Combining automatically and manually collected data for project monitoring and control

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Purpose In an extended research program, started about two decades ago, a number of models have been developed for monitoring and controlling construction. These include models for the control of materials, earthmoving equipment, guardrail installation and labor. All these models convert data on the actual project performance that is obtained through Automated Data Collection (ADC) technologies, into information that can be compared with the project plan. Tests that were conducted with these models indicate that the use of ADC can substantially improve project control, but that in the areas that were studied manually obtained data is required as well, due to the limitations of existing ADC technologies, and due to the complexity and unpredictability of human actions. The proposed paper will discuss how manually and automatically collected data can be combined for project monitoring and control. **Method** In addition to ADC, manual data is currently required to support project monitoring – i.e., the identification of deviations from the planned performance that will likely lead to significant problems in the project. For example, tests show that in order to obtain information on the actual duration of activities, a manual recording of their completion time is required in addition to the automated tracking of workers. This can be facilitated through the use of data taken from a computerized daily site report. These data are transformed by a progress monitoring model into information regarding the actual progress, and then transferred to scheduling software. Project control involves taking the measures necessary to correct or minimize significant deviations. However, it is often difficult to automatically identify the actual impact these measures might have on the project. To facilitate project control, a graph-based model that can be used to identify the project elements affected by proposed measures, is expanded to include data that is manually added by users. This data includes tacit knowledge regarding existing buffers in the project, and decisions by project team members on the way in which measures will be implemented. **Results & Discussion** Different methods can be used for the integration of data from manual and automated sources. A model that uses the daily site report for project monitoring was implemented in a computerized prototype and tested in a construction project. Another model, that combines a graph-based representation of the project with manual data from project team members for project control, was tested in simulations with experts. The results of these tests were positive, and demonstrated the usefulness of the proposed approach.

Keywords*: automation, project control, automated data collection*

INTRODUCTION

A number of models for monitoring and controlling construction projects have been developed in an extended research program, called Automated Project Performance Control (APPC), which started about two decades ago[5]. These include models for monitoring materials[6], earthmoving equipment[3,10], guardrail installation[9] and labour[1,7]. All these models use, as an input, data on the actual project performance that is obtained in real-time, through Automated Data Collection (ADC) technologies. The models convert this data into information regarding the project performance indicators (PPI) — such as cost, schedule, productivity, inputs consumption etc. These PPI can be compared with the project plan to identify deviations[4].

Research on the use of ADC technologies was motivated by the deficiencies of existing practices of collecting data through site inspections, extracting planning data from drawings, plans and databases, and comparing these through extensive calculations. All these actions are performed manually, and are therefore labour intensive, error prone and infrequent. A second major driver for the APPC program is the rapid technological developments in ADC technologies and their declining costs. Readily available technologies allow:

- Tracking workers, equipment and materials using Barcode, Radio Frequency Identification (RFID), Ultra-Wide Band (UWB) and Global Positioning System (GPS) technologies.
- Recording construction progress through video cameras, image processing systems and laser scanners.
- Continuous updates of an integrated computer-based project model

Executing construction projects while adhering to the planned performance requires two main processes (Figure 1):

1. *Project monitoring* – the identification of those deviations from the planned performance, in the actual execution of the project, which are likely to lead to significant problems in the project.
2. *Project control* – taking the measures necessary to correct or minimize significant deviations.

Project monitoring involves: (a) a comparison of data that is collected on the construction site with the planning data; (b) an identification of any discrepancies between the two datasets; and (c) an analysis of the deviations to identify those that are indicators of significant problems in the project, and which therefore require controlling actions.

Project control involves: (a) the proposal of measures to solve the identified problems and reduce further deviations; (b) an analysis of the proposed measures to identify their impact on the project; (c) an approval of measures that are identified as having the desired impact; and (d) an update of the project plan according to the approved measures.

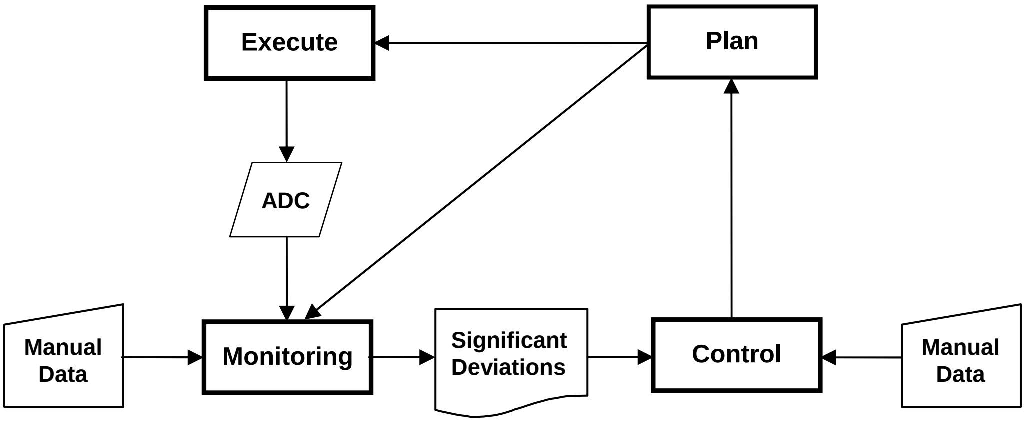

Fig. 1. Project Monitoring and Control

Tests that were conducted with the models that were developed in the APPC program demonstrate that ADC technologies can help overcome some of the current limitations of manual construction project monitoring. However, they also indicate that in the areas that were studied, some manually obtained data is still required in addition to the automatically collected data. One reason for this is the limitations of existing ADC technologies, which make it difficult to use them for all the aspects of monitoring construction projects. A second reason is the complexity and unpredictability of human actions, which accordingly require human knowledge and judgement to analyze and control them. Manual input is required both for the identification of significant deviations that have occurred, as well as for the identification of the measures that are suitable for controlling these deviations. In light of these findings, this paper discusses how manually and automatically collected data can be combined for both project monitoring and project control.

Project Monitoring

All the project monitoring models that were developed in the APPC program relied on ADC technologies for their input (Table 1). However, they also required some manually collected data (Table 2). Thus, a model for monitoring construction materials was successfully developed and implemented in an ongoing building construction project[6]. The model can issue up-to-date reports on: the materials required for construction; materials that should be ordered; actual material flows (materials that arrive to the site, that are dispatched for use, and that remain in stock); and open purchase orders. Barcode or RFID were proposed as technologies for tracking the materials. However, these technologies cannot be used to track bulk materials, since barcode or RFID tags cannot be attached to such materials. Thus, bulk materials would still have to be manually tracked on the site. Damaged materials have to be manually identified as well.

Table 1. Inputs of different models for monitoring construction projects

Project monitoring area	**Model input**	
	Existing digital documentation	**From ADC**
Materials	• Project schedule • Planned inputs for activities • Catalogues of construction materials	• Incoming materials • Materials dispatched for use (Potential technologies: Barcode or RFID)
Earthmoving equipment	• Physical design • Project schedule • Planned productivity	• Equipment location (Experiments conducted with GPS)
Guardrail installation	• Physical design • Project schedule • Relevant safety regulations	• Guardrail location (Potential technology: sensors on guardrail posts)
Labor	• Physical design • Project schedule • Planned labor inputs	• Worker location (Potential technology: RFID; Experiments conducted with video analysis)

Table 2. Outputs of the models and additional required data

Project monitoring area	**Model output**	**Missing data required for monitoring**
Materials	• Required materials • Materials to be ordered • Material flows • Open purchase orders	• Bulk material flows • Quality (e.g. damaged materials)
Earthmoving equipment	• Actual vs. planned productivity • Actual vs. planned progress	• Quality Assurance Testing
Guardrail installation	• Dangerous areas • Dangerous activities • Scheduled guardrail installation • Missing guardrails in current dangerous areas	• Project risk assessment
Labor	• Actual vs. planned labor inputs	• Time of completion of activities

Other models similarly required some manual input. A model for monitoring earthmoving equipment relied on GPS technology to track the location of the equipment3,10. The model uses algorithms to convert the data that was collected through GPS, and to identify deviations of the actual productivity and progress of activities from the project plan. However, certain manual quality assurance activities are still required to capture all the data. Data from sensors on guardrail posts was proposed as an input for another model, for planning and monitoring the installation of guardrails to prevent fall accidents [9]. This model can issue reports on: dangerous areas and activities in the project; scheduled guardrail installation activities; and guardrails that are missing in currently dangerous areas. However, a manual risk assessment by the project management team is also required, based on general characteristics of the project such as the construction method, number of floors, height of a typical floor, and the type of construction (e.g., residential, commercial).

An additional labour monitoring model uses automatically collected data on the location of workers to identify and report deviations of actual labor inputs from the project plan1,7. The model associates specific workers with certain planned activities, by identifying their location within the predefined work envelopes of these activities. These work envelopes are defined in relationship to the components for which the activities have been planned.

Tests that were carried out with the labour monitoring model used video cameras to simulate an automated tracking of workers, in order to identify the duration of their presence within a work envelope. A model was then used to calculate the duration of activities based on this data. However, when these calculated durations were compared with the actual, manually recorded durations of the same activities, significant discrepancies of up to 115% were observed. A statistical analysis revealed that the relative size of these discrepancies varied in accordance with the duration of the activity, and the profession of the worker. Thus, the discrepancies for workers carrying out short formwork activities were relatively much larger than those for workers carrying out long concrete pouring activities.

The main reason for the discrepancies between the inputs that were identified with the labour monitoring model and the actual inputs, was the inability to automatically indentify, in real-time, the exact moment at which an activity had been concluded. Clearly, some manual recording of the conclusion of an activity can solve this problem. The question remains, how such manual data can be efficiently combined, within the same model, with the data obtained through ADC technologies. In order to achieve this, the manual data has to be recorded in a computerized database, which is integrated with the project planning database and the monitoring models.

The APPC program included an attempt to achieve such an integration, through the development of a model that uses data taken from a computerized daily site report (DSR) to generate monitoring and control information[8]. The DSR holds a vast amount of detailed and up to date manually recorded data on the project, including on work that has been accomplished. Currently, this data is not normally used for the management and control of an ongoing project – it is used instead for litigation regarding claims and other disputes. The progress monitoring model that was developed uses data from a computerized version of the DSR, together with data that is extracted from the project planning database, to generate information regarding the actual progress in the project. This information is then transferred to scheduling software in order to update the project schedule, and identify deviations from the plan. The model was implemented in an ongoing construction project, in which a computerized DSR was used. The results of this test were positive.

The APPC program is currently focusing on ways in which project monitoring can be further improved through a seamless integration of both manually and automatically collected data. For example, data on the workers currently engaged in activities on the site, which is automatically collected by tracking the workers' locations, can be combined in one model with data on the completion of activities, which is manually recorded in a computerized DSR. Such a model could accurately monitor in real time the actual labour inputs in a project, and avoid the problems which occur when a fully automated or fully manual approach is employed. By linking such a model with the project schedule, significant deviations from the schedule could be identified. The significance of deviations depends, of course, not only on their size, but also on their knock-on effects, which may cause additional deviations in the future. These effects can be identified by updating the schedule in real-time according to the deviations that have occurred.

Project Control

While project monitoring deals with the identification of significant deviations from the planned project performance, project control deals with the measures necessary to correct or minimize these deviations. Controlling measures include corrective actions such as rescheduling activities, requesting design changes and allocating additional resources. Such measures often have an unexpected indirect impact on the entire project, which may eventually cause the project to deviate even more from the planned performance. For example, an attempt to reduce a deviation from the schedule by carrying out additional activities simultaneously may cause conflicts and difficulties in integrating these activities, resulting in additional downstream work and further delays. The indirect impact of such changes on the project is difficult to predict, and often becomes clear only after the changes are fully implemented.

The APPC program included the development of a graph-based model to facilitate the assessment of the possible impact of changes, prior to their implementation in the project[2]. Different graph-theoretic tools and algorithms are used in order to integrate and update the information in the model, and to automatically identify the project's elements (e.g. resources, construction activities, building components) and objectives (e.g. duration, cost, performance) that could be affected by a proposed measure. Once the affected elements are identified, the possible magnitude of the impact of the proposed measure on these elements has to be analyzed. It was found, however, that for a quantitative analysis of the size of an impact, a manual input is required as well.

The attributes of project elements often include tolerance margins, or buffers, in their definition. Buffers are a gap between the (required) minimal and (actual) defined attributes of an element:

- The specification of requirements in the building program which exceed the minimum necessary to accommodate the planned user activities.
- The design of building components with a capacity larger than that required in order to fulfill the requirements in the building program.
- The allocation of resources in the project plan which exceed the minimum required for the planned tasks.

Such buffers may partly or wholly absorb the impact of a change before it reaches a project element. For example, it may be possible to absorb the impact of additional work through time buffers in the schedule, so that it will not cause any delays. Some buffers, such as contingencies in the budget and time buffers in the schedule, are explicitly documented, and can be automatically identified. Yet, other buffers are often not recorded when decisions are made to allocate them, and are difficult to identify automatically. For example, tolerance margins that are incorporated in the design are often not documented (though they may be revealed through the use of building simulation software). Furthermore, the size of buffers that can be used to absorb the impact of changes may vary during a project, depending on external factors. Commitments by sub-contractors to other projects, for example, may reduce resource buffers in the project plan.

Team members may have tacit knowledge regarding certain buffers, when these are not explicitly known. For example, a member of the design team is likely to be able to assess the tolerance margin that has been incorporated in a subsystem he has designed. A sub-contractor can probably assess how much additional work he can carry out in the project.

Data on buffers that was manually elicited from project team members was incorporated in the graph-based model. This model was then used for both an automatic identification of the elements that might be affected by a proposed measure, and a manual assessment of the size of this impact. The model was tested through simulations in which experts used it to identify the implications of changes that were presented to them. The model allowed the participants in these tests to make a more accurate assessment, which took into account additional information. As a result of using the model, the participants were reminded of implications they had previously overlooked.

CONCLUSIONS

The preliminary results of the APPC program for the development of models for monitoring and controlling construction projects indicate that both automatically and manually collected data are required in these models. In order to incorporate data from manual sources in the models, it has to be represented in a standardized computer-based form. The development of a monitoring model that uses data from a computerized daily site report, and generates information on the actual progress in the project that is then transferred to scheduling software, demonstrated the feasibility of such an approach. The possibility of combining manual and automatic data sources to facilitate better project control was demonstrated with a model that indicated the indirect implications of proposed controlling measures, based on information elicited from project team members, as well as on information produced by graph-theoretic algorithms. While such a hybrid approach shows promise, additional research is still required in order to develop the databases and methods required to fully realize it.

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