model for Ship Structural Systems developed by Michael Girardi of Bath Iron Works [Gerardi90]; and the Reference Model for Distribution Systems developed by Douglas Martin of NASSCO [Martin89].

There is a great need for additional PDES/STEP research in the U.S. building industry. Though foreign building industries and American ship and aircraft industries are taking advantage of the benefits made available through the automated exchange of product model data, the building industry has made little progress toward this end.

Unfortunately, the ship models are of limited value to the building industry. The Ship Structural Systems Model contains many representations of data structuring that would not be required in a building and lacks many representations that would be necessary. For example, a ship's structure consists mainly of bulkheads and flat plates while a building system contains a greater variety of structural shapes. Therefore, the Ship Structural Systems Model cannot easily be used in the building industry, and a separate model may need to be created.

The next section discusses the Building Systems Model, the Reference Model for Ship Structural Systems [Gerardi90], and the Reference Model for Distribution Systems [Martin89]. If these models are to be used in the building industry, they will need to be tested by modeling an actual building of substantial size, complexity and diversity, allowing researchers to determine their suitability.

3.1 Building Systems Model

The Building Systems Model is an AEC complete building representation that was the first attempt at developing an integrated building systems model. It concentrated on the development of various building system models (structural, HVAC, electrical, etc.), yet within any one of these provides only abstract entities (e.g., beams and columns). As these models evolved, though, it was realized that there was no basis, by which to compare these models or to standardize their development. Therefore, a general system framework was put forth in an effort to provide that basis for future modeling. Each individual system that was to be integrated within the Building System Model would have followed the basic framework.

The Building Systems Model components that were developed consist of a spatial systems model, a building structural systems model, a building structural space frame model, and a building enclosure model. Each model was to be integrated within the entire Building System Model, with future models to include HVAC, electrical, and piping systems. At present, the level of detail attained in each of the four developed models has not progressed further than the systems level.

The various systems included in the Building Systems Model are graphically described using the Nijssen Information Analysis Method (NIAM) or the IDEF conceptual modeling language. Each system follows the general framework described above, resulting in associations with properties, components, component ports, and component port joints. The Building Systems Model data representations include both project dependent and independent data.

System properties consist of the inherent properties of the overall system. The *system components* are the elements that make up the system. The *component ports* and *joints* describe the location and method of association of the components to the system. For example, the structural system is a system contained within a building. One structural system property could be a measure of the systems' collective rigidity. A system component may be the structural assembly that, in turn, would consist of other subcomponents, namely structural elements like beams and columns. Finally, component ports and their joints would consist of the locations and methods of connections. For example, one would be able to describe a beam, its properties, the weld connecting it to another beam, and the location of that weld.

In general, objects within a modeled system possess location, orientation and representation information. Location information to be contained in the Building Systems Model includes local reference points, global station geometry (global reference points or a global reference line), and distances from the reference points. Orientation has one local reference point and either an orientation vector or an axis identifier and an angle. Lastly, a representation can be a geometric, analytic, or graphic description.

The Building Systems Model is the beginning of a full attempt at an integrated AEC building model. Most of the required details of the model have not been included, leaving only a shell structure of the model. However, this existing model could serve as a foundational structure for a complete model or could be used as a good example for another AEC building modeling endeavor. Our study of this model specifically revealed the following:

- Most components, attributes, and constraints are left out. Thus the model achieves no suitable level of detail and retains no ability to represent building components or maintain component attributes and constraints.
- Currently there is an indeterminate level of detail used in describing "intelligent" objects, though such details are necessary for these objects to be accurately represented.
- Further development is needed in order for this model to be able to integrate the various building systems into a single, homogeneous model.

3.2 Reference Model for Ship Structural Systems

The purpose of the Reference Model for Ship Structural Systems is to provide an information model containing a framework adequate for the formation of a PDES/STEP data exchange standard for a ship's structure [Gerardi90]. A goal of the project has been to automate digitally, via PDES/STEP, data exchange between two different CAD/CAM modeling systems. Although the model is not complete, it has been submitted to the PDES effort with the expectation that the model will be continuously updated. Furthermore, it has been suggested by others that besides being used for ships, many of the concepts and entities presented by the model can be applied to other steel structures such as bridges, buildings, and offshore platforms.

The Reference Model for Ship Structural Systems incorporates data from several other PDES/STEP models: geometry, topology, form features, material properties, mechanical products, and FEM. As PDES evolves, this information model is expected to separate into both an Application Resource Model (ARM) and an Application Protocol for these topical models for the shipbuilding industry.

This model was developed using NIAM and verified through the generation of a Neutral Data Model (NDM) using Control Data's PRECISE PC-IAST NIAM tool. The Express version of the model has been generated directly from the NIAM binary model. NIDDESC and the AEC committee intend that NIAM be the baseline modeling methodology.

In this model, the basic modeling objects for a ship's structural system are chosen to be hull form, surfaces and volumetric subdivision, plate part and stiffeners, material properties, holes and other part features, assemblies, and joints. This list is not exhaustive, but is a fundamental approach to object role modeling. It is suggested that to model each specific item separately would be an improper concentration on function, rather than a simultaneous consideration of function and shape representation via topological and geometric definition.

Surfaces, structural entities (parts), and features (openings, endcuts) along with their associated boundaries are defined topologically; allowing a regeneration of any or all of the geometry on the host CAD system. This allows any design change, maintenance, or other life cycle modification to be quickly and effectively incorporated into the model. This AEC view of topology differs from the view presented in either the topology model or the shape representation model. As the capability of this model matures and the AEC committee becomes more experienced, this integration will be more complete.

3.3 Distribution Systems Model

This model defines information necessary to represent distribution systems in ships [Martin89]. Distribution systems are engineering systems whose required function is to distribute fluids, electricity, or signals through piping or ductwork. Although this particular model was created for ship building, substantial review by non-shipbuilding personnel has shown that the content and structure of the information presented is applicable to other areas of the AEC industries. The Reference Model for Distribution Systems integrates explicitly, on an application level, with the Reference Model for Ship Structure Systems. All modeling sections of the Reference Model for Distribution System were created using NIAM and modeled in the Express modeling language.

This model's intent is to accurately portray detailed design parts of a distribution system including: part connectivity, size and orientation, route geometry, joint/connection configuration, insulation characteristics and geometry, and part attachment configuration.

The model uses a part hierarchy scheme to define relationships between distribution parts. The major types of attribute data are generic, specific, and occurrence. The generic level contains attributes common to all the parts of a system; the specific level contains attributes common to several parts of a system; and the occurrence level contains attributes common to one specific part.

The Reference Model for Distribution Systems consists of a series of smaller models defining separate distribution systems. These models consist of:

- the AEC Parts Model which contains specification guidelines on part catalogs, part levels, part attributes, approval attributes and integration points to other models;
- the Distribution Parts Model which contains specification guidelines on distribution parts, attachments, insulation, joints, and integration points to other models;
- the Piping Parts Model which includes specification guidelines on piping parts, pipe joints, and integration points to other models; and
- the HVAC Parts Model which contains specification guidelines for HVAC parts, access openings, HVAC joints, and integration points to other models.

4 AEC/PDES Research Directions

The development of a universal model of the size and scope of the PDES/STEP effort is an immense undertaking. Much work has already been done but much remains. This section outlines at least a portion of a potential research agenda in this area. We present this agenda to show the overall scope of the required research and enable the reader to gain a better perspective of the proposed research. We specifically address the Building Systems Model, suggest consideration of other models, define developments related to EXPRESS specifications and graphical representations, and suggest the formal evaluation of models.

4.1 Building Systems Model (BSM)

This section outlines recommendations for future research related to the Building Systems Model which are necessary for future development of the model. If this model is to become a working AEC model, many aspects still require inspection.

4.1.1 Level of Detail

The Building Systems Model lacks an appropriate level of detail to pass real descriptions into and between files. As was noted earlier, the model's focus is at a system level. Details are lacking to describe a building's items of interest. In other words, there does not exist a data description system for entities. Therefore, there is no standard method of data input. This area would be an excellent research effort, resulting in the extension of the model to greater levels of detail and accuracy. Increasing the model's level of detail would be the first step in achieving a practical model for the AEC building industry.

4.1.2 Extension of the Building Systems Model's Component Scope

Future research could concentrate on expanding the Building Systems Model's component scope. As the model is applied in practical situations, aspects that are excluded would require inclusion into the model. Application of the model would invariably expand the model's scope from generic elements and relationships to broader, more inclusive elements as specific situations and problems arise and require modeling. Some of these elements could include manufacturer's data from a source like Sweet's catalogs, cost data, and thorough component specifications. This might be referred to as dealing more extensively with project independent detail data.

4.1.3 Extension of Building Systems Model's Functional Scope

Research could also focus on expanding the Building Systems Model's functional scope. The main aspect of this research would be to examine the expansion of the model into areas that were previously incapable of being modeled such as the construction and design processes. As the model becomes more expansive (and more efficient), processes not previously included in models may be integrated with the other systems. Perhaps these elements would include scheduling and inventories, design guideline data (as in Architectural Graphic Standards), office design guidelines, and typical details. If successful, models could become all-encompassing representations of building projects.

4.1.4 Model Implementation and Efficiency

Another item of research is to enter building designs into the Building Systems Model in an effort to critically evaluate the model through testing. Deficiencies that may not be apparent in conceptual analyses could be discovered through applications. Increasing model efficiency is a goal that, if attained, would make the model more attractive to the AEC industry. The AEC industry would be more committed to introducing and using a reliable model of known efficiency to save money, time, and increase productivity rather than to spend its time "debugging" models that are to be considered for standardization.

4.1.5 Model System Integration

Further research is needed to fully understand the representational relationships between components of different building systems so that the achievement of greater levels of detail is attainable in a somewhat generic sense. The topological and geometrical representation needs of electrical conduit, mechanical piping and ductwork, and structural components, for example, must also be further explored to determine commonalities and differences. A similar assessment also needs to be made for non-spatial attributes. A number of full scale implementations will need to be made to accurately assess the efficiency and functionality of the resulting model.

4.2 Other Models

This section outlines additional research that may be necessary to assess the value of models other than the Building Systems Model. These models may have certain uses in the AEC industry and some efforts should focus on assessing their applicability in the AEC domain. These models include the Ship Structures Model and the Ship Distribution Systems Model.

4.2.1 Ship Structures Model

One issue to investigate is the possibility of introducing a building's elements into the Ship Structures Model to assess the model's representational power in the building domain. Initial sentiment about this process is that the model is not sufficiently capable of representing a building because of the differing aspects and elements that are dealt with in a ship. This opinion should be further analyzed because the model may contain valuable aspects even if the model as a whole isn't directly applicable.

4.2.2 Ship Distribution Systems Model

Though the Ship Structures Model apparently possesses limited modeling accuracy for building structures, the Ship Distribution Systems Model may be a beneficial tool in describing the HVAC, electrical, and piping systems of a building. Investigation of these systems may show that the ship model can be used to represent those respective building systems accurately. If this is the case, then modelers would possess a model comparative to the Building Systems Model (excluding the structural system). This comparison could result in improvements of the Building Systems Model, or building systems could possibly be modeled using the Ship model.

4.2.2.1 Ship Model Integration

As one would like to integrate all building systems into the Building Systems Model, a study of the integration of the two ship models could provide insightful information. In addition, if a building's systems can be accurately modeled using the ship models, an integrated ship model would provide an alternative to allow for comparisons and developments of the Building Systems Model.

4.3 Model Specifications and Graphical Representations

The focus of our discussion has been on model development. This section suggests that additional research must be done in the conveyance of the model to users. Just as project specifications and working drawings convey the conceptual representation of a constructed facility, a similar means of conceptual conveyance is necessary for a building systems model. Both written specifications and graphical representations have been developed to do so. These are discussed below.

It is possible to suggest that the specifications and representations themselves can be enhanced. However, we are suggesting that the development of these textual and graphical representations be done by others. Here we acknowledge the need to translate between these common tools and other tools as described below. Research in the following areas could lead to a truly applicable, standardized modeling procedure.

4.3.1 NIAM and IDEF

The present Building Systems Model uses NIAM diagrams to graphically represent the elements of the model. In addition, future models may incorporate IDEF: One research issue is how to most efficiently and accurately transform the information from the model's diagrams to relational databases (or other applications). A first effort may be to manually restructure the NIAM or IDEF diagrams into suitable formats for structuring a database schema. In an attempt to use standards put forth by PDES/STEP, restructuring of the diagrams would be done using EXPRESS, translating the EXPRESS to SQL text, and then entering the information into a relational database. The goal of this research would be to develop a method to automate the transformation process.

4.3.2 EXPRESS

To transfer the model data from NIAM or IDEF models to databases, EXPRESS is to be used, allowing for the universal standardization of information specification. However, few automated ways exists to convert EXPRESS code into a database structure. There exist EXPRESS-to-SQL and EXPRESS-to-Smalltalk translators. Perhaps a universal translator could be developed. If not, other translators should be developed to assist in EXPRESS conversion to many, if not all, possible databases.

4.4 Model Evaluation and Validation Measures

There exists no tangible sets of measures to evaluate model quality. Model development has no "measuring sticks" with which to compare. Therefore, there is no base of knowledge for model development or improvement. Studies of models and modeling schemes would lead to a base measure of model requirements and attributes that would be necessary for a certain minimum model efficiency. Further research could lead to an outline of model improvements. If research could form evaluation measures, model development could follow paths toward improved evolution.

5 Conclusions

The aforementioned research has presented two major avenues of future research which require consideration.

- **Further AEC PDES/STEP efforts.** The standardization efforts, both internationally and in the United States, must continue with renewed support from the AEC building industry. If progress is to be witnessed in this industry, standardization of data representation and transfer is the crucial next step. As it has been witnessed in other industries, this progress is possible; but only through support by the building industry. Presently, that support is lacking in the U.S. The building industry should step forward and take part so that international standards are not dictated by foreign countries through default.

- **Commitment to AEC model development.** Even with the support of industry, some organization must develop the draft standard AEC building model. A joint commitment must be put forth by industry itself, PDES/STEP, and academia. Without a full commitment, an integrated effort will not evolve; and a model will not be developed. The building model is the "missing link" in the PDES/STEP standardization effort. If a building model is developed, the gap in building model standardization efforts can be filled, resulting in the basis for a fully integrated design process being made available to the AEC building industry.

The solidification of a model for AEC building systems will provide a foundation for discourse and design/construction data exchange throughout the industry. This will lead to the development of standardized databases and enhance data exchange. Furthermore, it will enhance the integration among commercially developed CAD/CAE/CAM software products.

Clearly, the commercial applications of the research proposed herein are indirect. The proposed research itself will not result in the development of a commercial product, but it will establish a standard for commercial developments by industry participants in the computing and computational aspects of the AEC industry.

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