Data Modeling Issues in Simulating the Dynamic Processes in Life Cycle Analysis of Buildings

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Abstract

Typically, in simulating the dynamic processes in buildings, data modeling efforts require the modeling of the building geometry, its components and the relationship between these components, as well as the modeling of the process that is under study. For example, in simulating the life cycle of a building, one must simulate the flow of materials as well as the flow of information as part of the process modeling, while a component model is needed to represent the building as an artifact. A third aspect of this modeling effort constitutes the simulation of human intervention, i.e. the decision process that might affect the nature of the building itself as well as the process that acts upon it. For example, the decision to remodel a certain component clearly affects both the component itself as well as the process of aging, when life cycle of buildings is simulated. This paper looks at the data modeling requirements of the simulation of building life cycle within the context of the three parameters mentioned above: data model for buildings; process models and decision models. Temporal issues in data modeling, such as versioning for components, keeping track of data that are related to change and remodeling, and buildings as temporal-spatial entities for life cycle analysis purposes are also addressed.

1 Introduction

The conceptual framework provided by systems thinking has been particularly useful in understanding and modeling of dynamic processes, whether they have to do with phenomena in natural settings or within built environments. While researchers in the sciences have often used this paradigm in research, the use of dynamic modeling as a research methodology has been typically limited to urban planners in studies that have to do with the events in the built environment.

With the increase in research that is dedicated to investigating the impact of buildings on the environment over a building's life cycle, it became apparent that models and methods from environmental and ecological system research (Clarke, et. Al, 2002, Odum and Odum 2000) can be effectively employed to examine the dynamics of building life cycle. Modeling of processes that show variance over a period of time are best studied through systems approach, particularly when complex systems such as buildings with multiple components as well as a multitude of content objects must be considered. Among the earliest examples of modeling of dynamic processes in single buildings have been egress models, particularly those that deal with human behavior in fires (Ozel, 1992). On the other hand, with their finite element analysis approach, many fire and smoke spread models in buildings also model time dependent dynamic processes in single structures. Detailed computer models of dynamic processes can be developed and run as long as the parameters of the phenomenon studied are quantifiable. In this article, the description of buildings as complex systems and the simulation of use and building related processes will be presented within the framework of building life cycle analysis (Kohler 1997). Occasionally parallels with other simulation problems in the built environment will be drawn, with the intention to emphasize similarities as well as differences in the data modeling needs of diverse simulation efforts.

2 Building life cycle

The ideal of duration of a building has been a traditional preoccupation with architecture; Vitrivius considers ”firmitas” as one of the three main qualities of buildings. Even industrial products of the 19th century still considered duration as an important quality of buildings. The idea of the life span or the end of the lifetime of a building is a product of both modernism ideology and the reduction of the time frame due to economic considerations.

Environmental as well as product liability concerns have led to the extension of traditional product design and manufacturing cycles to include dismantling and disposal phases. This is by far not sufficient for buildings that are typically long time artefacts with life times that extend for decades to centuries. The resource consumption (materials, energy) as well as the accumulated costs and impacts due to the use of buildings generally far exceed the initial investment. Even if product models by definition include the life cycle phase, in case of buildings, life cycle models cannot just be an extension of the usual product models. They have to be developed from the bottom up, even if existing components can be integrated with the development process.

The basic idea of a building life cycle model is that the point of reference is "the building as built". Several authors came to the same conclusion earlier (Bjork, 1992) even if it has not been implemented in detail yet. The building as built is the starting point of the use phase and of its induced mass, energy, and monetary flows. This constitutes an ecological view of this modeling effort in contrast to the economic models in which upstream and downstream processes where nature constitutes the limits of the system are generally not taken into consideration. In the ecological models, economic and information flows can be superimposed onto physical flows. (Odum, 1983).

Prior to the use phase, the dominant flows are information (architectural and engineering design), physical (construction), and to some extent monetary flows. Design and planning steps which precede the building as built can be considered as temporary, uncompleted building or as not yet instantiated structures, corresponding to ”virtual” buildings (Levy, 1998). The design process reveals the building (it discovers the underlying structure, it instantiates a general building model). The notion of functional unit, which comes from Life Cycle Analysis (ISO, 1997), is therefore crucial, because as long as a functional unit has not been given a value through a design decision, it can be occupied by a default value (which could be the average value which this functional unit has in a large number of similar buildings, i.e. a prototypical functional unit). This allows the simulation of possible design outcomes which are not exact but which are plausible. The same principle allows the combination of elements that are at different states, i.e. at different degrees of realization in the planning, construction and management of buildings, leading to concepts such as average or default state, designed state, constructed state, refurbished state, etc. These clearly have data modelling implications that must allow multiple versions of a building.

One of the basic assumptions behind this is that buildings of a certain typology (housing, office buildings, hospitals, factory etc.) are much more similar than we generally tend to think. Their cost and environmental impacts during a building’s life-time can already be determined with design brief and performance specifications as well as through the consideration of performance targets and functional units. It also implies that simulation techniques can be used very extensively to verify whether these targets are reached during the ongoing design, planning and use process. Scalability and extensibility of the data model is therefore one of the key characteristics of life cycle models.

The question of how to integrate time into the life cycle models is another crucial point. Buildings can be seen as superimpositions of processes with different time constants from nanoseconds (information, light) to hundreds of years (life span of the building structure). It is important that they all refer to a common scale (Kohler, 1997).

In conclusion, multiple requirements for life cycle models of buildings such as the modelling of the building itself as a spatio-temporal entity, the scalability of the data model, and the simulation of the physical, information and decision flows, need a structured approach that can be best provided by a classical systems approach. This point is further elaborated below.

3 Buildings as systems

In its simplest term, a system is defined as a ”set of parts and their connected relationships” (Odum and Odum, 2000). Thus, a building qualifies as a system. Parts of a system can connect to each other and to the whole not only directly but also indirectly through processes that act upon them. In modeling of systems, outside influences, component parts, flows and relationships between parts must be considered. Thus a minimum of two major modeling efforts must be undertaken when dynamic processes in buildings are simulated:

1. *Building model:* Must include building components as well as their spatial and non-spatial relationships with each other. This model can also include the contents of a given building, whether it is occupants or stored goods, depending on the requirements of the process that is under consideration. The building model is composed of two structurally different parts: The (material) components like walls, pipes, doors and the (immaterial) spaces that are delimited by the components. The components are described by a large number of attributes related both to their material composition (static) and to the process which occur during the life cycle (production, aging, replacement etc.). The composition can be conveniently described in a hierarchical way. Spaces are described through geometrical, topological attributes, i.e. they are positioned in a unique way in a spatial framework. Through use functions they can be related to a large number of attributes both static and dynamic contained in the process model. The relation between components and spaces in building specific models has been elaborated in research (Björk, 1992) and major standardization efforts have been undertaken in recent years (STEP, IFC).

2. *Process model:* This is the modeling of dynamic processes that act upon a building. Dynamic processes not only affect the properties of a building's components over time in some manner, but are also affected by the component properties themselves. Thus, the process model will have to deal with different time parameters of buildings (such as use functions) and building components.

A third area of concern that is often overlooked, but is a major factor in the way dynamic processes take their course in a building is human intervention. Some dynamic processes develop without human intervention whereas others are very much affected by the decisions made by humans, therefore human decision making processes must also be modeled in order to incorporate their impact on the dynamic process that is being simulated.

3. *Decision models:* These capture the human intervention to the processes that are being simulated by putting emphasis on the modeling and simulation of human decision-making processes in the built environment.

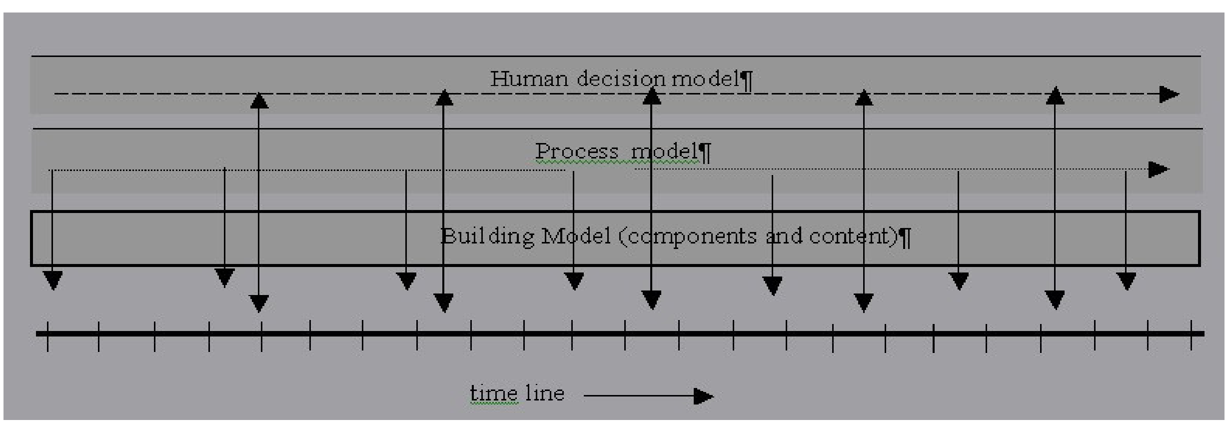

Figure 1. The structure of the simulation of a dynamic process in buildings, including human intervention (decision model).

In life cycle analysis and simulation, the “decision level” is constituted by electronic (information) flows; the “process level” by material flows of all types (mass, energy, persons etc.); and the third level, the components, is constituted by stocks (or sinks). Needless to say, all of these flows are concurrent. (Fig. 1)

Figure 1 presents an integrated view of the structure of a dynamic simulation model for a phenomenon in the built environment. Vertical arrows denote the interaction (the flows in life cycle analysis) that can happen between the *process model* and the *component model* as well as between the *decision model* and the *component model*. On the other hand, human decision-making can also affect the process model, which in turn affects the component model. Therefore, direct and indirect effects of the decision model must be considered (Fig.2).

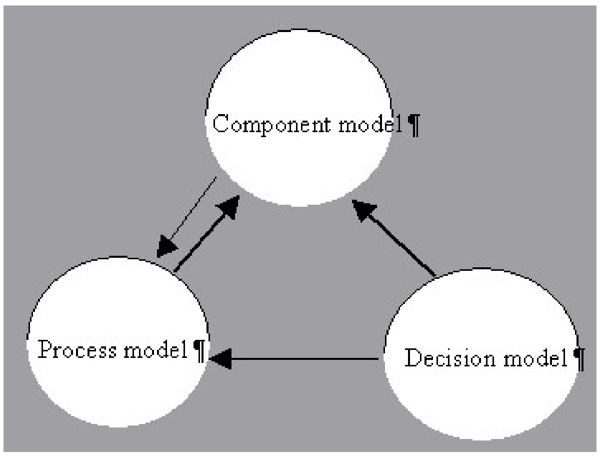

Fig 2 - The interaction of three different models

For example, when modeling human behavior during emergency egress, a simulated person leaving a room can decide to leave the door open, affecting a component of the building directly, while he/she can also choose to fight the fire, thus affect the process, which in turn can affect the component. Similarly, the decision to paint a building component such as a door, controls the aging process, thus affecting the component both directly and indirectly. Not only will the door now have a new color, but will also age differently due to the protection afforded by the paint. This constitutes a human decision that affects both the process and the component. Similarly, the decision to remove a burning component during a fire affects both the component model and the process model. These discussions also set the stage for developing a data model that will support computer simulation of dynamic processes in buildings.

4 Data modeling issues

The question of how to model a system with literally thousands of components, as it is required for buildings, is a major concern that requires detailed attention. Models are typically abstractions of a real world object or phenomenon, which by definition requires the simplification of the issue modeled by selectively including some features while consciously leaving others out. Obviously, what is included and what is not included completely depends on the purpose of the modeling effort that is undertaken. In the software industry that addresses the information management needs of the architectural/engineering/ construction world, there have been numerous efforts to standardize the data modeling of buildings due to concerns for interoperability (STEP, IFC (Industry Foundation Classes) of the IAI - (Industry Alliance for interoperability), etc.). While some researchers have advocated having a single central data repository that can meet the data needs of multiple constituents, others have questioned the practicality of such an approach and have advocated more of an incremental system where each application develop only the parts it needs while allowing other applications to interact with the basic model through a transparent data structure.

Considering the variety of simulation efforts that can be undertaken regarding buildings, the latter approach seems to provide a more feasible structure for data modeling. A scalable and transparent building definition that can be expanded based on the data requirements of the simulation developed is not only practical but also essential due to the fact that data may not be available at all levels of granularity. Furthermore, data modeling of a building at a fine level granularity may not be necessary for the type of simulation effort that is undertaken.

A case in point is the difference between simulation modeling of egress behavior of people in buildings as opposed to simulation modeling of life cycle of a building. In the former, all that is needed is the definition of the basic spatial organization of the building as well as the definition of exits and window openings at a very rudimentary level. For example, the type of glazing for a window is not as important in this simulation effort. On the other hand, for life cycle analysis of buildings, a very detailed component based definition is needed, while, unlike egress modeling, spatial organization is only a secondary concern. Furthermore, each individual component must be painstakingly matched with exact materials and production/manufacturing techniques so that mass and energy flow contribution of each component can be included in the final calculations for life cycle analysis. Therefore, the latter is a much more data entry intensive data modeling effort, while a greater level of abstraction and simplification is possible in egress simulation. On the other hand, in egress modeling, relating individual components to building spaces (rooms) can be a major challenge.

Therefore, the first step to be undertaken in data modeling is to decide:

a. whether to model spatial organization and component composition separately, or to integrate them into a single model.

b. in case of two modes, how to model the relationship of the components to the spatial organization

c. which different levels of granularity for purposes of simulation can be initially distinguished, and how to add supplementary levels of granularity as the model evolves.

d. the level of data entry needed due to the variations between the components modeled

e. how far must the data model be scalable due to incomplete data values.

There are also other concerns that have to do with the impact of the dynamic process on the building and its components. Expectations of the researcher from the data model of the building will be different depending on the nature of this interaction.

For example, the modeling of circulation of goods, materials or people through a building requires that at any point in time in the simulation, the system must know exactly which specific space is occupied by a given object while also knowing which specific component is interacting with the object. An example of this would be knowing where exactly a person is located in a building as well as which door or window he/she is opening. On the other hand, the simulation of life cycle of buildings requires much more of a global access to all components of a specific type, such as all doors or windows of a certain type, and thus imply data structures that are more amenable to relational database management operations such as set operations and ad hoc queries. This is one of the main reasons why life cycle analysis software such as Legoe (Kohler, 2002; LEGOE, 2000) are based on a relational database model which allow quick ad hoc querying and retrieval of sets of records (for components) as opposed to other data modeling efforts such as pure object oriented databases which are navigational and do not allow ad hoc querying as easily. On the other hand, egress simulation models work fine with object oriented data models since they don't require as much ad hoc querying, and the navigational structure of the model is desirable in finding the relationship between spaces and components.

5 Modeling of space-time systems

In the life cycle analysis of buildings, typical concern has to do with the flow of energy and mass due to initial construction, remodeling and demolition of buildings and their impact on the environment over a given period of time. Therefore, any effort to simulate this process must also incorporate spatial as well temporal data into its structure. Databases that support such simulations must handle time-dependent as well as spatially comprehensive data structures. Many deterministic models in applied environmental sciences end up including a time component in some manner (Godchild et. Al., 1996; Maidment, 1996). Different aspects of spatial-temporal databases are the object of considerable research in the GIS (geographic information systems) field. (DEXA, 1999)

On the other hand, simulation efforts that have to do with processes related to single buildings, such as energy simulation of buildings (Mahdavi, 1996), typically are not concerned with temporal data as it relates to the change in the physical and spatial nature of the building that is under study. These models are based on the assumption that the physical fabric of a building will remain static as the building ages, thus such simulations do not take into account any potential changes in the physicality of the building.

The only simulation model that comes close to the requirement that not only the process model, but also the data model and the decision model must incorporate temporal variables has to do with the emergency egress behavior of people during fires (Ozel, 1992). The BGRAF simulation model is based on the data structure of a CAD system that recognizes major building components such as walls, doors, windows, and staircases, thus provides a mechanism to incorporate properties that change over time. The process model on the other hand is the spread of fire and smoke in the building, which is affected not only by the building configuration, but also by the changes in this configuration over time, such as the opening and closing of the doors. Therefore, the data model must not only include a static representation of the building and its components, but also the change in these components over time. On the other hand, the decision model itself also changes over time, in fact stochastically, since as the events evolve through time, occupant's decisions regarding egress must depend on the nature of the immediate circumstances within the simulated building that is on fire. Thus, temporal variables must be incorporated into all three aspects of the data model: the building/component model, the process model and the decision model.

Similarly, and at a much greater extent, simulation models of the life cycle of buildings must incorporate temporal data into the building/component model, the aging process and the decision model for maintenance, refurbishment and remodeling. In fact, in this case the building/component model must handle a much wider range of components in much greater detail, while the other two models might act upon the building model at the individual component level as well as at the totality of the building level. Therefore, keeping track of temporal data for life cycle analysis of buildings tends to generate much larger data sets and must deal with multiple scales of changes and interactions between components.

In modeling buildings for life cycle analysis purposes, relational database management systems were found to be very effective such as the case for the commercial software LEGOE (LEGOE, 2002) which is based on building specification and building price databases used in practice. The building is described through elements and specifications and calculates in parallel at different levels of granularity and at different moments in the design process, building costs, energy consumption, and a complete life cycle assessment. It was developed through cooperation between several industry partners and the Institut fuer Industrielle Bauproduktion (IFIB) at University of Karlsruhe, Germany. In its current form, a relational database system is used not only to define available construction materials in general and their properties such as cost, mass, energy coefficients, etc., but also to define individual configurations of buildings that utilize these materials. In the effort to relate the data model of Legoe to other life cycle analysis applications, a number of decisions were made:

- Separating the data repository part of the model (construction materials database) from its transaction based section (i.e. the definition of the building itself), since being able to access either of these separately from other applications was a major consideration. Such a separation also allows the implementation of the transactional section, i.e. the building model as an object oriented database, either in pure or in hybrid format.

- In the projects at IFIB, most of the focus has been on residential structures as well as on industrial buildings. Another important issue was that the projects mainly dealt with existing buildings within a historical framework. Therefore, including temporal data was important. Change seen in individual structures and their components over time is an important issue in life cycle analysis.
- Because this change is closely related to human decision-making process, a model for this needed to be developed and implemented. Currently this decision model is rather simplified as a 4 step process:
  a. Initial construction
  b. Small scale remodeling
  c. Major remodeling, typically with change in spatial configuration
  d. Demolishing the building

Other decision models regarding the life cycle of buildings can also be developed. For example, Blanchard and Reppe (1998) include a decision model under the heading "Maintenance and Home Improvement Schedule …" for the two homes for which they have completed life cycle analysis. In this schedule, they list 21 different components (such as interior and exterior walls, floors, siding, etc.) as well as content elements (such as refrigerator, water heater, dishwasher, etc.) (Table 2-4, p. 14). For each of these objects, a time table for maintenance or remodeling is specified in years. Thus, in the simulation of such a decision model, each element must have an associated table that will include the scheduled year(s) for remodeling/refurbishment. For example, exterior painting is scheduled to happen at year 10, 20, 30, 40 based on home life of 50 years in Blanchard et. al's decision model. Whether a scheduled maintenance really happens or not can depend on other circumstances, and can only be modeled based on empirical data. Therefore, the decision model captured by the life cycle computer simulation must allow the flexibility to implement and test different decision models, in order to utilize the predictive power of the software in refurbishment decisions. In short, the decision model should not be built into the code, but be defined by the user in terms of scheduled maintenance and remodeling of components.

On the other hand, the building model must capture the impact of these decisions on the properties of the components and their relationship to each other. A versioning system must be implemented to capture this impact. The data model for a building must not exist without first specifying its time frame, thus a new entity called "space/time structure" must be developed. The initial data in the database for the space/time structure represents the building as it was originally built (as-built model). As the components change over time, additional data sets must be stored. To avoid needless duplication of very large amounts of data, the decision to only keep track of the changes was made.

The change over time can encompass one of the following aspects:

1. Change in the spatial configuration and the geometry of a component. This would typically lead to changes in the mass and energy contribution of the component, thus must trigger recalculation of related properties.
2. Change in any specific property such as the color, the surface texture, etc. May also trigger recalculation of some properties related to life cycle analysis.
3. Partial demolishing of building sections. Will lead to large scale mass and energy loss, thus triggers life cycle recalculation.
4. Change of a building system, such as the heating system that will trigger comprehensive

changes in the energy efficiency of the building, and thus lead to appropriate recalculation.

Handling the change management at ”component” level as well as at ”sub-system” (such as heating system) level is necessary, each with its own unique preconditions for life cycle analysis calculations. At this point, it will be necessary to implement an association table that will hold the object ID for the component that has been changed, the date of the change, and the change ID. The change ID will hold the most current state of the object. For example, a window may be replaced at year 22 after its initial construction. While the original definition of the window will remain in the initial table, the information about its replacement will be stored in another table and the two will be associated with each other through a third table (an association table) that will also store the year the change was made.

6 Summary and future issues

Taking into account dynamic aspects of buildings at different time scales (from decision and design process to the whole life span of buildings) will need a conceptual redefinition of building product models in the form life cycle building-product models. The realization of such models will integrate existing partial models and use different modeling paradigms as well as database management systems.

Simulation of dynamic processes in buildings must capture data regarding large number of components as well as complex relationships between them. While this was referred to as ”building data model” in this paper, the modeling of the dynamic process itself such as fire spread or aging of components was referred to as ”process model”. The need for a decision model was also emphasized since human interaction with the components and intervention in the dynamic process can have direct and indirect ramifications for the process modeled.

For life cycle simulation modeling of buildings, a component based relational data model was developed. On the other hand, the need to develop a flexible maintenance and refurbishment decision model that will capture decisions regarding individual components as well as sub-systems such as a heating system was proposed. This is an essential part of life cycle analysis of buildings, since different refurbishment decisions can lead to different results in life cycle simulation. For this, the need to capture ”change over time” was reiterated, emphasizing a temporal as well as a spatial data set. A relational data model was proposed in capturing this aspect of the data set. The necessity to provide a general explicit decision model in life cycle simulation of buildings also allows the coordination of the model development with ongoing efforts to model distributed cooperation processes and distributed data storage systems. (Mülle et al 2000).

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