Toward the integration of spatial and temporal information for Building Construction

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Abstract: Building construction is a kind of complex process that integrates activities regarding design, materials, personnel and equipments. Information systems that describe building construction need to represent both the spatial information of the building design and the temporal information of construction plan. We classify four levels of integration for spatiotemporal information in building construction. We consider that the classification is important for the guidance of our research for that it distinguishes levels of complexity and applicability of data models that integrates spatiotemporal information. A prototype system is developed and tested for providing us a means to gain more insights to the problem.

1. INTRODUCTION

Many construction projects follow the conventional designer/constructor sequence, in which the owner employs designers to prepare drawings and specifications for the constructor. Traditionally, in the design phase of a project the designer should not communicate with potential contractors to avoid collusion or conflict of interest. One of the major disadvantages of such designer/constructor sequence is the failure to revise design early enough to reduce construction time and cost. Decisions made at the beginning stages of a project life cycle have far greater influence than those made at later stages, as shown schematically in figure 1. Therefore, it is important that decision makers should obtain the expertise of professionals to provide adequate planning and feasibility studies for design development and construction planning in early stages.

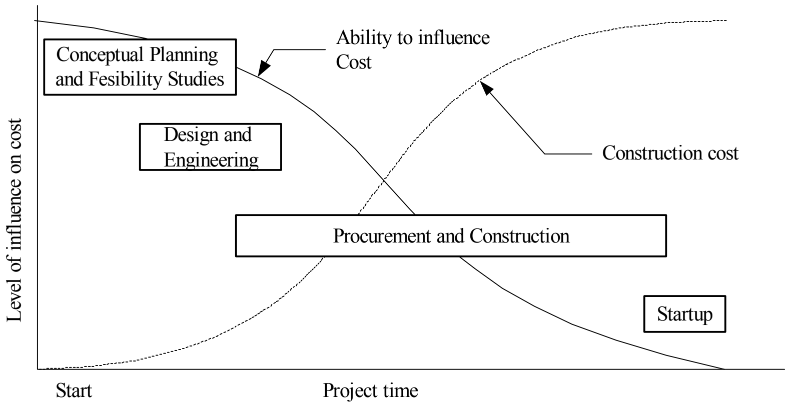

Figure 1. Ability to influence construction cost over time (redrew after Hendrickson, 1989)

Designers are concerned with the spatial status of the building that is to be built, while constructors emphasize on the timing and process of the construction. Drawing and specifications are the basic means of expressing the spatial status of the building. Powerful tools based on information technology have been developed to assist the manipulation and the integration of drawings and specification documents. The most often used representations of temporal information regarding construction processes are networks and charts. Computer applications for construction management have been made available since decades ago. However, what remains unavailable is the link between design and construction, which until now requires engineers to manually analyse the spatial and temporal information of the project in the process of design and construction planning.

The separation of spatial and temporal information is necessary and effective in regarding to the ease of manipulation and human comprehension, as well as for the application of conventional data processing techniques. Information technology has great advances both in terms of modelling systems that describe spatial information, as well as project management systems that manage the temporal information of planning and scheduling. Efforts heading for the integration of spatiotemporal information can also be found in previous works such as 4D CAD systems [Retik, Warszawski and Banai, 1994] [Mey and Heide, 1997][McKinney and Fisher, 1998], which add temporal attributes into building elements to describe the construction process of a building, and temporal GIS systems [Story and Worboys, 1995][Langran, 1993][Al-Taha, and Barrera, 1990], which consider the dynamic changes of geographic environments along the axis of time.

This paper describes our efforts in putting together concepts and techniques in 4D CAD and in temporal GIS systems to define the scope and the structure of an integrated environment that would assist decision-making for the design and planning of a construction project, emphasizing the representation and analysis on relations between design and construction. More specifically, the focus of discussion is on the data model that enables the representation and the analysis of the interrelationships between the spatial, declarative information defined in drawings, and the temporal, procedural information that are consisted in construction plan and schedule. We propose that the integration of spatiotemporal information would be useful and feasible for supporting designers, project managers, and construction planners in the designing and planning of construction projects. A prototype that links a design modelling system, a database management system and a project management system has been developed and evaluated. With further development, the proposed model might as well extend its applicability into the construction stage of the project.

2. SPATIOTEMPORAL INFORMATION

Designers work on spatial specification of a project with drawings, models and other documents to define the geometry, the material and the structure of the design that is to be constructed. Constructors use networks and bar charts to represent construction processes and schedule, which constitute the temporal aspects of the project. The representations of spatial and temporal information in a project are different and separated, yet the relation between the design to be constructed and the process to construct is important. A good project management would rely on the ability to integrate and analyse both spatial and temporal information of the project to assist decision-making in design and construction plan. It is expected that with good management, a design with required performance would be constructed in a reasonable process, spending minimal cost and time. Information in a project can be classified into the three categories, which are design, process, and cost. The diagram in figure 2 indicates that the three categories are closely interacting. Design is defined mainly in spatial information; process is defined with temporal information, whereas cost is related to both temporal and spatial aspects of the project.

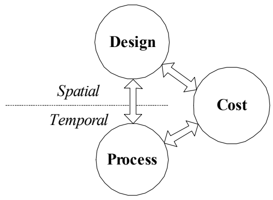

Figure 2. Categories of information in a construction project

Table 1 describes the contents of spatial information and temporal information in a construction project. Spatial information includes position and dimension; together with other attributes such as material and function define the spatial status of design components. A design can be regarded as a composition of primitive objects, each of which relates to others in some specific ways. Temporal information describes temporal aspects such as time and duration of activities, which are basic components that define construction processes. An activity may relate to other activities in regarding to procedural dependency, the use of equipments, materials, personnel and other resources. Spatial information may relate to temporal information in various ways. For example, a project may be divided into several phases of development. Different parts of the design might be in different stages in the life cycle of the project at a given time. Two construction activities may have spatial conflicts regarding working areas or spatial constraints, which are difficult to express in terms of process network and construction schedule. The use of equipment might be restricted by the spatial status of the site at some intermediate stages of the construction. Furthermore, the change of design might result in the change of form, quantity and material that may generate inconsistency that is difficult to foresee by analysing either design or construction schedule alone.

Table 1. Contents of spatial and temporal information in a construction project

Spatial information	Temporal information
Position	Time
Dimension	Duration
Component	Activity
Spatial relation/topology	Sequence and dependency

2.1 State, event and activity

There are various models for the representation of time and process. In this paper, we use the notion of state, event, and activity as elements to define the temporal aspect in a construction process. A state is a specific set of values that defines the status of one or a set of objects. An event marks a specific position at the time axis for the change of states. An activity consists of a starting event, an ending event and a state that connects the two events. An event occurs at one position in temporal axis. An activity has a duration that is measured by the distance between temporal positions of its starting event and ending event. Therefore an activity would divide the time axis into three parts, which are the period before the activity, the period when the activity is being performed, and the period after it has been completed. Conventionally, with CPM method, a construction process consists of a network of activities, each of which can be related to other activities by sharing its starting or ending event with other activities. The network expresses the temporal sequence of those activities.

2.2 Relations between spatial and temporal information

Spatial information of a building can be expressed as a set of objects, each of which consists of a set of attributes that define the geometric and non-geometric properties of the object. An event of the construction process triggers the change of states of some objects. A design object relates to an activity if its state changes upon the starting and the ending events of the activity. Therefore, the evolution of an object is divided by a relating activity into three states, namely, the pre-activity state, the in-activity state, and the post-activity state. Each object can be related to one or more activities, and each activity can be related to one or more objects. With this definition, the state of an object remains unchanged within the period when a relating activity is in progress, unless there are interferences of other activities.

3. SPATIOTEMPORAL INTEGRATION

We consider four levels of integration of spatiotemporal information. Each level is progressively more difficult yet more powerful than its precedent level according to the order in the following sections.

3.1 Level 1: The recording and presentation of sequential changes of objects over time

This first level of integration for spatial and temporal information is to store the construction sequence in the geometric model, such as the 4D CAD model that can be found in some commercial applications such as

Microstation schedule simulator. It is similar to the undo function, with which a user can trace back and forth a history of operations. Every operation that changes the state of the system is regarded as an event that can be stored, backtracked and replayed according to the temporal sequence. The same mechanism can be used to record and replay events of a construction process to show how the spatial status is changed in an arbitrary stage of the construction. As what is shown in figure 3, every state change of each object in the temple front construction is recorded and linked with related construction activities. The states of objects can be shown graphically in a drawing to represent the spatial status of a given time in the construction process. At this level of integration, an object in the drawing can be associated with events that change its state. For example, objects C1, C2, C3 and C4 are associated with starting and ending events of activity *setup_column* and activity *paint_column*. Underneath is a list of events marked with time of occurrences and related objects.

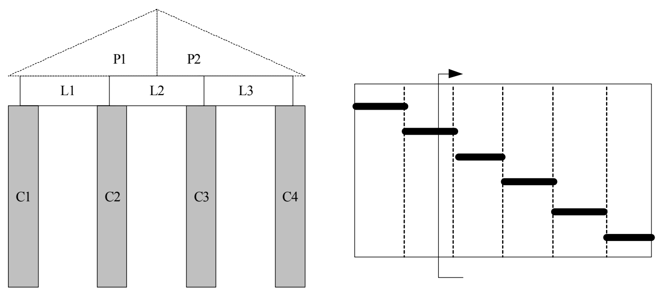

Figure 3. A presentation of the spatial status of a given time in the schedule

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(1 (setup_column starts) C1 C2 C3 C4)
(1 (setup_column ends) C1 C2 C3 C4)
(2 (place_lintel starts) L1 L2 L3)
(2 (place_lintel ends) L1 L2 L3)
(3 (place_pediment starts) P1 P2)
(3 (place_pediment ends) P1 P2)
(4 (paint_pediment starts) p1 p2)
(4 (paint_pediment ends) p1 p2)
(5 (paint_lintel starts) L1 L2 L3)
(5 (paint_lintel ends) L1 L2 L3)
(6 (paint_column starts) C1 C2 C3 C4)
(6 (paint_column ends) C1 C2 C3 C4)
```

3.2 Level 2: The cross analysis of spatial and temporal information in construction process

In the conventional way of representing construction schedule and drawings, analysis that considers both spatial and temporal information requires engineers to manually interpret the relating documents such as construction schedule and drawings. The integration of spatiotemporal information may support automatic analysis of spatiotemporal information to perform the following tasks.

- Analyze the influence on construction schedule when a change of design is requested.
- What activities are active at a given time in a given area?
- Find all occurrences in the construction process where there are more than one active activity in the same area at the same time.
- Show the working areas of activities that would need to use the same kind of equipments.
- Estimate the desirable quantity of some materials in a given working area at a given time.

Using the temple front example shown in figure 3, the system would be able to answer questions such as,

1. What is the total weight that has to be lifted in activity *place_pediment*? And what is the maximum weight and volume of one single piece to be lifted?
2. What are the working areas of *place_pediment* and *place_lintel*? Does it need different installations of weight lifting equipments for the two activities?
3. How much paint do we need in day 5, day 6, and day 7? How do we refine the schedule to level the labor that is needed to paint the temple front?
4. How many workers can most efficiently do the job of *paint_pediment*, considering the amount of work and the size of working area?

And it may assists design decisions regarding how the construction pieces of the temple front can be divided to shorten the construction schedule, and to make the use of equipments and personnel more efficient. Integration at this level requires a CAD model that incorporates much information concerning construction time and cost, such as material and quantities in addition to geometric attributes such as location and shape.

3.3 Level 3: Automatic analysis of spatial relationships between construction activities

The activity network of a construction has to be planed according to the relationship among construction activities for the project. The relationship depends on the use of resources, equipments, spaces, as well as the states of related objects before a specific activity can be started and after it is completed. The integration of spatiotemporal information may enable automatic analysis of the interdependencies of construction activities according to the states of related objects and spatial conflicts in the use of equipments and working areas. Descriptions on initial conditions that are required to activate an activity can facilitate the analysis of spatial relationships between activities. Considering the temple front example, we may refine the construction process. For example, column C1 and C2 has to be set up before L1 can be placed on top of them. The starting event of (place_lintel L1) requires C1 and C2 to be in the post-activity state of (setup_column). The dependencies of activities can be explicitly defined in the desirable relationships of events and states.

```
(starts place_lintel L1):
        ((C1 (post setup_column))(C2 (post setup_column))
        (L1 (pre place_lintel)))
(starts place_lintel L2):
        ((C2 (post setup_column))(C3 (post setup_column))
        (L2 (pre place_lintel)))
(starts place_lintel L3):
        ((C3 (post setup_column))(C4 (post setup_column))
        (L3 (pre place_lintel)))
(starts place_pediment P1):
        ((L1 (post place_lintel))(L2 (post place_lintel))
        (P1 (pre place_pediment)))
(starts place_pediment P2):
        ((L2 (post place_lintel))(L3 (post place_lintel))
        (P2 (pre place_pediment)))
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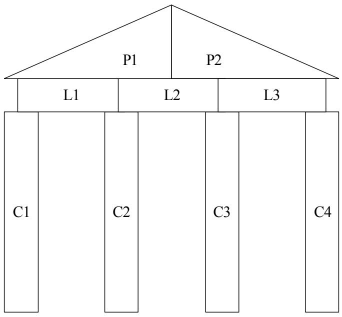
According to the list of dependencies, the process that build the structure of the temple front can be further refined as the network shown in figure 4.



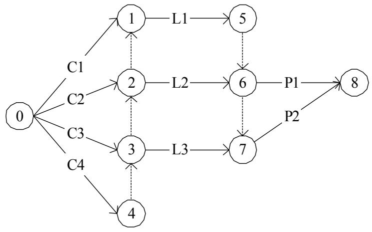


Figure 4. A construction plan for the temple front project

Furthermore, the schedule to carry out the construction plan must consider the use of equipment and labor. Suppose that the installation of the weight-lifting equipment is time consuming, and it is necessary to relocate it if the work is out of its reachable range, spatial analysis may help in the planning of construction schedule. In this case, if there is only one set of weight lifting equipment available, a refined sequence of activities can be C1 C2 L1 C3 L2 P1 C4 L3 P2.

3.4 Level 4: Graphical Simulation of the dynamic process of construction

Construction is a kind of dynamic process interlaced with interactions between personnel, material and equipments. It is not possible to foresee all possible consequences upon unexpected changes in the project. Simulation is a powerful means to supplement analysis to enhance the ability to manage a construction project. An ideal model for construction should provide necessary information to simulate the dynamic process of construction. It should go beyond merely visual animation of the process, but to simulate the execution of the construction plan upon possible situations that might result in unexpected consequences. We expect that a data model that describes the causal relationships between activities and state changes of object would form a computational basis for simulation. In addition, means of estimating how well an activity can be performed under a given condition has to be devised.

4. A PROTOTYPE

Based on the previous discussion regarding integration of spatiotemporal information, we have implemented a system to provide a test base. The framework of the system is shown in figure 5. The system is built upon the coordination among three modules, which are a modelling system (Microstation plus an architectural module called Triforma), a project management system (Microsoft Project) and a relational database management system (Microsoft Access).

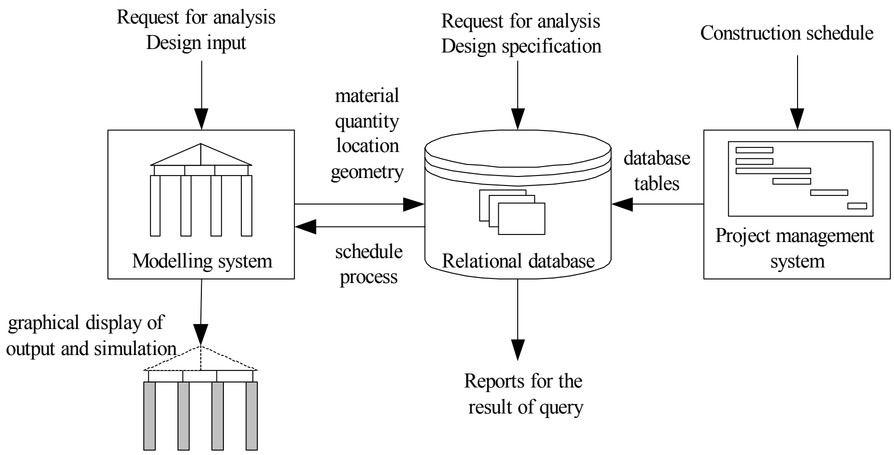


Figure 5. The framework of a prototype system

The modelling system is used as a front end for spatial information to model the building. Programs written in MDL (Microstation Developing Language) are used to provide graphical output, customized user interface, and necessary data processing for the connection to other modules. The project management system is used as a front-end for temporal information to input and to manipulate information regarding construction plan and schedule. The construction schedule is converted into tables and exported to the third module, a relational database, where spatial and temporal information are integrated. Objects in the building model is connected to the relational database using ODBC Data source and the database interface provided by Microstation. The connections between building elements and construction activities, as shown in figure 6 and 7, are made in the modelling system using a customized user interface. In our test case, elements of a 5 storey RC building are drawn as 3D objects in the modelling system (Microstation). Specifications of parts and components that are required in design and construction, such as steel, form, concrete, and finishing are defined by the architectural extension (Triforma) of the modelling system. The construction schedule is input with the project management system (Microsoft project). The schedule is converted into tables and sent to the relational database that is created as an ODBC data source. Links between building elements and construction activities are done manually in the modelling system.

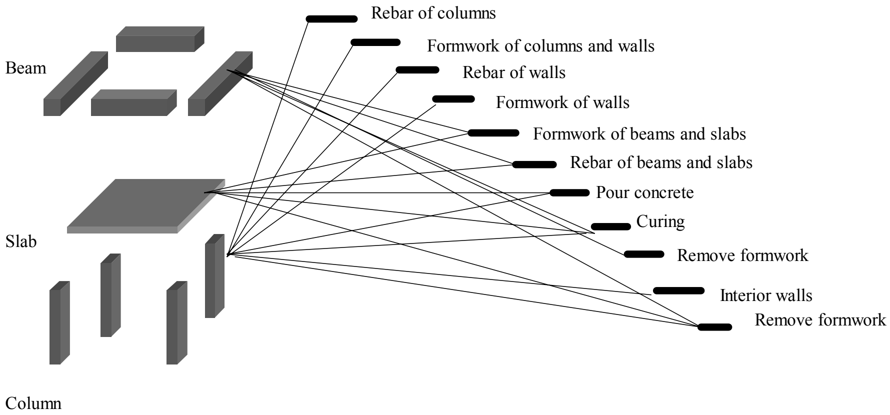


Figure 6. Links between drawing elements and construction activities

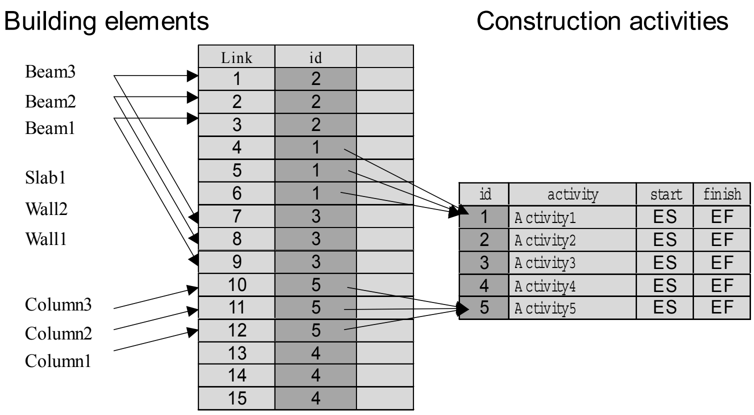


Figure 7. The many-to-many relation between building elements and activities

The analysis of the spatiotemporal information is performed through interactions between the modelling system and the database management system. In the modelling system, a request can be defined by indicating an area, selecting building elements, or none-geometrical data through the interface. The system would combine spatial data with temporal data stored in the database to perform necessary analysis and provide either textual output or graphical output. The system can be used to trace and replay the construction process graphically, as shown in figure 8. The system is also able to perform cross analysis on spatiotemporal information as the level two integration described in section three of this paper. For example, the user may indicate an area and ask what activities would be performed at this place at a given time, and what are the types and quantities of materials and labours will be used? It is potentially capable of calculating all examples described in the second level of integration, although some of them are not implemented. The user can also modify the building model and the system will recalculate the quantity of materials and labour that are needed. Automatic adjustment of schedule would be feasible if combined with a program that estimates the needed duration of construction activities according to the quantities.

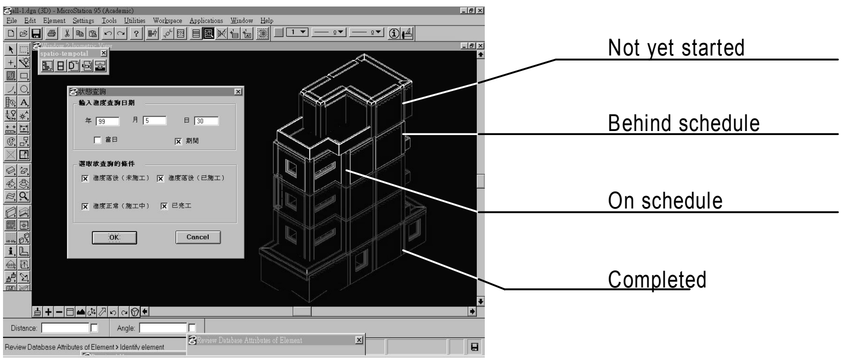


Figure 8. Graphical presentation of construction progress

5. CONCLUSION

The system is tested with a five storey RC building. With evaluation done by design and construction experts, conclusive remarks are made to direct the future development of research. First, the system is powerful, yet not practical in realistic projects. It requires too much work to prepare necessary data regarding the building model and construction process. It also requires tedious work to make links between every building element and its relating construction activities. It inherits some incompatibility regarding automatic calculation of material and cost to the construction profession in

Taiwan, where the system is developed and evaluated. A general opinion is that our future work should be directed toward decision-making support in the early phase of a project. It would be impractical if used for construction management, but could be helpful for design decision-making and construction planning.

Our current work has been heading to three objectives. First, it is important to provide higher levels of abstraction in the design model and construction schedule. In the early phase of a project, decision would be made based on more abstract data and rough estimation, rather than details in design and construction schedule. It has been tested on the integration of construction process with design study of building volume and site plan. Second, links between the building model and construction activities should be done more elegantly. For this purpose, a new module called spatial enquiry engine to select design elements and to provide spatial data is added to the system. The revised structure of the system is shown in figure 9. It is expected that the relation between construction activities and building elements can be pre-defined and stored together with construction plan. The links would be done upon the request of analysis on spatiotemporal information, instead of in the modelling of the building.

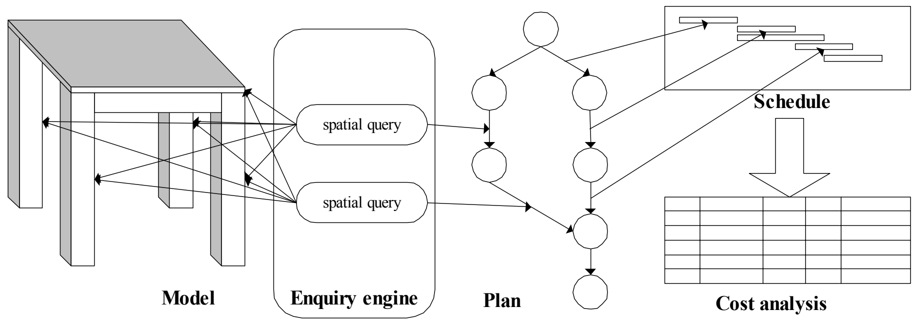


Figure 9. A revised system

Third, a new data model is being developed for the third level of integration, which is automatic analysis of spatial relationships between construction activities. Definitions of the initial state and final state of activities have to be added to the model, and the reasoning process has to be clarified.

6. ACKNOWLEDGEMENT

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