INTRODUCING A NEW CONCEPT AND APPROACH TO MODELING CONSTRUCTION

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ABSTRACT: Modeling construction is a critical step for understanding it and improving its performance. The thrust of this research paper is the need for the development of valid credible models as a logical precursor to automation. This article reviews the key models used to represent construction. Through this examination, it makes an important distinction between process and system modeling concepts. This distinction is the basis for concluding that no single tool, by itself, is accurately capable of fully modeling both construction system and construction work processes. Thus an integrated approach to modeling is required. Accordingly, the research conducted by the writers utilized a new integrated modeling approach that combines a set of descriptive tools to allow the development of various perspectives of construction. This article presents one of these tools as a new system modeling concept that overcomes deficiencies in current system modeling approaches. The power of this new model is illustrated in a detailed comparison among key current system modeling concepts.

INTRODUCTION

Modeling is a critical step for understanding and improving a system's performance. Also, the development of valid credible models is a logical precursor to automation. Those principles underlie the value of developing valid models. This paper identifies a major problem in current modeling concepts: the distinction between the objectives of process and system modeling concepts.

The paper first reviews the key models that have been used to represent construction. Through this review the paper demonstrates the advantages and disadvantages of each. Then it presents a new system modeling concept that overcomes deficiencies in the current modeling approaches. The power of this model is illustrated in a detailed comparison among the key system modeling concepts (Kartam 1994).

This article makes an important distinction between process and system modeling concepts. This distinction is the basis for concluding that the existing modeling concepts, in isolation, are insufficient to model construction. In response this paper recommends using an integrated approach to modeling. This approach utilizes a combined set of descriptive tools that can be used to model both construction systems and processes (Kartam and Ibbs 1996). The appropriateness of these tools has been validated by applying them in various case studies and demonstrating significant benefits in each one (Kartam 1995). These tools and their application in a case study with the United States Navy has been published in a previous paper (Kartam et al. 1995).

PROCESS VERSUS SYSTEM

A process is defined as a set of consecutive steps or activities with an end product or service being delivered. These activities can be identified as value adding or nonvalue adding activities. Nonvalue adding activities are those activities that add much more cost than value to the process. Thus waiting for materials, waiting for instructions, rework, and inspection are considered nonvalue adding activities for the construction process. Distinguishing the value adding from the nonvalue adding activities is a major objective of process modeling. On the other hand, a system model neglects the steps that constitute the process; instead it focuses on the process environment. Portraying the process with its inputs, outputs, directives, feedback loops, and interactions with other processes is a major objective of system modeling.

Thus, a process model gives a different perspective and accordingly serves a different purpose than does a system model. Both of these perspectives are necessary to fully and accurately model construction.

SYSTEM MODELS

Existing Key Models

Many system models exist in the general management literature. Three key models that relate most closely and recently to the construction industry are analyzed here.

Conversion Model and Walker's Adaptation

The conventional model dominating the manufacturing process view is the conversion model. It is the foundation for subsequent construction models. According to this model, production is understood as conversions of materials and labor inputs to product output. Furthermore, production processes can be hierarchically divided to subprocesses that, in turn, are also conversion processes. Walker applied this conversion model to the construction process as shown in Fig. 1 (Walker 1985). He developed an input-process-output model for a project.

To an extent this model and its corollary principles are acceptable for construction. For instance, it is generally consistent with estimating practice whereby total project cost is computed by adding the estimated cost of individual components. However, applying this conversion model to the construction

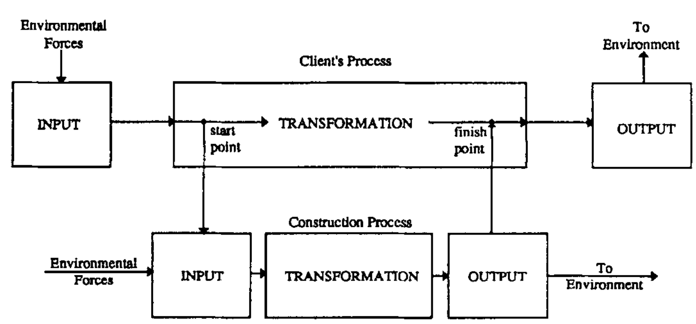

FIG. 1. Input-Process-Output Model of Process of Providing Project (Walker 1995)

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process to analyze and manage productive operations is misleading and often false (Shingo 1988). One of the key problems in the conversion model is that it does not differentiate between processing (value adding) activities and flow (nonvalue adding) activities. Another problem in the conversion model is that it neglects important aspects of resource flows. For instance, one of its key premises is that the total cost of a process can be minimized by minimizing the cost of each subprocess independently. This ignores synergistic and interdependence effects. In addition, it neglects output variation and rework. It assumes that work passes linearly and sequentially through a system (Koskela 1992). Moreover, the conversion model neglects the impact of poor quality inputs as well as the impact of variability and uncertainty.

These deficiencies of the conversion model, which has dominated manufacturing modeling, are a substantial problem. The conversion model's focus has been on making subprocesses more efficient, rather than more effective, through changing automation technology.

Dynamic Model and Sanvido's Adaptation

Alexander proposed a model to represent a dynamic system that static models have failed to represent (Alexander 1974). An example of such static models are PERT diagrams, bar charts, organization charts, and decision trees. Since construction is dynamic, Alexander's model is more accurate to view the process than those static models. The dynamic characteristic is captured by using output feedback for input control.

Sanvido (1984) realized the adequacy of Alexander's dynamic model to construction and adapted it to form his overview model of construction as shown in Fig. 2. This model identifies eight activities that constitute an on-site construction process. Sanvido developed this further until he reached his consolidated control model that follows the common hierarchical organizational structure (Sanvido 1984).

Sanvido's model still encounters the deficiencies of Alexander's model. One deficiency is the model's inability to differentiate between value adding and nonvalue adding activities. It also doesn't differentiate between inputs that are resources and those that are constraints. Moreover, it doesn't incorporate future learning capability in the model.

Structure Analysis, Design Technique (SADT), and Chung's Adaptation

The structure analysis and design technique (SADT) is a graphics language technique that was developed by SofTech Inc. It is one of several modeling tools developed in the software engineering discipline (Softech Inc. 1979). The SADT consists of a hierarchical series of diagrams. Each one consists of a set of boxes, each of which represents a transformation function. The functions have four types of data: input, output, control, and mechanism.

Chung (1989) developed an integrated building process model (IBPM) from the perspective of the owner of the facility, using the SADT as his basic framework. The model begins with an overview diagram of the primary process, which is "provide facility." Then it breaks this metaprocess into five major processes as shown in Fig. 3. Those processes are "plan for a facility," "design a facility," "construct a facility," "operate a facility," and "manage a facility." Each process is further broken down into several subprocesses. Each of these subprocesses is then decomposed to show greater detail. This results in a hierarchical breakdown of the process until the basic process elements are defined (Chung 1989).

This modeling technique has two major advantages over the previous models. One advantage is this model's ability to differentiate between inputs that are resources and those that are

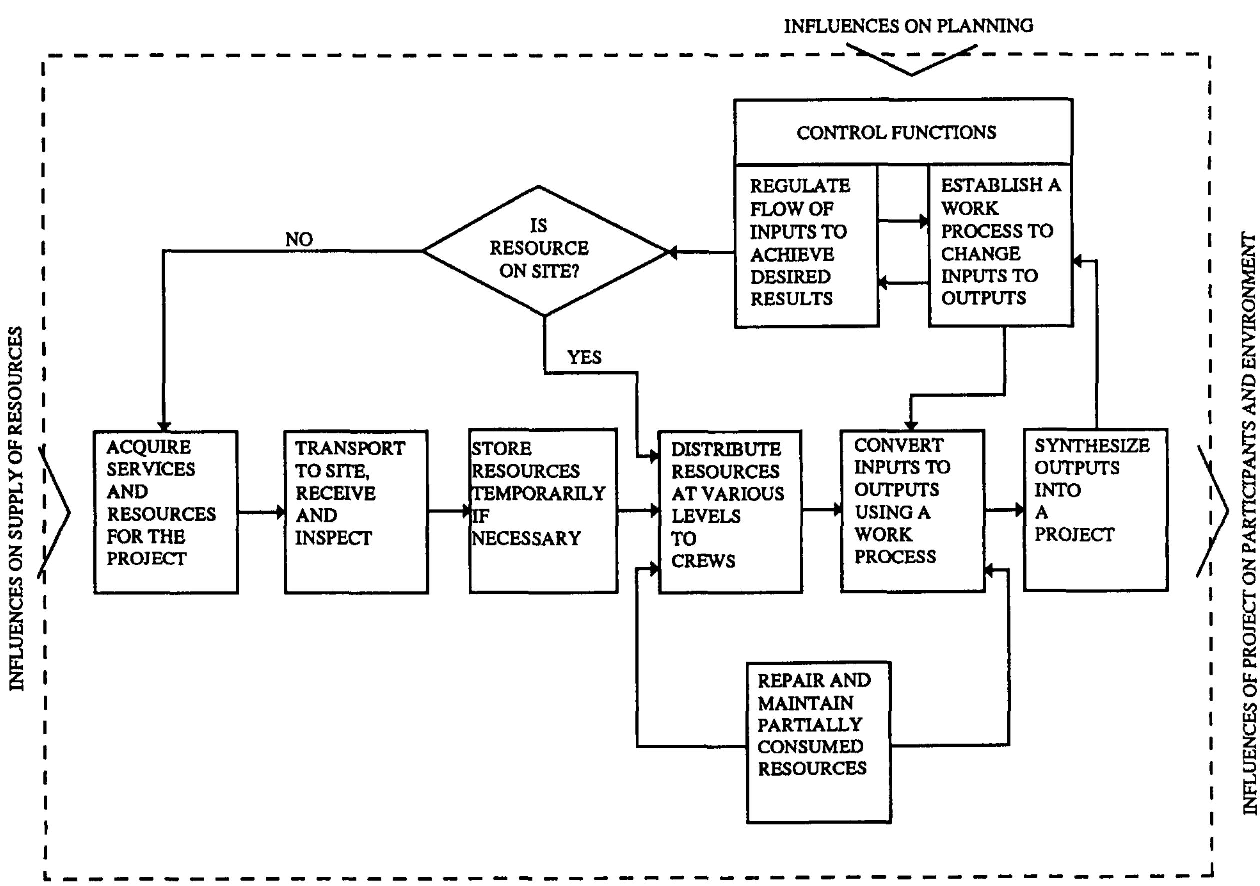

FIG. 2. Sanvido's Overview Model of Construction Process (Sanvido 1984)

J. Constr. Eng. Manage., 1997, 123(1): 89-97

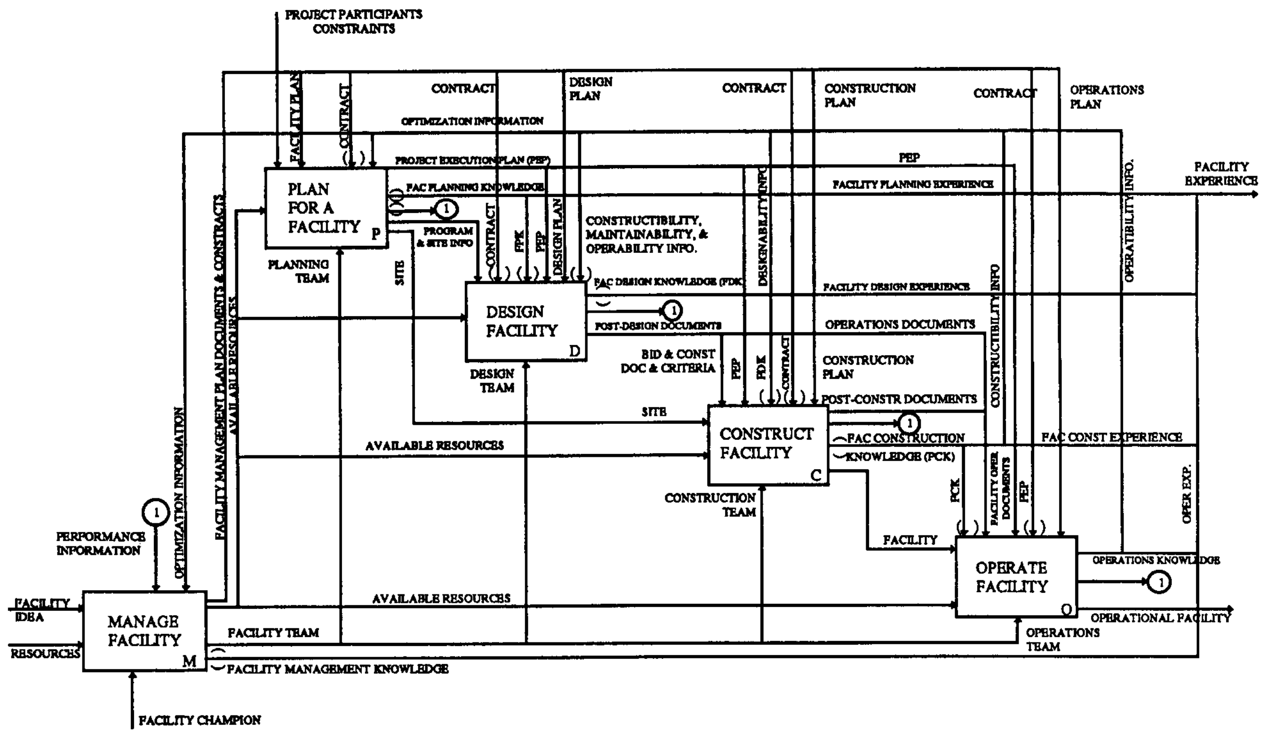

FIG. 3. Detailed Diagram of IBPM (Chung 1989)

constraints. The second advantage is the model's ability to incorporate future learning. This capability will allow the system to learn from past experience and thus serve as a preventive mechanism rather than only a corrective one. On the other hand, because it evolves from the conversion model, Chung's model still encounters the deficiency of concealing the value adding concept. Moreover, it is implicit in its structure making it difficult to interpret. That's because the model uses lines to represent inputs, outputs, constraints, and feedback; i.e., everything, but processes, are represented by lines.

PROCESS MODEL

The traditional production philosophy is based on the conversion model. It conceives production activities as sets of operations. These operations are controlled, operation by operation, for least costs, and improved regularly with respect to productivity by implementing new technology. Koskela (1992) realized this lack of unified conceptual framework for construction and proposed a new conceptual model for the direct production process. It is a generalization of different models suggested in different fields, such as the just in time (JIT) movement and the quality movement. His new production philosophy conceives production activities as materials and information flow processes. These processes are tightly controlled for minimal variability and cycle time, and improved continuously with respect to waste and value and regularly in regards to efficiency by implementing new technology.

Koskela's production theory seeks cycle time reduction, total waste elimination, zero defects, and flexible output. According to him, the model adequate to the new theory is a flow process model, in which production is conceived as a flow of materials and information through four types of stages: transport (moving), waiting (delay), processing (conversion), and inspection as shown in Fig. 4. This model has an advantage over the previous models because it differentiates between value adding and nonvalue adding activities. It also concentrates on process flow rather than only the exchange among the processes. As a rule, only processing activities are value adding activities in this model. Reducing the share of the nonvalue adding activities is the target for continuous improvement.

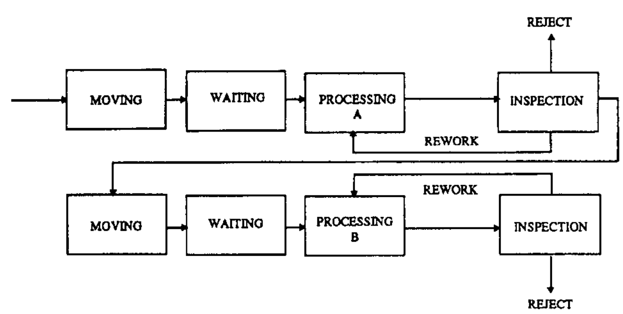

FIG. 4. Koskela's Production Model (Koskela 1992)

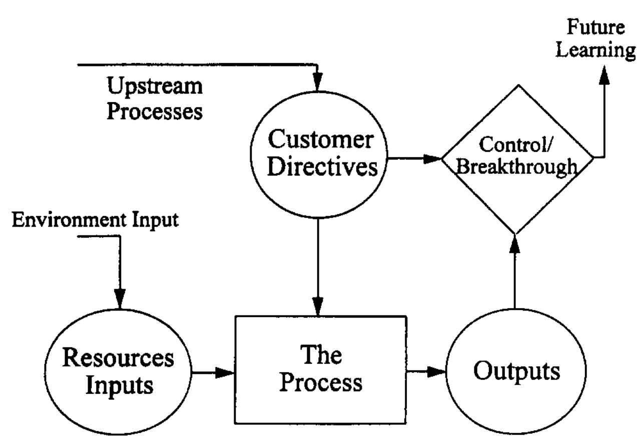

FIG. 5. General Format of Workmapping Model

Koskela's model is only a process model. It doesn't realize the system concept and ignores processes interactions and interdependencies. It does model the production process but doesn't very well model the management processes that affect production process, especially those that are administratively driven.

J. Constr. Eng. Manage., 1997, 123(1): 89-97

NEW SYSTEM MODELING CONCEPT: WORKMAPPING

Concept

The workmap is rooted in the conventional conversion model, in which outputs are provided by processing inputs. Also, it is rooted in the SADT, in which data is divided not only into inputs and outputs, but also to mechanisms and controls. This model was pioneered by (Ballard et al. 1994).

This concept represents the process in a rectangular box; the input, output, and directives in a circle; the feedback for control and breakthrough purposes in a diamond shape; and future learning in an arrow. Fig. 5 illustrates the general format of the workmapping model. It describes the processes with their outputs, the directives that drive them, and the resources they use. Moreover, it can portray the relationship between different types of systems, including production, resource management, planning, and contracting.

Practical Application of Workmap for Construction Planning

The best strategy for introducing and using the workmapping concept is to develop it more methodically. That means to first apply the concept to model a production process, then extend its application to management (administratively driven) processes. Thus, when applying the workmapping concept to the construction process, inputs are resources, outputs are completed work or deliverables, and directives are the plans produced by the planner. Then, applying this workmapping concept to the planning process, inputs tell the planner what work can be done while directives tell him/her what work or results are supposed to be accomplished. Those directives may range over a spectrum from simply specifying goals to specifying the actions to be executed in achieving those goals. These directives are the output of multiple processes, such as estimating, bidding, scheduling, budgeting, quality assurance, policy making, and so forth. Information about construction resources form the input to the planning process. These resources are the output of other processes, such as hiring, training, construction equipment leasing, materials fabrication, purchasing, transportation, information, and so forth.

In the workmap's control process, data are collected on quality, schedule, cost, safety, and other criteria and then compared with the directives. The situation to be analyzed, at this control process, is to whether the system work processes and outputs conform to system directives. It then generates both feedback to the planning process regarding current status of production and corrective action requests to the appropriate upstream decision makers. This may result in changes to the directives governing the on-site construction planning process as shown in Fig. 6. Thus the control process is better named the control/breakthrough process since it will be used not only to control the process, but also to promote breakthrough in the system performance. This function represents the future learning capability inherent by the system.

POWER OF WORKMAP AS EVALUATIVE TOOL FOR PLANNING

Workmap's Evaluative Vocabulary

A major advantage of the new model is its graphical vocabulary that can be used to drive appropriate criteria to evaluate system performance. The writers have utilized this feature

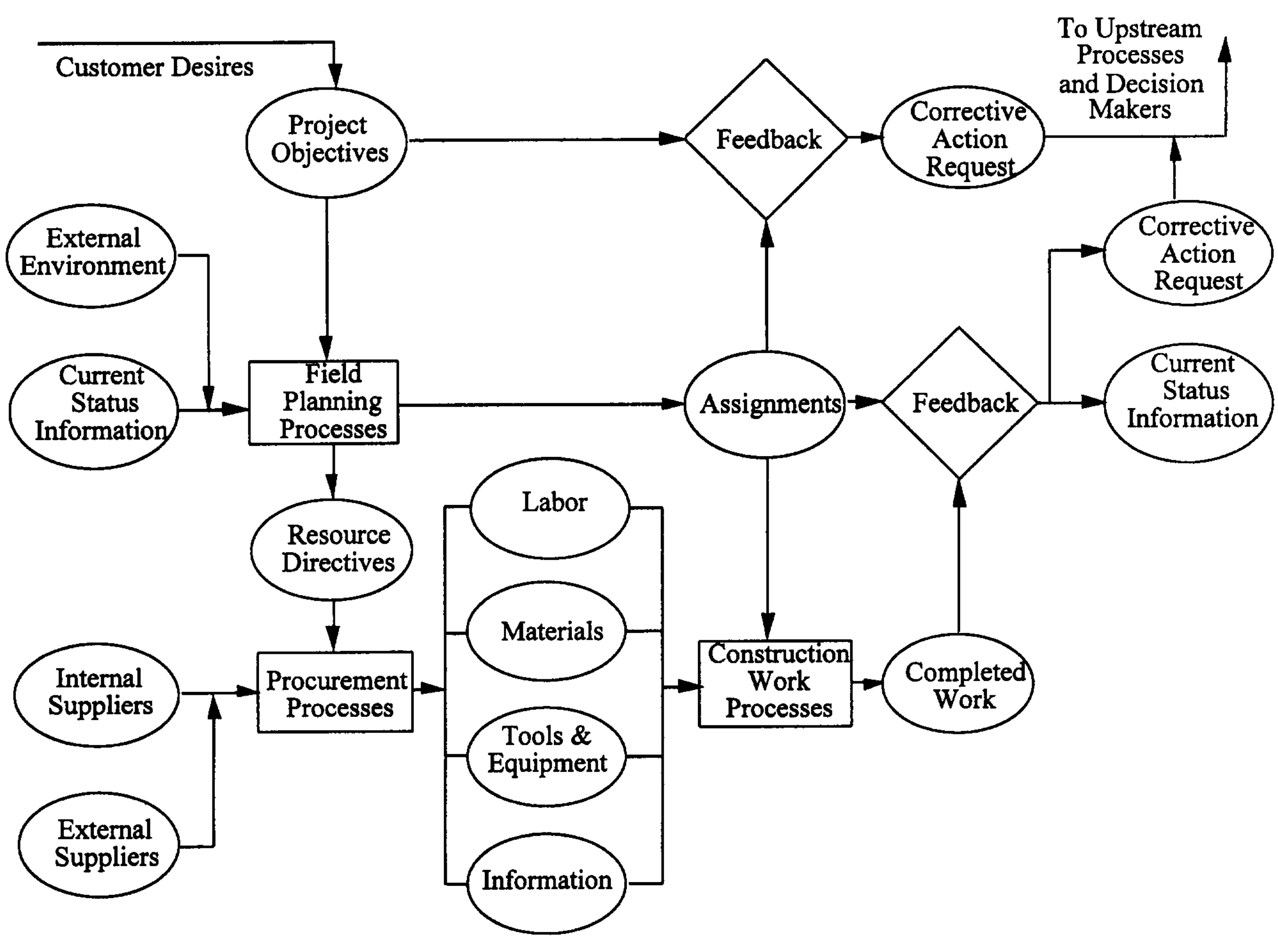

FIG. 6. Generic Construction Planning Workmap

in driving performance criteria for construction planning (Kartam 1995).

Fig. 7 illustrates the evaluative vocabulary of the construction planning workmap. The customer requirements represented in the project drawings, schedule, and budget form the directives or constraints for the planning process. These directives tell the planner what activities "should" be done. This planning process then needs information about resources. This input tells the planner what activities "can" be done. Now the task of the planner is to select from the "should" list the "will" list in view of the "can" list. The "will" list represents the activities that the planner is committing to perform within a specified short period, such as a two-week look-ahead schedule. This list becomes the directives for the construction process. After execution, collecting information on the activities that "did" get done and comparing this information with the "will" list serves to evaluate the executability of plans. Analyzing causes for the activities that did not get executed leads to identifying root causes of problems and evaluating the selection process of planned activities.

Quality Characteristics of Plans

The following can be identifed as quality characteristics of the preceding selection process:

- To select the right sequence of work
- To select the right amount of work
- To select practical work

The right sequence is one that is consistent with project schedules, execution strategies, and constructability. The right amount of work is that amount the planner judges his/her forces can complete after examination of the specific work to be done. Practical work means that all prerequisite work is in place and required resources are adequate and available (Ballard et al. 1994).

Before executing those assignments, a review done by upper management on the list of what "will" be done is a good preventive measure of potential problems. Screening "will" from "should" for those assignments that "can" be done is a prerequisite for insuring quality plans. The preceding quality characteristics guide the inspection process to make sure that the "will" list is consistent with the "should" list and that work selected is appropriate in terms of sequence, amount, and practicality.

Measuring Plan Execution

One key performance measurement developed for construction planning system is percent assignments complete (PAC). This percent can be calculated by dividing the number of completed assignments by the number of planned assignments. It measures the extent to which the planner commitment list, i.e., the "will" list, was realized. This percent, derived from a set of complex directives (project schedules, execution strategies, budget unit rates, and so forth) becomes the standard against which control is exercised. Assuming quality plans, a higher PAC corresponds to doing more of the right work with given resources, i.e., higher productivity and progress.

It is important to note here that the assignments are selected to a crew sized to their target productivity. Given that and the fact that assignments have been screened for workability, crews should not have to decide what work to do from the list

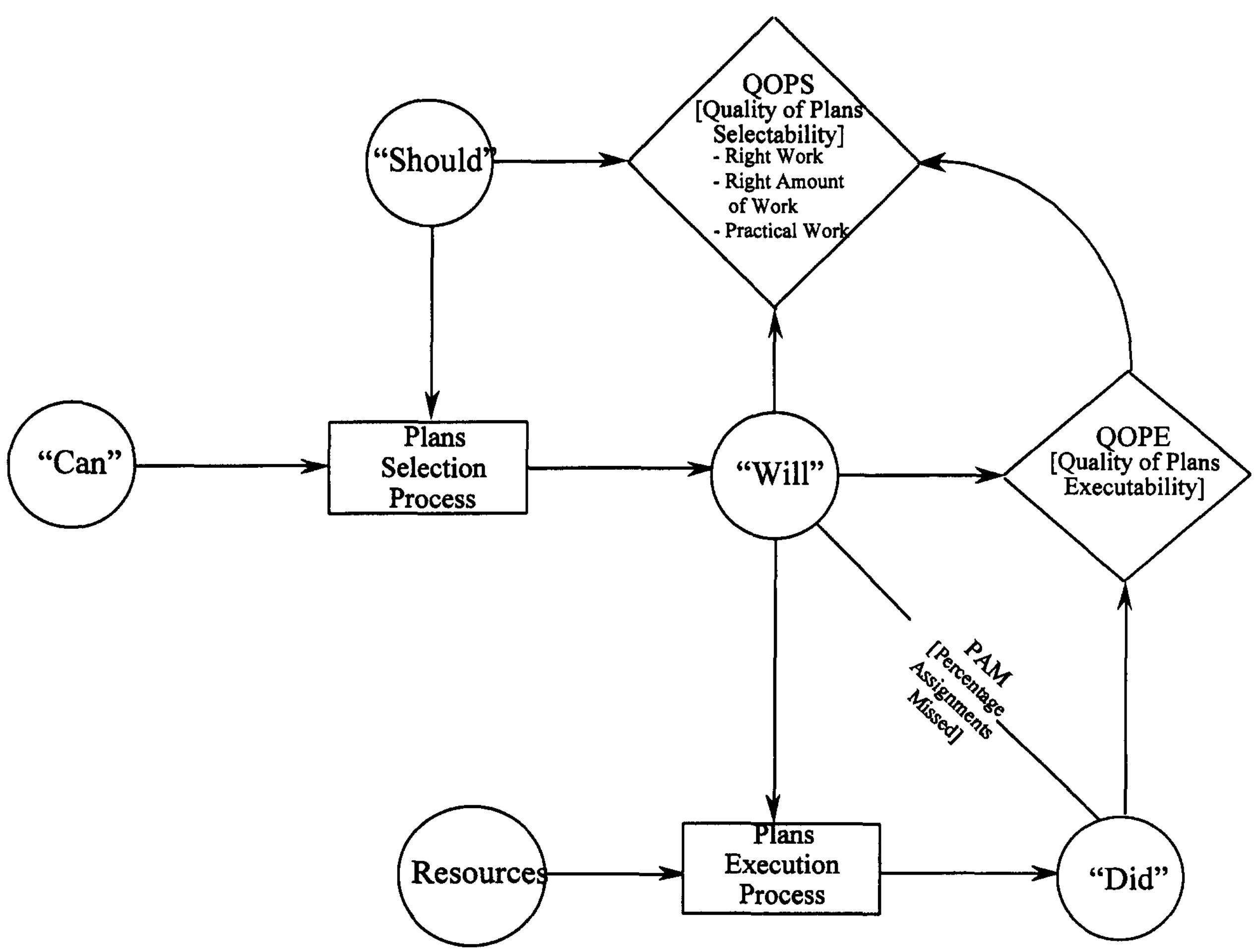

FIG. 7. Generic Vocabulary of Construction Planning System Workmap

J. Constr. Eng. Manage., 1997, 123(1): 89-97

of assignments, but should and should be able to do them all. This explains why the writers assign equal weights to the various assignments selected to be performed within a specific period of time. This also makes the process of calculating PAC much easier and faster.

Improving Percent Assignments Complete

Analyzing the causes for the mismatch between the "will" and "did" lists, which is the percent assignments missed (PAM), is helpful in indicating root causes of failures in planning. Some of those failures are due to execution, while others are due to plan quality. Those failures can be categorized to measure the quality characteristics of plans as mentioned earlier (Kartam 1995). The detailed presentation of these criteria will follow in a subsequent paper.

COMPARING KEY SYSTEM MODELING CONCEPTS

Since the conversion model only portrays a process in terms of transforming inputs to outputs, it neglects processes' interactions in terms of their interdependencies and feedback information; i.e., the "big picture." The dynamic model starts to resolve this deficiency by portraying process feedback. The

TABLE 1. Comparison among System Modeling Concepts

Model/characteristic (1)	Conversion model (Walker's basic model) (2)	Dynamic model (Sanvido's basic model) (3)	Structure analysis and design technique (Chung's basic model) (4)	Workmap model (The writers' basic model) (5)
Portraying the interrelationship among various processes (the big perspective)	none[a]	limited[b]	exists[c]	exists[c]
Inputs differentiation	none[a]	none[a]	broken into resource inputs and constraining inputs[c]	broken into resource inputs and directives (constraints)[c]
Graphic symbols for easier understanding	lines and squares[b]	lines and squares[b]	lines and squares[b]	lines, squares, circles, and diamonds[c]
Feedback loops	none[a]	only for control[b]	for control and future learning[b]	for control, future learning, and breakthroughs[c]
Processes differentiation	none[a]	none[a]	none[a]	uses different four-sided graphical shapes for different processes[c]
The ability to be used as an evaluative tool	doesn't exist[a]	doesn't exist[a]	doesn't exist[a]	serves to derive appropriate system performance criteria.[c]

[a]Disadvantage.
[b]Okay.
[c]Advantage.

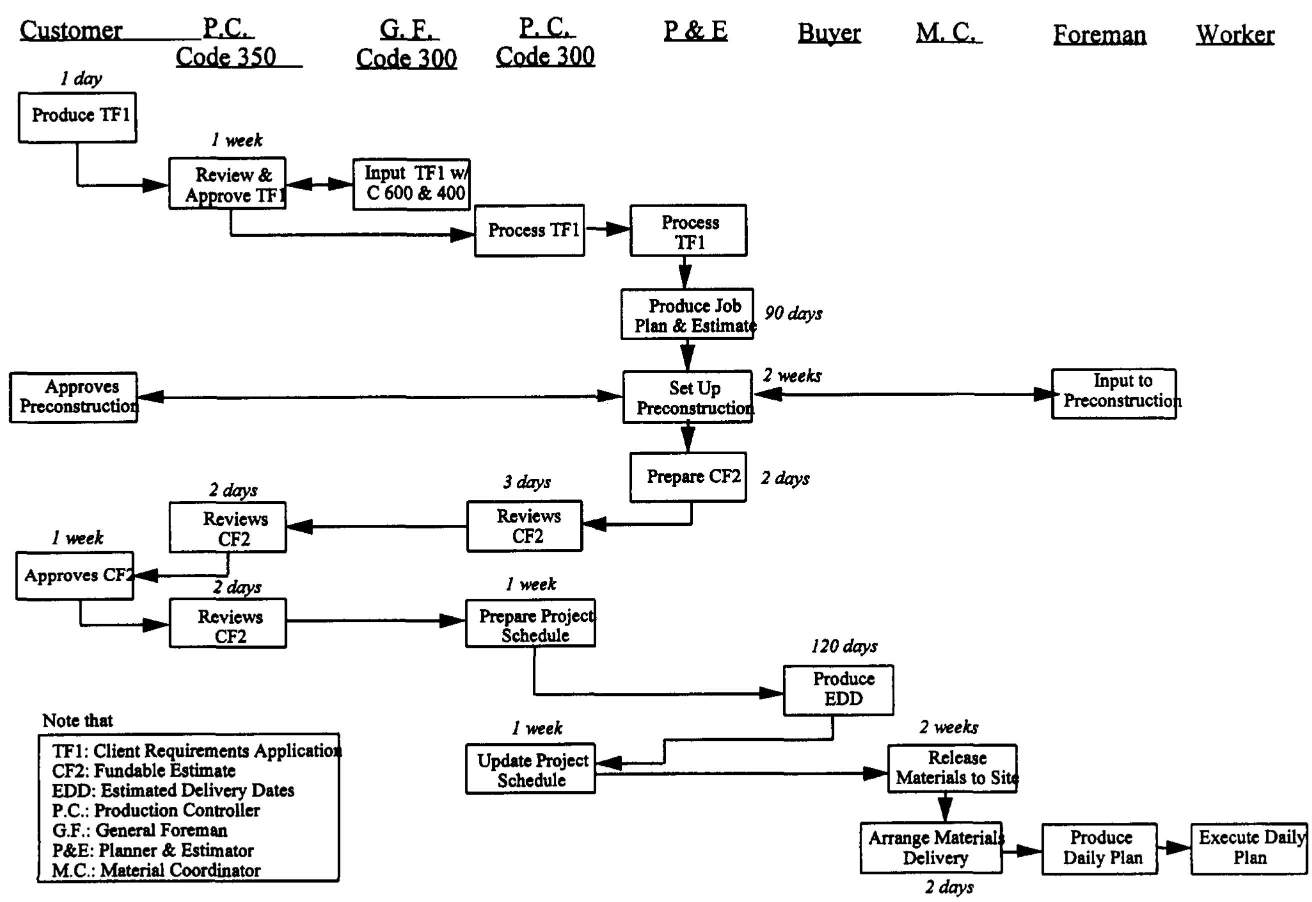

FIG. 8. Interaction Process Matrix

J. Constr. Eng. Manage., 1997, 123(1): 89-97

workmap model and the SADT contribute more to portraying the interrelationships and interdependencies among processes by differentiating between inputs that are directives that drive the production process, and inputs that are resources that are converted in whole or part. Moreover, these two models highlight the use of feedback loops not only for control purposes but also for breakthrough and future learning.

Thus the workmap model and the SADT both possess important modeling advantages over the other models. The major advantage of the workmap model over the SADT is the use of explicit graphic symbols for easier understanding and interpretation. In the SADT, resource inputs, directives, outputs, feedback, control, breakthrough, and future learning are all represented by lines. On the other hand, the workmap model portrays inputs, outputs and directives in circles, control and breakthrough in a diamond shape, future learning in an arrow; and different processes with different four-sided shapes. This characteristic makes the workmap an explicit graphical model that is easier to understand, interpret, update, and verify. Moreover, the detailed graphical vocabulary of the workmap gives it the ability to be used as an evaluative tool.

Table 1 summarizes the comparison among the various system modeling concepts presented earlier with respect to important modeling graphical characteristics. Two major conclusions can be drawn from this comparison

1. The workmapping modeling concept has major advantages over other current system modeling concepts.
2. All of these models are system models. That is, they all lack the value adding concept that a process model has. Thus, to fully model construction, both a system model and a process flow model need to be utilized (Kartam 1994).

CPR SYSTEM MODELS: NEW INTEGRATED APPROACH

In response to the distinction between system and process modeling concepts, the research conducted by the writers has integrated and utilized four different modeling concepts (Kartam and Ibbs 1996). These models have the ability to portray construction systems, processes, and management responsibilities as well as communication channels. The four models used are the communication model (C), the process interaction model (P), the responsibility matrix (R), and the workmapping system model; i.e., the CPR system models. The reason for giving these models this medical acronym is that they have been used successfully to revive management systems in order to be able to compete in the future. The workmapping system model was presented in the previous section. The following section will present the rest of the tools utilized in the new CPR system models approach.

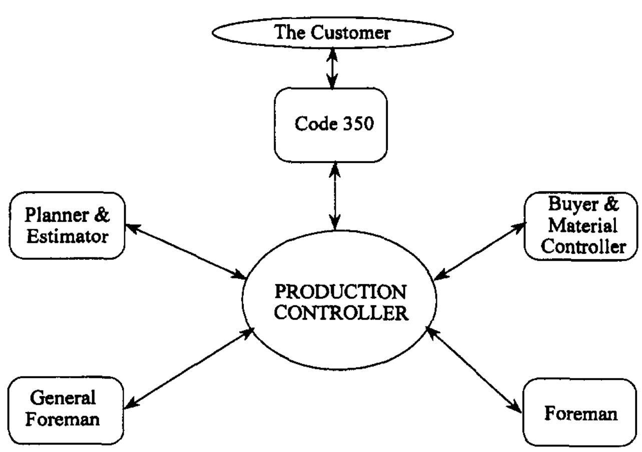

FIG. 9. Communication Process Model

PROCESS CHARTS

Introduction

Another tool used in this research is process charts. Just like workmaps, process charts can be applied to system design, improvement, training, and orientation. In fact, process charts are especially effective when combined with the workmap. While the workmap is a good tool for portraying the system perspective, process charts are good for distinguishing between value adding and nonvalue adding activities in the process. The process chart shows what's inside the workmap's boxes. Two types of process charts are utilized in the CPR system models approach: interaction process matrix and communication process model.

Interaction Process Matrix

The interaction process matrix shows the various steps in the process, their producers, the time consumed in each one, and their logical sequence; see Fig. 8. It illustrates the various steps that constitute the planning process with its duration and sequence along the vertical axis with the various players involved in each planning step across the top. Through this type of process chart, the nonvalue adding activities can be identified and eliminated wherever possible. Another benefit of the process chart is that the time consumed in each step can be analyzed and often reduced. Also overlapping of steps can be indicated. All these can serve to improve the efficiency and effectiveness of the process.

Communication Process Model

The communication process model is another very useful tool that was developed in the course of this research to indicate any communication flaws between the parties in a process. It captures the formal pipelines for information flow. Fig. 9 shows an example of this tool and how it can indicate communication barriers. It is important to note that this model represents only communication channels and doesn't represent authorities or responsibilities. For example, if it was indicated that there is a communication channel between a foreman and the client, it means that they can share information about project progress or clarifications. But it doesn't mean that the foreman has the right to directly approve or make changes to agreements already made with the client.

Responsibility Matrix

Another descriptive tool utilized in the CPR system approach is the responsibility matrix. It indicates how management assigns responsibilities in the current planning system status, and correlating these assignments to performance. Table 2 shows an example of a responsibility matrix as applied in this research. It illustrates the information inputs to resource planning across the top with the various players involved in their production along the vertical axis. It can highlight redundancies or absence of certain responsibilities. It can also indicate how management could assign responsibilities to improve system performance. In addition, the responsibility matrix can be used as an effective orientation and training tool for newcomers in comprehending the distribution of responsibility and how to improve it.

Interrelationships among Descriptive Tools

Each of the modeling concepts utilized in this thesis gives a different perspective of the construction planning system. The four models used are the communication model (C), the process interaction model (P), the responsibility matrix (R), and the workmapping system model; i.e., the CPR system

J. Constr. Eng. Manage., 1997, 123(1): 89-97

models. The reason for giving these models this medical acronym is that they have been used successfully in various case studies to revive management systems in order to be able to compete in the future. The workmap gives the system concept. It views the process in terms of its inputs, outputs, directives, feedback, future learning, and interrelationships with other processes. The interaction process matrix highlights the various steps involved in the process with their sequence and producers, and the time taken by each step. The responsibility matrix views the various parties involved in the process with their corresponding responsibilities to the various plans. The communication model views the information channels among the various parties. It also highlights any communication barrier that exists in the process.

From the preceding description, it can be concluded that each model represents a different perspective, and each one interrelates with other models and shares some of its information. Fig. 10 illustrates the interrelationships among these models. It can be seen that the outputs, inputs, and directives of the system model form the inputs to the responsibility matrix. Also, the rectangular box in the workmap representing a process is detailed in the interaction process matrix. In addition, the parties involved in the interaction process matrix are assigned specific responsibilities in the responsibility matrix

TABLE 2. Responsibility Matrix

Parameter (1)	Customer (2)	Production controller code 350 (3)	Production controller code 300 (4)	General foreman code 300 (5)	Foreman (6)	Planner & estimator (7)	Material department (8)	Worker (9)
Client requirements application (TF-1)	produces	reviews approves	—	inputs reviews	—	—	—	—
Fundable estimate	—	reviews	reviews	—	—	produces	—	—
Fundable estimate (CF-2)	reviews approves	reviews	produces	—	—	reviews	—	—
Job plan	—	reviews	reviews	reviews	—	produces	reviews	—
Pre-construction	inputs approves	reviews	reviews	—	—	produces	—	—
Draw. & Specific.	—	—	reviews	—	reviews	reviews	—	—
Material requisition inventory	—	—	reviews	—	—	produces	reviews	—
Dates materials required	—	—	produces	—	—	—	reviews	—
Estimated delivery dates for resources	—	—	reviews	—	—	—	produces	—
Project schedule	—	—	produces	reviews	reviews	reviews	—	—
Execution	reviews approves	—	—	—	reviews approves	—	—	produces
Customer evaluation	inputs	reviews	produces	reviews	—	—	—	—

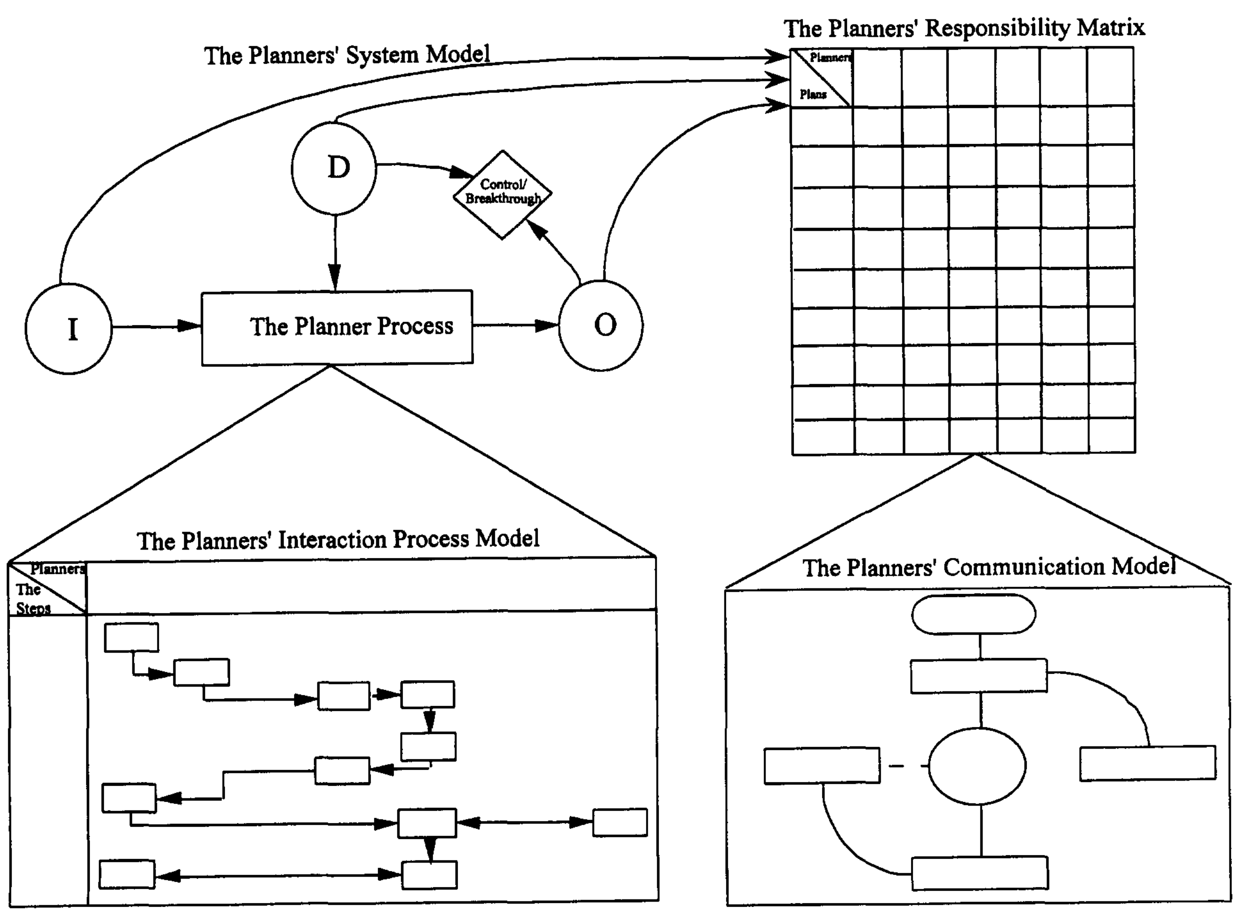

FIG. 10. New Integrated CPR System Models Approach

J. Constr. Eng. Manage., 1997, 123(1): 89-97

and their communication channels are portrayed in the communication model.

Benefits Gained from Applying CPR System Models

The CPR system models were applied successfully to reengineer the planning system of various construction companies. These case studies will be presented in subsequent papers. This paper will list some of the benefits that were achieved in two of these case studies.

One of these companies was the United States Navy Public Work Center in San Francisco Bay (PWCSFB). The Navy PWCSFB gained several benefits from reengineering its planning system. The average project duration was reduced by 50%. Also, the Navy's craft labor productivity improved by 36%. Moreover, the PAC was dramatically improved by 86%. It is important to note that this research succeeded in making all these improvements despite the impending base closure. The support of the Navy's top management was a critical factor in the success and continuation of this research (Kartam et al. 1995).

Another case study where the CPR system models were applied successfully was Dillingham Construction Company. Dillingham Construction gained several benefits from reengineering its planning system. The average project duration was reduced by 20%. Also, Dillingham's craft labor productivity improved by 37%. Moreover, the PAC was dramatically improved by 93%. It is important to note that these improvements occurred over a nine-month period. This indicates that this integrated approach can achieve improvements in a relatively short period of time. This was an important factor in getting everyone in the company to support the continuous implementation of this reengineering approach (Kartam 1995).

CONCLUSION

This paper first reviewed the key models that have been used to represent construction. Through this review the paper demonstrates the advantages and disadvantages of each. While Walker (1985), Sanvido (1984), and Chung (1989) highlight the need for more accurate graphical system models, and Koskela (1992) highlights the need for a process flow model, there should be a bridge to integrate these two modeling perspectives. This bridge is necessary given the important distinction, made in this paper, between process and system modeling concepts.

Thus, the paper presented a new integrated approach to modeling management systems as a response for the major problem in current modeling concepts in their ability to fully and accurately model construction when used in isolation. Each of the modeling concepts utilized in this integrated approach covers a different perspective of the construction planning system. Together they model construction planning systems, processes, and management responsibilities as well as communication channels. This integrated application of viable models to construction planning provides a foundation for effective reengineering effort.

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J. Constr. Eng. Manage., 1997, 123(1): 89-97