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Last thirty years of Construction Management Research

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Abstract

One way to approach construction scheduling optimization problem is to focus on the individual aspects of planning, which can be broadly classified as time scheduling, crew and resource management, and cost control. During the last four decades, construction planning has seen a lot of research, but to date, no paper had attempted to summarize the literature available under important heads. This paper addresses each of aspects separately, and presents the findings of an in-depth literature of the various planning techniques. For techniques dealing with time scheduling, the authors have adopted a rough chronological documentation. For crew and resource management, classification has been done on the basis of the different steps involved in the resource planning process. For cost control, techniques dealing with both estimation of costs and the subsequent optimization of costs have been dealt with separately.

Keywords— *Construction Planning Techniques, Time Scheduling, Resource Planning, Cost Control*.

I. Introduction

There are three main aspects of construction planning: Ttime scheduling, crew and resource management, and cost control. All these three aspects are closely inter-related and proper planning in each aspect is necessary for successful planning of a project. The sequencing of activities, their interdependence and estimates of their duration is essential for creating the basic framework of the overall project schedule. On the basis of this framework, resource allocation is done and costs are calculated. This framework, however, is modified again, subject to availability of resources and money.

The authors have undertaken a thorough review of the literature available that deals with construction planning techniques. Multiple reputed journals like the *Journal of Construction Engineering and Management, Automation in Construction, Practice Periodical on Structural Design and Construction, Journal of Management in Engineering, Journal of the Construction Division, Construction Management and Economics* and others, as well as technical papers presented in conferences were referred for the purpose of this review. During the course of this study, recurring themes were identified and the research has thus been classified into different categories under the three primary heads.

Different problems under each category have been identified and the relevant published research dealing with these problems has been subsequently enlisted. The examples of the papers mentioned herewith are not exhaustive, but have been chosen merely as representative of the specific scope that they deal with. For example, only a couple of significant publications by Zhang and Tem (2003) have been included to illustrate the use of soft computing in the category 'Resource and Material Procurement and Supply', under Crew and Resource Management.

II. Time Scheduling

The first category deals with the traditional methods used for time scheduling like CPM, PERT, LOB, etc. The next category deals with the modifications made to these traditional methods over the years. The third category deals with soft computing which involves application of fuzzy logic, genetic algorithms and other techniques in construction planning. Together, these categories exhaustively cover almost all aspects of the time scheduling process.

A. Classical Methods

The Critical Path Method (CPM) is probably the most widely used technique for construction planning purposes. The CPM model requires a list of all the activities required to complete the CPM project, their durations and the dependencies between the activities. Using these values the CPM model calculates the longest path of planned activities from the start to the end of the project also called the critical path. This critical path basically represents the time that would be required to complete a project. Essential to the success of CPM scheduling are two factors: realistic estimation of productivity of crews in the context of expected job management efficiency conditions, and inclusion of sufficient time buffers between dissimilar trades or crews [1], [2], [3]. These two factors cannot be accounted in the traditional CPM. Hence, it should only be used to calculate a rough estimate of the project completion time.

Another common method used in conjunction with the CPM is the Program (or Project) Evaluation and Review Technique, commonly abbreviated as PERT. PERT is a statistical tool which calculates project completion time based on optimistic time (the minimum possible time required to accomplish a task, assuming everything proceeds better than is normally expected), pessimistic time (the maximum possible time required to accomplish a task, assuming everything goes wrong (but excluding major catastrophes), most likely time (the best estimate of the time required to accomplish a task, assuming everything proceeds as normal. During project execution, however, a real-life project will never pan out exactly as it was planned. Deviation can result from subjective estimates that are prone to human errors, or it can arise from unexpected events or risks. The main reason that PERT may provide inaccurate information about the project completion time is due to this schedule uncertainty. The accuracy of the entire technique depends upon the proper estimation of optimistic, pessimistic and most likely durations. This inaccuracy is large enough to render such estimates as unusable.

One of the simplest methods used for construction planning is the Gantt chart. Gantt charts illustrate the start and finish dates of the terminal elements and summary elements of a project. Terminal elements and summary elements comprise the work breakdown structure of the project. Some Gantt charts also show the dependency (i.e. precedence network) relationships between activities. One of the main advantages of this method is its simplicity. Apart from that it also provides visual aid. However the application of this method is not feasible for large projects and also fails to take into account the actual uncertainties during construction. So, it is advisable to use this method for mini scheduling only.

Contractors always strive to minimize the project duration so as to obtain an advantage during a bid's evaluation. For example, they may 'crash' a project's duration (i.e., the shortest possible time for which an activity can be scheduled) by allocating more resources (if sufficient resources are available) to expedite construction activities. However, crashing a project's duration invariably increases the cost, as additional resources are required. This is due to the interdependency that exists between time and cost. For example, compressing a project's duration will lead to an increase in direct costs (plant and equipment, materials and labour cost) and a decrease in indirect costs (project overhead), and vice versa. Reda and Carr [4] describe a Time Cost Trade off technique in which they calculate the cost that will be incurred for different durations of the project. Using this method the duration for which minimum cost will be obtained can be calculated.

One of CPM's drawbacks is its inability to deal with repetitive projects like construction of roads, highways, etc. in a convenient manner [5] Linear scheduling techniques are known to be the most suitable methods for the overall management of such types of construction projects. The line-of-balance technique is one of these linear scheduling methods using known scheduling methods such as the critical path method (CPM), program evaluation and review technique (PERT), and bar chart, and it does not replace them [6]. Linear scheduling methods provide an alternative way of scheduling repetitive projects, to the commonly used network methods [7]. Chrzanowski, and Johnston [8] described the development of the linear scheduling techniques and its algorithms. The line-of-balance (LOB) method of scheduling is well suited to projects that are composed of activities of a linear and repetitive nature only. The challenges associated with LOB scheduling include developing an algorithm that handles project acceleration efficiently and accurately, recognizing time and space dependencies, calculating LOB quantities, dealing with resource and milestone constraints, incorporating the occasional nonlinear and discrete activities, defining a radically new concept of criticalness, including the effect of the learning curve, developing an optimal strategy to reduce project duration by increasing the rate of production of selected activities, performing cost optimization, and improving the visual presentation of LOB diagrams [9]. Arditi, and Albulak [10] showed the benefits and shortcomings of the LOB (Line of Balance) technique with the help of a highway construction project. It was determined that LOB is extremely sensitive to errors in man-hours, crew size, and activity duration estimates. There are also problems of a visual nature with the presentation of the diagram. Due to the various challenges associated with this method and its limited scope, very little research has been done in this method.

B. Modifications to Classical Methods

The main problem with most of the classical methods was their failure to account for the uncertainties during construction which lead to delays. Over the years a lot of research has been done in order to do away with this problem.

The main drawback of the critical path method was its inability to account for actual practical situations during construction. Often, during construction, activities are interrupted due to impacts of uncertain events like severe weather and unforeseen harsh geological conditions, resulting in altered critical paths. From a project management perspective, this means that given uncertain conditions, some non-critical activities have a likelihood of becoming critical during the project execution and vice versa. The classical CPM does not account for change in critical paths. Hegazy and Menesi [11] came up with a critical path segment (CPS) technique to predict the likelihood of an activity becoming critical during the construction process. Jung et al. [12] proposed a methodology to automatically generate CPM schedules for preliminary project planning. Historical labour productivity is utilized as a governing parameter to convey the previous experiences into a new project. Sturts Dossick and Schunk [13] suggested that it would be much more efficient if each subcontractor has a trade-specific critical path method (CPM) schedule. The interrelationship between the CPM schedule, internal reporting, schedule of values, and labour tracking is also shown. Over the years many authors compared the critical path method with other methods like linear scheduling, activity based simulation; design structure matrix method [14].

Cottrell [15] and Lu and AbouRizk [16] tried to modify PERT so that more realistic results could be obtained. The simplification is to reduce the number of estimates required for activity durations from three, as in conventional PERT, to two. The two required duration estimates are the ''most likely'' and the ''pessimistic.'' Since the number of estimates have been reduced, more accurate results would be obtained. People have even tried to modify Gantt charts so that it can be of use in modern times. Kannan and Carr [17] wrote a discussion paper on this. Melin and Whiteaker presented a computer graphics system which can be used by project managers and planners to display the project activities and the logical order of the activities on a time-scaled bar chart. The system called a "fenced bar chart" clearly displays the critical path and the path float on each of the other paths and emphasizes the logic order of, as well as when, the activities should be accomplished. Hegazy et al. [18] suggested a method for keeping better site records using Intelligent Bar Charts. They proposed bar chart guides the user through progress reporting by observing any conflict with the planned logic of the work. It automatically recognizes the occurrence of delays and asks the user to record the responsible party and the reasons. Based on percent completed and recorded delays, the bar chart recognizes the progress status of activities as being slow, suspended, or accelerated.

Relatively less research has been done in the field of linear scheduling models mainly due to its limited scope. In order to expand the scope of LSM, Reda [19] suggested a similar method called repetitive project modelling. This model incorporates a network technique, a graphical technique, and an analytical technique in a unified approach to model repetitive projects. Ammar [20] developed an integrated CPM and LOB. By combining the two techniques, most of their individual drawbacks are done away with. The method is applicable to both repetitive and non - repetitive projects and is both analytical and graphical. Suhail and Neale [21] also did research in this method. Yang [22] addressed the deficiencies of these two classical methods (CPM and LOB) and presents a new scheduling system, repetitive scheduling method (RSM). The application of RSM is demonstrated by scheduling a real-life pipeline project. It is shown that RSM helps perform the what-if analysis quickly and reliably with necessary modeling capability and calculation power. Zhang et al. [23] compared RSM to normal network models like CPM. Duffy et al [24] tried to expand the capabilities of linear scheduling to account for variance in production rates when and where the variance occurs and to enhance the visual capabilities of linear scheduling. Hegazy and Kamarah [25] applied this same method to high rise buildings which have similar floors.

C. Soft Computing

Soft computing techniques like fuzzy logic, genetic algorithm, etc. have also been used in construction planning. These methods have many advantages, like they can take into account the various uncertainties that occur in construction planning. Most of these techniques use computer simulation software so the manual work involved is quite less. However a detailed knowledge of these techniques is required in order to apply them in construction planning.

Fuzzy logic is a form of many-valued logic; it deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets (where variables may take on true or false values) fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. In the computer science field of artificial intelligence, a genetic algorithm (GA) is a search heuristic that mimics the process of natural selection. This heuristic (also sometimes called a meta-heuristic) is routinely used to generate useful solutions to optimization and search problems. Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover.

Many researchers have applied soft computing to construction planning. Lorterapong and Moselhi [26] presented a new network scheduling method based on fuzzy logic to estimate the durations of construction activities. The proposed method incorporated a number of new techniques that facilitate: (1) the representation of imprecise activity durations; (2) the calculation of scheduling parameters; and (3) the interpretation of the fuzzy results generated. Kumar and Reddy [27] also used fuzzy logic approach to forecast project duration of construction projects. Their methodology identifies the project duration by incorporating qualitative as well as quantitative factors of the construction industry. The qualitative factors are converted into numerical measures by giving suitable membership values. Zhang et al. [28] observed that it is always problematic to define uncertain information input for construction-oriented discrete-event simulation. Therefore, they proposed incorporating FST with discrete-event simulation to handle the vagueness, imprecision, and subjectivity in the estimation of activity duration, particularly when insufficient or no sample data are available. Zhang et al. opined that the duration and cost of each construction activity could change dynamically as a result of many uncertain variables, such as productivity, resource availability, and weather. Project managers have to take these uncertainties into account so as to provide an optimal balance of time and cost, based on their own knowledge and experience. For this reason, FST was applied to model the managers' behavior in predicting time and cost pertinent to a specific option within a construction activity. Chan et al. [63] presented a complete review of fuzzy techniques in construction management.

Some attempts have also been made to apply soft computing to line of balance technique and time cost trade off technique. Damci et al. [29] proposed a method to perform multi resource levelling in LOB scheduling. They develop a genetic algorithm (GA)-based multi-resource leveling model for schedules that are established by LOB. Feng et al. [30] argue that traditional time-cost trade-off analysis assumes that the time and cost of an option within an activity are deterministic. However, in reality the time and cost are uncertain. Therefore, in analyzing the time-cost trade-off problem, uncertainties should be considered when minimizing project duration or cost. So, they use fuzzy set theory and genetic algorithm to analyze this problem.

Genetic algorithm has been used with simulation techniques to provide an efficient and practical means of obtaining optimal project schedules while assessing the associated risks in terms of time and cost of a construction project. By using historical data even better strategies can be developed to complete the project at minimum time and cost. Lu [31] used artificial neural networks to enhance PERT. An artificial neural network (ANN)-based approach to estimate the true properties of the beta distributions from statistical sampling of actual data combined with subjective information is presented. The minimum and maximum values along with the lower and upper quartiles are four time estimates used to uniquely define a beta distribution.

Another drawback of the classical methods is their inability to modify the results based on the actual progress of the project. Construction projects are subject to unexpected factors such as weather, soil conditions etc., which cause frequent changes in baseline schedules. Hence, many simulation techniques have been developed which take all this into account. Oliveros and Fayek developed a fuzzy logic model that integrates daily site reporting of activity progress and delays, with a schedule updating and forecasting system for construction project monitoring and control.

I. Crew and Resource Management

Research in this area has been divided into five categories, which form the steps of the crew and resource management process. The first category here deals with the techniques used to decide *when and where*, for which activity, resources and labour have to be used, i.e. scheduling. The second category includes techniques describing *how* these resources and labour should be used: the optimum configurations, effective timetables and rotation, etc. The third category is concerned with the measurement of the crew's performance, so as to determine their productivity (which is used to allocate and/or adjust durations for different activities), as well as what factors affect said productivity. The fourth category details techniques dealing with modification in the schedules by taking into account real time data, thereby differentiating it from the first category which is mostly concerned with the initial planning stages. The fifth category mainly entails logistics planning techniques, with a focus on resource procurement and mobilization and the supply chain of the construction process. Together, these categories exhaustively cover almost all aspects of the resource and crew management process.

A. A. Crew and Resource Scheduling

For clarity's sake, let us define 'crew' and 'resources'. The term 'Resources' in this paper shall henceforth include labourers, earthwork equipment, transit equipment, and other multipurpose machinery, but rarely include construction materials. The term 'crew' shall exclusively refer to labourers, inclusive of but not limited to skilled and unskilled labour like masons, carpenters, helpers, et al. 'Labour' and 'Crew' are interchangeably used.

Many papers focus on integrating resource allocation directly into the primary schedule, as opposed to preparing a distinct resource calendar, so as to tackle the problem of delays in one calendar affecting the other. Lu and Li [2] addressed the fundamental problem of 'resource-critical activities' and the effect availability of resources has on the CPM schedule, by proposing a method called 'Resource-Activity Critical Path Method' Scheduling. This highlighted the dimension of resources in addition to activity and time, and defined start/finish times and floats of activities as attributes of both the activity and resources. Lu and Lam [32] then proceeded to tackle the problem of the effect of resource calendars on the CPM schedule, when resource calendars postpone activity start time, extend activity duration, prolong the total project duration, thereby bringing changes to the critical path identification. They analyzed the resource scheduling function in the popular software P3, and compared the results with a new method that they proposed, based on forward pass analysis alone. Perera [33] also worked towards integrating resource allocation into the primary schedule, and developed a method in which 'resource-hour units' are employed. The method used linear programming to determine the maximum rate of construction and the resource requirements in various activities.

Weekly crew scheduling was another issue taken up in many papers. The present standard is a 5-day, 8 hour work-week. Innovative crew scheduling techniques were also proposed, among which Gould [34] proposed a crew scheduling method called 'Rolling Fours'. This described a system having two sets of crews, which would work alternately for a period of four days consecutively for 10 hours each day, while the other crew would rest. This aimed at increasing leisure and resting time, so as to boost productivity. While this claimed to shorten duration by around 30%, it also led to increase in costs due to employee-related overheads, as well as more difficulty in supervision and coordination. Hanna et al. [35] surveyed the standard crew schedules including those that require crews to work 40 h per week, including five 8-h days, four 10-h days, or a second shift. They also considered overtime schedules which require crews to work additional hours beyond the standard 40 h per week. In addition to the standard and overtime schedules, other crew-scheduling techniques were considered, like rolling crews and complimentary crews. Their paper then came up with results about the impact of such crew-scheduling techniques on project performance.

More efficient usage of multi-skilled resources has also attracted substantial research. Hegazy et al. [36] were some of the first people to propose heuristic models for utilizing multi-skilled resources to a greater extent. They did so by proposing that a labourer be substituted to work for an activity he's not primarily supposed to do, but is capable to perform, if said activity faces a shortage of resources. Similar to this method in essence, but not in execution, was an idea proposed by Wongwai [37]. He too, advocated usage of multi-skilled labourers in multiple operations, but instead of substitution as proposed by Hegazy et al, he proposed that the critical activity claim all resources from its concurrent activities if the need be such, at the expense of their delay.

B. B. Crew Design

Gates and Scarpa [38] were among the early publishers in the field of crew design. They tried to tackle the problem arising from the experience curve theory, according to which, one man working 100 hours is more productive than 100 men working 1 hour or any other analogously paired data. This leads to contrasting conclusions about extended and contracted timetables. Gates and Scarpa formulated these circumstances, related them mathematically, and then solved to find the optimum manpower and the optimum construction time that minimizes costs.

Hassanein and Melin [39] published a set of papers investigating the methods used by contractors in designing the configuration of their workforce, or crews, for their daily activities. In 1997, they made attempts to clarify the methods adopted, particularly in the mechanical and electrical trades by examining and validating preliminary crew design algorithms for masonry and reinforced concrete construction contractors; and examining and developing crew design algorithms for the mechanical and electrical contracting areas of specialization. Earlier, Hassanein and Melin had investigated four major subcontracting areas, namely: (1) reinforced concrete; (2) masonry; (3) mechanical aspects; and (4) electrical aspects. Within each of the four subcontracting areas contractors were interviewed and rules of thumb for crew design and makeup were elicited and analyzed.

Maxwell et al [40] tried to develop and illustrate a technique for finding the optimum crew configuration from a range of possible configurations, assigned to complete a defined quantity of work in a timely and cost-effective manner. The concept of activity-based costing was used to define the scope of the work in terms of the activities to be accomplished and their associated productivity rates and cost of performance. An activity based, stochastic simulation program (ABC-SIM), was used to measure the elapsed time and activity cost for each of the candidate crew configurations. Jun and El-Rayes [41] tried to utilize multiple shifts and developed a multi-objective optimization model for the same, that was capable of generating optimal tradeoffs among project duration, project cost and utilization of evening and night shifts. Thomas et al. [42] introduced the concept of symbiotic crew relationships. A symbiotic relationship occurs when the work pace of one crew depends on the pace of a preceding crew. The used data from steel reinforcement activities from six commercial and residential projects in Brazil to demonstrate the negative effects of symbiotic relationships.

Soft computing techniques like fuzzy logic have also been employed. Dawood and Al-Bazi [43] wrote a paper about a crew allocation system using Genetic Algorithms-based simulation modelling. Christodoulou [44] proposed an Ant Colony Optimization (ACO) approach to resource allocation in repetitive construction schedules constrained by the activity precedency and multiple resource limitations. Other techniques like artificial neural networks have also attracted research, but direct application in the industry is limited, due to lack of knowledge among professionals.

C. C. Crew Performance Measurement

Measuring productivity and performance is a very important aspect of crew scheduling and design, which are based on some assumptions of output. A variety of studies measuring performance of crew as well as what factors have an impact on it have been conducted, and methods to conduct further such studies been suggested.

Thomas and Sakarcan [45] compared two approaches for comparing labour productivity. The first approach is to divide the current work-hour total by the percent complete (PC) of the activity. The second method used the factor model to develop a predicted labour-productivity curve. Actual deviations from this curve were reflected in the labour-productivity forecast at completion. The paper detailed how the predicted curve and the forecast are made.

Thomas and Daily [46] wrote a paper in which three methods of measuring the performance of construction crews were described and compared. These were Work sampling, Group timing technique; and Five-minute rating. By gathering data from a time-lapse film, the three methods can be compared for the same operation. Various parameters are calculated throughout, and it is suggested that over a period of time, these can be used to monitor crew performance. Kazaz et al [47] tried establishing clear and understandable criteria for the factors affecting labour. The factors influencing construction labour productivity in Turkey were determined, defined, and examined in detail by them. A survey was applied to 82 firms to obtain required data. According to results, the most effective factors group was found to be organizational factors.

Hanna et al [48] reviewed and furthered the studies of the impact of over-manning (defined as increase of the peak number of workers of the same trade over actual average manpower during project) on construction labour productivity.

Nepal et al. [49] wrote a paper that analyzed the effects that schedule pressure has on construction performance, and focused on tradeoffs in scheduling. The results of their survey data analysis indicated that advantages of increasing the pace of work—by working under schedule pressure—can be offset by losses in productivity and quality. Hanna et al. [50] studied the impact of overtime (hours worked over 40 hours a week) on construction labour productivity and came up with comparable conclusions.

This field has probably attracted the maximum amount of research in crew and resource planning. Factors affecting productivity in different countries have been studied, attempts have been made to quantify the effect of these factors. Different factors like motivational factors, supervision, timings, shift work etc. have all been documented in a multitude of papers.

D. D. Real Time Modification in Resource Allocation

Analysis of the actual on-site data, and required modification of the schedule and resource allocation in real time is something that is encountered by almost all contractors. Many a paper has focused on this aspect and tried to build models that take into account the progress of the project.

Tavakoli [51] presented guidelines are based on the best practices back then and modified management techniques to reflect their on-site implementation and the practical aspects of daily field records. His guidelines were for the following areas: (1) Progress scheduling (including the use of bar charts); (2) monitoring of progress (S-curves); (3) capturing of productivity rates and their utilization; (4) the feedback process; (5) settlement of claims and disputes through documentation; and (6) computer utilization and applications.

Mustafa Pultar [52] was another researcher who published a paper about progress-based scheduling, which used GANTT charts to overcome problem of fragmentation of activities during the application of the conventional critical path and precedence diagramming methods to construction projects.

To accommodate changes like weather, soil conditions, etc. that alter the baseline schedule, Horenburg [53] introduced a method to optimize construction schedules continuously based on the current progress considering all relevant resource capacities. Actual state data is progressed and variations in level of detail between construction works and the virtual model are levelled.

In conventional updating of CPM schedules, total floats need to be re-evaluated every time some activities are delayed to non-availability of resources, which requires backward or forward pass analysis of the entire schedule. To tackle this issue, Shanmuganayagam [54] proposed resources scheduling using a simple heuristic model described as the "current float" model. Current float is defined as the finish float available with respect to its latest finish time in the original network computations. The current float model allocates limited resources by giving priority to the activity that has the least current float.

Kim and Garza [55] presented a Resource-constrained Critical Path Method (RCPM) technique that capitalizes on and improves the Critical Path Method (CPM) and Resource-Constrained Scheduling (RCS) techniques, which have been mentioned earlier. Somewhat similar to Lu's resource scheduling technique discussed earlier in Category 1, this technique identifies real floats and the correct critical path, considering both technological and resource dependent relationships. A prototype RCPM system is integrated with Primavera Project Planner (P3), so that it reads real time project information directly from a P3 project, performs necessary RCPM procedures, and updates the P3 project to contain identified resource relationships.

Among the more modern techniques, Poku and Arditi [56] developed a system called PMS-GIS (Progress Monitoring System with Geographical Information Systems) to represent construction progress not only in terms of a CPM schedule but also in terms of a graphical representation of the construction that is synchronized with the work schedule. Other similar models that use Geographical Information Systems for resource allocation can also be found in literature.

Soft computing has also found extensive use in this field. Zhang and Tam [28] opined that timely resource allocation is a dynamic decision-making process dependent on real-time information during a construction process. Having considered operational and stochastic characteristics of construction operations and the fuzziness of multiple-decision objectives for an appropriate allocation policy, Zhang and Tam developed a fuzzy dynamic resource allocation based on fuzzy set/fuzzy logic and the fuzzy decision-making approach. They explained that this model can finally help improve construction productivity by making the best use of resource allocation.

E. E. Resource and Material Procurement and Supply

Handling of logistics and supply chain management have a great impact on any project schedule. For example, in India, one of the most common reasons for project delays is delay in the initial mobilization of resources. While certain processes from the manufacturing industry have been adopted into the construction industry to tackle this issue, not a lot of literature can be found dealing with handling of logistics. Some of the papers, however, which deal with this particular aspect, are enlisted below.

Ballard and Howell were among the first to have applied the popular optimization method 'Just-in-Time' used in the manufacturing industry to the construction industry. Manufacturing JIT is a method of pulling work forward from one process to the next "just-in-time"; i.e. when the successor process needs it, ultimately producing throughput. One benefit of manufacturing JIT is reducing work-in-process inventory, and thus working capital. An even greater benefit is reducing production cycle times, since materials spend less time sitting in queues waiting to be processed. However, the greatest benefit of manufacturing JIT is forcing reduction in flow variation, thus contributing to continuous, ongoing improvement. This method is applied in construction where precast concrete blocks or similarly prefabricated structures are used. Pheng and Chuan [57] wrote a paper discussing 'Just-in-Time' management of precast concrete components.

Ballard and Howell also wrote about the concept of Lean Construction, which is similar to the JIT philosophy. Lean construction focuses on reduction of waste and management of flows. A lot of literature can be found that investigates the extent of implementation of lean construction practices in different parts of the world, for example Collin Korana et al investigated its applicability to small construction projects in the Midwestern United States; Tezel and Nielsen [58] did the same for construction managers in Turkey.

Horman and Thomas [59], however, were some of those who conducted studies that critically analyzed the application of such philosophies in construction. In construction projects, where conditions are often uncertain and variable, some have suggested that buffers be sized and located according to the conditions. Horman and Thomas pointed out that inventory buffers, apart from affecting the time and cost aspects of the schedule, also have an impact on labour productivity. They then analyzed this relationship between inventory buffers and construction labour performance.

Jiang et al. [60] wrote a paper that measured performance of the supply chain management system in construction by means of a case study. Said and El-Rayes [61] pointed out that material procurement and storage layout are considered as two separate planning tasks in most research studies, without considering their critical and mutual interdependencies. The presented an optimization model that is capable of simultaneously integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites, using genetic algorithms.

Among the newer techniques that use soft computing, Ng et al. pointed out that many procurement selection models fail to address the fuzziness of selection criteria used for procurement selection. To tackle this problem, they used a modified horizontal approach to establish the fuzzy membership function of procurement selection criteria through an empirical study conducted in Australia.

Priluck [62] said that when scheduling logistic support for a project in conjunction with the project's critical path method (CPM) schedule, logistic support items should not be included as activities on the project CPM schedule. Logistics support should be scheduled using an algorithm that facilitates the early start of the CPM schedule activities. This approach avoids the unnecessary costs of procuring resources before they can be effectively utilized. This directly addresses the problem of mobilization delays prevalent in construction industries like India.

II. COST CONTROL

Planning of cash flows is a very important part of the construction planning process. This has two aspects: cost estimation – estimating the total cost of a project using prevailing market rates of the material and labour; and cost optimization – methods to ensure that the amount of money used is minimum. Different kinds of cost estimating techniques include usage of microcomputers, web-based tools, software packages, database warehousing, and some traditional paper-pen techniques followed by majority of engineering consultants in India. Estimation also involves probabilistic analysis, particularly useful in the scheduling of repetitive projects. Regression models, Time-Series Models, Statistical analysis, Case-based reasoning, and Neural Networks are some other techniques employed for the same.

A.

B. A. Cost Estimation

Introduction of microcomputers in the 1980s had a significant impact on the traditional data processing procedures of the construction industry. Copyrighted electronic spreadsheet packages such as VisiCalc and SuperCalc were then available to practically all microcomputer users. These spreadsheet packages provided construction contractors, owners and managers with a versatile management tool that could be applied to a wide range of construction-related problems [64]. A microcomputer system could perform the functions of estimating, cost control, and scheduling at the same time. It may make use of productivity of a crew of particular size, the materials and the equipment needed to generate time data related to scheduling and the cost data related to estimating and cost control. The software needed for implementing it was an electronic spreadsheet program, a data base management program and a time management program available for most microcomputers at a relatively inexpensive cost [65].

Database Warehousing involves having a well-prepared digitized historical project database (files containing past project records) which would contain observed crew productivities and a description of project conditions affecting productivity. A major improvement to the current computerized estimating methods would be to incorporate a mechanism in the software system that allows determining an appropriate productivity for a work item based on the conditions of the project being estimated. One way to accomplish this is by using the productivity information from projects that a company has taken up in the past. If estimating software were given access to a digital library of historical cases, it would be possible to query the library for an appropriate productivity for the conditions of the project being estimated [66]. However, its feasibility is an issue because of the questionable accuracy of the construction project data held by a contractor, as well as the fact that every construction project is vastly different.

Software packages can also be very handy in construction cost estimating. One such software, RACoPro, has been used in risk assessment of full-scale projects. It has also been used for computing probabilities of costs using cases, by combining probabilistic analysis with case-based reasoning. Using RACoPro, the probability distribution functions of independent variables and their relationships with dependent variables are constructed through an analysis of relevant past projects. These are then used to compute the joint probability distribution functions using statistical techniques such as Monte-Carlo simulation and numerical integration [67]. Another such software is ProCost, a cost estimating package, based on Artificial Neural Network technology, which is used to produce single figure estimates of the total building cost [68]. Software based on Artificial Neural Networks fare better in accuracy as compared to those relying on regression analysis.

Niknam and Karshenas [69] proposed “A Semantic Web Service Approach to Construction Cost Estimating”, in which the semantic web technology structured data according to formal ontologies intended to promote machine understanding, Semantic web services provided interfaces for publishing information. The proposed estimating approach required that suppliers encapsulate their product information within appropriate interfaces and made this information available to contractors through web services. Estimating software applications could then retrieve the latest cost data from suppliers’ web services. This method could easily do away with the hassles of estimating via statistics/cost indexes.

Regression analysis, probability, time series models etc. are some of the statistical methods of construction cost estimating. Such estimating techniques are tested on the basis of their accuracy, that is, the more accurate the estimating technique, the better suited the technique is.

Isidore and Back [70] simultaneously applied range estimating and probabilistic scheduling to the historical data. This procedure addressed some of the major shortcomings of least-cost scheduling. It provided compressed schedule duration and cost estimate that had a higher overall confidence of being achieved.

Regression analysis is quite commonly used for prediction of construction cost indexes, which are ultimately used to predict construction costs for different activities. A price index is a normalized average of price relatives for a given class of goods or services in a given region, during a given interval of time. It is a statistic designed to help to compare how these price relatives, taken as a whole, differ between time periods or geographical locations. Lowe et al. [71] suggested use of multiple regression techniques to predict construction costs. Hwang [72] proposed two dynamic regression models for the prediction of construction cost index. Comparison of the proposed models with the existing methods (linear regression, multiple regression etc.) proved that the new models were far more accurate than the existing methods. In 2011, he built two time series models by analyzing time series index data and comparing them with existing methods in the present study. The developed time series models accurately predicted construction cost indexes.

A combination of regression analysis and bootstrap resampling technique can also be used to develop range estimates for construction costs. The bootstrap approach includes advantages of probabilistic and parametric estimation methods, as it involves the integration of these methods. At the same time it requires fewer assumptions compared to classical statistical techniques [73]. Apart from construction cost indexes, regression can also be used in accuracy testing of cost estimates. Trost and Oberlender [74] tried to predict accuracy of early cost estimates using factor analysis and multivariate regression. They tried to develop a model that could enable estimators and business managers to objectively evaluate the accuracy of early estimates. The five most important factors in determining accuracy of the estimate, in order of significance, came out to be basic process design, team experience and cost information, time allowed to prepare the estimate, site requirements, and bidding and labour climate.

Kim et al. [75] examined the performance of three cost estimation models. The examinations were based on multiple regression analysis (MRA), neural networks (NNs), and case-based reasoning (CBR) of the data of 530 historical costs. Although the NN estimating model gave more accurate estimating results than either the MRA or the CBR estimating models, the CBR estimating model performed better than the NN estimating model with respect to long-term use, available information from result, and time versus accuracy tradeoffs.

Williams et al. [76] analyzed bidding statistics to predict completed project cost. Ratios were constructed relating the second lowest bid, mean bid, median bid, maximum bid to the low bid for highway construction projects in Texas to study if there are useful patterns in project bids that are indicators of the project completion cost. It was found that the value of the ratios tend to be larger for projects where the completed cost deviates significantly from the original low bid.

Rasdorf and Abudayyeh [77] discussed the issues and needs in cost-and-schedule control integration. They provided an overview of cost-and-schedule-control functions, defined the desired control cycle, and discussed the problems and needs of cost- and schedule-control functions. The work-packaging model was briefly described and was suggested as the most likely existing model to achieve the desired cost and schedule integration. Finally, the conceptual design of a foundational data model for control, based on relational concepts, was provided. The recommended design adopted the conceptual structures of the work-packaging model.

Liu and Zhu [78] proposed “Improving Cost Estimates of Construction Projects Using Phased Cost Factors”. They attempted to identify the critical factors for effective estimation at various stages of typical construction projects. Drawing from organization control theory and cost estimating literature, their note develops a theoretical framework that identifies the critical factors for effective cost estimation during each project phase of a conventional construction project. The underlying logic is that as a cost estimating effort progresses, both task programmability and output measurability improve. As a result, control effort shifts from input-oriented control to a combination of output and behavior control.

Abdul-Malak and Azhar [79] came up with a paper named “Use of Historical Overhead Costs for Estimation and Control Purposes”. Their paper examined the components of the project overhead costs through a thorough study of actual cost data from building-type projects undertaken by a major contracting firm. To this end, their paper made a comprehensive classification of such costs and presented statistics that can be useful in assisting cost professionals in both estimating and controlling this project’s crucial cost component.

C. B. Cost Optimization

Cost optimization, an integral part of construction planning, has seen extensive research work. Optimization techniques vary from Time-Cost tradeoffs to Discounted Cash flows to Genetic Algorithms to integrated methods. Theories and methods to reduce construction costs by controlling the cost of material purchases and procurement have also been proposed. Cost can be minimized either by proper scheduling of activities or by utilizing cost-effective materials and techniques.

One of the most popular techniques is Time-Cost Trade-Off (TCT) among related activities. A paper written by Reda and Carr [4] on this topic describes the practical approach that construction planners use in performing time-cost trade-off (TCT). The authors of the paper declared the computerized TCT techniques to be inefficient because such techniques separate the plan into activities, each of which is assumed to have a single time-cost curve where all points are compatible and independent of all points in other activities' curves and that contain all direct cost differences among its methods. These assumptions are not true for construction projects. In practice, activities in a construction project depend on each other. Normally, the right method of trade-off would be the planners cycling between plan generation and cost estimating at finer levels of detail until they settle on a plan that has an acceptable cost and duration; keeping in mind that crashing activities would require changes from normal, least-cost methods and resources. TCT can also be applied using Maximal flow theory [80]. This theory makes use of the Maximum Flow-Minimal cut concept (piping arrangement) and computer applications to automate and optimize the time-cost trade-off process. Ammar (2011) came up with a paper related to a similar topic named, “Optimization of Project Time-Cost Trade-Off Problem with Discounted Cash Flows”. He stated that Traditional time-cost trade-off TCT analysis wasn’t accurate since it assumed constant value of activities’ cost along the project time span, which is generally not the case. The value of money decreases with time and, therefore, discounted cash flows should be considered when solving TCT optimization problem. Optimization problems in project management have been traditionally solved by two distinctive approaches: heuristic methods and optimization techniques. Although heuristic methods can handle large-size projects, they do not guarantee optimal solutions. Other methods include the LP/IP Hybrid method suggested by Liu et al. [81] as a method of analyzing the construction time-cost trade-off. LP/IP hybrid method, is a combination of linear and integer programming. This method first establishes the lower bound of the time-cost relationship of a project using linear programming. Based on the linear programming solutions, regions of desired time and cost can be selected to find the exact solutions by integer programming in a fraction of the time required to solve the entire problem using only integer programming. This combination of linear and integer programming provides the efficiency and accuracy for solving time-cost trade-off problems. Several other techniques like Ant Colony Optimization [82] and Harmony Search [83] are still under research and development and may be used for performing Time-Cost trade off in the future.

Genetic algorithms (GAs) are also one of the most suitable ways to tackle time-cost optimization problem. GAs reduce computational costs and significantly increase the efficiency in searching for optimal solutions [84]. Practicability can be achieved through the integration of a project management system to the GA system. Through GAs it is ensured that all scheduling parameters, including activity relationships, lags, calendars, constraints, resources, and progress, are considered in determining the project completion date, thus allowing comprehensive and realistic evaluations to be made during time-cost optimization [85]. GAs can also solve time-cost trade-off problems. In fact, the computer program TCGA provides a practical tool for practitioners to apply it in solving optimization problems. Using GAs, front approach and computer programs to implement algorithms, the problem of optimization could be easily solved, especially in large scale optimization problems, where mathematical and heuristical methods may fail [86]. However, existing genetic algorithms (GA) based systems for solving time-cost trade-off problems suffer from two limitations. Firstly, these systems require the user to manually craft the time-cost curves for formulating the objective functions and secondly, these systems only deal with linear time-cost relationships. Combining Machine learning concept with GA systems can provide a remedy to such limitations. In fact, in [87] is presented a computer system called MLGAS (Machine Learning and Genetic Algorithms based System), which integrates a machine learning method with GA. The machine learning method automatically generates the quadratic time-cost curves from historical data and also measures the credibility of each quadratic time-cost curve. The quadratic curves are then used to formulate the objective function that can be solved by the GA. Comparisons of MLGAS with an experienced project manager indicate that MLGAS generates better solutions to nonlinear time-cost trade-off problems. Genetic algorithms can also be used with simulation techniques to come up with a hybrid solution for solving the time-cost trade off problem. While the simulation techniques solve the uncertainty problem of time and cost, genetic algorithm comes up with optimal solutions [88].

Ringwald [89] applied the Bunching (Queue's) theory to minimize cost. The theory's roots lie in rather complex mathematics involving the assumption that a specific Poisson distribution applies to both loading time and hauler travel time. He developed the Bunching theory into a quickly applicable set of curves. When these curves were realistically applied, the most economical match-up of hauler fleet size per loader was ensured. Sarma and Adeli [90] suggested research on cost optimization of realistic three-dimensional concrete structures, especially large structures where optimization can result in substantial savings; and additional research on life-cycle cost optimization of structures where the life-cycle cost of the structure over its lifetime is minimized. Similarly, Sirca Jr. and Adeli [91] presented a method for the total cost optimization of precast, pre-stressed concrete I-beam bridge systems, by taking into account the costs of the pre-stressed concrete, deck concrete, pre-stressed I-beam steel, deck reinforcing steel, and formwork. The problem was formulated as a mixed integer-discrete nonlinear programming problem and solved using the robust neural dynamics model of Adeli and Park. Therefore, apart from mathematical models, neural networks can also be used for cost optimization of structures.

One of the most comprehensive solutions cost optimization problem was proposed by Hegazy and Wassef [92]. They proposed a practical model for scheduling and cost optimization of repetitive projects. The model objective was to minimize total construction cost comprising direct cost, indirect cost, interruption cost, as well as incentives and liquidated damages. The model was based on four aspects: (1) full integration of the critical path and the line of balance methodologies, thus considering crew synchronization and work continuity among non-serial activities; (2) time-cost trade-off analysis considering a specified deadline and alternative construction methods with associated time, cost, and crew options; (3) it was developed as a spreadsheet template that is transparent and easy to use; and (4) it utilized a non-traditional optimization technique, genetic algorithms, to determine the optimum combination of construction methods, number of crews, and interruptions for each repetitive activity. To automate the model, macro programs were developed to integrate it with commercial scheduling software. However, this model is only useful for cost optimization of repetitive projects.

III. SUMMARY AND CONCLUSIONS

Solving the construction schedule optimization problem involves a trade-off between time, resources and cost. While each of them affects the other two, these aspects of construction planning can, to a certain extent, be treated independently so as to achieve efficiency at all levels and thereby improve overall performance.

As far as time scheduling is concerned, it is suggested that the classical methods like CPM, PERT, LOB, etc. are obsolete and should not be used in their original forms. These methods fail to take into account the uncertainties and delays that occur during construction. However, a basic knowledge of these methods is required since these are the methods on which newer techniques are based. If they are being used for construction scheduling, they should only be used to get a broad idea of what the completion time would be like. Most of the modifications to the traditional methods only address a specific problem of a traditional method. Thus they have very little scope and can be applied to specific cases only. Soft computing, which involves use of advanced methods like fuzzy logic, genetic algorithm does seem to be the way forward. However, a thorough knowledge of these methods is required before applying them to construction planning. The software and hardware is available now which makes application of soft computing methods much simpler. The biggest advantage of soft computing methods is that they take into account the uncertainties that are there during construction and also have a very large scope. Thus they can be applied to most construction cases. More research should be directed towards integrating traditional methods with soft computing in order to get even better construction scheduling tools.

Among the most prominent issues in crew and resource scheduling is the integration of resource calendars into the activity precedence diagrams, so as to avoid the trickle-down effects of disturbance in one schedule to the other. While a variety of weekly and daily crew scheduling techniques exist, all have their merits and demerits some definitive research which helps in assigning crew schedules to different situations is yet lacking. Progress-monitoring methods have come a long way, and mathematical models, software-based models, Geographical Information Systems, and even soft computing techniques like fuzzy logic have been applied. Design of crews, their configurations and the 'how' of their usage is an area which has not seen as much research as compared to the other categories, probably owing to the fact that all contractors have their own ways and practices of micro-schedules which are hard to bring about changes in. Nevertheless, research has been done to find out what kind of thumb rules and heuristic techniques contractors employ for the same. Crew performance measurement has probably attracted the most amount of research. Models to measure and forecast performance have been developed, and analysis of factors affecting productivity has been carried out. Optimization of the supply chain in the construction process and handling of logistics has also been recognized an important step in resource management. Techniques originating from the manufacturing industry, like Just-in-Time management and Lean Construction have been applied to construction, and means to provide logistical support also been developed.

Finally, the study of cost estimating techniques reveals the fact that the traditional methods of cost estimating are obsolete and require a lot of assumption work. They do not take into account the various uncertainties involved in a construction project. One way of estimating future construction costs might be probabilistic analysis, which involves either regression or neural networks, with neural networks (NN) being the clear winner as far as accuracy is concerned. But the applicability of NN for long-term cases still remains an area of concern. Case-based Reasoning approach rectifies this concern, and is perhaps the better model than NN, when it comes to long-term use, available information from result, and time versus accuracy trade-offs. Database Warehousing is one of the applications of the case-based reasoning approach which is currently lacking in implementation. As far as cost optimization is concerned, the present least-cost scheduling, cash flow methods of minimizing construction costs do not fare well either. A better solution appears to be application of genetic algorithms (GAs) in optimizing construction costs, and it has been proven that GAs are more accurate compared to the traditional methods. However, a thorough knowledge of this subject cannot be expected in industry professionals, and software that incorporate these algorithms would serve the purpose.

This paper has attempted to break down the planning process into its three basic components, so that exact problems under each head can be identified with ease and dealt with individually. Improvements at the bottom-most levels of hierarchy in the construction process will naturally lead to increase in overall efficiency.

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