Building Project Model Support for Automated Labor Monitoring

R. Sacks[1]; R. Navon[2]; and E. Goldschmidt[3]

Abstract: In current project control practice, deviations from planned performance can only be reported after significant time has elapsed. Manual monitoring on construction sites is costly and error prone. Consequently, an automated model for monitoring labor inputs, based on automated data collection (ADC), offers a solution to the problem. Integration with a computerized building project model (BPM), including the physical geometry of the building, the resources active in its execution, and the planned construction activity schedule, is essential for the operation of such a model. Integration with an existing BPM requires that the BPM be expanded to support interpretation and accumulation of the monitoring results. To this end, appropriate project model classes and relationships have been implemented and tested. Experimental data were collected, using an ADC system, from the job site of a reinforced concrete building. The data were processed, within the BPM, with the aid of a prototypical location interpretation module.

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Introduction

The need to control construction project performance has been widely discussed (Ciesielski 2000; Cheng and Chen 2002; Echeverry and Beltran 1997; Gould and Joyce 2000; Kannan and Vorster 2000). A recent survey of a large-scale project management information and control system (monitoring over 1,500 public works projects) showed that the need for data entry at the project level was the major obstacle to the success of the system as a whole (Futcher 2001). This was attributed to the lack of benefit from the system to the site managers in relation to the effort required of them in reporting project progress data. In fact, McCullouch (1997) reported that, on average, 30–50% of the time of field supervisory personnel is spent recording and analyzing site data. In practice, however, little has been done to address this problem; most of the research efforts in the field of project control still focus on the development of cost control models (Hastak et al. 1996).

This state of affairs leads to the conclusion that automating control of on-site construction performance is essential in order to enable management to take corrective measures in real-time (Navon and Goldschmidt 2003a). Advanced technologies that can be used for real-time on-site measurement of performance indicators are rapidly emerging and their costs are declining (Ciesielski 2000). Consequently, efforts are being made at the Technion-Israel Institute of Technology to automate the reporting of project performance, in the framework of the automated project performance control (APPC) initiative. Project performance control broadly refers to the activities taken by the project (or company) management in order to ascertain that the performance of the project is as close as possible to a set of desirable values. Performance is measured in terms of project performance indicators, such as cost, schedule, labor productivity, materials consumption or waste, etc. Much of the research has focused on automated-data-collection and interpretation, both in building and in earthmoving (Navon and Goldschmidt 2003a,b; Navon et al. 2003).

Interpretation of the monitored data to provide valuable information is only possible in the context of information about the physical, spatial, organizational, and scheduling aspects of the project as a whole. This paper proposes that full integration of automated data monitoring systems with building project models (BPM) is an effective method to enable such interpretation, and demonstrates how integration can be accomplished. First, the principles of APPC and automated data collection (ADC) are reviewed using the example of automating the measurement of worker locations and interpreting them to determine labor inputs (the term ''labor input'' is used throughout this paper to denote a quantity of labor hours consumed in execution of a task by a worker or a team of workers). Next, a brief definition of BPM, in the context in which it is used in this research, is provided. The conceptual interface between monitored data and project information, as stored in a BPM, is developed. New object classes, which enable seamless communication between the labor monitoring module and other modules that use the BPM, were developed and are presented. The results of the integration are demonstrated for data collected in an eight-story faculty building currently under construction (Navon et al. 2003).

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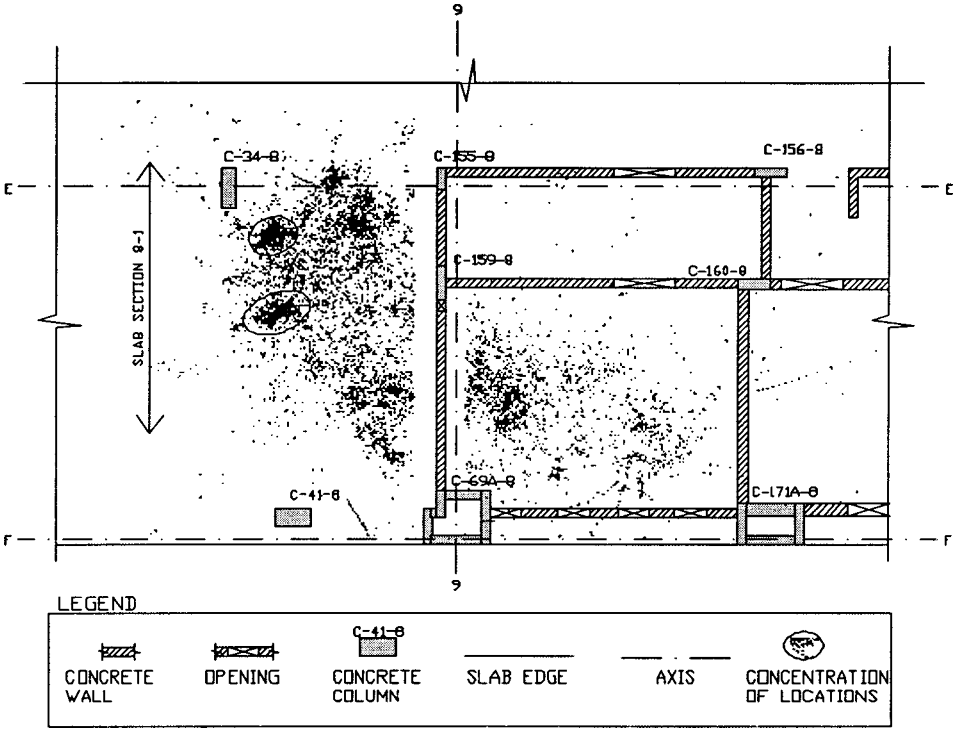


Fig. 1. Mapping of raw GPS data on construction plan

Automated Measurement of Worker Location Data

One of the most advanced efforts in this regard is CALIBRE (2000) which is a measurement technique that uses human observers who patrol the site at regular time intervals and record the tasks being undertaken on a hand-held computer. This is commendable because it enables real-time labor control, but it still requires full-time observers. A fully automated model was introduced by Navon and Goldschmidt (2003b). The concept behind this development is that workers' locations are measured automatically at regular time intervals. From this data, labor input information can be deduced using computerized algorithms. In the first stage, the model was implemented in a concept-proving prototype (Navon and Goldschmidt 2003b). A full-scale prototype is currently being developed.

At the current stage of the research, global positioning system (GPS) technology has been used to measure workers' locations on site. GPS can be used for civil engineering activities in open spaces, such as earthworks, building frame construction, bridge construction, highways, etc. (Roberts et al. 1999; Ciesielski 2000; Kannan and Vorster 2000; Navon et al. 2003). To check the suitability of GPS technology for tracking workers, a GPS receiver was mounted on a worker's construction helmet and tested during construction of an eight-story faculty building. Fig. 1 shows the locations of a formworker, measured as he worked on the eighth floor, mapped onto a portion of a floor layout drawing. The background drawing was produced automatically using the BPM information, and shows part of the floor, concrete columns, concrete walls, openings in the walls, and the edge of the slab. The building elements shown are those for which building of concrete formwork could feasibly begin at the time the monitoring was performed. Coordinates measured by the GPS system were translated from their original global reference system to a local 3D Cartesian system, whose origin was set in relation to the building layout grid. The raw data (Table 1 shows a sampling) was made available as a list of location coordinates in the local 3D system, together with a time stamp (at 2 s intervals) for each location record and the identity of the worker who carried the receiver. These were then mapped onto the drawing. In fact, the worker was occupied in preparing formwork for Columns 34, 69A, 159, and 171, and the walls between them; hence the density of locations recorded at arm's length from the wall (the concentrations of locations away from the wall will be discussed later).

Interpreting Labor Input Data

A model for interpreting the worker location data has been developed (Navon and Goldschmidt 2003b). The model includes a data

Table 1. Formworker's Location Raw Data after Translation to Local Building Coordinate System

Data number	GPS time	Time (HH:MM:SS)	*X* (m)	*Y* (m)	*Z* (m)
1	170.3555787	8:32:02	15.96	5.31	25.80
2	170.3556019	8:32:04	15.91	5.33	26.21
3	170.3556250	8:32:06	15.82	5.27	26.80
4	170.3556481	8:32:08	15.89	5.20	27.15
5	170.3556713	8:32:10	16.00	4.88	26.86
6	170.3556944	8:32:12	15.81	5.15	27.21
7	170.3557176	8:32:14	15.89	5.20	27.35
8	170.3557407	8:32:16	15.93	5.23	27.31
9	170.3557639	8:32:18	15.96	4.78	27.25
10	170.3557870	8:32:20	15.89	4.90	26.71
…	…	…	…	…	…
6,778	170.5124537	12:17:56	24.82	7.36	26.93
6,779	170.5124769	12:17:58	25.39	8.21	26.89
6,780	170.5125000	12:18:00	25.94	9.23	26.90

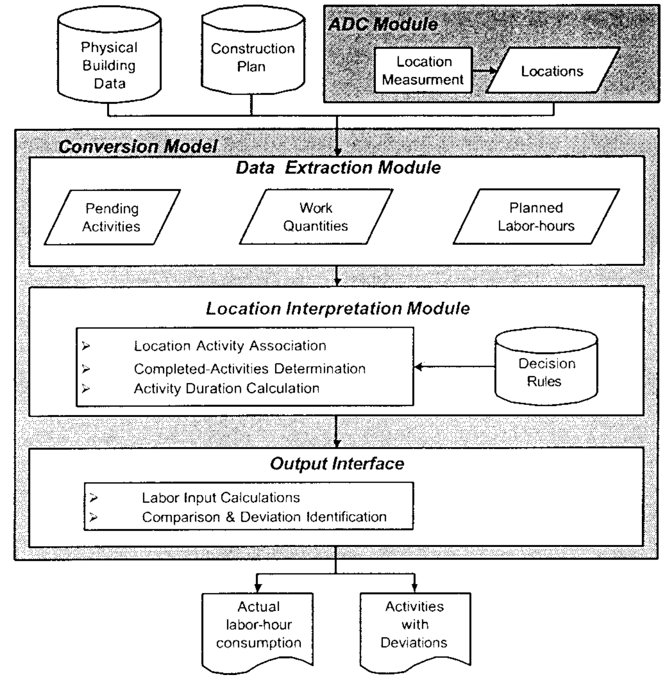


Fig. 2. Labor control model—transformation of worker location data into labor input information

extraction module, a location interpretation module, and an output interface (Fig. 2). There are two types of data source:

1. Planned: physical building design data (geometry and materials) and construction plan (schedule, planned labor inputs, resource assignments); and
2. Measured: data describing the actual performance, as measured by the ADC module (the location of each worker in a local building coordinate system, measured at regular time intervals). The actual performance data are stored in the "locations" file.

The data extraction module filters the activities to identify all those that can be performed on a given day. These are termed the "pending activities." This limits the list of potential activities that the workers could be engaged in, making the interpretation algorithms in the location interpretation module more efficient. 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 further calculations.

In the next step, the location interpretation module associates the locations of the workers, and the time spent at each location, with pending activities. This is done using algorithms and decision rules as detailed in Navon and Goldschmidt (2003b). The algorithms also 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 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 conversion model, and the results of its processing must be returned as new project information. These conditions are fully supported by the BPM paradigm, as will be shown in the following sections.

Building Project Models

BPM are intended to provide comprehensive sharing and integration of all the information describing a building construction project, including both the building product, as designed and as built, and the process activities and resources employed in the building's design and construction. The project model concept can be traced to the *product* modeling efforts which are embodied 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. Each industry domain has application protocols (AP) specific to its products. AP 225 provides the basis for complete description and transfer of the data describing the geometry of a building's physical parts. However, the information required to describe building projects extends far beyond its geometry alone. Early efforts to define building framework models include the architecture, engineering and construction (AEC) building systems model (Turner 1988), the general AEC reference model—GARM (Gielingh 1988), and RATAS (Bjork 1994). The building construction core model (ISO 1996) aimed to develop a broad reference model within STEP for the domain of building construction. The more recent industry foundation class models (IAI 2001) incorporate process information together with the product description and are sometimes termed "project models." To date however, no single generic construction industry-wide standard building model is available, mainly due to the enormous complexity of such an undertaking (Amor and Faraj 2001).

The various technical aspects of building product modeling—such as classification, aggregation, decomposition hierarchies, data management, etc.—have also been the subject of many research efforts, which are comprehensively presented in a recent book by Eastman (1999). Object-oriented design has been shown to be the most suitable paradigm for project modeling. Object-oriented product modeling language EXPRESS and its graphical editor, EXPRESS-G, have been formally adopted by the ISO (1994).

Project modeling has begun impacting the construction industry with efforts that focus on specific construction methods. Exchange of project information in the structural steel industry is becoming increasingly common with the growing use of the CIMSTEEL Integration Standard V2.0 (CIS/2) product model (Watson and Crowley 1997), 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 (PCSC 2001). Progress is also being made in development of the IFC 2.X integration standards (IAI 2001) for more general construction applications. Adoption of these technologies in the construction industry makes the assumption of availability of building project models in the near future reasonable.

Table 2. Sample Labor Control Rules and Data Requirements

Sample-rule	Input information	Output
(a) Samples for rule Set 1		
A 3D work envelope is defined as the confluence of a basic activity, the geometry, and location of the element worked on, and the construction method.	Basic activity trade and work method, list of elements built by the basic activity, typical work envelope types and offsets for each element—trade pair, element geometries, and locations	Geometry and location definitions of each work envelope
If a basic activity requires equipment or materials from an on-site material store or preassembly area, then create a temporary work envelope for the store or work area.	Basic activity trade and work method, list of materials or equipment required to perform the basic activity, work-area or store locations and geometries, typical store or work-area envelope geometries	Geometry and location definitions of each work envelope
(b) Samples for rule Set 2		
If a worker's location reading is within the geometric space of one work envelope, and the monitored worker was assigned to the execution of the basic activity associated with the work envelope, then accumulate the elapsed time with the work envelope and the resource (worker).	Geometry and location of work envelopes, ID and trade of resource, labor assignments for the resource (basic activities), coordinates and time frame of worker location reading	Duration added to the accumulated time worked in the work envelope by the resource
If a reading was associated with more than one candidate basic work envelope, or could not be associated with any such envelope, then assign the worker's time for that reading to the basic activity that was performed by the team to which he/she belonged.	ID and trade of resource, team and labor assignments for the resource (basic activities), time frame of worker location reading	Duration added to the time worked on the basic activity by the resource
(c) Samples for rule Set 3		
If a basic activity has no preceding basic activities, or if all of its precedents are confirmed complete, its status is set to pending.	Basic activities and their predecessor information, status of each basic activity	Updated basic activity status
If a labor reading is found within the basic work envelope of any pending basic activity, its status is set to in process.	Basic work envelope accumulated time for the current scanning, associated basic activity	Updated basic activity status

Building Project Model Support for Labor Control Model

Data Processing Requirements

The first step in establishing the scope of the information integration requirements of the labor control model was to systematically list the rules driving the location interpretation process. The rules can be classified into three distinct sets:

- Set 1: Rules to layout basic work envelopes for each element to be built in each of the pending basic activities (the ''pending'' status is set in Rule Set 3).
- Set 2: Rules to associate labor location readings with basic activities.
- Set 3: Rules to determine the status of basic activities after scanning worker location data for the current reporting period (the basic activities scanned in a consecutive reporting period are those whose status are ''considered complete,'' ''in process,'' ''pending,'' and those immediately following any ''pending'' basic activities).

Table 2 provides two typical rules for each of the three sets, together with the information input they require and the output they generate. The following terms used have specific meaning in the context of the BPM:

- Element: a basic building part, such as a wall, beam, column, flooring section etc.
- Basic activity: The work performed by a particular labor resource (as defined below) to build all of the elements of a work assembly in a given space: e.g., placement of reinforcement in all concrete columns of a particular structural floor by a team of reinforcement workers. A basic activity is not usually scheduled in a construction plan—scheduling is commonly done at a lower level of detail, using ''tasks'' or ''activities,'' which are more general, i.e., contain a number of basic activities (e.g., build all the columns of a particular floor—including laying out, formwork, reinforcement, casting, and stripping).
- Work envelope: The 3D space around an element in which the worker is presumed to be located when working on the element. A work envelope is unique for any combination of element, basic activity type, and construction method. A similar concept was used by Akinci et al. (1998) to analyze the effects of time space conflicts on construction scheduling.
- Resource: In this context, the workers composing the team assigned to perform a basic activity.
- Space: A distinct region with a defined perimeter within a building or on a building site.

The information required can be grouped into four basic categories: *product* information (building elements and their components), *space* information (building areas such as floors, temporary work areas), *activity* information (construction tasks at various levels of detail), and *resource* information (labor, material, and equipment resources). In most construction projects today, this information is not available in any integrated or coherent computerized format. Product information is available in computer-aided drawing files as graphic symbols (lines, curves, text, etc.), which are not machine interpretable as building products, or in textual specifications. Similarly, space information is available only in graphic format on paper. Activities are often computerized using scheduling software and at a level of detail that does not descend to the level of specific building elements. Resource information may reside in a company database system such as Enterprise Resource Planning, or may be stored directly in the scheduling packages. This state of affairs makes operation of the labor control model difficult: data must be imported from a variety of disparate sources, requiring much data (re)entry work, thus diminishing the benefits of automated data collection. A much better approach would be to integrate the labor control module with a BPM of the type described. This approach was adopted in the present research and is described in the next section.

Building Product and Project Models

The information analysis revealed the need for a number of classes and attributes, such as work envelope, temporary work spaces, recordings of accumulated labor inputs invested in basic activities and status of basic activities, which are not commonly found in the models discussed. The models available in the STEP framework (ISO 1994) do not extend beyond product information. The most advanced application protocol in the field of building construction, AP 225, deals only with building geometry and topology (Eastman 1999). The building aspect models (such as COMBINE and CIMSTEEL) generally do not carry space, activity, or resource information (Augenbroe 1994; Watson and Crowley 1997).

The IFC 2.0 classes (IAI 2001) on the other hand, offer much of the functionality required for integrating the labor control model with project information. The product and space domains are well defined. In the process domain, the following classes describe activity and resource information (Froese and Yu 1999):

- *IfcWorkTask* describes work packages. They can be nested to provide multiple levels of detail to describe basic activities, and they include a *WorkMethod* attribute to describe the construction method. They can also carry attributes for budgeted, estimated, and in-place quantities of finished work product, but no information on actual labor inputs. An attribute inherited from the *IfcProcess* class, *productivity*, carries a direct measure of output/time in terms of product output—however, this is a measure of production rate, not of labor productivity.
- *IfcWorkScheduleElements* provide the scheduling relationships for *IfcWorkTasks*. These objects, when stored together with *IfcScheduleTimeControls*, are the IFC equivalent to tasks in scheduling software packages.
- *IfcScheduleTimeControl* has an optional attribute called *TaskStatus*. The status of work tasks is central to the labor control analysis processing. However, this is maintained at the level of scheduled activities, and not that of basic activities, as is necessary for labor control. Also, only five values are enumerated in the *IfcWorkTaskStatusEnum*, namely Completed, Started, NotYetStarted, UserDefined and NotDefined. Additional status conditions, such as "pending", would need to be added.

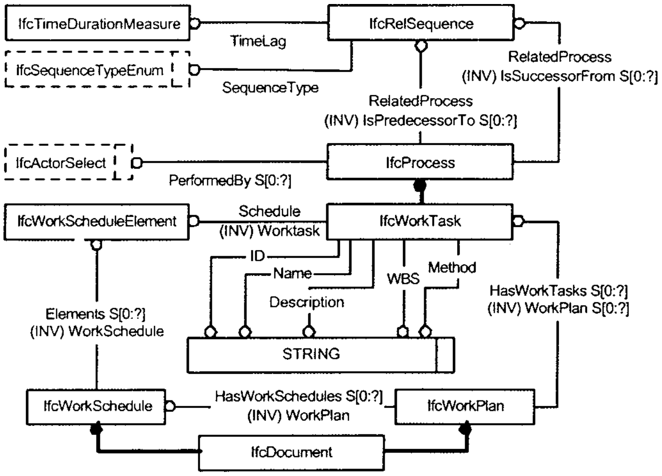


Fig. 3. IFC 2.0 classes for work planning and scheduling (Froese and Yu 1999)

- *IfcLaborResource* objects can be related to *IfcWorkScheduleElements* using the *IfcRelUsesResource* relationship, although the allocation is simply defined using a resource consumption enumerator (occupied, partially occupied, not occupied), rather than being quantified.

Fig. 3 shows the subschema of IFC classes for work planning and scheduling. The model can express much of the information required as input to the location interpretation module. However, in its present form, it falls short in two aspects. A minor drawback is that no "work envelope" type objects exist in the IFC model; these could conceivably remain internal within the location interpretation module. More significantly, the model cannot accommodate the output results that are used for real-time project control; these *must* be integrated with existing and future project control applications.

The project model selected for this research was the building project data model (BPdM), originally developed for the automated building system (ABS) (Sacks 1998). This model was selected for the following reasons:

- The model has three levels of detail of activities, including basic activities (which can be generated automatically from the activities and the work assemblies using ABS routines). These are stored at a level of detail that is most appropriate for rule processing and reporting as envisaged for automated project performance control (Navon and Goldschmidt 2003b).
- The model integrates space, product, activity, and resource (i.e., process) information in one model. All of the information noted 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.

No project model was available for the building selected for the initial labor-control monitoring experimentation undertaken in this research. The physical, geometric, and organizational aspects of the project were therefore loaded directly into the building project model using scripts.

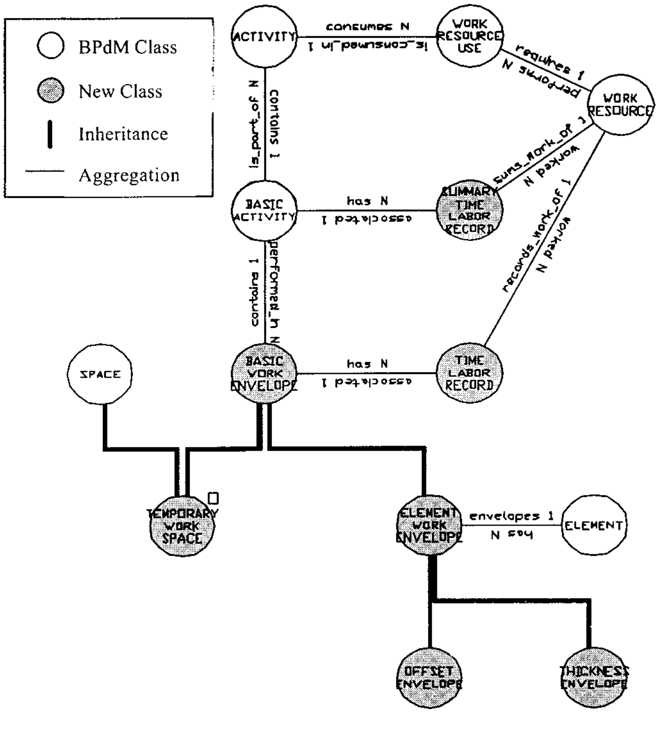


Fig. 4. Object classes for integrating labor control data in BPM

Adaptation of BPM for Automated Labor Control

The labor control model 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 BPM 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.

Fig. 4 shows the section of the schema with the new classes (shown with gray background) and their relationships to preexisting BPM classes (shown with white background—their definitions are essentially the same as set out in the previous section). Further detail can be found in Sacks and Warszawski (1997).

First among the new objects is the "work envelope." The "*basic work envelope*" is an abstract class that 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 of the work being performed and the construction method employed, and on whether the work can be directly associated with any one particular building element.

In the latter case, the form of the *element* also influences the shape and dimensions of the work envelope. To date, two kinds of "*element_work_envelope*" have been defined to describe the activities considered in the experiments:

- The "*thickness_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 "*offset_envelope*," which is used for all other elements, such as columns and walls. These have six attributes, defining offsets from the element's extreme surfaces (above, below, front, back, left, and right).

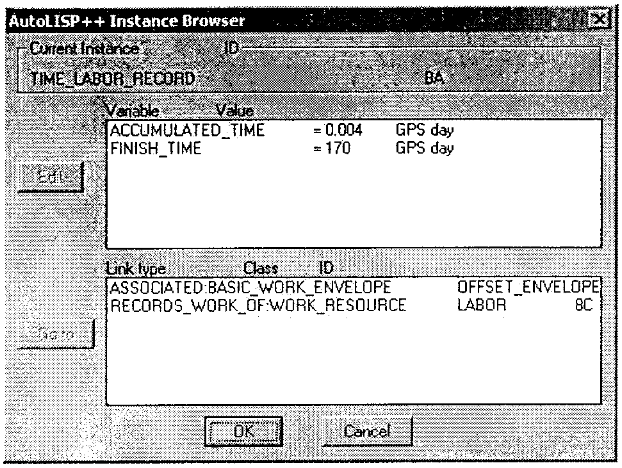
Note that the values for the attributes of any particular *element_work_envelope* instance are not only dependent on the element type, but also on the nature of the *basic_activity* being performed. For example, formwork for a slab is performed in an envelope that extends 1.0 m below and 1.8 m above the soffit of the slab; concrete pouring is performed between the soffit of the slab and 2.1 m above its top surface. A database of such parameters was prepared for the research work, but clearly much further research is required to establish reliable libraries of values.

Riley (1994) identified 13 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. The former are dealt with using *element_work_envelopes*; a different approach is required for the latter. Initial experimental observations using the GPS data collection system showed that a significant portion of a worker's time is spent in preparation of materials in locations that cannot be associated directly with any one particular element. For example, in Fig. 1, two concentrations of recorded location points are plainly discernible to the left of the wall on which the formworker was busy. In this case, the worker had set up a temporary workbench for sawing lengths of wooden planks for the concrete forms. This is typical of many trades, particularly in work that requires preassembly of parts, mixing of materials, or bringing parts from temporary stores.

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 *space* classes of the BPM. It is not related to any specific building *element*. In certain cases its' location may be known (such as temporary work stations for cleaning forms, tying reinforcement cages, etc.), while in others they may be ad-hoc (such as placing trestles for sawing planks).

In the envisaged architecture of the labor control model (Fig. 2), the measurement data are stored in a data recorder through the working day. Once a day, the data are read from the recorder. The first step of the location interpretation module is to associate worker locations with work envelopes. This is 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 2003b). In the latter case, a cluster of readings may indicate the presence of an ad-hoc *temporary work space* that should be instanced. 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 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 Fig. 5.

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 critical-path method scheduling software. At this level, labor resources are allocated,



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Current Instance                ID
TIME_LABOR_RECORD               BA

Variable            Value
ACCUMULATED_TIME    = 0.004    GPS day
FINISH_TIME         = 170      GPS day

Link type                          Class            ID
ASSOCIATED:BASIC_WORK_ENVELOPE     OFFSET_ENVELOPE
RECORDS_WORK_OF:WORK_RESOURCE      LABOR            8C
```

Fig. 5. Sample BPM time labor record instance shown using AutoLISP++ instance browser

with quantities that are recorded in "*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*).

Example

Processing of the raw data through the first stage of the location interpretation module (Navon and Goldschmidt 2003b), which associates worker locations with basic activities, is illustrated by the following example. The experimental data used record one formworker's activity for 3 h and 46 min at 2-s intervals (shown in Table 1). The sequence of processing the data, in accordance with the processing rules, is as follows:

1. The candidate pending basic activities for the worker monitored in this data are determined. In this case, "Column formwork #8" and "Wall formwork #8" are identified.
2. Basic work envelopes are generated for each pending basic activity for all relevant elements (e.g., Column formwork #8—Column 34, Column formwork #8—Column 41, etc.).
3. The raw data are geometrically associated with the basic work envelopes.

The results for the first 240 data points [of a total 6,780 available (see Table 1)], with reference to Fig. 1, are plotted along a timeline for two representative elements—column 69A and the adjacent wall (Wall 3) in Fig. 6 and summarized in Table 3. Interpretation is intended to be done daily, after which the durations are accumulated in the appropriate time-labor record instances (e.g., a record associated with Formwork on Column 69A). The details of this association are discussed in Navon and Goldschmidt (2003b).

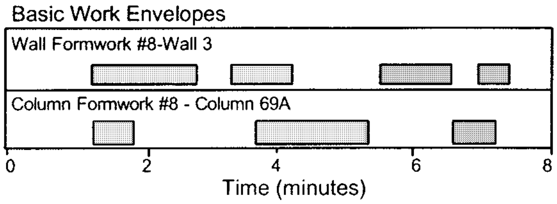

Fig. 6. Association of worker locations with basic work envelopes

Table 3. Accumulated Results for Experimental Data for Column Formwork #8

Building element	Duration in work envelope (seconds)
C-34-8	1,696
C-41-8	240
C-69A-8	2,452
C-155-8	46
C-156-8	2
C-159-8	676
C-160-8	64
C-171-8	838
Other	7,546
Total	13,560

Discussion

The level of detail at which worker location data is accumulated is dependent on the level of detail at which one wishes to draw conclusions about deviations in the work plan. Three levels of detail are possible:

1. Labor inputs are accumulated at the level of the basic activity (e.g., hours spent on formwork for columns on the 3rd floor);
2. Accumulation at the level of the work envelope/element (e.g., hours spent on formwork for Column C-159 on the 8th floor); and
3. Storage of all the worker location readings with their associated work envelopes (e.g., at 8:30 a.m. worker ID.1234 was working on Column C-159 on the 8th floor).

Note that the third level requires storage of records for individual workers, while in the first and second levels work-hours are accumulated for all the workers of a given trade in a team.

The first level is supported by *summary time labor records*. One of the key advantages of automated project performance control is the ability to monitor and control the construction process in real-time (at least once a day). In general, monitoring and control with longer response times (a week or more) can be achieved using nonautomated methods. Since basic activities generally continue over a number of working days, this level of detail is insufficient. The second level is supported by *time labor records* and enables monitoring at the level of individual elements. The third level is not directly supported, since there is no planning at this level of detail with which results may be compared, and so no meaningful information can be deduced.

Due to the quantity of location readings, their interpretation requires apparently significant computing power. For just one worker, measured at 30 s intervals, working an 8 h day on a work assembly containing 50 elements, the number of possible basic geometric association tests alone is in the order of 48,000. On a typical building site, there will be a large number of workers and potentially many work assemblies and basic activities being performed simultaneously. However, various algorithmic approaches can be adopted to drastically reduce the computation effort required. This is beyond the scope of the present paper.

Monitoring can provide a mountain of data. One of the problems in project management is maintaining focus. Data per se is distracting and can be harmful to the task of managing the project and managing the company. Even after the data is transformed into information, the quantity of information is still too large to be useful. It becomes useful when it is interpreted—in particular, when exceptions are identified. Reports of minimal or excessive labor inputs in any given task are not sufficiently meaningful in identifying exceptions, unless they are correlated with other information about the project's progress, such as when basic activities are actually completed (i.e., the required value is actually added to the building). It is only in an environment of comprehensive data integration, such as is available in projects using a true project model, that valuable information can be isolated and delivered in real time to the project and company management. Development of an expert system for interpretation, capable of integrating information from a number of monitoring sources, is an important future research goal.

Conclusions

A prototype labor control model, based on measurement of worker locations using ADC technology, has been integrated with a BPM. This has been achieved by defining the classes and their relationships to the root objects of the BPM, which are required to support the functionality of the labor control model. The seven object classes and the relationships, which have been added to the BPM, appear to be adequate. However, the appropriate parameters for work envelopes have yet to be thoroughly investigated, and further research is required in order to establish a database of values for each element/basic activity type pair. Similarly, the level of detail of accumulation of time-labor record results is under investigation.

A building project model is essential for effective use of the automated labor monitoring system:

- The labor control model requires up-to-date activity, resource, and product information describing the project for every reporting period. In most construction projects, such information is not static—design changes during the life of the project execution are common, and organizational and resource changes are the rule rather than the exception: In a building project model environment, all relevant information can be stored once, and updated at source. In any other system setup, it would be necessary to either input or translate the updated data for every scan of the location interpretation module. This would negate the goal of full automation, and add an overhead that may make such a control system impractical.
- It is apparent that monitoring data from any single source (labor, material, equipment, budget, or schedule) does not provide a full picture of progress on a project. Therefore, information must be collected from multiple sources and processed together, which would be more efficient and practical on a common information platform. In addition, a single platform ensures that information from the different sources is recorded at the same level of granularity, which allows direct comparison.
- The purpose of the labor monitoring system is to provide real-time (i.e., once a day) feedback to project managers at all levels. Simply supplying data is not effective and can be harmful—real benefit can only be derived if the information is placed in the context of the whole project. This is very difficult to implement in a fragmented project-information environment.

The research has explored how a labor control model, if integrated with a building project model, can provide labor monitoring information. This alone is insufficient for a production APPC system, but does represent an important advance compared with currently available technology. Ultimately, a project manager could be assisted by an expert system, which could provide reporting of exceptions from planned execution based on information generated by a multisource automated monitoring system. A sophisticated system might even be programmed to make recommendations as to remedial measures that could be taken to improve project performance. Further research is recommended in monitoring additional project indicators, integrating multiple monitoring sources using improved project data models, and in developing expert interpretation systems.

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