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A Survey on Operations Research Applications in Construction Management

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Abstract
In today's competitive world, construction companies should integrate the expertise of multiple disciplines to remain in the business. Interdisciplinary application areas in construction management involve concepts such as total quality management, risk management, human factors, resource management, cash flow management, and knowledge-based systems for resolving issues such as developing the activity network topology and resource allocation. Our aim is to summarize the related research and the applied contributions to construction projects from different fields and to indicate possible future areas of interdisciplinary applications.

Özet
Günümüzün rekabet ortamında, inşaat firmalarının, farklı disiplinlerin uzmanlıklarını bünyelerinde bütünleştirmeleri kaçınılmaz olmuştur. Yapım yönetiminde disiplinlerarası uygulama alanları; toplam kalite yönetimi, risk yönetimi, insan faktörleri, kaynak yönetimi, nakit akışı yönetimi ve bilgiye dayalı sistemler gibi kavramları içermektedir. Amacımız, bu konudaki ilgili araştırmaları ve farklı alanlardan inşaat projelerine yapılan katkıları özetlemek ve disiplinlerarası uygulamaların gelecekteki olası kullanım alanlarını belirtmektir.

Keywords: Construction management, operations research techniques, soft computing methods

1. Introduction

Similar to other sectors, a company which is active in the construction sector has to use management tools in order to achieve an effective allocation of various resources in order to remain competitive in today's dynamic markets. The efficiency of a construction firm's numerous activities such as bidding, project management, project risk assessment, equipment management, can be increased by introducing analytical management techniques from the Operations Research (OR) discipline. From the organizational perspective, the organizational structure of the company and interrelationships among varying management functions should also be exposed to continuous improvement which results in adopting modern management approaches such as team work and Total Quality Management (TQM). This survey involves a summary of contributions in both analytical and organizational fields in construction management. Since it is not possible to cite all related references, applications selected as prototypes for each specific area are included in this survey. Prototypes are selected due to some of their interesting features that reflect a multidisciplinary approach.

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Here, we discuss in separate sections, the specific contributions to construction management where OR tools and techniques are used in the literature. We classify these contributions according to the following: Modeling aspects in construction management (with and without uncertainty considerations) that include contributions in resource and cash flow management, research on repetitive construction projects, risk analysis where different risk factors are specifically considered and a varying range of uncertainty models are described; contributions from modern management concepts to construction management; and, contributions to construction engineering and management from the field of Computer Science, where expert systems and computer based problem-solving techniques such as Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithms (GA) and Neural Networks (NN), are described.

2. Modelling Aspects in Construction Management

We organize these contributions under classifications: the first group of contributions consists of theory and applications where deterministic working conditions are assumed. In these models, the computational difficulty of problems such as resource and cash flow management in projects are discussed and algorithms based on OR theory are proposed. The second group consists of models where different risk aspects are considered and solution techniques ranging from simulation to fuzzy logic and Analytic Hierarchy Process (AHP) approaches are described. The group consists of models specifically developed for the efficient management of repetitive projects which stand mid-way between batch production and production on a project basis.

2.1. Models without Uncertainty Considerations

Models for Resource Management

The issue of resource management is inevitable in construction projects where resources of different nature are utilized. Resource management can be realized by resource leveling or by considering constrained resources throughout the project.

In resource leveling the aim is to smooth the resource utilization profiles over the project span. This objective is reasonable if no tight deadlines are imposed on the project duration and the resources are to be acquired (leased) by the contractor for the sole purpose of the current project. Resource leveling might also be a tool for sharing the available resources among multiple projects and allocating the appropriate quantities of resources to each project [22]. Seibert and Evans [80] discuss the variability of resource requirements in different phases of time-constrained construction projects and suggest that leveling should be carried out by using activity early start and late start resource profiles. Constraints such as craft, budget and personnel availability should be abided while developing the initial resource profiles. In time-limited projects, Demeulemeester [18] proposes to minimize the levels of available resources rather than their fluctuations over the project span. The author, thus, minimizes the maximum resource limit which is going to be valid throughout the project. This objective becomes valid when a fixed number of resources are to be acquired by the contractor.

In resource constrained projects, the contractor already has available resources and cannot acquire more during the project span. Such cases may occur when a project is carried out at a geographically distant site (may be out of the country where the contractor operates), or the legal regulations for temporary acquisition of resources are prohibitive. Sometimes, the contractor's financial situation does not allow for additional resource acquisition. A most interesting point is that most authors deal with this problem rather than the former [5, 17, 42, 44, 73, 93]. An extensive survey in the area of resource constrained project scheduling is provided in Özdamar and Ulusoy [65].

In the literature, resources are classified under two major headings [89]. Resources such as regular labor and equipment are available every day at the same quantities (if no breakdowns or absenteeism occurs) and therefore, they are called renewable resources. On the other hand, when the contractor starts with a given amount of cash, expenditures (wages, equipment rents, overhead, material costs) consume the available quantity and available cash might be driven to zero unless a progress payment takes place. This type of resource is called nonrenewable, because we need to track down the cumulative cash inflows and outflows in order to calculate the current level of the resource. Materials are also classified as nonrenewable resources.

Resources are related to activities and they are included in the definition of an activity. The resource requirements of an activity indicate the amount of resources required every period that the activity is in progress (renewable resource) or they indicate the quantity of nonrenewable resource consumed by the completion time of the activity. Using this type of activity definition, one can also model the different technologies that can be used to execute an activity. For instance, an activity can take 8 days with 2 workers and a semi-automatic machine, whereas it can be completed in 2 days with one supervisor and an automated machine. Naturally, one can also model discrete time-resource-cost considerations in this representation, i.e., an activity can be executed in 3 days by one worker and in 1.5 days by two workers. Such realization options are modeled as multiple execution modes for an activity and the contractor should choose a single realization from the alternatives depending on the effects on project duration, costs and project net present value. An example of multi-mode activity definition arises in earthwork optimization where the amount of cut in meter cubes to be hauled from a road section to fill another section depends on the selected plant fleet. In fact, in the integer programming model developed by Jayawardane and Harris [36] all operations involving road construction projects are tied to multiple alternative fleets. A resource-oriented modeling and simulation tool for construction is proposed by McCahill and Bernold [51]. The authors develop a model (with a specific earthwork example) where activities can be assigned to one of the nonhomogeneous resources available on the site, such as trucks with different capacities or dozers versus trucks. Furthermore, each resource is affected by differing conditions, e.g., dozers are affected by weather conditions, but trucks not. Risks, e.g., failure rates, can also be related to alternative resources. The authors describe a very realistic model where the construction project can be simulated according to user-defined rules for activity sequencing and activity-mode selection.

Li and Willis [46] elaborate further on alternative resource combinations by defining mutually inclusive, mutually exclusive and partially mutually related resources. Mutually inclusive resources indicate that the specified resources must go together, e.g., pipes and timbers versus rollers used in a transformer transfer and installation job. Mutually exclusive resources are the ones that will not be required together, such as a forklift versus rollers. Partially mutually related resources are the ones that are used in more than one alternative, such as labourers.

Although such activity representations provide the contractor with realistic alternative project realizations, the number of decisions to be made, and hence, the number of binary variables in the mathematical model increases to an extent which makes even small projects mathematically intractable. However, a scenario analysis including resource constraints helps the contractor in cost estimation and bidding as well as in the resource acquisition plan in the initial phase of the project. Hence, many researchers attempt at solving this problem optimally or with heuristics [10, 19, 55, 64, 68, 71, 89].

Models for Cash Flow Management

Cash flow management is essential in a construction project, because lack of liquidity is the main reason of many bankrupt projects. Hence, managing cash flows plays a crucial role in construction projects. Several authors have attempted to handle this problem by employing different techniques. As indicated in the resource management section, cash is considered as a nonrenewable resource which should not be driven below zero level. Thus, it is important to schedule activities so that progress payments related to activities are made in time to prevent negative cash levels and provide sufficient means to continue with critical activities in order to minimize project duration. The cash flow management problem becomes more complex as realistic business operations such as external borrowing (repaid with added interest) are included in the model.

There are different models which represent the occurrence of cash outflows and inflows. Cash outflows may take place at the beginning of an activity (such as payment for all the materials necessary for the activity) [66] or cash is consumed during the activity (labour and material costs are accrued every day) linearly or in lumps [67, 71], or at the end of activities [96]. Cash outflows may also be tied to major events which indicate the end of a project phase (such as the completion of plumbing installation and the start of fine work such as tiling) [69, 77]. Similarly, cash inflows may be tied to events indicating payment upon completion a certain project phase, or there might be regular payments at given time intervals [38], or there might be progress payments which are calculated as a percentage of the cost of each major activity and acquired by the contractor when the activity is completed. In the last case, the owner holds back the contractor's profit plus a percentage of his costs until the project is completed. The project reward may also be paid to the contractor as a single lump sum at the completion of the project [85]. Hence, the way cash inflows occur depend on the contract signed between the owner and the contractor.

Herroelen et al. [30] discuss and classify contract types such as fixed price contracts and cost plus contracts. The authors elaborate on the implications of different contract types and discuss additional features such as bonus and penalty. Next, they provide the current state of the art in modelling cash flow patterns including event-based and activity based cash flow models in resource constrained projects, and describe the methods proposed to solve them. This survey is the most extensive one in the current literature.

There are two phases to be resolved in the issue of cash flow management. The first phase is to determine the timing and amount of payments on the contract so that a compromise solution is found both for the contractor and the owner. The second phase is to schedule activities such that given the payment terms on the contract the contractor does not reduce the project net present value or the project does not go bankrupt. Yet, these two phases are not independent of each other, because the contractor should identify feasible payment alternatives in order to bid for the project and reach a mutual agreement on the contract with the owner.

Since cash flow management is a very difficult problem when resources are constrained, researchers try to solve the cash flow management problem assuming a specific payment model indicating cash inflows and outflows tied to activities or events. That is, they deal with the second phase of the problem which is also NP-Complete [8, 88]. When the contractor wishes to maximize the net present value of the project, there is a dilemma between scheduling activities with negative cash flows at their late start times or earlier. Given that an activity's immediate cash flow is negative, in the short run it may seem beneficial to schedule it as late as possible. However, due to resource bottlenecks, this activity may impede others which result in big positive cash flows and furthermore, if they are critical, they even avoid a lateness penalty. In an interesting article by Smith-Daniels and Smith-Daniels [86], project net present value is attempted to be maximized under two nonrenewable resource constraints: capital and materials. In this case, inventory holding costs also take place in the objective function and material acquisition necessary to start certain activities induces cash outflows as fixed ordering costs. Consequently, in the optimal schedule activities with similar material requirements are scheduled at close time periods in order to reduce ordering costs. On the other hand, since progress payments are tied to activity completion times, it is hard to calculate the optimal trade-off between cash inflows (progress payments) and cash outflows (fixed costs + inventory holding costs) as well as ensure the continuation of the remaining project activities with additional capital enabled by new progress payments.

When a project bonus or penalty exists in the contract for early and late completion (with respect to a given project deadline), or, when there exists overhead costs accrued every period until the project is completed, the objective of maximizing project net present value interacts with the objective of minimizing project duration [94]. Thus, without enumerating all possible start times for all activities in the project it is not possible to determine the optimal solution. This problem becomes even more difficult when activities have several execution modes.

Dayanand and Padman [16] deal with the first phase of the cash flow management issue. That is, they aim to determine the amount and timing of payments. The authors present payment scheduling models as a decision making tool for bidding where the decisions include the specific activity/event to which each progress payment is tied and to its amount. They examine five different mathematical models for the simultaneous determination of the amount and timing of progress payments in a project with the objective of maximizing the contractor's NPV and analyze each model's solvability. In all models, progress payments are determined by a given percentage of the expenses made by the contractor up to that point in time. The total amount of payments does not change during the project. In the first model both progress payments and activity expenses are tied to event occurrence times. In the second model the timing of progress payments are discrete rather than continuous. The third model converts a nonlinear model into a linear one. In the fourth model, payments and expenditures are tied to activities. The final model incorporates into event-based models the property of incurring cash outflows at the required date imposed by the project due date. The authors conclude that the modified event-based model provides the maximum flexibility for determining a payment schedule.

Models for Repetitive Projects

The nature of repetitive projects enables the utilization of learning curve theory and line-of-balance (LOB) technique in planning and scheduling. However, when the network of the typical unit is complex and has many branching paths, LOB becomes insufficient. Suhail and Neale [87] offer a new methodology which integrates the merits of the critical path method (CPM) and LOB by attacking the novelty of using resource leveling and the float times calculated by CPM in the LOB. CPM/LOB was applied by the first author to housing, precast bridges, schools and repetitive electrical substations projects, and was found to be a promising tool in repetitive projects.

Cole [14] considers the problems of planning and monitoring construction projects in his study. He argues that construction work has to be monitored closely in terms of economic, technical and continuing control grounds, and reviews two planning models. These models, as revealed by research and industrial experience, are the basis of the most commonly used planning techniques. The first model which is based on the concept that a project consists of a series of discrete tasks, is the critical path model. On the other hand, the second model, assuming a project incorporating a series of repetitive tasks, is the linear scheduling-flow line model. This model is, in fact, an enhanced version of the LOB technique. Cole presents six successful case studies that are typical examples of the application of appropriate scheduling techniques to the problems of planning and monitoring construction projects. The first two is the application of CPM; the second two deals with the utilization of flow line method, and the last two cases are complex projects that use a combination of both systems. The author concludes that CPM is best suited to nonrepetitive projects, and flow line is best suited to repetitive projects. However, since most contracts have dual characteristics, no single system can meet all of a contractor's requirements for the planning and monitoring of construction work.

Lutz et al. [49] present the methodology used to model the learning development phenomenon in repetitive construction. Learning development is the realization of improved production performance for subsequent cycles due to increased knowledge about the task being performed and increased familiarity with the job site. The learning development enhancement is coded in the MicroCYCLONE simulation program. The developed procedure is used to model and simulate seven illustrative example operations consisting of 43 processes. The results indicate that significant improvement in individual processes may not always result in a significant improvement for the overall system due to production operations imbalance. Therefore, after modeling the learning development phenomenon, production for the overall system should be balanced to eliminate potential bottlenecks. Lutz et al. claim that the utilization of learning development modeling coupled with system balancing should provide for more realistic production forecasting, more accurate scheduling and budgeting, more competitive bidding, and improved system performance.

Moselhi and El-Rayes [58] propose a model for identifying the optimal crew size (among many alternatives) for each activity in repetitive projects with the objective minimizing overall project costs. A two-phase dynamic programming approach is developed; the first being a forward process to identify locally optimal crew sizes at the individual activity level; the second being a backward process to optimize crew formations at the overall project level.

Shtub et al. [83] develop a mixed integer 0-1 model where crews are assigned to repetitive tasks and the learning effect is explicitly considered in calculating the completion time and costs of each unit in the project. Earliness/tardiness costs as well as total unit building costs are a function of the number of times each task is repeated during the project.

2.2. Models with Uncertainty Considerations

Models for Risk Management

"Risk" is defined as the exposure to the chance of occurrences of events adversely or favorably affecting project objectives as a consequence of uncertainty [4]. In other words, risk can be considered as a function of uncertainty of an event, and potential loss or gain from the event. "Risk management" is defined, in the project management context, as a formal orderly process for systematically identifying, analyzing and responding to risk events throughout the life of a project to obtain the optimum or acceptable degree of risk elimination or control [4]. In construction, it is observed that the risk management function has been closely linked with insurance, and that many contractors think of risk management as insurance management. However, it should be noted that risk management has a broader meaning and involves more than just insurance management. This fact has led to the application of various operations research techniques to the area of risk management. Among these techniques; simulation, Synergistic Contingency Evaluation and Response Techniques (SCERT), uncertainty analysis, Analytic Hierarchy Process (AHP), decision trees and utility theory are the most commonly employed ones.

SCERT [13, 41] arose from the needs of risk management in large gas pipeline installation projects. In the first phase of SCERT the criteria, such as cost, duration or quality, which define exposure to risk are identified. In the second phase, the interaction between the risks and their responses are formalized. The third phase involves the determination of numerical estimates of the uncertainties associated with the identified risks. In the fourth phase contingency plans are developed to deal effectively with exposure to risks.

Tsimberdonis and Murphree Jr. [92] address the problem of equipment maintenance and management of failure. Simulation is used to prepare Operational Failure Costs (OFCs) charts which indicate failure costs versus failure duration and fail time. Fail time indicates the point in time, the failure of the equipment takes place, i.e., at the beginning, or towards the end of an activity. OFC charts help the managers to decide on the assignment of equipment to operations, on the equipment utilization rates, the relative equipment importance, the evaluation of spare parts inventory and the strategic plans of preventive maintenance.

Ioannou and Martinez [32] apply simulation to a technology selection problem. The authors use a general-purpose simulation program to evaluate two different tunneling techniques, conventional and New Austrian Tunneling Method, in the construction of a two-track railway tunnel. The different technologies involve varying installment and operating costs, depending on the tunnel geology which is modelled as a discrete state, discrete space Markov process. Consequences such as support and placement rates, cost and time delays associated with switching to a new ground class are observed in the simulation.

Skibniewski and Chao [84] make use of the AHP technique in evaluating advanced construction technologies. The four-level hierarchy incorporating both favorable and unfavorable factors, in terms of benefit and cost, is used to evaluate two tower crane alternatives; traditional and semi-automated. Moreover, the effect of managerial judgments on the acceptability of a new technology alternative is demonstrated via a sensitivity analysis.

An application of utility theory in risk analysis can be found in the paper of Lutz et al. [48]. They propose a system for evaluating the expected utility of a new building technology, and for aiding the decision maker in making an appropriate and logical decision in implementing a new building technology. The system consists of three phases: technical assessment, economic assessment and risk assessment. The overall assessment factor which is a product of these three factors, provides a measure of the potential utility of the new technology. Four possible outcomes can result from the evaluation, ranging from large-scale implementation, to discarding the technology from further consideration.

Another study that employs simulation is by AbouRizk and Wales [1] in which the effects of weather conditions on project progress are analyzed. A combination of discrete event process simulation and a continuous process such as weather conditions is implemented in simulating the effects of weather on project completion time. The productivity of activity work in relation to weather conditions is determined by classifier neural networks. In other words, the neural network produces a productivity value when given the weather conditions for the day. These input values consist of daily average temperature, daily precipitation and cumulative precipitation over the previous seven days. Then, new weather conditions are simulated and fed into the neural network. According to the output of the neural network, activity durations are adjusted more realistically than PERT or Monte Carlo simulation.

Uncertainty analysis is another technique that is used in risk management. Paek et al. [70] determine bidding prices of a construction project using fuzzy logic. A risk pricing method is proposed for analyzing and pricing construction project risks. Various profit losses as different possible consequences of a construction risk (such as earthwork) are assigned fuzzy membership values which are then converted to a crisp number by a certain ranking method. This is due to the fact that the bidding price of a construction project should be decided as a real number rather than an interval value, but the total net loss, estimated as a fuzzy number, may be an interval value. Fuzzy sets theory was developed specifically to deal with uncertainties that are not statistical in nature [98]. The central concept of the theory is the membership function, which represents numerically the degree to which an element belongs to a set. In fuzzy logic, an estimate of a profit loss may partially belong to the set of possible losses whereas in conventional set theory, a profit loss is either in the set or out of it. The use of fuzzy sets in this case, is justified because profit losses are claimed by construction experts and a high degree of uncertainty exists in the estimated loss values. The bidding price is determined by adding the crisp profit loss, the actual cost (direct, indirect and overhead cost) and contractor's profit.

Similar to Shipley et al. [81], Lorterapong and Moselhi [47] use fuzzy set theory instead of Monte Carlo simulation in determining and assessing project duration results. Different estimates of activity durations are assigned fuzzy membership values and forward and backward CPM passes are executed according to fuzzy set operators. This approach facilitates the interpretation of the fuzzy project duration as well as the calculation of scheduling parameters. Hapke et al. [28] use a similar logic in calculating CPM in their proposed heuristic for solving the resource-constrained project scheduling problem. Naturally, PERT and simulation [74] are more conventional tools for estimating project duration under user defined uncertainty [20, 23, 27].

A research paper dealing with risks related to probabilistic cash inflows rather than probabilistic activity durations is provided by Özdamar and Dündar [67]. The authors consider housing projects where an initial capital covers activity expenditures in the starting phase of the project, and then, customers who arrive randomly over the project span provide the necessary funds for continuation.

The goal is to maximize financial returns, i.e., the project NPV. Here, capital is considered as a limited nonrenewable resource which is reduced by activity expenditures and augmented by the sales of flats. A flexible heuristic scheduling procedure is proposed to solve the problem, which may be used to construct and re-construct project schedules given the present state of affairs at any decision time while the project is in progress. The algorithm is tested by using a typical housing project with real data and also by using hypothetical test problems. The results indicate that the schedules generated are satisfactory with regard to meeting the target project due date and maximizing NPV.

Mustafa and Al-Bahar [59] utilize the AHP to analyze and assess project risks during the bidding stage of a construction project, and to overcome the limitations of the traditional approaches currently used by contractors. The authors apply the methodology to assess the risk of constructing a bridge in Bangladesh. In the three-level hierarchy they propose, the first level factors are financial and economic risks (having three subfactors), political risks (having two subfactors) and acts of God (having three subfactors). At the last level, they evaluate three risk levels (high, medium and low). Mustafa and Al-Bahar conclude that, due to its advantages, AHP can be applied to support decision making in bid evaluation, equipment selection, staff selection, corporate stability and competitiveness, and to other areas.

Dozzi et al. [21] develop a utility theory model that uses 21 criteria in the bidding decision. These criteria are concerned with environmental factors, company factors and project factors. Environmental factors are further subgrouped as geographical, economic and historical. Each bidding criterion is represented by a utility function, and to each criterion a scaling (or weighing) factor is assigned for distinguishing the preferences or trade-offs between criteria. The scaling procedure employs the AHP technique described by Saaty [78]. Then, the utility values of each criterion are combined to form an expected utility for a project scenario. And finally, the markup utility function transforms the expected utility value into a bid markup recommendation. In another study employing AHP, Riggs et al. [75] suggest a computerized method for integrating technical, cost and schedule risk components in project management. The methodology starts with representing the technical, cost and schedule preferences as the project manager's utility function.

The expected value for the utility function is calculated for various alternatives, in the context of a decision tree. The AHP is used to derive the utility functions and to assign probabilities to the decision tree. Finally, the series of decisions (path) that maximizes the expected value for the decision tree is selected as the best alternative. By automating the tasks that will be required by the dynamic nature of a project management environment, the developed software enables the application of this methodology to real world problems.

Jaselskis and Russell [35] also apply decision trees in their work related to risk analysis. They address one of the basic problems of project owners, which is the selection of the evaluation method for determining the qualification level of construction contractor candidates. The importance of the problem comes from the fact that a better contractor evaluation will enhance the likelihood of achieving satisfactory project outcomes. The authors develop a decision tree containing the contractor evaluation methods and performance outcomes. Significant inputs to the evaluation process are identified as person hours expended for evaluation per contractor, total program evaluation cost and monitoring cost during construction. Relationships among the amount of evaluation effort, the project cost and the schedule performance are also revealed. The results indicate that the smallest expected increase in project duration occurs when the owner performs a good evaluation and does not require a surety bond. Jaselskis and Russell state that firms that spend significant amounts of money on monitoring the contractor's performance during the construction phase may redistribute these funds more effectively to evaluate construction contractors while achieving better schedule performance at a lower total project cost.

Forecasting Models

The vital importance of cost and cash flow management in housing construction projects arises the need for systematic forecasting approaches. Williams [95] proposes to apply back-propagating neural networks to predict changes in the construction cost index. The inputs to the model include recent trends in the index, the prime lending rate, number of housing starts and the month of the year. The output from the neural network models is compared with the predictions made by exponential smoothing and simple linear regression, and the results indicate a greater error than the two simple forecasting techniques. The authors conclude that, due to the numerous complex factors influencing construction prices, cost indexes cannot be predicted by a back-propagating neural network model.

A computerized company-level cash flow management model is developed by Navon [62] for forecasting cash flow. The author presents a comprehensive background including mathematical models for cost/cash flow management and related work on cost/schedule integration. Most of the mathematical models are developed for cost flow forecasting only, while cash flow forecasting models are based on forecasting the cost flow first and later translating it into cash flow. Navon states that, since the mathematical models are based on generic data, they are inaccurate, and most of them do not take time lags into account. Moreover, the income flow ignores the billing period. However, he adds that there are also studies which have applied mathematical models successfully. The author tabulates the results of a survey conducted among construction companies to give an idea of common practices in cash flow estimation. Navon claims that the developed computerized system is unique in the sense that it is flexible, requires no human involvement in cash flow generation, is accurate and is a typical management tool.

2.3. Modern Management Concepts in Construction Industry

Organizational Issues

In addition to the factors such as time, cost, quality and speed, organizational structure also plays an important role in measuring project performance. Naoum [60] has designed a conceptual model for comparing project success in a sample of management and traditional contracts. These contracting types differ basically in their organizational structures. Management contracting is defined as a method of carrying out a construction project by appointing a contractor at the preconstruction stage who is paid on a fee basis to manage and deliver the project. All construction work is carried out by subcontractors, who are selected and appointed in consultation with the client and his professional advisors. The method highly benefits from the integration of design and construction. On the other hand, traditional contracting is defined as a method of procuring a building in which independent professionals (i.e., architects, engineers, quantity surveyors) are employed by the client to complete the design work. Then, the client enters into a separate contract with a building contractor, who constructs the designed building. The statistical analysis carried out by the author suggests that management contracting performs significantly better in projects with higher complexity and faster building rates. However, the research did not provide enough evidence to support the view that management contracting can reduce the overall building cost, or that the system can increase the quality standard.

The impact of organizational structure on project performance is also considered in the study by Alarcón and Ashley [3]. They present a methodology for evaluating project performance which consists of a conceptual, qualitative model structure and a mathematical model structure. The evaluation is based on construction experts' knowledge and experience, decision analysis modeling techniques, and cross-impact analysis. Project options such as organizational structures, incentive plans, and team-building alternatives have been incorporated into a model knowledge base. The methodology is demonstrated using analysis examples for a base project. The authors conclude that: i) the methodology provides a systematic and structured process for a project-team discussion on relevant project planning issues, ii) it supplies a model framework for capturing and formalizing construction experts' knowledge and for integrating research information, and iii) researchers should benefit from the flexible knowledge structure of the methodology as a tool for testing new management strategies in an easy and low-cost way.

Construction management which involves the complex task of coordinating the labour, equipment, material acquisition and financial functions among multiple projects taking place in different sites can benefit from organizational evolutionary processes such as business process reengineering and learning organizations [24, 63].

Total Quality Management Applications

Total Quality Management (TQM) is achieved through an integrated effort shared among personnel throughout all organizational levels of the company. The main theme in TQM is continuous improvement in performance aiming at a higher level of customer satisfaction all the time. In the literature, different features of TQM are taken into consideration. Quality management in construction industry is one of the topics which is addressed by authors. Burati et al. [11] present the findings of a research project conducted to identify attributes of effective quality management systems in the construction industry, the results indicating that most of the companies implement TQM. The use of pilot projects is considered as the most effective method for building in TQM principles in a company. The authors discuss that since construction requires about 50,000 different materials, in different quantities and at different times, the concept of sole-sourcing is impossible in terms of vendors.

In a succeeding study by Burati et al. [12], the process for applying TQM principles in construction industry is discussed. Although there seems to be some potential implementation problems, such as transient work force and the competitive bidding environment, the authors believe that the construction industry can find solutions to overcome these problems and successfully implement TQM.

Ledbetter [43] applies the quality performance management system (QPMS) of the Construction Industry Institute to a heavy industrial project. QPMS is a simple tool involving labor costs only. These costs are tracked in three main categories: normal work, quality management work (prevention and appraisal), and rework (deviation correction). QPMS was implemented by all parties (the owner, the two designers, and the constructor) at the beginning of the design phase and continued throughout the construction phase until the facility was mechanically complete. The system is found to promote awareness and improve the understanding of the quality process, to facilitate communication, to focus management on where quality improvements can be made, and to reduce the overall cost of quality.

Bernold and Treseler [9] highlight the importance of the vendor selection process in the construction industry. They give a list of possible selection criteria, and propose a vendor rating system in which several potential vendors can be compared and ranked based on their individual ratings. The individual rating of a vendor is based on the average of all the past purchase performance data of the vendor for a given project or purchase. Fifteen selection criteria are employed in the vendor assessment procedure, such as timeliness of submittal, lead time for release, response time to rejected submittals.

The topic of international standards and construction is addressed in the study conducted by Yates and Aniftos [97]. They summarize a research project that was conducted on the development and use of international standards and the ISO 9000 series of quality standards in the construction industry.

Quality function deployment and quality circles which are among the most popular tools of TQM, are promising tools for the construction industry as well. Mallon and Mulligan [50] claim that, with the continuing emphasis on quality within the construction industry, quality function deployment (QFD) may make the difference between success or failure in an ever-increasing competitive environment. As defined by Akao [2], QFD converts the customers' demands into "quality characteristics" and develops a design quality for the finished product by systematically deploying the relationships between the demands and the characteristics. In order to discuss the steps of QFD, the authors apply the methodology to a hypothetical personal computer workroom facility which is considered for renovation.

Rosenfeld et al. [76] discuss the applicability of the participative-creative approach of quality circles in construction industry. Due to the prototypical nature of construction projects, short-term relevancy of problems, instability of the work force, and low benefit-to-cost-ratio, quality circles seem unsuitable for construction. Yet conversely, some other arguments indicate that quality circles have a special merit in construction. In order to obtain a realistic appreciation of quality circles in the construction industry, the authors apply the process to real field settings. The results of the study are promising, and the most important practical indication is that the quality circle approach and techniques are highly favorable in improving both productivity and quality-of-life at construction sites.

Different measures representing project quality are discussed in the literature. For instance, Pinnel and Busch [72] suggest that quality can be measured by the time it takes, its cost and conformance to project specifications. Short [82] measures quality in terms of schedule variance which is defined as the discrepancy between cost realization and cost budget.

Mathematical models incorporating the concept of quality can also be found in literature. In the study of Babu and Suresh [7], it is suggested that the project quality may be affected by project crashing. In order to meet the prespecified due date for project completion, expedition of the project becomes necessary. This implies the completion of some of the activities faster than normal. However, crashing an activity increases the cost while saving time. The authors develop linear programming models that would assist in expediting a project, weighing the time-cost-quality trio. Each of the three models developed optimizes one of these three entities by assigning desired levels (bounds) on the other two. The overall project quality is a function of quality levels attained at the individual activities. The results support the authors' intuitions, and indicate that by allocating higher budgets and allowing for longer project times, it will be possible to attain higher quality levels.

In their mixed integer formulations, İçmeli-Tükel and Rom [34] measure quality in terms of the fraction of work being reworked. They assume that the cost of rework increases as rework time gets longer and as activities are executed at the final phases of the project [15]. They propose to minimize rework time and cost and relate both factors to activity difficulty and the time interval in which the activity is completed in, namely, if the activity is completed later it is more susceptible to rework.

3. Contributions to Construction Engineering and Management from Computer Science

3.1. Expert Systems

Artificial intelligence (AI), which is a subfield of computer science, has been formed by researchers concerned with symbolic processing and human problem solving. This scientific field is concerned with developing computer systems that produce results normally associated with human intelligence [90]. AI can be divided into three areas: natural languages (developing programs that read, speak or understand conversational language), robotics (developing smart robots that recognize objects), and expert/knowledge systems (replicating the thought process of experts).

An expert system is a computer program that incorporates experience and heuristic knowledge in solving problems traditionally solved only by a human expert. Because of their characteristic attributes of combining factual knowledge with judgment, their ability to handle incomplete and uncertain data and to communicate with their users in the natural language, expert systems have a special appeal for the construction profession [54]. According to Levitt and Kartam [45], the main reasons for using expert systems in construction are the need for fast decision making in an experience-based industry, the involvement of managerial issues in decisions, and the need for smart robots in automation. In the literature, various expert system applications in the construction industry can be found [45, 54]. These applications deal with a large range of decision problems ranging from the more comprehensive topics such as project planning, staffing, scheduling, control; contract management; bidding, and dynamic site layout management, to the more constricted issues such as a diagnosis system for malfunctioning elevators, or for repainting wooden facades, or for the selection of ready-mix concrete types. Here, we concentrate on AI tools dedicated to management issues and imbedding OR techniques.

The first group of prototype applications includes expert systems designed for planning and scheduling construction projects. Sathi et al. [79] develop CALLISTO which is a distributed intelligent project management system which consists of a constraint directed negotiated approach to activity management including associated risks, milestones, work packages and temporal relations; to resource management including personnel, work centers, tools, parts, shifts of work, stocks, vendors, supervisors; and to product configuration management involving hierarchical bill-of-materials type of parent-component definitions and techniques for managing changes in the bill-of-materials according to project specifications. Hendrickson et al. [29] develop the knowledge-based system PLANEX that provides a project plan starting from defining the elements which make up the activities and their precedence relationships, and then determining the amount of work and materials required to execute these activities while selecting and allocating alternative resources to activities. Cost estimation as well as the scheduled activity start times are the outputs of the system. Moselhi and Nicholas [56] develop the hybrid expert system ESCHEDULER which helps to construct the project network and communicates with a given external project scheduling module to obtain a deterministic schedule which is then updated by the expert system to include variational factors such as weather conditions, site congestion and re-assignment of labour. Kim and Schniederjans [39] develop a conceptual framework for a multi-project expert system. In the prior analysis phase, multiple projects are combined artificially into a single project and goals and their respective aspiration levels are established. In the search phase activities are scheduled using inter-goal bargaining (resolving tie-breaker situations by changing goal priorities) and intra-goal bargaining (lowering aspiration levels). In posterior analysis, utility measures are used if the solution turns out to be unsatisfactory.

The second group of selected prototypes includes the equipment selection systems described by Touran [91] and Amirkhanian and Baker [6]. The expert system by Amirkhanian and Baker [6] is a rule-based system for earthwork which consists of rules interpreting particular soil conditions, operator performance, and the required earthwork operations. The output of the system is the selection of the most suitable equipment among 14 different types of equipment including dozers, scrapers, excavators, etc. On the other hand, Touran [91] describes an expert system integrated with a simulation module which performs a simulation analysis under a given set of job conditions. The outputs of the system are costs and production rates.

The third group involves systems for automatic generation of precedence networks, which is a specifically important issue in multistory building construction. Levitt and Kartam [45] provide a system with an object-oriented approach to reduce the number of activities which can be represented by the same generic operators. Hence, a domain-independent network planner is developed. Navinchandra et al. [61] propose a system that starts with an infeasible precedence network with all activities in parallel, and then attempts to turn the network into a feasible one by introducing linearizations wherever activities cannot be done in parallel by using inheritance and refinement critics.

McGartland and Hendrickson [52] provide a knowledge-based expert system that executes time and cost control by acquiring information on estimated percent complete, expenditures to date, actual quantities of labour, equipment and material each week for every activity. Early warnings on potential overruns and time delays are provided by the meta-rules in the system before the problems become critical.

3.2. Computer-Based Algorithms as Problem-Solvers

Since the last decade, many difficult OR problems with non-polynomial complexity are tackled with approximate probabilistic search techniques based on computer power. These techniques provide good enough solutions rather than optimal ones. Among them, SA, GA, TS and NN are found to be the most promising approaches.

SA is a stochastic single point search technique where, given a starting point, a neighbour solution is generated randomly and replaces the current solution if it is better [40]. Else, it is rejected or accepted according to a probability of acceptance, which depends on the current temperature and the amount of deterioration in the objective function value. The temperature is reduced gradually so that the search may converge to the optimum solution while escaping from local optima by accepting worse solutions. SA produces satisfactory results in resource-constrained projects [37] where a solution is represented by integer activity start times moved one time unit to the left or to the right when a neighbour is created. Resource infeasibilities are penalized in the objective function of minimizing project duration.

In TS [25, 26], given a current solution, its whole neighbourhood is generated and the best solution within the neighbourhood replaces the current solution whether or not it improves it. In order to prevent the re-visiting of same solutions, a tabu list whose length is defined by the user, stores the last *n* solutions obtained by the search. In the TS application given by İçmeli and Erengüç [33], project net present value is maximized given resource and precedence constraints. A solution is defined by activity completion times and a move is carried out as described in Jeffcoat and Bulfin [37].

GAs [31, 53] conduct a random search on a population of solutions (chromosomes) and they involve asexual reproduction, crossover (or sexual reproduction) and mutation. Through crossover and mutation new chromosomes are added to the population while unfit old chromosomes die out. Thus, populations get better in each generation. In the GA applications [55, 68] developed for resource constrained project scheduling (with multiple-modes) a solution is either represented by the activity sequence in the schedule or by the priority rules according to which the n^{th} activity considered for scheduling is to be selected. The computational results provided in both articles [55, 68] and by Lee and Kim [44] who try all three approaches (SA, TS, GA) indicate that most difficult models can be solved in efficient computation times using computer-based search algorithms. `Although the references cited here involve resource management issues specifically, computer-based search algorithms are not restricted to this area. Efforts in identifying optimal payment amounts and timing, optimal staff assignment, and the optimal set of decisions in dynamic environments (representing conditions under risk) are the topics of current research in GA and SA designs.

Moselhi et al. [57] propose a general NN approach for modeling construction problems such as site selection, schedule and cost estimation, bidding, diagnostic problems in facility defects, real-time applications in time-dependent material costs, inflation rate, etc., and optimization of resource allocation. However, for each problem, a different network type (e.g., perceptron, Boltzmann machine, Hoppfield network), and an associated learning algorithm have to be conceived.

4. Conclusion

In this survey, we discuss application areas in construction management where multidisciplinary approaches involving operations research techniques are deemed suitable as solution methods. Modern management concepts (e.g., TQM), probabilistic OR tools used in risk analysis (e.g., AHP), combinatorial optimization solution techniques in resource and cash flow management, basic project monitoring techniques (CPM, LOB), and AI techniques and soft computing methods (SA, TS, GA, NN) integrated with conventional OR tools (simulation and combinatorial optimization techniques) proposed for different practical problems in construction engineering and management, are discussed in detail. The references cited in this survey are not exhaustive, but they are selected prototypes demonstrating the multidisciplinary approach adopted to solve different problems. From the contents of this survey, one can conclude that further cooperation between researchers from construction management and OR fields will lead to the mutual benefit of both fields resulting in even more efficient solutions to the needs of construction industry while providing more realistic modeling opportunities for OR people.

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