Life Cycle Requirements for Building Product Models

CHARLES M EASTMAN*

ABSTRACT

If progress is to be made in developing integrated computer models for representing buildings, then a careful understanding of the uses and criteria regarding building information over the complete life cycle is needed. This paper sets forth the expected use and general criteria regarding the phases of [redacted]lanning, construction and [redacted] Some generalizations of these criteria are identified that have implications for the [redacted]t.

Key Words
building product models; lifecycle; computer-aided design

INTRODUCTION

A goal of current research is to develop one or more computer representations of building information that can supplant all the current documentation now residing on paper. This information ranges from drawings, written specifications, spreadsheets and analysis datasets to facility management data. This computer model, in various forms, is expected to represent the building product throughout its lifetime, evolving as the building evolves, always representing its essential properties for use in design or re-design, for managing its operation, and eventually, for planning its demolition. These "cradle to grave" goals for building models are the expressed goals for the ISO STEP activities (Smith and Rinaudat, 1988).

An electronic building model is expected to resolve the many existing issues of data availability and integration, during design and later throughout the building's life cycle. The potential benefits of such models include improved information availability, supporting an open-ended set of further analyses and applications, reducing the space and time to store and transmit information, and at the same to expand the base of information.

Not only will such models depict the physical description of individual buildings, they will also provide the basis for organizing most architectural and construction knowledge. For example, the component parts and the rules for different methods of construction, knowledge about the functionality of different space uses, and methods for checking for rain or moisture leakage in construction details, will all be represented eventually in a form easily

* *Professor, Graduate School of Architecture and Urban Planning, University of California, Los Angeles, CA 90024, USA.*

applied to and integrated with future building models. [redacted]. Taken in this light, the issues associated with building models are larger than just the issues of how to integrate today's applications, or how to represent some building part so that it can be fabricated.

We have only begun moving down the path towards the goal of developing building models that can achieve any of these ends. Much careful planning and scoping of issues are needed so that goals can be mapped onto the various functional parts within the model definition. Important issues of this type are being addressed within the STEP committee activities (Kramer et al, 1992), (Danner, 1988). However, much more is required. It is important to more carefully study the [redacted] how they are composed and maintained and how they will support a variety of applications and uses, some of which cannot be anticipated.

In this paper, I attempt a small step in further structuring the issues associated with building models. Building models can be classified over several dimensions. One dimension addresses the different stages of the building life cycle. Another addresses support for multiple participants or actors within the building process within any stage in the life cycle. In another paper I reviewed the vertical requirements during the design stage (Fereshetian et al, 1991). Here, I consider the horizontal requirements over the building life cycle. The different stages of the building product life cycle have been articulated previously, for example by Geilingh (1988). The different uses and goals for a building model vary greatly over these stages. At the same time, most work in building models has not been explicit about the stage of model. Here, I attempt to articulate and distinguish the different goals, based on the life cycle of use. Given these requirements, we can better discriminate the overall architecture of a building product model.

General Concepts About Building Model Life Cycle

During the early stages of its life, a building model has the role of supporting decision making, regarding alternative plans or designs. For other stages, its role is mostly one of monitoring and management of an existing facility. Thus the stages of a building model introduce different fundamental roles.

When data is used to investigate alternative decisions, representation and management of the alternatives require certain capabilities:

1. [redacted]: keeps track of changes as they are made and guarantees use of a consistent set of data. It also allows the representation and management of alternative designs, incorporating varied assumptions (Katz, 1990).

[redacted] building models carry within their data a number of relationships that a complete model must satisfy. Some involve relations within the data itself, regarding consistency of the representation. Other relations involve the semantics of the domain of the model; including sizes of components, types ofjoining, relations defined by different kinds of physical performance, construction practices and possibly aesthetics. These relations are not resolved immediately, but may be defined at various times and resolved later. Some actions may invalidate a relation that was satisfied earlier. Thus means need to be provided to manage the status of these relations. A detailed discussion of these issues have been laid out in (Eastman and Kutay, 1991). Later, the building exists and it is assumed that all the semantic relations regarding it have been satisfied.

[redacted] of operations: the purpose of a building model is to support wide access for a variety of uses. However, during some stages of a model's life, there are many actors using the model and modifying it in parallel. In other stages, there may be many people accessing the data, but only one group modifying it. When multiple modifications of the model need to be made in parallel, concurrency control methods are needed to maintain model consistency (Barghanti and Kaiser, 1991).

[redacted] for many stages of a building model's life, its structure is relatively static, changing only infrequently. During the early stages, the structure of the model changes as design decisions are made: for example, regarding the type of structure and mechanical system used. Issues of model extensibility must be addressed in those stages when it is dynamically evolving (Eastman, 1981), (Banerjee et al, 1987).

These four different dimensions of a building product model provide one basis for assessing its different uses and roles over its lifetime.

Another basis for considering building models is the type of representation involved. A building model, during each stage of its life, involves both a [redacted] description of the building and also a [redacted]al description. These are two distinct kinds of information and knowledge. The *state description* is what is normally defined in a design, the geometry and material properties. It defines the building at some "state", just after construction. But most material properties and geometrical decisions, are based on building behavior. The [redacted] of a building is its interaction with its surroundings. Thus behavior includes energy consumption and effective comfort. It includes the elevator response algorithms, the stress within the structure, due to gravity, wind loads, earthquakes, etc and possibly the behavior of the people and things within the building; for example, the behavior of pedestrian and cargo flow within an airport. Behavioral information is important during all stages of a building's life, but the kinds of behavior of interest varies. This is another important dimension by which the stages of a building model can be assessed.

There are different ways to define building behavior. It is typically defined procedurally. The concept of building behavior is parallel to and may be represented by abstract data types, as implemented in various object oriented systems (Kim and Lochovsky, 1989). However, the definition of such objects, the need to structure building behavior at different levels of abstraction, and how to deal with different behaviors over the building's lifetime (including adding new behaviors) is a set of open issues requiring serious research.

For this paper, I have adopted the building life cycle laid out by Geilingh (1988). Geilingh distinguishes building product models into six life cycle stages, listing both a stage and its interpretation:

1 as required	functional unit	feasibility study
2 as designed	technical solution	design
3 as planned	planned physical unit	construction planning
4 as built	physical unit	construction
5 as used/as maintained	operational unit	operation
6 as demolished	demolished unit	demolition planning

Geilingh focuses on the transition points between stages, such as the transition between feasibility studies and the design stage. I am interested in the requirements within each of these stages as well. It is within these stages where information sharing issues are greatest. On the right, I identify the previous stages for each transition defined by Geilingh.

Building Feasibility (Functional Unit)

The initial stage is the generator of the building model and thus influences the design and later stages. This stage also plans and sets goals, at a general level, for all the other stages. This stage is formalized to the degree that the building client intends to control the result that will be gained. It is primarily quantitative in form, representing the building in a completely abstract, that is, non-geometric manner. At the most direct level, this stage defines the purposes of the building project and assesses if the resources are appropriately matched with the project scope.

The behavior of interest of the building model during this stage is the balance of its cost in resources and time and its general support for some quantified level of human function. Costs and time estimates are often complex to make, involving the costs of design, construction and possibly operation. This phase balances these costs with the function of the building. Function is defined in terms of the amount of space provided, the levels of environmental support, and other less tangible considerations, involving image and ambiance of a building.

Models have been commercially developed in the U.S., based on expert system techniques, that will project typical design times, bidding and approval times, construction schedules, materials and labor costs, financing costs throughout construction, for large scale projects, such as hospitals and schools (SARA Systems, n.d.). These programs incorporate extensive databases regarding material costs, typical construction times for different units of building, and a variety of time estimates for design work, bidding, procurement, and so forth. We tend to not consider such information as part of a building model, but at the feasibility stage, they define the context for certain behaviors of great significance for the financial and functional success of the building project.

APPLICATIONS	TYPE OF DATA	BEHAVIOR
total units, rental or usable space in terms of functional service provided	building quantities and qualities	units of function
project schedules, from conception to operation other time-based models of planning, design and construction	time	building process times
project costs: design, construction, license and bonds	money	building process costs
operating costs: amortization, utility and other operating costs	money	building operating costs
cash flows	money	money per unit time
market absorption models	building quantities over time	functional units per unit time
material and labor quantity availability	units of labor and materials over time	constr. units per unit time

Figure 1. Applications and Data to be Supported During the Building Feasibility Stage

Very large projects tax the ability to produce or acquire particular materials. Thus for special projects, material quantities may be estimated at this stage, not so much to determine their cost, but rather their availability from regular sources.

The planning done at this stage of the building model often involves developing many different feasibility models and comparing them in different dimensions. Thus it is important at this stage to support the representation of multiple model versions. New criteria and relations are added or subtracted, requiring extensibility. As relations are added and deleted, some level of integrity management is needed.

The output of this stage is a building model judged feasible if realized within the behavior parameters estimated. These parameters include units of construction, giving the size of the project in terms of units, floor area, number of seats, or other appropriate unit. It will also include estimates of the cost, in terms of money, other resources, and possibly time.

A listing of the possible applications to be supported and the range of behaviors of interest during this stage, is shown in Figure 1. This and later figures list different classes of application and the general types of information they require. The applications shown are generally made by a small group of people. Concurrency control is not a significant issue, though version management is.

Many of the functional requirements used later in the design, and many of the cost and time figures associated with resources used as targets throughout the building's life cycle, are derived during this stage. It is valuable to be able to re-construct the assumptions and numerical values upon which these goals were derived, in assessing variations that will arise later. It usually is not considered part of a building model to include: current interest rates, the efficiency of lending agencies and building societies, as part of the contents of a building model. But to the degree that such figures are the basis for later estimates of costs and time, they should be included in the model at this stage.

Building Design (Technical Solution)

Design involves the translation of functional criteria (behavior) developed in the feasibility models into detail enough descriptions of the building project to allow fabrication and process planning. Design also involves assessing that the facility will achieve its intended functions. Because of the scale and complexity of this task, complex procedures have evolved over time to achieve it.

Abstractions

It is impossible to immediately move, in design, from a large functional description for a building project to the size of piping and concrete reinforcing. [redacted] enough to span such a breadth of issues. Design involves making such transitions incrementally. It may begin with a general definition of the overall structure at a high level, and with an articulation of prescribed parts. These are then both articulated at ever greater levels of detail, and logically linked, until the needed level of detail is achieved and the various partial descriptions are logically consistent. In information modeling terms, the design is defined as a variety of *abstractions*, where each abstraction is a partial description of the final building definition. The notion of abstraction is well developed in information and database theory (Smith and Smith, 1977). Each abstraction level allows checking and assessment as to the appropriateness of the design at that level in comparison to other levels. Variations are often made within each level of abstraction until consistency with some other abstractions has been achieved.

The intermediate abstractions used in building design vary greatly. Some abstractions, such as a rough spatial layout (often called a bubble diagram) are useful for all building types. Others, such as critical sections and sightlines, are used only in auditoriums and stadiums. Some abstractions may be in terms of general physical elements, such as "wall", "roof" or "slab". Alternatively, a building may be defined initially in terms of more functional abstractions, such as "visual barrier", "security area", or "heat source". The different abstractions are used for many different reasons: to achieve particular kinds of functional integration, to support particular kinds of evaluations or analyses, or for stylistic reasons,

As design proceeds, there is a convergence toward the materials used in construction and the space types utilized in different building types. Both the material construction and space types have abstractions for representing them. The support of this duality: of the definition of the constructed elements and also of the spaces that are defined by the constructed elements, is fundamental to a building model (Bjork, 1992), (Eastman and Siabiris, 1992).

As one of the oldest fields of human endeavor, building construction has as resource a rich range of construction technology, ranging from simple concrete frame structures to prestressed shells, to stone or rubble infill to curtain walls. This richness is suggested by the range of applications shown in Figure 2. This richness of design vocabulary applies to the building's structure, to its enclosure system, to its environmental controls and many other functions Different technologies have different components, different rules of composition, and oftentimes, different methods of performance analysis. Each technology subsystem can be articulated with a suite of applications that structures the knowledge about its proper use and evaluation.

The same richness occurs regarding building types and their translation into space types. Building type knowledge can be derived from articulation of the activities enclosed in the type. The articulation of needed spatial and environmental conditions in schools, in hospitals, and housing (Panero and Zelnik, 1979), are examples of how architects and others develop more humane and better performing facilities. Development of computer applications can be expected that address various requirements, good practices and provide means to evaluate conditions within a particular space or building type (Eastman and Siabiris, 1992).

APPLICATIONS	TYPE OF DATA
CAD system, defining geometric layout and all materials	geometry, material properties
analyses of design in terms of: - construction costs - structural safety - energy costs for heating - vibration, other special performance dimensions	 money material performance units
simulation models showing building behavior in terms of: - lighting simulation - acoustic simulation - people and traffic flows - mechanical system operation - elevators and transport systems	 lighting units reverberation time human densities, speed energy units time
automatic design and detailing for: - standard design situations - standard detailing conditions - particular stylistic intentions	 geometry and materials
expert system support, for example advising on - energy efficient design - material and part selection - operating and maintenance issues - construction guidance - water and moisture	 geometry and materials, knowledge base of technical information in various areas
building code evaluation, for such issues as: - fire safety - structural safety - earthquake safety - access for handicapped - habitability, fresh air and light	 geometry, use data material data, energy and movement
site development, in terms of: - grading - road, walkways, planters and landscaping water and drainage systems - wind simulation	 site contours groundcover soil types wind conditions

Figure 2. Applications and Data to be Supported During the Building Design Stage

Note: A wide range of applications are likely to be aplied at the building design stage. Typical behaviors to be satisfied are shown on the left. Thus a separate column was not used.

This range of combinatorial possibilities means that any single building model will have to be extremely broad and rich, to incorporate the range of knowledge commonly used within the construction industry. New technologies, based on object oriented programming and dynamic object linking, suggest that a modular approach, relying on dynamically linked modules, may be a more practical way to bring together the kinds of information needed for a particular building project (Eastman, Chase and Assal, 1992). Modular software allows piecemeal maintenance and replacement and allows open ended refinement.

Integrity Management

The mapping between various functional goals, expressed in functional requirements and the materials and equipment selected to achieve those levels, are both part of the design building model. The relational mapping between the functional objectives and the material and geometric specification to realize the objectives is carried by the analysis or simulation models used to evaluate the design. The analysis provides a logical relationship between means and ends, it also carries with it various assumptions about how behavior is estimated and computed, that may be questioned later, for example in case of accident or other liability.

Some functional requirements are defined at the outset. Other goals or relations are technical in nature and are defined as design proceeds, for example, certain shear or other structural loading conditions or the heat loads generated by mechanical equipment. Moreover, if relations are tracked, it can occur that they are later satisfied for a period of time, then unsatisfied as changes are being made, then satisfied again, then unsatisfied. Design is not a linear but a converging process. With constant changes, version control is required. Because the different behaviors of interest are often addressed by different people -- structural, mechanical, soils engineers, architectural designers, -- there is need for concurrency control.

Design involves an open-ended set of criteria and considerations. Each consideration or goal involves a particular set of properties of the design, defined at some level of abstraction, and various tests or analyses that provide feedback or assessment on the consideration or goal. With electronic building model data, it is to be expected that the range of such goals and considerations will increase, evolving into an ever more complex information structure, always balancing the costs of information management with the infinitely extensible scope of concerns that can be applied.

As changes are made, it is extremely important to keep track of the various assumptions, technical requirements and goals, so as to monitor which ones are satisfied and which are not. Integrity management is a crucial capability to be incorporated into a building model that supports design. This capability involves keeping track of which evaluations have been made on the current data, rejecting older tests whose input conditions have changed, and checking that the input assumptions of various applications have been satisfied. Integrity management is the only way that a computer can contribute to managing the state of the design as it proceeds.

The result of the end of the design stage is a specification of an acceptable building product, described in normative terms, that is, in terms of nominal dimensions, sample materials, nominal dimensions, etc. All integrity conditions and all behaviors associated with the design have been satisfied (or eliminated). The specification is assumed to be a translation of the functional requirements given at the beginning of the design process into a material and geometric description of the building. The quality and details of that translation should be auditable. The specification defines a small abstract space of buildings, that when an instance within the space is constructed, will satisfy the functional requirements. Associated with the building model is the set of intentions, technical criteria, functional goals that guided the design and the mappings used to relate these issues to the building state description.

Construction Planning (Planned Physical Unit)

The construction planning phase involves the bidding and tendering processes that develop a construction plan and estimates construction costs. In manufacturing, this phase would be called developing a "process plan". In order to develop such a plan, the state specification must be augmented by a process plan, defining units of work and materials required to construct the design. The process description is typically generated by extracting from the state specification the units of materials required. These units are then associated with industry based estimates of the units of labor required to put the related material in place. Many material placement operations involve a precedent sequence of preparatory tasks, such as excavation or formwork, which must be included in the planning. Empirically derived databases are of critical importance here, for dealing with material and labor costs. These units of work and material are the basis for cost estimates and later procurements and scheduling (Adrian, 1973).

The process plan is an entirely new representation of the building project. It identifies construction sequences and assembly operations for each unit of the building. The dominant units are not geometrical, but rather quantities, time, manpower and equipment units. The behavior of interest is work rates, for both people and machines. The process plan cannot be deduced from the design, but rather involves the addition of strategies for construction sequencing, methods of lifting, assembly and so forth. That is, there is a large space of possible process plans. These are searched for the one that best responds to a mixture of goals that typically include: time to completion, construction costs, various risk factors, manpower and equipment constraints. Construction plans typically involve multiple versions and the extensions defining different types of construction methods. Process plans are generated by a small group of people and may or may not require concurrent operations. Process plans are typically represented over a timeline, so as to allow scheduling. These estimates can have associated statistical distributions, resulting in probabilistic values for different variables.

Like other forms of complex problem solving, construction planning involves many rules and conditions that must be satisfied by the final plan. These conditions are likely to be defined as strategies are identified, but only satisfied later. For example, for some on-site operations, a staging area will be required. The staging area may only be designated later. Like design, such conditions involve integrity conditions, which are represented as relations or constraints. Means to support partial integrity during construction planning is required.

This new representation, the process plan, is typically considered separately from the state specification produced during design. However, it can also be considered in a more integrated fashion, as one associating the materials and the units of labor applied to produce some unit of construction with the corresponding units of geometry and material specifications in the design. A time schedule of when that labor is applied can be included. In the future it may become standard to represent the process plan as a cross-linked representation with the building state specification. A few tools supporting such integrated representations are available today (Wickard, Yoshinaga and Yoshida, 1991).

Conceived in this way, it is obvious that the process plan would provide information that is likely to suggest changes in the design, resulting in reduced time or material in producing the building. Such feedback, based on integrated design and construction planning is not often possible today, due to current building procurement practices, but it may become more common in the future, leading to more widespread use of such integrated state-process representations.

During construction planning, the building state description developed during design can be significantly simplified. The performance properties and linkages to behavior are not needed, except to the degree that on-site changes lead to redesign. The design abstractions used by the architect are not relevant to construction. Construction, however, may introduce new abstractions, based on methods of assembly. Thus the grouping of physical elements may require reorganization so as to define the units used in construction.

During this stage, materials and equipment that are to be out sourced (procured from outside vendors) are translated into specific product specifications, which are put out to bid. The decision trading off outsourcing versus local production of units of the construction become interesting when large scale prefabrication is considered. The prefabricated bathroom units in Richard Roger's Hongkong Bank Building is an example that may become more common in the future. Tools for evaluating such trade-offs include the full gamut of design and construction planning tools, used to estimate local costs versus tendered offers.

Detailed investigation of the construction site is carried out at this stage, including borings and geological investigations Temporary construction is planned during this stage, including public safety shields and scaffolding. On certain very large scale projects, certain materials or labor requirements may exceed local production or resource availability. These capacities must be identified and alternative procurement plans developed.

APPLICATIONS	TYPE OF DATA	BEHAVIOR
CAD system description, defining geometric layout and all materials	geometry, material properties	(state descript.)
construction task planning - determination of in-place material quantities - association of units of work w/ units of in place material	material units time and work crews	(state descript.) production rates
detail product specifications		performance specs.
site investigation: - soil and stone boring - geological studies	locational data, soil and geological coding	soil state, absorption, runoff rates stability
temporary construction layout planning: - scaffolding and shoring design - site layout use and scheduling	geometry and material properties, site locations, time	(state descript.) behavior of newly placed material
regional resource planning for large projects - production capacities for local materials - availability of regional labor pools - acquisition plans to deal with shortages	material or work units over time	production capacities

Figure 3. Applications to be Supported During the Construction Planning Stage

In summary, this representation, whether separate from the state description or integrated with it, does not replace the state description, but rather provides a critical augmentation to it. The new representation incorporates decisions based on costs and units of time that are incorporated into the representation. Later, the estimated process plan will be used as the targets for the actual construction.

Construction (Physical Unit)

The Construction stage executes the construction plan. In doing so, it adds additional tools and representations, in order to facilitate the execution of these tasks. This includes further detailing of the process plan, including the assignment of individual work crews and equipment to tasks, adjusting these for weather and other environmental conditions. It includes relating each construction task to the materials and equipment procurement required to complete it.

Off site fabrication requires additional design information, now represented in shop drawings. In the future, we can expect that each subcontractor will receive a state specification (eg design model) of the building component, from which they will define both a detailed fabrication design and a process schedule for their components, for both on- and off- site work. The new information must be integrated into a detailed state description of the overall project, to see that on site work does not interfere with the work of other sub-contractors, and the process plan must be integrated also, to check for crews working in the same area, etc. Thus the transfer of these individual designs and process plans into the master plan, managed by the contractor, will be of critical importance. Since the contractor manages all input, the need for concurrent entry is minimal.

Work crew tasks are facilitated according to the communication of their work, its sequencing, the materials they require, and various quality control issues. It has been proposed that the development of custom work plans for construction crews could result in significant savings (Bjork, 1989).

An aspect of importance during construction is dimensional mapping from the design to the construction site. Surveying and geodesy capabilities, related to the building state description, is typically required. As work proceeds, there is typically requirements to summarize the expenses and percentage completion, for example for partial payments.

The Construction stage supports the transformation of a design specification and construction plan into a realized, singular building. As construction operations are taken, variations typically occur, due to on-site needs or mistakes. These are often not captured or recorded. In some cases they are, in the form of as-built drawings. In our model phasing, this corresponds to the definition of an as-built, as delivered, state description of the building model. Such a model is extremely useful for later stages and is likely to become a regular product of the building process in the future, for at least some types of projects.

APPLICATIONS	TYPE OF DATA	BEHAVIOR
CAD system description, defining geometric layout and all materials	geometry, material properties	(state descript.)
- PO procurement scheduling and tracking - inventory management	POs, dates, actions	purchasing & delivery
detail construction task planning - detail layout planning: - interference checking - assembly simulation	geometry, material properties	work rates
- task breakdown and sequencing	tasks, time	
- heavy equipment leasing and/or scheduling	equipment, time	
- job scheduling, tracking and status reporting		
- work crew assignment	people, time	
surveying and geodesy for construction layout	3-D geometry	(state descript.)
custom drawing for production crews	geometry, process plans, materials	cognitive processes
temporary construction: - scaffolding and shoring	geometry, materials	behavior of unstable materials
as-built documentation	geometry, materials	(state descript.)

Figure 4. Applications to be Supported During the Construction Stage

To summarize, the building construction model must support translation of partial shop design information from a variety of outside sources. The same translation is required for construction scheduling. There is no requirement for the schema for these two types of information to change, however, during construction. Thus the construction schema can be static. Because it supports some amount of detail design, there may be a need for partial integrity and integrity management.

At the end of construction, much of the procedural and state information is no longer regularly used and can be archived. The as-built building model characterizes "what is", with an emphasis on the single description of parts rather than hierarchies of abstractions. The process plan has been executed and no longer relevant to building issues. Thus there is a great reduction of information at the end of this stage.

It should be noted that there is no clear demarcation between the actions taken for Construction Planning and those associated with Construction. The distinction between these two phases is only significant for work that is bid upon after design is complete. There are several other forms of construction organizations where such a distinction is irrelevant, eg design-build and negotiated contracts. It is included here to remain consistent with Geilingh's lifetime model.

Facility Operation (Operational Unit)

What was a building project for architects and contractors is a facility for the operations people. But quite often, a building project is an addition to a campus of buildings or is part of a larger facility, whether it be a hospital, factory or college. In this latter case, a project level description is merged into a more aggregate level description. For building operations, it is this more aggregate description that is operated upon and managed.

As a building is operated, the issues concerning it fall within three general areas:

1. *facilities management*. This aspect, involving the use of the building's space, addresses the allocation and utilization of space as a resource. It reflects the organizational structure in space ownership and changes to space definitions due to changing wall partitions, adding or blocking doors, etc. Space management usually tracks utility and telecommunications distribution and access, the location and inventory of furniture and equipment and other capital investments of the organization. Space management is especially needed in large organizations, such as universities and hospitals (Hales, 1985).

The information needs for space management includes schematic floorplans for space allocation and management, electrical and telecommunications diagrams for tracking changes in these areas, and tabular data showing equipment allocations. Space management programs thus involve simple graphics support (in comparison to CAD) and fairly rich database support. Space management requires a well integrated reporting structure, that captures changes as they occur. Thus they are typically tied into building maintenance and remodeling systems.

In addition to the recording of actions taken, space management systems often involve decision support systems that can generate good or optimal space allocation plans, in terms of communication, material transport or other costs. Other applications evaluate these properties of the layout.

2. *mechanical equipment operation*. Mechanical equipment typically has operating cycles, such as the schedules and algorithms used by elevators over the day, by the air-conditioning system, and by other mechanical equipment installed within the building. This equipment and other parts of the building

consume energy and utilities at some rate usually are metered. This data, along with other data involving building use and outside climatic conditions, provide a basis for assessing the performance of the mechanical equipment, in terms of efficiency and possibly of quality service. Such data is often collected and monitored as a means to better operate the dynamic aspects of the building.

Mechanical equipment requires regular schedules for maintenance. The actual maintenance records need to be recorded against these schedules, providing a record of the reliability of the equipment and of the building operations that service the equipment.

3. *building maintenance and repair.* Fixed parts of a building also receive occasional major maintenance, ranging from window cleaning to stone or wood refinishing, to re-caulking of weatherstripping. Records of such actions are also recorded, so as to better track total building expenses.

With the increasing automation of buildings, ranging from security systems, to mechanical equipment, to solar energy capture, there is increasing opportunities for real-time data capture as part of the control process. Over time, the building model will include large amounts of control system data that can be used to tune building behavior and maintenance. In general, the building model changes serially with time. Version control is a needed capability.

It is apparent form summarizing these uses that building operation involves recording large amounts of tabular data, associated with the physical location of the material, space or equipment. The initial information for this stage model come from the as-built information, which is continuously augmented by building operation and maintenance information. Extensibility will be needed only occasionally, as new forms of reported or data collection are implemented.

In addition to these three uses, there is also the need to archive the more detailed description of the as-built facility, so as to support later remodeling, major maintenance and other major changes to the building fabric. An important criterion for data archiving is *version independence*. The later use of archived data is likely to be on different hardware and different design applications than originally generated the data. The data representation must be stable over long periods (10 years or more) and allow input into systems with quite different capabilities than were used to generate the data. It is likely that special services will emerge to undertake data translation to support such conversion.

The last stage of a building model is in support of demolition. Demolition can be viewed as a special form of remodeling operation, likely to require as-built design information.

APPLICATIONS	TYPE OF DATA	BEHAVIOR
CAD system, defining geometric layout and all materials	geometry, material properties	(state descript.)
facilities management:	space IDs, attributes	space utiliz.
- allocation of space	circulation flows	
- assignment of furniture and other movable items		
- re-assignment of telecommunications, utility services		communic. flows
- changes to interiors and services		activities w/in spaces
maintenance data:	dates and actions taken	
- maintenance records of surfaces, weatherstripping, other fixed aspects of building		behavior of materials
- repair records for equipment		behavior of equip.
- assembly and material failures		behav. of water & air
mechanical equipment operations:	actions, time	
- real-time elect. monitoring of equip.		real-time behavior
- equipment specifications		
- operating instructions		
- recommended maintenance schedule		
layout of electrical, telecommun., other utilities	topology, controls	utility use
- connections and circuits		
archiving for later use in remodeling, re-design or demolition		(state descript.)

Figure 5. Applications to be Supported During the Building Operation Stage

The Architecture of Building Models

The purpose of this review was to outline criteria for building models over each of the stages of a building's lifetime. Much of the literature and research regarding building models considers them generically, undifferentiated as to the issues being addressed within the building life cycle. Others address certain checking or evaluation at the completion point of a building life cycle stage. Of course, this is only appropriate if no changes are required, else the checking or evaluation should be done within the stage. Hopefully, future studies will begin to focus on the different stages and the correspondingly different requirements associated with each.

The review shows that the requirements within a stage are different from those at the end of a stage. The information requirements at the end of a stage are relatively simple and can be supported by standards and translators. We should expect to see standards emerge in this area first.

The standardization of building models to support diverse applications within a stage are summarized in Figure 6. Version control is a requirement for all stages. Extensibility and integrity management is required for those stages before the building is complete. Only a little work has addressed these issues (Eastman, 1992) and much more needs to be done.

Given the range of requirements, and given the range of applications requiring support, it is clear that a single monolithic building model will never be developed that will support the building life cycle spectrum. Even though CAD vendors would like to capture customers by providing this width of applications, the following issues suggest against monolithic solutions:

- huge programs are hard to implement and even harder to maintain. It is unlikely that any one vendor has the resources to cover such a range of applications
- it is likely that multiple applications will be developed for the same operations over the building life cycle. For example, multiple applications for hospital design, or for facilities management. It is highly desirable for markets to exist for such applications, supporting competition and incremental improvements. Separate applications facilitate maintenance and technical improvements.

STAGE	Concurrency	Versions	Integrity Management	Extensibility
Feasibility	--	X	X	X
Design	X	X	X	X
Construction Planning	?	X	X	X
Construction	--	X	?	--
Operation	--	X	--	--
Demolition	--	X	X	--

Figure 6. Comparison of System Architecture Issues Over the Building Model Life Cycle

Note: *Some common dimensions of building a model architecture and their relative importance in different life cycle stages of a building model. An 'X' signifies those having an important role.*

Growing critiques are arising in the software community of the ever larger size of existing applications, such as in CAD and word processing. These programs do not have the level of integration we are talking about yet the maintenance of even these large, mostly monolithic programs, are thought to be a looming software development crisis.

The proposed answer to this crisis, now under development for inclusion in future operating systems, but not yet proven in use, is object oriented systems, with dynamic linking of applications. These capabilities suggest an architecture for CAD systems that can solve the issues of complexity and integration. In the same way that when working in a word processor, one would like to open a figure and build a spreadsheet, using a linked-in spreadsheet program (a scenario not yet available, but will soon be in new applications), one can see the development of a design and the dynamic linking of a curtain wall detailer into a facade object, and using multiple different applications, as needed, by linking them, as needed during design (Eastman, Chase and Assal, 1992). The problems of design integration will be significantly served by new object linking technologies now being explored for introduction within the new generation of operating systems from Taligent, Apple and Microsoft. CAD system developers should be exploring these technologies for their use in developing a new generation of modular systems and where possible advising on their development.

CONCLUSION

In this review, some opportunities for new directions of application development are identified. As building model information becomes readily available throughout the building life cycle, more and more technical information and knowledge will be embedded in applications that interface with it.

What is needed for significant progress in developing production quality building models is a [redacted]. Identification of those areas that are now solvable and those that require new research is needed. Resolution of many of the technical issues is not yet available. At the same time, we must think about how the construction industry will move, step-by-step, from its current position, relying almost exclusively on paper documentation, to the position of fully utilizing building models. Institutions change slowly and the path for their evolution must be clear and the rewards for doing so apparent.

I am pleased to see a growing number of papers appearing in the literature that address various issues in the definition, development and application of building models (Bjork, 1992), (deWaard,1992), (Augenbroe, 1991). At the same time, I have been concerned by the naive push to quick solutions, often arguing for information and building models that would surely fail if one applied them to construction.

Acknowledgement: This work has been supported in part by the National Science Foundation, grant number DDM-8915665. I wish to thank my collaborators in building modeling research, especially Scott Chase and Hisham Assal, for their many valuable comments.

References

Adrian, James, J (1973), *Quantitative Methods in Construction Management*, Elsevier, N.Y.

Augenbroe, G (1991), Integrated Building Performance Evaluation in the Early Design Stages *Proc. 1st Intern. Symposium on Building Systems Automation-Integration*, U. of Wisconsin.

Banerjee, J, W Kim, H Kim and H Korth (1987), Semantics and implementation of schema evolution in object-oriented databases, *Proc. ACM SIGMOD 1987 Annual Conf.* 16:3, pp.311-322.

Barghanti, N and G Kaiser (1991), Concurrenty control in advanced database applications, *ACM Comp. Surveys*, 23:3, pp. 269-318.

Bjork, B C (1989), Basic structure of a proposed building product model, *Computer-Aided Design*, 12:2, pp. 71-78.

Bjork, B C (1992), A conceptual model of spaces, space boundaries and enclosing structures *Automation and Construction*, 1:3, pp. 193-214.

Danner, W (1988), A global model for building product information: analysis of conceptual structures. Center for Building Technology, *Report NBSIR 88-3754*, April, Gaithersburg, Md.

Eastman, C M (1981), Systems facilities for CAD databases, *Proc. 17th Design Auto. Conf.* ACM, pp. 50-56.

Eastman, C M, S Chase and H Assal (1992), System architecture for computer integration of design and construction knowledge, *2nd Annual Building Systems Automation and Integration Conf.* Dallas, TX. (June, 1992).

Eastman, C M and A Kutay (1991), Transaction management in design databases, in D. Sriram, R. Logcher and S. Fukada, *Concurrency in Engineering Data Management*, Springer-Verlag, N.Y.

Eastman, C M (1992), A data model analysis of modularity and extensibility in building databases, *Building and Environ.*, 27:2, pp. 135-148.

Eastman, C and A Siabiris (1992), The incorporation of building type information in the conceptual modeling of buildings, Design and Computation working paper, G.S.A.U.P., University of California at Los Angeles, CA. 90024; in process, *J. Architect. and Planning Res.*

Fereshetian, N and C Eastman (1991), A comparison of information models for product design, *CIB Workshop on the Integrated Building Future*, Eindoven, The Netherlands.

Gielingh, Wim, (1988), General AEC Reference Model (GARM), ISO

TC184/SC4 Document 3.2.2.1 (Draft), (October), TNO-IBBC.

Hales, H L ed. (1985), *Computerized Facility Planning*, Industrial Engineering Management Press, Norcross GA.

Katz, Randy (1990), Toward a unified framework for version modeling in engineering databases, *ACM Comp. Surveys*, 22:4, December, pp. 375-408.

Kim, W and Lochovsky, F (eds) (1989), *Object-oriented Concepts, Databases, and Applications*, Addison-Wesley, Reading, Mass.

Kramer, T R, M Palmer and A B Finney (1992), Issues and Recommendations for a STEP protocol Framework, *NISTIR 4755*, National Institute of Standards and Technology, January 17.

Panero, J and M Zelnik (1979), *Human Dimensions and Interior Space*, Whitney Library of Deisgn, N.Y.

SARA Systems, (n.d.) Specification for SARA Facility Developemnt System, Sara Systems, Inc., Wichata, KS. 67203.

Smith, B and G Rinaudat (1988), Product Data Exchange Specification: First Working Draft, *NISTIR 88-4004*, National Institute of Science and Technology, U.S. Dept. of Commerce.

Smith, J M and D C Smith (1977), Database abstractions: aggregation and generalization, *ACM Trans. Database Sys.* 2:2 (March), pp.105-133.

de Waard, Marcel, Computer Aided Conformance Checking, Ph.D. thesis, Delft University of Technology, 1992.

Wickard, D T, Yoshinaga and N Yoshida (1991), Automation in Construction Planning, *CIB W-78 Conference on Construction Automation*, Tokyo, Japan.

c. 1993, Management of Information Technology for Construction, K. Mathur et al (Eds), World Scientific Publishing Co., Singapore.