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Project portfolio management: An integrated method for resource planning and scheduling to minimize planning/scheduling-dependent expenses

Zohar Laslo *

Faculty of Industrial Engineering and Management, SCE Sami Shamoon College of Engineering, P.O. Box 45, 84100 Beer Sheva, Israel

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Abstract

It is well known that the progress of *R&D* projects has more and more begun to rely on the availability of individual experts who are generally scarce and expensive. The matrix structure considers periodic staffing of project teams which has been found to be efficient for non-scarce human resources but is impractical for individual experts. Our objective is to develop and evaluate an alternative approach for resource planning and scheduling that might be useful for project portfolio management. The method we suggest is an extension of a recently developed optimization model for a job-shop with several machines and chance-constrained deliveries. Our method determines in advance the hiring and releasing points of individual experts that maximize economic gain subject to chance-constrained delivery commitments. For this purpose, we use a simulation based on a greedy priority dispatching rule as well as a cyclic coordinate descent search-algorithm. A benchmarking of the staffing of project teams and the integrative methods shows that integrated planning and scheduling is a very useful tool for the decision-making process in project portfolio management.

Keywords: Project portfolio; *R&D* projects; Chance-constrained scheduling; Resource planning; Individual experts

1. Introduction

Project Management (*PM*) refers to the creation of a group of individual specialists from different parts of an organization who are brought together for a limited period of time to contribute towards a specific project. Once a project is complete the group is disbanded and its members are assigned to new projects. *PM* is a complex decision making process involving the unrelenting pressures of time and cost. The traditional approach to *PM* is to consider corporate projects as being independent of each other. Yet, the relations between projects within the multiple-project environment have been recognized as a major issue for corporations (Payne, 1995; Ghomi and Ashjari, 2002). Therefore, research in this field has recently shifted towards *Project Portfolio Management* (*PPM*). In order to maintain agility while avoiding wasteful investments, a strong discipline of *PPM* is needed. This requires continuous attention and balancing corporate resources against projects' operational risks. In a multiple-project situation the vast majority of projects share resources with other projects and thus the major issue is to find a way of handling resource scarcity according to the overall strategic direction of the corporation (Cusumano and Nobeoka, 1988). The competition among projects for the allocation of individual experts leads to disagreements (Platje et al., 1994; Payne, 1995; Laslo and Goldberg, 2008) and an intensification of internal lobbying activities (Chi and Nystrom, 1998; Bernasco et al., 1999). Furthermore, attempts to optimize resource allocations are confounded by differences in project activities, due-dates, and the nature of penalties for projects that fail to meet their objectives (Lock, 2000; Meredith and Mantel, 2000). The matrix organization of *R&D* projects results from setting up multi-functional

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* Tel.: +972 8 6475 640; fax: +972 8 6475 643.
E-mail address: zohar@sce.ac.il

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teams who are in charge of leading projects with particular objectives. This form enables flexible resource planning that takes into account the availability of scarce resources and the need for special knowledge (Hendriks et al., 1998). Each project is wholly geared towards realizing its delegated objectives through optimal use of allocated resources, especially a skilled workforce (Kerzner, 2000; Bourgeon, 2007). One way to do this is to transfer individuals from their original functional department to the projects for a defined period of time in order to take advantage of their expertise (Katz and Allen, 1985).

PM problems typically consist of resource planning and scheduling decisions. When resource planning decisions are taken, it is extremely important to identify and evaluate the corporate strategic variables in terms of the future posture of the corporate projects with regard to constraints on existing resources (Laslo and Goldberg, 2001). Accelerated technological development strengthens the position of the individual experts who are scarce, expensive and "pampered" resources. Multiple projects contending for limited resources such as individual experts complicates the task of resource planning and scheduling that arises in the daily management of corporations (Vals et al., 2009). An additional important issue that looms high in the management of *R&D* projects is that of uncertainty, ambiguity, and complexity (Pich et al., 2002). In practice, managers frequently create programs and schedules based on the expected values of activity durations. However, many real-world planning and scheduling problems are subject to change, to resources becoming unexpectedly unavailable or tasks taking longer than expected. If these disturbances are significant, then optimal solutions to the original problem may turn out to be deficient in practice, i.e., the probability of completing those projects within a prescribed due-date might be unacceptably low (Williams, 1999; Bregman, 2009; Wu et al., 2009).

Resource planning and scheduling have generally been considered separately in the literature, but the benefits resulting from their integration merit an extensive work in this direction (Tormos et al., 2002). Similarly, new paradigms in project planning and control due to the increased complexity of projects, especially relative to uncertainty, are needed. In particular, *R&D* multi-project corporations need an integrative resource planning and scheduling optimization method that optimizes (minimizes) the total planning/scheduling-dependent expenses subject to its chance-constrained contractual delivery commitments.

The present paper aims at determining such an optimization method by taking into consideration the following factors: (1) the idiosyncrasy of several individual experts as scarce resources; (2) the diverse costs of employing each of the individual experts and the diverse lead-times of their recruitment; (3) the random durations of the project activities executed by the individual experts and other human resources; (4) the typical precedence constraints of project activities (a *Partial Ordered Set* (*POSET*) of activities); (5) the diverse project due-dates and determined chance constraints to accomplish the projects on time; and (6) the diverse delay penalty functions in case of failure to meet the contractual due-dates.

In Section 2 we give an overview of alternative resource planning and scheduling models in the context of *PM* optimization problems and *Job-Shop Problem*s (*JSP*s). The statement of our optimization problem is presented in Section 3. In Section 4 we present a greedy priority dispatching rule that delivers resource scheduling for minimizing definite planning/scheduling-dependent expenses. The integrated solution of the individual experts' planning and scheduling problem via a cyclic coordinate descent search-algorithm, namely "the integrated method", is presented in Section 5. An analysis of virtual implementations on a realistic project portfolio with alternative resource planning and scheduling (the integrated method vs. one of the staffing project team models) is detailed and analyzed in Section 6. On the basis of this analysis, in Section 7 we discuss the implications of implementing the integrated method on both short-term and long-term objectives.

2. Overview: current models for resource planning and scheduling optimization problems

The project scheduling literature largely concentrates on the generation of a precedence and resource feasible schedule that optimizes the scheduling objectives for executing the project. In this literature, the scheduling problems assume a number of projects with several scarce (non) renewable resources at any time and a set of non-preemptive activities, each with a set of predecessors, a set of successors and a set of resource requirements (Pritsker et al., 1969). The *JSP*, where multiple jobs are routed through a workshop with a number of dissimilar machines, is similar to the well-known *Resource-Constrained Project(s) Scheduling Problem* (*RCPSP*). Instead of considering *POSET*s of project activities, the *JSP* is obligated to solving linear ordered sets (of job operations). Both these problems are frequently studied as *NP-hard* optimization problems (Błazewicz et al., 1983). A remarkable improvement of both heuristic and exact solution procedures to solve these problems has been pointed out in several surveys (Ozdamar and Ulusoy, 1995; Herroelen et al., 1998; Kolisch and Hartmann, 1999; Gonik, 1999; Hartmann and Kolisch, 2000; Kolisch and Padman, 2001; Demeulemeester and Herroelen, 2002).

Models with stochastic execution durations necessitate heuristic solution procedures for *RCPSP*/*JSP*, but since these problems are recognized as *NP-hard*, the solution procedures for large models with deterministic execution durations are solved via heuristics as well (Kiran, 1998). The heuristics generally define a scheduling policy that makes decisions at any current decision points throughout the project's life cycle (Igelmund and Radermacher, 1983a,b; Mohring et al., 1984; Mohring et al., 1985). A common decision is to immediately start precedence and resource feasible set of activities, exploiting only information that has become available up to the decision point.

The current versions of the *RCPSP*/*JSP* models are inadequate for our purpose. Some models do not take into consideration the diversity of resources, projects and contracts (e.g., Haupt, 1989). Moreover, they are not pertinent to real-life situations (Laslo, 2001). Other models are dedicated to a single economic objective (e.g., Sobel et al., 2009) or to evaluating the scheduling process by a substitute that represents a single economic gain (e.g., minimization of the makespan). But, real-life problems deliver mostly multi-objective goals. Models with deterministic execution times (e.g., Schmidt, 2000) do not represent project activities, especially *R&D* activities (Elmaghraby, 2005). When pre-given resource constraints are considered (e.g., Golenko-Ginzburg and Gonik, 1997,), resource planning is pointless.

Some planning scheduling optimization models have been introduced for a single resource/machine (e.g., Trietsch, 1993; Elmaghraby et al., 2000). But it is obvious that in *PM* there is an interrelationship among the individual experts' hiring/releasing timetables that prevents us from attaining an "optimal" comprehensive solution by optimizing the timetable and the schedule of each individual expert separately. Laslo et al. (2008) have extended these models by expanding the problem to a model with several machines. The solution of this problem was generated by a cyclic coordinate descent search-algorithm seeking minimum total costs. A special dispatching rule was implemented in the scheduling simulation in order to simultaneously satisfy the scheduling restrictions and minimize (optimize) the job-shop's expenses.

The optimization method developed for *JSP* by Laslo et al. (2008) considers linear ordered sets of job operations, i.e., a chain of operations for each job. In contrast, *PPM* considers problems with *POSET*s of project activities. Therefore, *JSP* is concerned with competition on the same resource among jobs and never among operations within the job while *PPM* is concerned with competition on the same resource among projects and among activities within projects. Moreover, for *PPM*, the determination of the distribution density of the job's and the project's completion times are performed differently than they are for *JSP*. When job operations are linear ordered, for a known distribution density of the execution durations one can determine the distribution density of the job's completion time, and as a consequence, the probability to accomplish the job on time. However, it should be mentioned that the presence of *POSET*s of project activities complicates the determination of the distribution density of the project's completion time and simulation tools are required for this purpose. These significant differences between *JSP* and *PPM* situations require that the method developed by Laslo et al. (2008) for the *JSP* should be extended and modified to the situation of *PPM* problems.

3. The statement of the optimization problem

We consider a project portfolio, where each project is denoted by a *Directed Acyclic Graph* (*DAG*), *Activity-on-Arc* (*AOA*) network. Each project has a known acceptance (arrival) time, a known contractual completion time and a pre-given confidence probability (chance constraint) of its accomplishment on time. The penalty cost for not completing the project on time (to be paid once to the customer) and an additional penalty to be paid for each time unit of delay are known beforehand as well. Each project activity has a random execution duration with a given distribution density. The actual start of the project execution is random, but depends on the availability of an appropriate individual expert and can never occur before the project is accepted. Since we consider that once the project activity execution starts the execution proceeds continuously until the activity is accomplished, the random actual completion time of the project activity is determined as its start time plus its execution duration, both of them being random. The partial order of the project activities determines that the start of the project activities execution requires that all its predecessor activities are accomplished. The project is accomplished when all its activities, or more specifically, when all the project activities ending at the project's sink node are accomplished. The random end of the makespan is by definition the point of time when all the projects are accomplished.

The project is executed by several individual experts and unconstrained capacity of non-scarce human resource types. Project activities may be executed by any combination of non-scarce human resource types with or without an individual expert, but never by a combination which includes several individual experts. Each of the individual experts who is not currently employed can be hired once at a certain time which has to be determined beforehand (because of their scarcity), and fired at the time when the last project activity that requires his expertise is accomplished. All types of non-scarce human resource types, whether internal or external reinforcement (outsourcing), can be hired and fired several times. Thus, non-scarce human resources are considered to be available for full satisfaction of the projects' requirements for the workforce at any time within the makespan. The salary of each of the individual experts per time unit within the period of their employment is known. The total salary of the non-scarce human resources is random and in theory should not be planning/scheduling-dependent since the flexibility of the non-scarce human resources' hiring and releasing enables us to avoid situations in which non-scarce human resources are idle. Therefore, the non-scarce human resources salaries per time unit are not of our interest here.

Our problem is to determine the individual experts' hiring/releasing timetables in order to minimize the expected scheduling expenses within the makespan, subject to the chance-constrained project completion on time. Since the total costs comprise the scheduling expenses, the costs to take into consideration are the costs of the idle individual experts' salaries within the makespan and the delay penalty expenses.

For the reader's convenience, let us first introduce the following terms:

$A_{k,i,j}$	the activity of kth project that can be executed continuously within the period between the occurrences of events (nodes) i and j, $1 \leqslant i \leqslant q_k - 1$, $2 \leqslant j \leqslant q_k$, $A_{k,i,j} \in G_k$ (q_k – number of nodes in DAG G_k)
C_h^I	the cost (salary) of individual expert I_h per time unit within the period $\left[T_h^*, T_h^{**}\right]$ (pre-given), $1 \leqslant h \leqslant n$
C_k^d	the fixed component of the penalty cost function for not completing the kth project on time D_k, $F_k > D_k$ (pre-given)
C_k^v	the variable component of the penalty cost function per time unit of delay within the period $[D_k, F_k]$ if $F_k > D_k$ (pre-given)
D_k	the contractual completion time of the kth project, $1 \leqslant k \leqslant m$ (pre-given)
F	the makespan end time, $F = \underset{k}{\mathrm{Max}}(F_k)$
F_k	the actual completion time of the kth project, $F_k = \underset{i}{\mathrm{Max}}(F_{k,i,q_k})$ (a random value)
$F_{k,i,j}$	the time when project activity $A_{k,i,j}$ is actually accomplished, $F_{k,i,j} = S_{k,i,j} + t_{k,i,j}$ (a random value)
G_k	the DAG that describes the initial $POSET$ of the kth project activities, $1 \leqslant k \leqslant m$ (m – number of projects)
G_{k_t}	the DAG that describes at time t the up-to-date $POSET$ of the kth project activities $A_{k,i,j} \mid R_k \leqslant t < F_{k,i,j}$
I_h	the hth individual expert, $1 \leqslant h \leqslant n$ (n – number of experts)
$n_{k,i,j}$	the index of the individual expert to execute the project activity $A_{k,i,j}$, $1 \leqslant n_{k,i,j} \leqslant n$ (pre-given)
p_k^*	the required confidence probability (chance constraint) of the kth project to be accomplished before or at the contractual completion time D_k (pre-given)
$S_{k,i,j}$	the time when project activity $A_{k,i,j}$ actually starts (a random value)
R_k	the time when the kth project is accepted, $1 \leqslant k \leqslant m$ (pre-given)
T_h^*	the planned time of hiring individual expert I_h (an optimal variable, to be determined beforehand)
T_h^{**}	the time of releasing individual expert I_h (a random value)
t	the scheduling decision point of time within the makespan $[0, F]$
$t_{k,i,j}$	the random duration of $A_{k,i,j}$ with expected value $E(t_{k,i,j})$ and variance $V(t_{k,i,j})$
Z	the planning/scheduling-dependent expenses, i.e., expenses dependent on $\{T_h^*\}$ within the makespan $[0, F]$, $Z = Z_1 + Z_2$
Z_1	the cost of the idle individual expert salaries within the makespan $[0, F]$
Z_2	the delay penalty expenses

The optimization model for this problem is as follows:

$$E(Z) = \underset{\{T_h^*\}}{\mathrm{Min}}[E(Z_1) + E(Z_2)], \tag{1}$$

subject to:

$$S_{(k,i,j) \in G_k} \geqslant R_k, \quad 1 \leqslant k \leqslant m, \tag{2}$$

$$S_{(k,i=x,j) \in G_k} \geqslant \underset{i}{\mathrm{Max}}(F_{(k,i,j=x) \in G_k}), \quad 2 \leqslant x \leqslant q_k - 1, \tag{3}$$

$$S_{(k,i,j) \in G_k} \geqslant T_h^* \ \text{ if } n_{k,i,j} = h, \ 1 \leqslant k \leqslant m, \ 1 \leqslant h \leqslant n, \tag{4}$$

$$\left[S_{z,x,y}, F_{z,x,y}\right] \cap \left[S_{(k,i,j) \neq (z,x,y)}, F_{(k,i,j) \neq (z,x,y)}\right] = \phi \ \text{ if } \ n_{z,x,y} = n_{k,i,j}, \tag{5}$$

$$\Pr(F_k \leqslant D_k) \geqslant p_k^*, \quad 1 \leqslant k \leqslant m. \tag{6}$$

The costs of the idle individual experts' salaries within the makespan can be calculated as follows:

$$Z_1 = \sum_{h=1}^{n} C_h^I \left(T_h^{**} - T_h^* - \sum_{k=1}^{m} \sum_{i=1}^{q_k - 1} \sum_{j=2}^{q_k} t_{k,i,j} \delta_{k,i,j}^h \right), \tag{7}$$

where the random time of releasing individual expert I_h is:

$$T_h^{**} = \underset{(k,i,j) \in G_k}{\mathrm{Max}} (F_{k,i,j} \delta_{k,i,j}^h), \quad 1 \leqslant k \leqslant m, \tag{8}$$

and

$$\delta_{(k,i,j) \in G_k}^h = \begin{cases} 1 & \text{if } n_{(k,i,j) \in G_k} = h \\ 0 & \text{otherwise} \end{cases} \quad 1 \leqslant h \leqslant n. \tag{9}$$

The project delay penalty expenses can be calculated as follows:

$$Z_2 = \sum_{k=1}^{m} \gamma_k \left[C_k^d + C_k^v (F_k - D_k)\right], \tag{10}$$

where

$$\gamma_k = \begin{cases} 1 & \text{if } F_k > D_k \\ 0 & \text{otherwise} \end{cases} \quad 1 \leqslant k \leqslant m. \tag{11}$$

The objective function (Eq. (1)) minimizes the total planning/scheduling-dependent expenses, while Eqs. (7) and (10) denote the planning/scheduling-dependent operational expenses. Restrictions (2)–(4) denote that the execution of any project activity cannot start before: (i) the project's acceptance time (Eq. (2)); (ii) before all its predecessor activities are accomplished (Eq. (3)); and (iii) before the required individual expert who can execute the activity is hired (Eq. (4)). Restriction (5) denotes that any individual expert cannot execute more than one project activity at any time within the makespan, while restrictions (6) are the chance constraints.

This optimization problem (Eqs. (1)–(11)) is complex and can be solved by a combination of a heuristic decision-making rule based on probabilistic forecasting as well as an approximate optimization method.

4. The solution of the resource scheduling problem

The resource scheduling problem is solved via simulation, on the basis of the heuristic decision-making rule that chooses a project activity from alternative eligible project activities to be executed by one and the same individual expert. The rule is an essential modification of the previously developed heuristics based on a pair-wise comparison (Golenko-Ginzburg et al., 1995; Golenko-Ginzburg and Gonik, 1997,; Golenko-Ginzburg and Gonik, 2002; Golenko-Ginzburg and Laslo, 2004; Laslo et al., 2008) of long-term forecasting to calculate, at a certain time t, the probability to meet the contractual completion time of the kth project, D_k, i.e., $\Pr(F_k \leqslant D_k)$.

At time t one or several project activities are executed or are ready for execution. The unaccomplished project activities of the kth project at time t is denoted by G_{k_t}. Assuming that the following project activities will not wait for their execution, the random project remaining time at t can be simulated via *Monte Carlo Simulation* (Van Slyke, 1963) for each of the projects. The idle (available) individual expert at the same time t is I_h. No scheduling action can be taken if no eligible project activity is waiting to be executed by the available individual expert I_h at t. If there is only one eligible project activity, the individual expert is allocated to this project activity without competition. If more than one project activity is eligible for execution by the available individual expert I_h, we suggest that the decision be based on a pair-wise comparison. The decision-making procedure is carried out by applying a pair-wise comparison to the couple ($A_{(k,i,j)_1}$, $A_{(k,i,j)_2}$). The winner will compete with project activity $A_{(k,i,j)_3}$, etc., until only one winner is left, to which the individual expert is allocated.

Two competitive alternative decision options are examined:

(1) individual expert I_h will execute project activity $A_{(k,i,j)_1}$ first, and $A_{(k,i,j)_2}$ afterwards.
(2) individual expert I_h will execute project activity $A_{(k,i,j)_2}$ first, and $A_{(k,i,j)_1}$ afterwards.

If project activity $A_{(k,i,j)_\mathrm{First}}$ is scheduled first to be executed by the individual expert I_h at time t, its completion time will be $t + t_{(k,i,j)_\mathrm{First}}$. This means that the individual expert I_h will be occupied with the project activity $A_{(k,i,j)_\mathrm{First}}$ until the time $t + t_{(k,i,j)_\mathrm{First}}$. Therefore, the completion time of the project activity $A_{(k,i,j)_\mathrm{Second}}$ will be $t + t_{(k,i,j)_\mathrm{First}} + t_{(k,i,j)_\mathrm{Second}}$. The remaining execution time of each of the project activities that are in process at time $S_{k,i,j} < t < F_{k,i,j}$, is $\mathrm{Max}[t_{k,i,j} - (t - S_{k,i,j}),0]$. These datum enable us to predict via *Monte Carlo Simulation* the projects' probabilities to be accomplished before or at the contractual completion times, $\Pr(F_k \leqslant D_k)$.

Should the *Monte Carlo Simulation* show that one of the competitive alternative options is superior, i.e. it satisfies $Pr(F_k \leqslant D_k) \geqslant p_k^*$ for the related projects while the other does not, this alternative is chosen. Should both or none of the competitive alternative options satisfy $Pr(F_k \leqslant D_k) \geqslant p_k^*$ for the related projects, the winning criteria will be the contribution of the related projects to the expected delay penalty expenses. The option with the minimal $E(Z_2)$ of the related projects will be the preferred competitive alternative option that will determine which of the two competing project activities is the winner.

Implementing the decision-making rule enables the assignment to be controlled in real time or to be simulated by random sampling of the duration of the project activities. In both cases, when more than one project activity is waiting for one and the same individual expert, decision-making has to be introduced at multiple decision points t. Simulating the assignment many times enables evaluation of the expected total expenses $E(Z)$.

5. The integrated method: the integrated solution of the individual experts' planning and scheduling problem

It is well recognized that determining individual experts' hiring timetables $\{T_h^*\}$ fully defines all the parameters that are required for the individual experts' planning and scheduling. These parameters enable the simulation of the assignment in order to test the fitness of the suggested model for minimizing the planning/scheduling-dependent expenses. Thus, via simulation, one can obtain the set of near-optimal values $\{T_h^*\}$ to minimize the expected total expenses $E(Z)$. We solve the optimization problem (Eqs. (1)–(11)) as follows. The heuristic algorithm consists of an optimization algorithm that undertakes a search of the hiring timetables for the individual experts who are not employed at the start point ($t = 0$), together with a simulation model that consists of the decision-making rules outlined above. After obtaining a routine search point $\{T_h^*\}$, the simulation model is applied to obtain representative statistics via numerous simulation runs. The values T_h^*, $1 \leqslant h \leqslant n$, at each search point are input values for a simulation that:

(1) calculates at the beginning of each simulation run values $\mathrm{Max}(R_k, T_h^* \delta^h_{(k,1,j)\in G_k})$, $1 \leqslant k \leqslant m$;
(2) determines project activities eligible for execution seeking one and the same individual expert;
(3) allocates individual experts to the eligible project activities according to the decision-making rule outlined above;
(4) calculates the multi-objective function $E(Z)$ according to the optimization problem (Eqs. (1)–(11)) within a simulation run;
(5) monitors the project activities' executions according to the initial data matrix;
(6) simulates the duration $t_{k,i,j}$ of project activity $A_{k,i,j}$ at time $S_{k,i,j}$;
(7) calculates the timing of essential times t, when: (i) either the execution of a project activity terminates; or (ii) there is an idle individual expert to execute project activities which are waiting to be executed by that individual expert; or (iii) a project denoted by G_k is accepted at time R_k;
(8) simulates random time values T_h^{**} to release individual experts I_h, $1 \leqslant h \leqslant n$;

(9) simulates random time values when the projects are accomplished, F_k, $1 \leqslant k \leqslant m$;
(10) calculates the frequency to meet the project contractual completion times, $\Pr(F_k \leqslant D_k)$,$1 \leqslant k \leqslant m$ and $E(Z)$ on the basis of simulated statistics via numerous simulation runs.

In the course of a simulation run, the simulation model examines step-by-step all the essential times and undertakes decision-making by means of decision-making rule.

The hiring timetables for individual experts who are unemployed at $t = 0$, $\{T_h^*\}$, fully defines the assignment parameters. The multi-objective function $E(Z)$ is a very complicated non-linear continuous function of values T_h^*, $1 \leqslant h \leqslant n$, which can be optimized by using coordinate descent methods. These methods, which are quite easy to implement (Luenberger, 1973), have been used successfully both in production control and in *PM* (Golenko-Ginzburg and Kats, 1996; Gonik, 1999) and were recently implemented in job-shop planning (Laslo et al., 2008). The approximate solution to the optimization problem (Eqs. (1)–(11)) via the cyclic coordinate descent search-algorithm can be obtained by minimizing $E(Z)$ with respect to the n coordinate variables $\{T_h^*\}$. The idea is to begin by changing the first coordinate T_1^* while all other coordinates are fixed and remain unchanged. After obtaining the quasi-optimum value of T_1^*, we proceed by optimizing the second coordinate T_2^* (with the newly obtained and fixed T_1^* and fixed $T_3^*, \ldots, T_n^*$), and so on through T_n^*. The process is then repeated starting from T_1^* again, until the relative difference between two adjacent iterations becomes less than the pre-given accuracy $\varepsilon < 0$. Note that several of the n coordinate variables $\{T_h^*\}$ which represent the employed individual experts at $t = 0$, are irremovable and remain with the value 0 throughout the coordinate search.

When using the coordinate descent method, the coordinate search is carried out only for independent variables T_h^*. As for the search-algorithm, for each coordinate T_h^*, $1 \leqslant h \leqslant n$, a constant increment Δt_h (the time step) is pre-given. The multi-objective function $E(Z)$ is calculated at two opposite points $\left[T_1^*, T_2^*, \ldots, T_h^* - \Delta t_h, T_{h+1}^*, \ldots, T_n^*\right]$ and $\left[T_1^*, T_2^*, \ldots, T_h^* + \Delta t_h, T_{h+1}^*, \ldots, T_n^*\right]$ to determine the direction of the function's decrease. The search is undertaken along that direction, i.e., values $Z_{\left[T_1^*, T_2^*, \ldots, T_h^* + q\Delta t_h, T_{h+1}^*, \ldots, T_n^*\right]}$, $q = \pm 1 \pm 2, \ldots,$ are calculated. The iterative process terminates either at a local minimum point or upon reaching a boundary point of the set $\{T_h^*\}$ (usually the upper and lower bounds for each value T_h^* are pre-given).

6. Benchmarking of the two alternative methods for resource planning and scheduling

The expected performances of the integrated method in which the resource planning and scheduling are subordinated to the availability of the individual experts were compared with the expected performances of the staffing project teams method that considers the *Profit and Cost Centers Resource Allocation Policy* (Laslo and Goldberg, 2008). The resource scheduling is performed by the *SPAR-1* algorithm (Wiest and Levy, 1977) using the *Minimum Slack* (*MINSLK*) dispatching rule, which has been found to be the most effective rule for minimizing the project completion time (Davis and Patterson, 1975) (see: Appendix A). The benchmarking was performed for the following scheduling/planning-dependent expenses:

- the expected project delay penalty expenses (Eq. (10));
- the expected costs of the idle individual experts' salaries within the makespan (Eq. (7));
- the expected individual experts' mobilization costs (paid once for each hiring);
- the expected costs of the integration of individual experts into the project teams (paid once for each joining team);
- the expected costs of the idle non-scarce human resource salaries within the makespan;
- the expected non-scarce human resource mobilization costs (paid once for each hiring);
- the expected costs of the integration of non-scarce human resources in the project teams (paid once for each joining team);
- the expected losses incurred from precipitous outsourcing.

The projects' execution costs are not of interest since these costs are neither dependent on the individual experts' planning nor on their scheduling.

A static portfolio of nine long-term projects taken from an Israeli *Information Technology* (*IT*) company was used for the benchmarking. Five projects had been in progress and the other four were approved for execution. Each project has a contractual completion time, a pre-given chance constraint of its accomplishment on time, and a specific penalty function that is affected by the delay length. One hundred and thirty-nine project activities were included, each having a random execution duration with a given distribution density. Individual experts were involved in the execution of 56 project activities (40% of the activities), but only a single individual expert executed each of these activities. To accomplish the project portfolio, three types of non-scarce human resources and four individual experts were required. As shown in Fig. 1, each of the individual experts has one or several specific skills that are required throughout the different stages of the project life cycles. Realistic values were considered for costs (delay penalties, salaries, mobilization costs, integration costs and avert outsourcing costs) and mobilization lead-times.

As shown in Table 1, the simulated results for this specific project portfolio showed that the staffing of the project teams model enables six chance constraints to be met in order to avoid project delay. Before performing the search-algorithm, the scheduling which is subordinated to

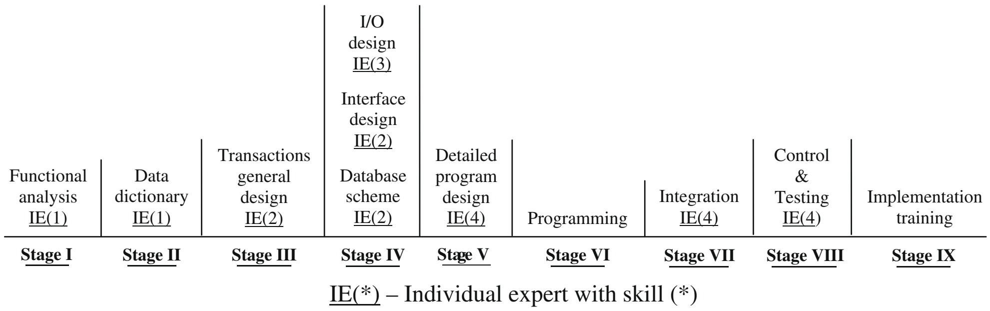

Fig. 1. Skills of individual experts to be implemented throughout the different stages of the project life cycles.

Table 1
The simulated project timetables (in weeks).

Project	Contractual completion time	The staffing project teams model		The integrated method	
		Expected start	Expected finish	Expected start	Expected finish
A	78	10	61	12	53
B	169	26	135	25	79
C	156	13	206[a]	13	116
D	169	0	83	39	136
E	65	0	50	1	52
F	221	13	172	7	166
G	247	39	245[a]	19	179
H	338	26	270	7	219
I	234	5	269[a]	0	190

[a] Unsatisfied chain constraint.

the availability of the individual expert enables eight of the nine chance constraints to be met in order to avoid project delay.

In Table 2 we can see the simulated timetables of the individual experts within the makespan and their expected idle times during their employment as well.

Five iterations of the search-algorithm were sufficient for obtaining the approximate solution to the optimization problem (Eqs. (1)–(11)) that attains all the chance constraints be met in order to avoid project delay. The economic advantages and disadvantages of the integrated method, before and after performing the search-algorithm, vs. the staffing of the project teams model for this project portfolio are shown in Table 3.

The benchmarking results show that the two scheduling/planning-dependent types of expenses decrease drastically when the integrated method is implemented. In addition, the expected project delay penalty expenses also decrease as a result of implementing both the heuristic pair-wise rule and the search-algorithm. The implementation of the integrated method without carrying out the search-algorithm increases the expected costs of the idle individual expert salaries. The reason for this is that in this stage all the individual experts are employed at the beginning of the makespan. The implementation of the search-algorithm reduces the interval of the individual experts' employment and accordingly drastically reduces their expected idle time and the expected salaries paid for it. The expected individual expert mobilization costs decrease drastically since the integrated method considers that each of the individual experts is mobilized once within the makespan, whether or not the search-algorithm is carried out. On the other hand, irregular participation of the individual experts in the project teams drastically increases the average costs of the integration of individual experts into the project teams. Furthermore, the implementation of the search-algorithm does not provide a significant decrease of these costs.

Table 2
The simulated individual expert timetables (in weeks).

Individual expert	The staffing project teams model			The integrated method		
	Expected hiring point	Expected releasing point	Expected idle times	Expected hiring point	Expected releasing point	Expected idle times
1	5	46	3	0	39	0
2	13	81	1	8	75	0
3	0	2	0	25	57	7
	22	29	0			
	48	56	0			
	74	82	0			
4	10	65	9	12	183	0
	88	148	4			
	164	188	0			
	203	249	0			

Table 3
Benchmarking methods for resource planning and activity scheduling – the economic aspect.

Scheduling/planning-dependent expenses (K$)	Staffing project teams model	Integrated method			Saving as a result of implementing the integrated method (%)
		Implementation of the heuristic pair-wise rule	Implementation of the search-algorithm	Saving as a result of carrying out optimization (%)	
Expected project delay penalty expenses	162.4	86.0	14.2	83	91
Expected costs of the idle individual experts' salaries	62.2	81.0	21.6	73	65
Expected individual experts' mobilization costs	34.9	8.7	8.7	0	75
Expected costs of the integration of individual experts into the project teams	22.7	36.7	35.6	3	(57)
Expected costs of the idle non-scarce human resource salaries	121.8	75.4	67.5	10	45
Expected non-scarce human resource mobilization costs	37.3	48.9	46.7	(4)	(25)
Expected costs of the integration of non-scarce human resources in the project teams	51.2	60.9	61.9	(2)	(21)
Expected losses incurred from precipitous outsourcing	18.9	33.8	33.6	1	(78)
Summarized scheduling/planning-dependent expected expenses	511.4	431.4	289.8	33	43

Although the integrated method is subordinated to the availability of the individual experts, it also requires flexibility in hiring and releasing the non-scarce human resources. This is the reason for the drastic decrease in the expected costs of the idle non-scarce human resource salaries when the staffing project teams model is replaced by the integrated method. Furthermore, according to the benchmarking, the implementation of the search-algorithm moderately decreases the expected costs of the idle non-scarce human resource salaries. From Table 3 we can learn that flexibility in hiring and releasing the non-scarce human resources drastically increases the expected non-scarce human resources mobilization costs, the expected costs of integrating the non-scarce human resources to the project teams and the expected losses incurred from precipitous outsourcing. Moreover, implementation of the search-algorithm does not have any significant effect on these costs.

To sum up, for this project portfolio, the integrated method is by far superior to the staffing project teams model, in terms of the scheduling/planning-dependent expected expenses, especially after implementing the search-algorithm. Thus, the results of the benchmarking clearly indicate the great extent to which our integrated method saves planning/scheduling-dependent expenses. For this reason, we believe that the method we proposed is a very practical and promising tool for improving *PPM* performance.

7. Discussion

We have presented an integrated method for optimizing resource planning and scheduling. In particular, our method provides individual experts' hiring/releasing timetables that minimize the corporate planning/scheduling-dependent expenses under chance-constrained contractual delivery commitments.

In the course of the optimization process, several resource constraints are taken simultaneously into consideration. The integrated method separates the individual experts from the project teams. This method requires enlarging of the non-scarce human resources' reinforcement flexibility by outsourcing their work when their temporary shortage causes unemployment of currently employed individual experts or in cases of expected delivery delays of contractual commitments.

Probable debate about the applicability of the method proposed may arise by arguing that *PM* is very concerned with so called long-term objectives that are less relevant for manufacturing systems. Such objectives might be staffing quality (McComb et al., 2007) and collective learning (Bourgeon, 2007) which demand stable project teams and encouraging innovation (Chen and Huang, 2009) which requires stable employment of specific individual experts. Our answer is that the optimized resource planning and scheduling by the integrated method should not always be considered as the final program but as a base-line for the decision-makers. To illustrate, after determining the lower-bound of the planning/scheduling-dependent expenses, it might be decided to keep core teams of non-scarce human resources in several projects or to enlarge the individual experts' employment periods. Moreover, we argue that the ability to separate between the unavoidable planning/scheduling-dependent expenses provided by the method proposed, and the additional expenses paid for obtaining long-term objectives with benefits that are mostly immeasurable in quantitative terms is of great importance in the course of the *PPM*'s decision-making process.

Appendix A. A periodic project team staffing approach – the simulation procedure

1. Determine the projects priority position within the portfolio of projects;
2. deploy the needs during the projects' life cycle for each of the resource types, assuming expected activity duration as deterministic times and assuming "earliest start" scheduling of eligible activities;
3. calculate the projects' average need for each of the resource types in each of the planning periods;
4. sum up the periodic requirements of the portfolio of projects for each of the resource types;
5. compare the total requirements for each resource type in each of the planning periods to the current (initial) resource capacity and as sequence adjust the company resource capacities:
    - if the periodic resource capacities disable the full satisfaction of the requirements, expand the capacities of the succeeding planning periods taking into consideration the mobilization response time by:
        - the average shortage during the mobilization response time plus the average shortage/redundancy in the three following planning periods if the sum shows shortage, for individual experts, or,
        - the average shortage/redundancy in the three following planning periods if the sum shows shortage, for normal workforce;

    - if the periodic resource capacities show overflows, discharge the capacities of the succeeding planning periods to the discharge response time by:
        - the average shortage/redundancy in the three following planning periods to the discharge response time when the sum shows redundancy;

6. for each of the resource types, compare the total requirements vs. the available capacity in the current planning period:
    - if full satisfaction is possible:
        - allocate the required capacity to each of the projects, and the remaining capacity keep in the functional unit (as unemployed capacity);

    - otherwise:
        - for individual experts – allocate the individual expert to the project in which its employment during the current planning period is maximal;
        - for normal workforce – outsource the incomplete capacity and allocate the required capacity to each of the projects;
7. sample 1000 sets of project activity durations;
8. schedule repeatedly under resource constraints each of the 1000 project activities sets by the *MINSLK* heuristic dispatching rule (*Monte Carlo Simulation*);
9. calculate the outputs of the *Monte Carlo Simulation*.

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