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PROJECT MODELING OF LABOR INPUTS FOR AUTOMATED CONTROL IN BUILDING CONSTRUCTION

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ABSTRACT
Effective control of construction projects requires reliable resource consumption data. Corrective measures can only be taken once the project manager is alerted to deviations. However, manual monitoring and reporting of resource consumption, and of labor in particular, is both expensive and inefficient. A fully automated system for controlling labor inputs is being developed at the Technion – Israel Institute of Technology. The theoretical model is complete and an experimental Global Positioning System (GPS) based data collection system has been built. A computerized Building Project Model (BPM) is a basic requirement for such a system. The BPM must contain data describing not only the physical geometry of the building, the resources active in its execution, and the planned construction activity schedule, but also additional data describing the monitoring results and supporting their automated interpretation. This paper will report on extension of a pre-existing BPM to support the control system. To date, all of the necessary data objects and relationships have been defined and implemented. Data have been collected on the job-site of a reinforced concrete building using the experimental hardware, and have been successfully represented using the extended BPM.

KEYWORDS
Construction Automation, Global Positioning System, Labor, Monitoring, Productivity, Project Control

1. INTRODUCTION

Current project control practice suffers from a number of drawbacks which hamper the ability of management to respond to changes and deviations in project performance. Among the significant problems (Futcher, 2001, Hastak et al. 1996, McCullough, 1997):

- Measurement of job-site performance relies on manual data collection – usually, observation by a supervisor or site engineer, sometimes backed up by timesheets, checklists or worker's clocking in and out. These methods are costly and prone to inaccuracies, and often suffer from lack of support from site management personnel, who do not benefit directly from the effort invested.

- Construction schedules, when updated at all, are usually updated to reflect the dates of activities completed. This allows forward planning, and is therefore considered worthwhile: however, it offers no information at all that could be used to detect deviations from plan as they occur. Schedules of planned activities which become detached from reality also undermine the basis for control (comparing actual and planned performance).
- The frequency of reporting is commonly monthly. This coincides with accounting reports, which include payroll and material invoicing information. As a result, once information is processed at head office, exceptions can only be identified from between two to six weeks after their occurrence.

As a result, the primary use of monitoring in most construction contracting organizations is to improve future performance - commonly through some combination of the following corrective actions: personnel changes; investment in plant and equipment; organizational changes; improving bidding accuracy. While these are worthwhile and necessary pursuits, fully automated monitoring of resource consumption on site can provide greater control of construction projects. Automated monitoring and interpretation of the data in the context of comprehensive on-line project information can enable construction managers to make real-time corrections to equipment and labor allocations and work methods, thus improving performance and correcting deviations as they occur. This paradigm is termed “Automated Project Performance Control. (APPC).”

On-site, real-time automated performance measurement is becoming increasingly feasible as cheaper and more advanced technologies become available (Ciesielski, 2000). However, for monitored data to be of real use to construction managers, it must be interpreted and transformed.
Figure 1 describes, by means of an example, how monitoring can provide data, which must be interpreted, in the context of overall project information, to provide new information about the actual current levels of consumption. The information must then be evaluated in the context of planned levels to identify exceptions, which provide a basis for making recommendations for corrective action. Each arrow in the figure represents a specific processing stage in an Automated Project Performance Control scenario.

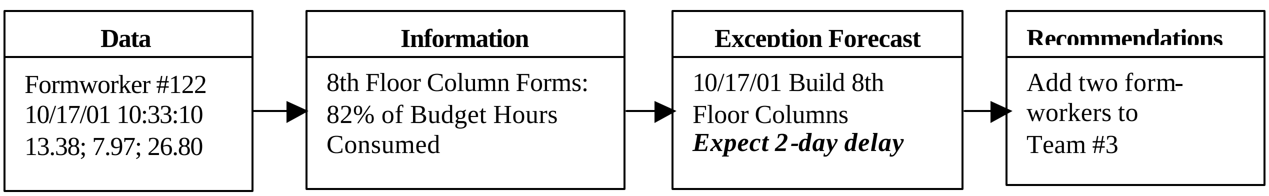

Figure 1: An Example of the Transformation of Monitored Data into Information Useful for Project Control

2. THE AUTOMATED PROJECT PERFORMANCE CONTROL INITIATIVE AT THE TECHNION – ISRAEL INSTITUTE OF TECHNOLOGY

A comprehensive program of research into Automated Project Performance Control has been initiated at the Technion, Israel Institute of Technology (Navon et al. 2001). In addition to specific research projects, an ongoing joint industry-academia forum explores current construction control practice and seeks to identify practical directions for developing the concepts and implementing the technologies of APPC. Current research programs include:

- development of the theoretical models for interpreting monitored data collected from various sources (Navon and Goldschmidt 2001a),
- automated monitoring and interpretation of locations of construction workers and of earthwork equipment using Global Positioning System (GPS) technology (Navon and Goldschmidt 2001b, Navon et al. 2001),
- monitoring of material delivery and consumption,
- interpreting data collected from primary construction lifting equipment,
- exploration and development of the interfaces with other construction information technologies, and with Building Project Models in particular.

Interpretation of monitored data requires access to on-line information on the building product, activities, resources and construction plan. Integration with Building Project Models is therefore central to the APPC concept. This is the focus of the current paper, which describes the development of specific project model classes and relationships to support interpretation and accumulation of worker location data. In the Labor Control Model concept (Navon and Goldschmidt 2001b), worker's locations are recorded and then interpreted using information about the candidate activities the worker may have performed. In an experimental implementation, a GPS receiver was mounted on a construction workers' helmet as he worked on the eighth floor of a reinforced concrete structure. The readings were recorded through time and translated into X,Y and Z coordinates in the local floor coordinate system.

3. PROJECT MODELING TO SUPPORT THE LABOR CONTROL MODEL

3. 1 Building Project Modeling

Information is a key resource generated and used in all construction projects. It describes both the physical constructed product, as designed and as built, and the process activities and resources employed in its design and construction. Building Project Models (BPM) are intended to provide comprehensive sharing and integration of all this information through the project's lifecycle. The concept has its source in other industries, and can be traced to the *product* modeling research efforts which resulted in ISO 10303 'STEP' (STandard for Exchange of Product information) (ISO 1994), which defines formats for communication of product data between all of the participants in the design and delivery process of physical products. Early efforts to define building framework models include the AEC Building Systems Model (Turner 1988), the General AEC Reference Model - GARM (Gielingh 1988) and RATAS (Bjork 1994). The more recent Industry Foundation Class (IFC) models (IAI 2001) incorporate process information together with the product description, and are sometimes termed 'Project Models'. Various aspects of building product modeling are comprehensively presented by Eastman (1999). Project modeling efforts driven by specific construction industry sub groups have begun to have real impact. Exchange and integration of project information in the structural steel industry is becoming increasingly common with the growing use of the CIS/2 version of the CIMSTEEL product model, which has been adopted by the American Institute of Steel Construction (AISC). The North American Precast Concrete Software Consortium (PCSC) is developing integration tools and a data product model for precast concrete buildings (Eastman et al. 2001). Adoption of these technologies in the construction industry makes the assumption of availability of building project models in the near future more reasonable.

3.2 The Need for Information Integration for Project Control

The following discussion details the nature of information required in computer accessible form in order to allow conversion of monitoring data into useful project control information in the Automated Project Performance Control paradigm. Although worker location monitoring is used as an example, the underlying concept of integration with a Building Project Model is equally valid for other forms of automated on-site performance monitoring. A model for interpreting worker location data has been developed (Navon and Goldschmidt 2001b). It is referred to as the 'Labor Control Model' (LCM). The model has two types of data source: and '*as measured*'.

The planned data include the following aspects:

- Complete description of the physical building design (geometry and materials), which may still be subject to design changes and corrections during construction,
- Construction plan (schedule, planned labor inputs, resource assignments), evolving as the project progresses.

The measured data describe the actual performance indicators as monitored automatically. In general, performance indicators in this context may include project progress, labor inputs, material consumption, etc. In the specific case of the LCM, an indirect performance indicator is used - location of each worker in a local building coordinate system, measured at regular time intervals. Figure 2 shows the two input information types with the LCM and the information output.

The first step in each processing cycle of the LCM is to process the product and process (schedule) information to identify the 'pending activities'. These are the construction activities that may be worked on in the current cycle (usually one day): i.e. all those whose predecessors have been completed, or those which have already begun, and excluding those which have been confirmed to have been completed. A set of knowledge rules is processed in order to compile the list. Then, the planned labor rates and the work quantities required to complete each activity are used to calculate the *expected* labor inputs as a basis for comparison.

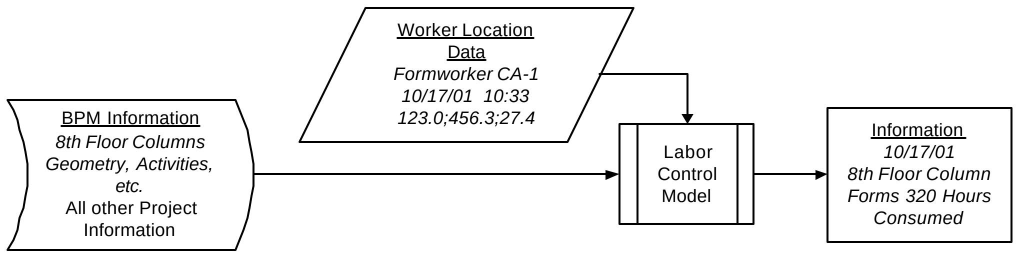

Figure 2: The need for Building Project Model support for the Labor Control Model

In the next step, the monitored data is processed. The locations of the workers, and the time spent at each location, are associated with pending activities. This is done using algorithms and decision rules as detailed in Navon and Goldschmidt (2001b), which rely on identifying the presence of workers within predetermined physical spaces (called 'work envelopes') surrounding building elements. The algorithms also attempt to identify activities that have been completed; their actual durations are calculated on the strength of the amount of time crews spent performing them. The labor rates are computed based on the calculated actual durations and the work quantities determined previously. Actual rates can then be compared to planned rates. The output is of two types: (1) a report of actual labor inputs and rates, and (2) a list of the activities in which labor inputs and rates deviated from their planned values.

The external information required to perform the interpretation described above encompasses all aspects of the construction project: the physical elements and assemblies, the activities, the spaces and the resources required. The information must be correlated - product, activity and space information must be compatible, i.e. have the same granularity at different levels of detail. It must also be accessible in a form directly usable by the LCM, and the results of its processing must be returned as new project information. A Building Project Model can fully support these information integration needs, since it can encompass all of the project information, and can accumulate the newly generated information as well, exposing it for future use.

3.3 The Experimental Project Model Employed – Building Project data Model (BPdM)

The Building Project data Model (BPdM), originally developed for the Automated Building System (ABS) (Sacks and Warszawski, 1997), was used for this research. It was selected for the following reasons:

- The model has activities at three levels of detail, including basic activities, which are stored at a level of detail most appropriate for rule processing and reporting as envisaged for APPC (Navon and Goldschmidt 2001b). They can also be generated automatically from the activities and the work assemblies using ABS routines).
- The model integrates space, product, activity and resource (i.e. process) information in one model. All of the information noted above can be carried.
- Additional classes for work envelopes and accumulating monitoring results can be added easily. The model can be readily adapted due to the availability and accessibility of the AutoLisp++ tools (Sacks 1998), with which the base BPdM was built. These include a graphic schema editor, an instance browser, an object-oriented LISP interpreter and a rule-processing module.

The physical, geometric and organizational aspects of the project monitored in the experimental work were loaded directly into the building project model using scripts (no model of this kind was used by the buildings' designers or contractors).

3.4 Class and Relationship Definitions to Support Interpretation of Worker Locations

The LCM requires entirely new conceptual data object types for its operation. Defining a minimum number of these new object classes, and linking them directly to the Building Project Model core through inheritance and aggregation relationships (directly within the schema of the model), is considered the optimum way to achieve maximum integration of the labor control Modules in the construction information process.

Figure 3 shows a section of the schema with existing Building Project data Model classes, new classes required for the location interpretation phase, and the relationships between them. The 'Space', 'B
classes are defined in the BPdM itself. Each is part of one of the three main axes of information in the model, representing spatial, product and organizational aspects of the project (more detail can be found in Sacks and Warszawski, 1997). The root of the new classes is the abstract 'Basic Work Envelope'. It defines the volume in space in which a worker is assumed to be present when performing a specific activity. The shape and dimensions of a generic work envelope are dependent on the nature the work being performed and the construction method employed, which can be accessed through the 'Basic Activity'.

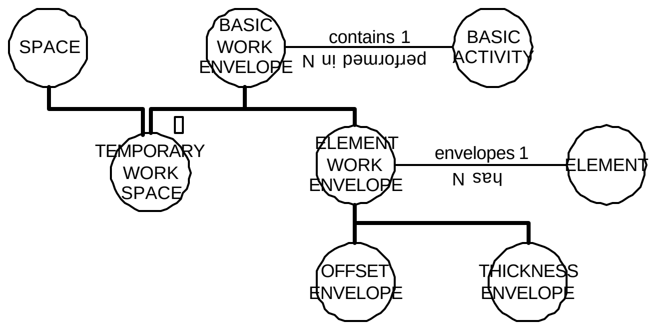

Figure 3: Project Model Classes and Relationships to support Worker Location Interpretation

If the work performed can be directly associated with a particular building element, the geometric form of the *'Element'* influences the shape and dimensions of the work envelope. Two kinds of '*Element_Work_Envelope*' have been defined to describe the structural activities considered in the experiments. These are:

- The *'Offset_Envelope*', which is used for planar elements, such as concrete slabs, and has only two geometry attributes – the offset of the envelope above and below the slab.
- The *'Thickness_Envelope'*, which is used for all other elements, such as columns and walls. These have six attributes, to describe offsets from the extreme surfaces of the element (above, below, front, back, left and right).

The values for the attributes of any particular 'Element_Work_Envelope' instance are dependent on the nature of the 'Basic_Activity' being performed as well as on the element type. For example, **reinforcement fixing** for a column is performed in an envelope that includes the volume of the column itself, and an additional space, which is *offset* up to 0.5m in every direction from the column face. **Concrete pouring** for a slab is performed in an envelope defined by the slab's perimeter and with a *thickness* from the soffit of the slab up to 2.1m above its top surface.

Riley (1994) identified twelve unique types of spaces required by activities: work elements, layout area, unloading area, material path, personnel path, storage area, staging area, prefabrication area, work area, tool and equipment area, debris path, protected area and hazard area. These can be classified into those whose location is directly related to the location of the building element and those whose location is not related to any building element (such as pre-assembly of parts, mixing of materials, bringing parts from temporary stores). The former are dealt with using 'Element_Work_Envelopes'; a different approach is required for the latter. A special 'Temporary Work Space' object was defined to enable the system to express and use these locations in rule processing. This object has the characteristics of a 'Basic Work Envelope' but must also have distinctly defined boundaries. It is consequently implemented with inheritance from both the 'Basic Work Envelope' and the basic 'Sp
Project Model. It is not related to any specific building 'Element'. In certain cases its location may be known in advance (such as equipment stores, or stationary equipment for mixing mortar); in other cases, they may be identified 'ad-hoc' during processing, when concentrations of location readings are identified (an example might be the location of a palette of blocks placed by a crane near a masonry wall).

3.5 Class and Relationship Definitions to Support Data Accumulation

The suggested frequency for processing and reporting is one working day. The location monitoring data are stored in a data recorder through the working day. As rule-processing progresses, the Location Interpretation Module stores the results in *'Time_Labor_Records'*. These are instanced for each new association of a worker's presence with a work envelope: for each subsequent such finding, a duration equal to the standard sampling rate between consecutive readings is added to the previously accumulated time in the existing '*Time_Labor_Record'*. The record is associated with the work envelope in which it is located, and with the instance describing the worker involved ('Work_Resource'), as can be seen in Figure 4. The '*Work_Resource'* class, like the '*Basic_Activity'*, '*Space'* and '*Element'* classes, is defined in the basic BPdM.

'*Time_Labor_Records'* are useful within the current reporting period and for a limited number of subsequent days. Continued accumulation of data at this level of granularity (a particular type of work executed on a particular element – e.g. formwork for a specific column) is both impractical and unnecessary. It is impractical due to the enormous amount of data, and unnecessary since no planning takes place at this level (and so no control can be performed - in fact, construction planning is at the level of the '*Activity'*, which is equivalent to a 'Task' in scheduling (CPM) software. At this level, labor resources are allocated, with quantities that are recorded in BPdM '*Labor_Resource_Use'* objects). Instead, data is accumulated at the level of the basic activity (e.g. formwork for all the columns) in the '*Summary_Time_Labor_Record'*. If expected labor rates are known, this still allows detection of exceptions at a level of detail greater than that of the activity as a whole (i.e. for a '*Basic_Activity'*).

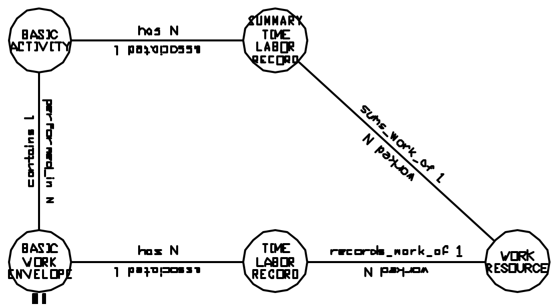

Figure 4: Project Model Classes and Relationships to support Accumulation of the Information

4. EXPANSION OF SUPPORT FOR AUTOMATED PROJECT PERFORMANCE CONTROL

Two significant research directions emerge from the current work. The first concerns expansion of the project model to support additional modes of automated monitoring, and the second concerns development of the knowledge based concepts for correlating data from different sources and interpreting it in order to reach conclusions about project performance exceptions. Early findings indicate that the accuracy and reliability of the conclusions drawn about the progress of work on site can be enhanced by using data collected by monitoring more than one indirect indicator. For example, interpretation of worker location data alone can be a complex procedure, since it is very common for locations to fall within overlapping work envelopes, or to fall outside any work envelope (Navon and Goldschmidt 2001b). In the latter case, additional data might clarify the situation – e.g. indication that a load of formwork equipment had been delivered to a particular location by a crane could be correlated with a concentration of worker locations outside of any element work envelope. This would allow interpretation of the worker's activity in that location with a higher degree of certainty.

As a result, additional modes of monitoring indirect performance should be investigated. According to the Automated Project Performance Control concept, the proviso should be that they be fully automated. Monitoring the delivery and consumption of construction materials, and the movement of construction equipment, such as in road construction, are currently being investigated (Navon et al. 2001). An additional project, involving monitoring of main construction lifting equipment, is also underway. Figure 5 indicates how additional sources of information may be added to the overall model. As is apparent, other modes also rely on the existence of a Building Project Model, which can integrate updated project information with the monitored data, to allow interpretation and return of the results. Note also that in Figure 5 additional 'Other Control Models' are shown in parallel to the 'Labor Control Model'. An alternative arrangement would feed all monitored data into each control model, enabling drawing of conclusions as detailed in the example above. Yet another arrangement would employ just one complex control model. These issues must also be researched in future work.

The difficulties that can be expected in preparing the groundwork for eventual comprehensive automated identification of performance exceptions include the following:

- Interpretation will rely on knowledge-based rules, which must be elicited from experts in construction management. Elicitation of expert knowledge is a difficult task.
- The number of possible situations is combinatorial, and increases as more information sources are added. A systematic method for assessing combinations of readings will be required.
- Any system of rules would have to be calibrated against actual situations recorded on construction sites. At present, no comprehensive sets of correlated monitoring data form different sources on the same site are available.

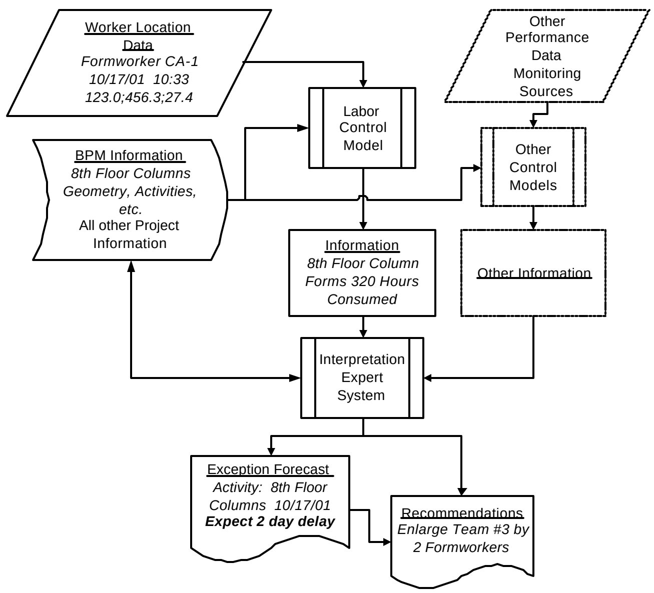

Figure 5: Transformation of Data into Information, and Interpretation to Generate Exceptions and Recommendations

5. CONCLUSIONS

Construction project control practice could be greatly enhanced if exceptions in performance indicators could be reported in real-time. The data obtained by monitoring construction activities (whether automatic or manual) do not provide immediately meaningful information for project control. They have use only when transformed into information, which can only be done through comparison with up-to-date project information. Such an environment of comprehensive data integration can be provided by a Building Project data Model that covers conceptual project spaces, physical building element geometries and properties, and construction methods, activities and resources.

A Building Project Model has been adapted to support the information needs of an automated Labor Control Model. Conceptually new classes have been defined to represent the 'work envelopes' required for processing the worker location readings, and additional new classes support the accumulation of interpreted information over a project's lifetime. Experiments with the Labor Control Model and the Project Model of an eight-story building under construction have shown that the integration is feasible and can support the interpretation of the workers' location data. An important drawback at present is that Building Project Modeling at the required level of sophistication is not commonplace. With the expansion of contractor driven efforts in this direction (such as the IAI), and the impetus provided by industry-wide implementation projects (such as CIS/2 and the PCSC project), project models will be increasingly available.

Further research directions have been identified, and can be grouped in two spheres:

- Development of additional modes of automated monitoring of construction activities.
- Investigation of the feasibility of compiling knowledge-based systems which are capable of interpreting multi-source monitoring data, in the context of an integrated Project Model, in order to identify exceptions in performance indicators in real-time.

Efforts in these directions are currently underway in the framework of the Technion Automated Project Performance Control initiative.

6. ACKNOWLEDGEMENT

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