Amirkabir University of Technology
(Tehran Polytechnic)
Vol. 47, No. 1, spring 2015, pp. 21- 32

Amirkabir International Journal of Science & Research
(Modeling, Identification, Simulation & Control)
(AIJ-MISC)

Developing Robust Project Scheduling Methods for Uncertain Parameters

I. Bossaghzadeh[1*], S. R. Hejazi[2], and Z. Pirmoradi[3]

1- MSc of Industrial Engineering, Isfahan University of Technology, Isfahan, Iran
2- Professor of Industrial Engineering, Isfahan University of Technology, Isfahan, Iran
3- PhD of Product Design and Optimization Lab, Simon Fraser University, Surrey, Canada

ABSTRACT

A common problem arising in project management is the fact that the baseline schedule is often disrupted during the project execution because of uncertain parameters. As a result, project managers are often unable to meet the deadline time of the milestones. Robust project scheduling is an effective approach in case of uncertainty. Upon adopting this approach, schedules are protected against possible disruptions that may occur during project execution. In order to apply robust scheduling principles to real projects, one should make assumptions close to the actual conditions of the project as much as possible. In this paper, in terms of uncertainty in both activities duration and resources availability, some methods are proposed to construct the robust schedules. In addition, various numerical experiments are applied to different problem types with the aid of simulation. The main purpose of those is to assess the performance of robust scheduling methods under different conditions. Finally, we formulate recommendations regarding the best method of robust scheduling based on the results of these experiments.

KEYWORDS

Project Scheduling, Uncertainty Modeling, Robustness, Simulation.

---

[*] Corresponding Author, Email: rehejazi@cc.iut.ac.ir

1. INTRODUCTION

The vast majority of the research efforts in project scheduling assume complete information about the scheduling problem to be solved and a static deterministic environment within which the pre-computed baseline schedule will be executed. However, in the real world, project parameters are subject to considerable uncertainty, which is gradually resolved during project execution. Herroelen and Leus [1] reviewed fundamental approaches for scheduling under uncertainty: stochastic project scheduling, fuzzy project scheduling, sensitivity analysis, robust scheduling and reactive scheduling. Most efforts on stochastic project scheduling concentrate on the so-called stochastic resource-constrained project scheduling problem. This problem aims at scheduling project activities with uncertain durations in order to minimize the expected project duration subject to zero-lag finish-start precedence constraints and renewable resource constraints [1]. The advocates of the fuzzy activity duration approach argue that probability distributions for the activity durations are unknown due to the lack of historical data. As activity durations have to be estimated by human experts, often in a non-repetitive or even unique setting, project management is often confronted with judgmental statements that are vague and imprecise [1]. The approach sensitivity analysis addresses ‘‘What if...?’’ types of questions that arise from parameter changes. The approach of robust scheduling is one of the recent approaches to handle uncertainties of the project parameters. Using this approach, the baseline schedule can be constructed so that the parameter variations during a project’s execution cause the least possible disruption in the schedule [1]. A schedule is called robust if variations do not cause significant changes in the value of the baseline schedule objective function [2]. Two types of robust scheduling are of importance: *quality robustness* and *solution robustness* [3]. Under quality robustness, the baseline schedule can be constructed so that the parameter variations cause the least delay in the realized completion time of the project in comparison with the committed deadline. The most common quality robustness objective function is the expected project completion time (makespan). One notable recent development in this field is Critical Chain approach developed by Goldratt [4]. On the other hand, solution robustness helps constructing schedules in which the parameter variations cannot cause significant delay in realized starting times of the activities in comparison to the baseline starting times. The solution robustness objective function measures sum of the weighted deviations between the baseline schedule and the expected realized schedule. Note that, this paper concentrates on the solution robustness issue for project scheduling. Another approach to handle uncertainties in projects is reactive scheduling. The main role of this approach is to correct the schedule after disruption [5]. If disruption occurs during implementation of the project, the current schedule might lose feasibility. Under such condition, the managers should invoke in-time policies to return the schedule to a feasible mode so that the new value of the objective function deviates only little from the baseline schedule.

Most of the recent articles recognize Goldratt`s CC/BM[1] approach as one of the most remarkable recent improvements in the project management literature [6]. The main purpose of this approach is to construct a robust schedule under the condition of uncertain activity durations, and by using the quality robustness. In this approach, a robust schedule is constructed based on the chain and buffer concepts. Herroelen and Leus [6] studied the merits and pitfalls of the CC/BM approach. Al-Fawzan and Haouari [7] considered both the completion time and robustness as the objectives of the RCPSP[2] and used the total free float of the activities as a surrogate function of robustness. Danka [8] presented a primary-secondary-criteria robust scheduling model for RCPSP with the makespan as primary and the NPV[3] as secondary criterion. In this paper, financial issues is combined with robustness concept in project scheduling. In the approach, it is assumed that each activity duration and each cash flow value is an uncertain-but-bounded parameter without any probabilistic or possibilistic interpretation and characterized by an optimistic and pessimistic estimations. The evaluation of a given robust schedule is based on the investigation of variability of the makespan as a primary and the net present value as secondary criterion on the set of randomly generated scenarios given by a sampling-on-sampling-like process. Danka`s model can be classified as a multi-objective RCPSP so that quality robustness is the primary criteria. Note that, to formulate the primary criterion, only activities duration assumed uncertain, while cash flow as an uncertain parameter doesn`t have any role in the primary criterion formulation. Once, all but one of the parameters has been assumed deterministic.

One of the initial important references on project scheduling with solution robustness is the Herroelen and Leus’s paper [9]. Basic assumptions of their research were unbounded resource availability and “just in case” scenarios for uncertain durations, which allow only one

---

[1] Critical Chain/ Buffer Management

[2] Resource Constrained Project Scheduling Problem

[3] Net Present Value

activity duration to change during the project implementation. Van de Vonder observed a trade-off between the quality robustness and solution robustness [3]. In their model, scheduling was performed without the resource constraints and with recognition of the duration uncertainty. Various tests have been conducted, based on simulation. Van de Vonder also examined the trade-off between quality and solution robustness, this time with resource constraints [10]. he has also proposed heuristic algorithms for constructing robust schedules under duration uncertainty and with a solution robustness objective [11]. Lambrechts's paper is the first source in which resource availability rather than activity durations contains the uncertainty; the author assumes that resources can exhibit unexpected failures [12]. Their purpose was the development of robust scheduling procedures with solution robustness. Another paper from Lambrechts et al. is also about consideration of the impact of unexpected resource breakdowns on activity durations [13]. They developed an approach for inserting explicit idle time into the project schedule in order to protect it as well as possible from disruptions caused by resource unavailability. This strategy was compared to a traditional simulation-based procedure and a heuristic developed for the case of stochastic activity durations.

In practice, almost all of the project parameters have an uncertain nature. In order to apply robust scheduling principles to real projects, one should make assumptions close to the actual conditions of the project as much as possible. This paper aims to develop methods for the *solution robustness*, which provide the most accordance between the constructed schedules and the actual condition of the project. Therefore, assuming uncertainty in two project parameters in our research, the STC[4] method is developed to construct robust schedules. The structure of this paper is as follows: section 2 sets out the proposed problem formulation. In section 3, we explore developing the STC method. For assessing the performance of the methods, several numerical tests are performed by simulation. The applied tests and their results are explained in section 4. Section 5 contains the conclusion and finally, we suggest some issues for further research in section 6.

2. PROBLEM STATEMENT

Two parameters are assumed uncertain in constructing a robust schedule with solution robustness: the activity duration and the resource availability. These parameters are assumed to take probabilistic values and their probability distribution functions are known. This problem can be formulated as:

$$Min\ Z = \sum_{j=1}^{N} w_j (E(S_j) - s_j) \tag{1}$$

$$S_i + D_i \le S_j \quad \forall (i,j) \in R \tag{2}$$

$$\sum_{i \in WIP_t} r_{ik} \le A_{kt} \qquad \forall t = 1,2,\ldots,\delta, \quad k = 1,2,\ldots,K \tag{3}$$

$$s_j \le S_j \quad \forall j = 1,2,\ldots,N \tag{4}$$

$$s_N \le \delta \tag{5}$$

Relation (1) shows the objective function for a project with N activities. Note that activities 1 and N are dummy activities with a duration and a resource usage of 0. Activity 1 indicates the start of the project whereas activity N signals the end. Variables sj and Sj denote the baseline starting time and the realized starting time of activity j, respectively. Every activity j has a weight wj that denotes the marginal cost of deviating Sj during execution from sj. Uncertain parameters Dj and Akt are stochastic variables that denote the realized duration of activity j and the available units of renewable resource k at time t, respectively. Relation (2) imposes the precedence constraint to the model. In this relation, set R includes couple activities (i,j) in which, activity i is predecessor for activity j. Relation (3) is also necessary to assure feasibility of the scheduling due to the renewable resource constrainedness. In this relation, r_{ik} denotes the used units of renewable resource k by activity i. In addition, WIP_t is the set of activities that are being implemented at time t. One of the important aspects of solution robustness is the so-called railway mentality according to which, no activity is allowed to start earlier than its baseline starting time [2]. The related constraint is shown in relation (4). Relation (5) is also needed due to the presence of the deadline. This constraint precludes the baseline completion time to exceed δ. Our problem is classified as $m,1,v\tilde{a} \mid cpm, \tilde{d}, \delta \mid \sum w(E(S) - s)$ [14]. The first field specifies the resource characteristics: ($m,1,v\tilde{a}$) refers to an arbitrary number of renewable resource types, each with a stochastic availability that varies over time. The second field refers to the activities characteristics; cpm shows the precedence constraints of a finish to start type with zero time lags. Symbol $\tilde{d}$ refers to the stochastic duration of the activities. In addition, symbol δ represents existence of

---

[4] Starting Time Criticality

the project deadline. At last, third field shows the objective function.

Note that the parameter s is the only decision variable of this model, while parameter S is a dependent variable. The probability distribution function of S is not known and it might be difficult or impossible to calculate, because its value is dependent on 3 factors. It is firstly dependent on the baseline schedule, because in ideal condition each of the activities must start on its baseline time. The second effective factor on S is the parameter`s uncertainties; the reason is that the baseline starting times may be affected by parameter`s variations. The last one is a reactive scheduling procedure; when disruption occurs, the corrective actions should be taken through reactive scheduling procedures in order to retain the schedule feasibility. Since RCPSP is NP-hard, the proposed problem also has at least the same complexity, because the RCPSP is a special case of our problem. As discussed before, the baseline schedule is the first influential factor on the realized starting time of the activities. On the other hand, the realized starting times information is required for solving the model. Due to this mutual relation and because of the other dependences of variable S, no direct solution is available for the model. That is why, in this paper, a heuristic method is developed to construct a baseline schedule.

3. DEVELOPING THE STC METHOD

STC method is known as one of the most effective methods to allocate time buffers to the activities [11]. The basic idea is to start from an initial unbuffered schedule and iteratively create intermediate schedules by adding a one-unit time buffer in front of that activity that needs it the most in the current intermediate schedule, until adding more safety would no longer improve stability. The starting time criticality of an activity j is defined as:

$$stc_j = P(S_j > s_j) \times w_j = \gamma_j \times w_j \tag{6}$$

where γ_j denotes the probability that activity j cannot be started at its baseline starting time.

The iterative procedure runs as follows. At each iteration step the buffer sizes of the current intermediate schedule are updated. The activities are listed in decreasing order of the stc_j. The list is scanned and the size of the buffer to be placed in front of the currently selected activity from the list is augmented by one time period such that the starting times of the activity itself and of the direct and transitive successors of the activity are increased by one time unit. If this new schedule has a feasible project completion ($s_{N \leq \delta}$) and results in a lower estimated cost ($\sum stc_j$), the schedule serves as the input schedule for the next iteration step. If not, the next activity in the list is considered. Whenever no feasible improvement is found, a local optimum is obtained and the method terminates. Regrettably, the probabilities γ_j are not easy to compute. This value can be estimated only for the case of uncertain durations [11]. In this method, lack of attention to the uncertainty of other parameters is a considerable weakness. Therefore, we try to find proper estimations of γ_j assuming uncertainty in both activity duration and resource availability.

A. Simulation

The analytic evaluation of the objective function is very cumbersome, so that one usually relies on simulation [12]. In this paper, we try to run the simulations close to the condition of real projects. Note that in all of the simulations, the railway mentality has been followed. The first precondition of simulation is to determine the probability distribution function of uncertain parameters. It is assumed that activity`s durations follow the Beta distribution. This parameter is assumed to follow the Beta distribution in most of the related researches [11]. The main reason for using this distribution is its compatibility with real conditions of activities duration in which, Lower bound, upper bound and average of the beta distribution are equivalent to optimistic, pessimistic and most likely duration of the activity, respectively. Since the failure rate and the repair rate of the resources are the effective factors on variation of the resources availability, MTTR[5] and MTBF[6] are used for determining the distribution function of resource availability. MTTR and MTBF are supposed to follow exponential distributions for resources. The use of the exponential distribution is supported by empirical evidence as well as by mathematical arguments [12]. Using these properties and the queuing theory concepts, determination of the distribution function for the resource availability will be possible.

Since after occurrence of disruption, a corrective scheduling procedure should be selected for simulating the schedule, another precondition of simulation is to determine a reactive scheduling procedure. The reactive scheduling procedures used in this paper are based on the activities priority list. This list shows the scheduling priorities for project activities. The priorities are obtained based on EBST[7] rule (greatest lateness weight as tiebreaker). This procedure is called EBST1 reactive

---

[5] Mean Time To Repair
[6] Mean Time Between Failures
[7] Earliest Baseline Starting Time

scheduling. In EBST1, after occurrence of disruption, the incomplete activities are ordered non-decreasingly based on their starting time in the baseline schedule. Note that the activities are scheduled based on SGS[8] method and according to the railway mentality. In SGS method, the next unscheduled activity in the priority list is selected and assigned the first possible starting time that satisfies the precedence and resource constraints. In this method, average value of the uncertain parameters can be used. According to the LW rule, if there are activities with the same baseline starting time, the activity with the greatest lateness weight gets the highest priority. Note that the sequence in the priority list should match the predecessor relations of the activities. It is shown that EBST1 produces good results [5]. Moreover, for each schedule, simulation is also done by a random reactive scheduling procedure. In this procedure, after occurrence of disruption, incomplete activities are scheduled randomly under the constraint of feasibilities. This procedure can be a proper benchmark for the EBST1 method.

Determination of the succession to implement the activities after preemption is another precondition for the simulation. Generally, the way an activity would be implemented after preemption is one of the following cases: preempt-resume, preempt-repeat, and preempt-setup [6]. Preempt-resume implies that whenever an activity is interrupted and preempted, it can be continued from the point where execution was halted whenever the reason for the interruption is removed. Preempt-repeat implies that all the time and effort was invested in the execution of that activity until the time of the interruption is lost. This scenario is encountered in practice whenever an activity must be executed without interruption. Of course, both cases are often a simplification of reality. It can be imagined that in practice a mixed form is more likely. Usually, activities will not have to be restarted all the way from zero after they were preempted but it will probably also not be possible to carry on as if nothing happened. The third possibility is therefore that whenever an activity is preempted, a setup time has to be taken into account when restarting this activity. Therefore, it has called this variant preempt-setup. In this paper, the implementing of the activities after preemption is assumed to be the preempt-resume or preempt-repeat, and the robust scheduling methods are discussed separately for these types.

B. Methods

In this paper, a two-stage procedure is applied for constructing the robust schedules. In the first stage, an initial semi-active schedule is generated using the SGS method. A semi-active schedule is a feasible schedule where none of the activities can be locally left shifted [15]. In such schedules, no idle-insert is allowed. In the second stage, time buffers are allocated to the initial schedule. The purpose of this stage is to protect the baseline starting time of the activities against possible parameters variations during the implementation of the project. This two-stage procedure is illustrated in Fig. 1.

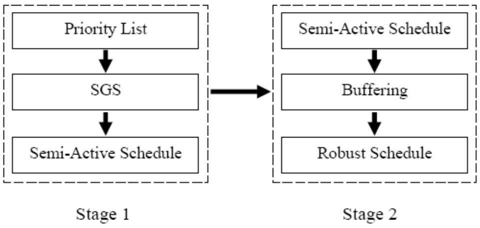


Fig. 1. Fig. 1. Two stages procedure of constructing robust schedules

i. *Initial scheduling*

To construct the initial schedules, the only step is to generate the activities priority list. The methods applied for creating the priority list are explained below:

- Solving the RCPSP

Allocation of time buffers to activities can increase project completion time. Due to presence of the project deadline constraint, time buffers can be added to the schedule only if the project completion time does not exceed the deadline. Therefore, if the project completion time is shorter in a schedule, it is more possible to allocate time buffers to that schedule. Since the objective of the deterministic RCPSP is to minimize the project completion time, the schedules constructed by solving the RCPSP can be the proper initial schedules. In this model, all of the parameters are assumed to have deterministic nature and the average value of the uncertain parameters can be used for them. In the schedules obtained by solving the RCPSP, the activities will be placed in the priority list based on non-decreasing order of their starting time. Various algorithms can be used for solving the RCPSP. It is shown that HGA[9] is one of the most effective algorithms for solving the RCPSP. For medium and large-scale problems, this algorithm provides better results than any other algorithms and for small problems, it compares favorably to the best current algorithms [16]. That is why; this meta-heuristic algorithm is used for solving the RCPSP in the paper.

- Using CIW[10] Index

---

[8] Schedule Generation Scheme

[9] Hybrid Genetic Algorithm

[10] Cumulative Instability Weight

In this method, a precedence feasible priority list is constructed with the activities in non-increasing order of their CIW index (tie-breaker is the lowest activity number). This index is defined in equation (7), where Suc_i denotes the set of direct and indirect successors of activity i [12]. In other words, for an activity, this index is defined as sum of the lateness weights for that activity and all of its successor activities. Because disruptions propagate throughout the schedule, activities for which a change in starting time would have a high impact on the objective function value are now less likely to be severely disrupted than activities with a lower impact since the former are scheduled earlier in time and are thus less prone to disruptions.

$$CIW_i = w_i + \sum_{j:j\in Suc_i} w_j \tag{7}$$

- Solving a MADM[11] Problem

Actually, this method is an extension of the CIW index method for generating the priority list. In the CIW index, only the cost of starting delay is considered and lack of attention to uncertainty of the parameters is a considerable weakness of this method. This weakness is handled and removed in the index obtained by MADM. In this method, three different attributes are used to generate the priority list. Note that in most of the decision making problems, no ideal alternative may be obtained with highest rank for all of the defined attributes [17]. Here, by MADM techniques, a final value is calculated for each activity and then the activities are sorted based on the descending values of this index. In order to solve this problem, a decision matrix is generated for which, the project activities are the problem alternatives. This decision matrix is shown in Table 1.

TABLE 1. THE DECISION MATRIX FOR SOLVING THE MADM PROBLEM

Attributes Activities	ADU	RLU	CIW
1	ADU_1	RLU_1	CIW_1
2	ADU_2	RLU_2	CIW_2
…	…	…	…
N	ADU_N	RLU_N	CIW_N

The ADU and RLU denote the activity duration uncertainty and resource availability level uncertainty. Moreover, the CIW is the disruption cost for each activity that is calculated using the equation (7). The values of this matrix also represent the attributes values for each activity of the project. The activities with more uncertainty in duration should be scheduled as late as possible in order to cause less disruption in the successor activities. Therefore, variance of the activities duration is used as the ADU value for the activities. Note that, higher ADU value means lower priority for an activity. On the other hand, resource failure can result in preemption. In order to prevent delay in starting times of other activities, the activities with a higher probability of facing resource failure should be scheduled as late as possible. When the resource consumption percentage is less than 100%, if one unit of the resource fails, one available unit of that resource type can replace the failed resource and therefore preemption will not happen for that activity. Since the priority list is being generated in this stage, no information is available about the resources consumption percentage per time unit. Therefore, it is not possible to exactly determine the probability of preemption for activities. It is obvious that if no failure occurs for the resources of an activity, preemption will not happen for that activity. According to this, the activity with less probability of resource failure will have more chance for getting higher place in the schedule. So, the probability of failure-free for all related resources of an activity is used as RLU value for that activity. Note that, higher RLU value means higher priority for an activity.

Equation (8) shows the probability of failure-free for all related resources of an activity with average duration d. In this equation, E_{ikt} denotes the event of failure-free for i^{th} unit of the resource type k in time t for the related activity. Also the terms k and r_k denote the number of resource types and the consumption units of resource k for the activity, respectively. Note that the distributions of different resource types and also different units of a particular resource are independent. This assumption is in accordance with the conditions of real projects.

$$RLU = \prod_{k=1}^{K} \prod_{i=1}^{r_k} P\Big(\bigcap_{t=1}^{d} E_{ikt}\Big) \tag{8}$$

Now, the probability of failure-free for the unit i^{th} of the resource type k during the activity implementation can be calculated as equation (9) shows:

$$\begin{aligned} &P\Big(\bigcap_{t=1}^{d} E_{ikt}\Big) = \\ &P(E_{ik1}) \times P(E_{ik2} \mid E_{ik1}) \times P(E_{ik3} \mid E_{ik1}, E_{ik2}) \times \\ &\ldots \times P(E_{ikd} \mid E_{ik1}, E_{ik2}, \ldots, E_{ikd-1}) \end{aligned} \tag{9}$$

since time between two consequent failures follows the exponential distribution, the equation (9) can be simplified by using properties of the markovian processes. It means that if the system state is known at time t-1, then the state of that system at time t is independent of its state at times

---

[11] Multi Attributes Decision Making

before t-1. Using this property, the equation (9) will be simplified into equation (10):

$$P\left(\bigcap_{t=1}^{d} E_{ikt}\right) = P(E_{ik1}) \times P(E_{ik2} \mid E_{ik1}) \times P(E_{ik3} \mid E_{ik2}) \times \dots \times P(E_{ikd} \mid E_{ikd-1}) \qquad (10)$$

Now, the probability of failure-free for unit i^th^ of the resource type k in the first time unit is calculated as the first term of the equation (10). This probability value can be calculated using the birth-death processes. Assume that the diagram of Fig. 2 shows the availability rate of one unit of resource; where, 0 and 1 denote being failure-free and failure, respectively.

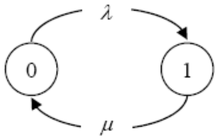


Fig. 2. Fig. 2. The availability rate to one unit of resource

In this figure, parameters λ and μ denote the failure rate and the repair rate for the related resource. The failure rates are assumed to be similar for all units of a resource type, and so are the repair rates. Therefore, equation (11) shows the probability of failure-free for each unit of resource k in the first time unit of implementing the related activity. This value is obtained by solving the balance equations of the related birth-death process.

$$P(E_{ik1}) = \frac{\mu_k}{\lambda_k + \mu_k} \qquad (11)$$

Memory-less property of exponential distribution is used for calculating the remaining terms of equation (10). Equation (12) shows how these terms can be calculated. This equation holds for all values of i.

$$P(E_{ikt} \mid E_{ikt-1}) = P(X \ge t+1 \mid X \ge t) = P(X \ge 1) = e^{-\lambda_k} \qquad (12)$$

In this equation, X is an exponential random variable with parameter λ_k which shows the remaining time before failure of the related resource. Therefore, the equation (10) can be shown in form of equation (13). Now, the RLU can be simply calculated for all of the activities.

$$P\left(\bigcap_{t=1}^{d} E_{ikt}\right) = \frac{\mu_k}{\lambda_k + \mu_k} \times e^{-(d-1)\lambda_k} \qquad (13)$$

After establishment of the decision matrix, TOPSIS method is applied for prioritizing the activities, as one of the current methods for solving the MADM problem. In this method, higher priority is given to activity that is closest to the ideal alternative and has the largest difference with the negative ideal alternative [17]. It should be noted that similar weights are assigned to all of the three attributes. Fuzzy normalizing method is used for normalizing the attributes. This method is adaptable to the conditions of our problem.

ii. Time buffers allocation

By allocating time buffers, the initial schedule leaves its semi-active property. Therefore, for describing such schedules, it is necessary to use a buffer list in addition to the priority list. Elements of the buffer list represent idle inserts assigned to each activity. The buffer list is the main output of time buffers allocation methods. It worth noting that allocating time buffer to an activity provides float for its predecessors. Three methods are proposed to allocate time buffers: STC, SB-STC[12] and SBM[13].

- STC

STC method is shown to be one of the most effective methods for allocating time buffers to the activities when durations are uncertain [11]. The STC exploits information about both the lateness weights and the variance of the durations. The basic idea is to start from an initial unbuffered schedule and iteratively create intermediate schedules by adding a one-unit time buffer in front of the activity that needs it the most in the current intermediate schedule. The process is stopped when allocation of time buffers cannot improve the objective function value anymore. The starting time criticality of each activity is defined as equation (14) where, γ_j denotes the probability that activity j cannot be started at its baseline starting time. Due to computational complexity, no method is suggested for computing this probability value. This value can be estimated according to equation (14) as:

$$stc_j = P(S_j > s_j) \times w_j = \gamma_j \times w_j \qquad (14)$$

- SB-STC

Due to the lack of a method to estimate the value of γ under uncertainty of the resource availability, the SB-STC method is used here to estimate these values. The main difference of the SB-STC with the STC is the way of calculating γ. In the SB-STC method, it is tried to find a

---

[12] Simulation Based STC

[13] Simulation Based Method

proper estimation of γ for the activities by simulating the schedules in each step.

- SBM

In this method, one unit of time buffer is temporarily added to a project activity. Then, the schedule is updated. By simulating the new schedule, the value of the objective function is calculated and this process will be repeated for all of the activities. At last, the activity will be selected that adding time buffers to it, makes the largest improvement in the objective function. Then, one unit of time buffer will be permanently added to the selected activity. On the same basis, the time buffers are also allocated in next steps and this process will be continued by the time that no more improvement can be obtained in the objective function value.

4. COMPUTATION RESULTS

A. Experimental Setup

The algorithms for all of the above mentioned methods have been coded by C++. Then, the problems are solved by a Pentium IV PC with 3.2 GHz CPU. The problems used for this study, were randomly selected, using RANGEN II which is one of the most powerful softwares in generating project scheduling problems [18]. In this software, it is possible to assign values to several parameters of the project. Some of these parameters are related to the resources and the others are related to the project network structure. The main parameters of this software are the number of project activities, complexity of predecessor relations, resource factor, and resource constraint. Greater values for complexity of predecessor relations show the existence of more relations among the activities and therefore less possibility of simultaneous implementation of the project activities. In addition, greater values of the resource factor, indicates existence of more resource types for the activities. On the other hand, greater value of the resource constraint parameter shows that the average consumption of each resource type is higher for each of the activities.

In this paper, different values are assigned to each parameter for performing the computational tests. The assigned values are shown in Table 2.

The purpose of this procedure is to generate diverse problems and project types with diverse structures. Since three different values are supposed for each parameter, 81 problem types are produced by a combination of these parameters. In this paper, 10 problems are randomly produced for each of the problem types and therefore 810 problems have been considered and tested in whole. These problems have been produced by 4 renewable resource types and by 10 available units per time unit

TABLE 2. THE PROJECT PARAMETERS VALUES IN RANGEN II

Value / Parameter	Low	Medium	High
No of activity	30	60	120
Complexity of predecessor relations	0.2	0.5	0.8
resource factor	0.5	0.75	1
resource constraint	0.3	0.5	0.7

Using the discussed methods, three different priority lists are generated for each of these problems. Another priority list is also randomly generated. The main purpose of using a random list is to examine if applying systematic methods for generating a priority list will provide better results than a random list. On the other hand, time buffers are allocated to each initial schedule based on the three methods introduced above. Since robustness of the schedules generated by STC method is expected to be poor, this method also can serve as a proper benchmark for other methods of allocating time buffers.

After allocating time buffers, with the aid of simulation, the objective function value for the solution robustness is calculated for each schedule. Note that every solution is simulated in two cases: preempt-repeat and preempt-resume. As discussed before, the EBST1 and random reactive scheduling procedures are used in this paper for simulations. Since each problem is solved by 4 methods to generate the priority list and 3 methods to allocate the time buffers, for each problem 12 different solutions will be obtained. Then, 4 simulation types are applied to each of the solutions. This process is illustrated in Fig. 3.

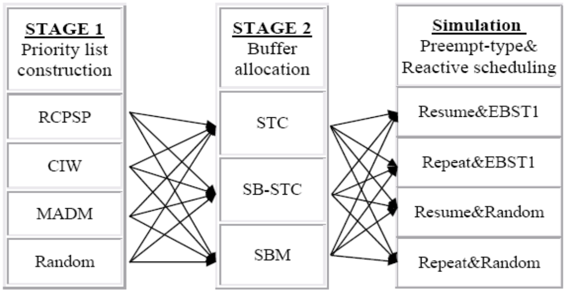


Fig. 3. Fig. 3. The problem solving and simulation process

For each schedule, the simulation is run 100 times. In these tests, the realized duration of activities follows a discrete right-skewed beta-distribution with parameters 2 and 5. In addition, 3 levels of high, medium and low uncertainty are considered. The activities duration randomly match one of these levels. According to this, in high level of uncertainty, for an activity with average duration d, the lower bound and the upper bound of the Beta distribution are 0.25d and 2.875d, respectively. These bounds are 0.5d and 2.25d in medium level of uncertainty and 0.75d and 1.625d in low level of uncertainty, respectively [11]. Fig. 4 shows the distribution functions from which the realized durations are drawn for an activity with expected 3-period duration.

In these tests, for each resource, MTBF parameter takes a random integer value from the range [0.5C$_{max}$, 1.5C$_{max}$] in which, C$_{max}$ is the minimum project duration. This value is obtained through solving the deterministic RCPSP for each problem. It is noted that this model is solved by the HGA algorithm. Moreover, for each resource, the MTTR parameter takes a random integer value between 1 and 5 [12]. It should also be noted that the deadline δ for each of the problems is equal to [1.3C$_{max}$] [10]. The lateness weights are drawn for each non-dummy activity j from a discrete triangular distribution with equation (15):

$$P(w_j = q) = (21 - 2q)\% \quad \forall \quad q \in \{1, 2, ..., 10\} \tag{15}$$

This distribution results in a higher probability for low weights and in an average weight w$_{avg}$ =3.85. The weight w$_n$ of the dummy end activity denotes the marginal cost of not making the baseline project completion and will be fixed at [10w$_{avg}$]=38 [11].

B. Analysis

In tables blow, the average value for the objective function of the solution robustness is shown for different types of problems. For each time buffer allocation method, a value is calculated which is called “best percentage” here. This value is the proportion of simulations in which a priority list has provided better results than other lists.

In the Table 3, the simulation results of problems with 30 activities in the preempt-resume case are shown for the two reactive scheduling procedures.

Comparing the according values of the two types of reactive scheduling given above shows that using a systematic procedure for removing the schedule disruptions (the reactive scheduling procedure), will result in less disruption in the next times of the project. As can be seen, the poorest values among time buffers allocation methods is resulted from the STC method that can be due to uncertainty of the resource availability parameter. Since the random priority list has provided very poor results, it can be concluded that for constructing robust schedules, systematic methods generate better priority lists. According to Table 3, most of the best values are obtained by MADM and SBM methods. In some of the problems, the best value is obtained by the MADM list and in some others by the RCPSP list. Generally, the MADM list has performed better than the RCPSP one. On the other hand, the CIW list in most of the cases has provided poor results compared to the MADM and RCPSP lists. It is remarkable that in most of the problems for which the complexity of predecessor relations was 0.8, the RCPSP list performed better than the MADM list. Therefore, it can be concluded that the effectiveness of the RCPSP list is higher for problems with more complexity in predecessor relations, and for other problems MADM list will provide better results. In Table 4, the simulation results for problems of 30 activities in preempt-repeat case are shown for the two reactive scheduling procedures.

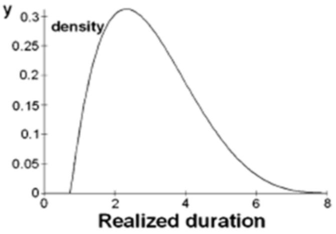
For problems of 30 activities, the provided results in the preempt-repeat case are almost the same as those of the preempt-resume case. Of course, the corresponding values in the preempt-repeat case are fairly higher than the preempt-resume case. The reason may lie in the probability of more disruption in the preempt-repeat case. For problems of 30 activities, except the RCPSP list, the average computing time (in two preemption cases) was less than 0.1 second for generating the priority lists, while, this time was about 1 second for the RCPSP list. Moreover, the average computing time for STC, SB-STC, and SBM time buffers allocation methods were about 2, 24, and 195 seconds, respectively. In Table 5, the results for problems with 60 activities are presented in Table 5.

The values provided by the SB-STC and the SBM time buffers allocation methods are not shown here. This is due to the high computing time of these methods resulted from large number of the project activities and enormous simulations. In problems of 60 activities, the average computing time was less than 0.1 second for generating all the lists except the RCPSP one and about 3 seconds for the RCPSP list. The average computing time for the STC was about 5 seconds. It is notable that for problems of 60 activities, other methods of allocating time buffers did not provide any result even after 1 hour of processing. The results for problems of 120 activities are presented in Table 6.

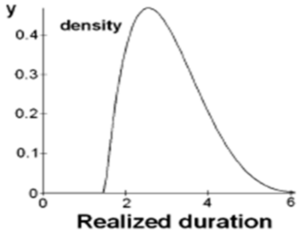
The provided results for the problems of 60 and 120 activities are almost similar to those of 30 activities. It is obvious that if the project activities increase, the value of the objective function for the solution robustness will increase. In the 120 activities problems, again the average computing time was less than 0.1 second for all the lists except the RCPSP list. This time was about 15 seconds for the RCPSP list. In addition, the average computing time for the STC time buffers allocation method was about 32 seconds.

TABLE 3. THE RESULTS FOR 30 ACTIVITIES & PREEMPT-RESUME

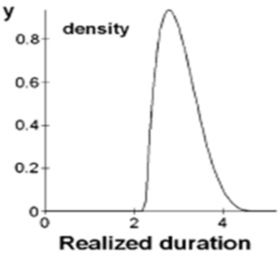
Reactive Scheduling	*EBST1*			*Random*		
Buffering *Priority list*	*STC*	*SB-STC*	*SBM*	*STC*	*SB-STC*	*SBM*
RCPSP	*401.7*	*325.8*	*307.4*	*641.8*	*531.5*	*489.7*
%Best	*43.1*	*36.0*	*29.6*	*36.0*	*40.7*	*36.9*
CIW	*445.4*	*373.5*	*341.5*	*718.0*	*598.5*	*539.5*
%Best	*0.3*	*0.5*	*0.1*	*0.2*	*0.1*	*0.1*
MADM	*375.4*	*293.3*	*289.3*	*636.2*	*466.6*	*458.8*
%Best	*56.6*	*63.5*	*70.3*	*63.8*	*59.2*	*63.0*
Random	*589.6*	*495.9*	*448.6*	*909.0*	*860.5*	*832.2*
%Best	*0*	*0*	*0*	*0*	*0*	*0*



a) High Uncertainty



b) Medium Uncertainty



c) Low Uncertainty

Fig. 4. Fig. 4. Distribution functions for low (a), medium (b) and high (c) duration variability if E(d)= 3

TABLE 4. THE RESULTS FOR 30 ACTIVITIES& PREEMPT-REPEAT

Reactive scheduling	*EBST1*			*Random*		
Buffering *Priority list*	*STC*	*SB-STC*	*SBM*	*STC*	*SB-STC*	*SBM*
RCPSP	*664.3*	*529.7*	*479.5*	*980.7*	*841.9*	*720.4*
%Best	*51.5*	*44.4*	*25.9*	*44.1*	*37.0*	*44.4*
CIW	*813.7*	*620.5*	*529.2*	*1153.4*	*936.4*	*797.0*
%Best	*0.4*	*0.2*	*0.7*	*0.2*	*0.7*	*0.2*
MADM	*673.3*	*490.1*	*462.4*	*914.1*	*822.8*	*698.1*
%Best	*48.1*	*55.4*	*73.4*	*55.7*	*62.3*	*55.4*
Random	*1004.3*	*777.4*	*719.7*	*1654.8*	*1242.9*	*1113.0*
%Best	*0*	*0*	*0*	*0*	*0*	*0*

TABLE 5. THE RESULTS FOR 60 ACTIVITIES

Case	**preempt-resume**		**preempt-repeat**	
Reactive scheduling	***EBST1***	***Random***	***EBST1***	***Random***
Buffering *Priority list*	***STC***	***STC***	***STC***	***STC***
RCPSP	*760.5*	*1202.2*	*1365.8*	*1767.9*
%Best	*40.5*	*34.3*	*28.7*	*44.3*
CIW	*865.5*	*1423.9*	*1454.4*	*2082.0*
%Best	*0.2*	*0.5*	*0.3*	*0.1*
MADM	*724.8*	*1141.1*	*1345.1*	*1729.1*
%Best	*59.3*	*65.2*	*71.0*	*55.6*
Random	*1004.5*	*1765.8*	*1987.7*	*3044.3*
%Best	*0*	*0*	*0*	*0*

TABLE 6. THE RESULTS FOR 120 ACTIVITIES

Case	***preempt-resume***		***preempt-repeat***	
Reactive scheduling	***EBST1***	***Random***	***EBST1***	***Random***
Buffering *Priority list*	***STC***	***STC***	***STC***	***STC***
RCPSP	*1651.3*	*2414.8*	*2902.6*	*3735.3*
%Best	*30.2*	*44.2*	*22.2*	*45.0*
CIW	*1738.9*	*3111.9*	*3149.5*	*4196.6*
%Best	*0.1*	*0.2*	*0.1*	*0*
MADM	*1485.0*	*2405.0*	*2885.1*	*3727.3*
%Best	*69.7*	*55.6*	*77.7*	*55.0*
Random	*2128.2*	*3718.8*	*4302.9*	*6490.7*
%Best	*0*	*0*	*0*	*0*

5. CONCLUSION

In this paper, by mutually considering uncertainty of activities duration and resource availability, a number of methods were proposed to construct robust schedules. For this purpose, a two-stage procedure has been applied. In the first stage, an initial schedule is constructed using the SGS method. Then in the second stage, time buffers are allocated to the initial schedule. The input of the SGS method is a priority list in which scheduling consequences are determined for the activities. In this paper, some methods are proposed for generating the priority list; solving the RCPSP, CIW index, and solving a MADM model. On the other hand, for allocating time buffers to initial schedules, STC, SB-STC and SBM methods have been applied. The set of problems tested in this study have been generated by RANGEN II and various computational tests have been performed on each of the generated problems. The purpose of these tests was to assess performance of different methods which are used to generate priority lists, and different methods of allocating time buffers. The tests have been performed with the aid of simulation in two preemption cases: preempt-resume and preempt-repeat. According to the obtained results, it was observed that for each of the time buffers allocation methods, the MADM list and then the RCPSP list have better performance. In addition, for each of the priority lists generating methods, the SBM method is superior to other existing methods of time buffers allocation. Of course, this method is applicable to only small problems due to its long computing time.

6. SUGGESTIONS FOR FURTHER RESEARCH

Because of the time buffers allocating methods based on the simulation takes too much processing time, developing other efficient heuristic methods to allocate time buffers with short computational time can be an interesting issue for future study.

Furthermore, there is not any procedure to find an optimum solution for the model with solution robustness objective function as a NP-hard problem. Hence, developing and considering surrogate functions for the model is another interesting issue as a future research. Note that, surrogate-based optimization is a methodology to find the local or global optimal solution for a problem, indirectly and quickly.

7. ACKNOWLEDGEMENTS

The authors would like to thank Professor Roel Leus for his valuable suggestions that have led to several improvements.

REFERENCES

[1] W. Herroelen, R. Leus, “Project scheduling under uncertainty: Survey and research potentials: On the merits and pitfalls of critical chain scheduling,” European Journal of Operational Research, vol. 165, pp. 289-306, 2005.

[2] R. Leus, “The generation of stable project plans,” Ph.D. dissertation, Department of applied economics, Katholieke Universiteit Leuven, Belgium, 2003.

[3] S. Van de Vonder, E. Demeulemeester, W. Herroelen, R. Leus, “The use of buffers in project management: The trade-off between stability and Makespan,” International Journal of Production Economics, vol. 97, pp. 227-240, 2005.

[4] E. M. Goldratt, “Critical chain,” The North River Press Publishing Corporation, Great Barrington, 1997.

[5] S. Van de Vonder, F. Ballestin, E. Demeulemeester, W. Herroelen, “Heuristic procedures for reactive project scheduling,” Computers & Industrial Engineering, vol. 52, pp. 11–28, 2007.

[6] W. Herroelen, R. Leus, “On the merits and pitfalls of critical chain scheduling,” Journal of Operations Management, vol. 19, pp. 559-577, 2001.

[7] M. A. Al-Fawzan, M. Haouari, “A bi-objective model for robust resource constrained project scheduling,” International Journal of Production Economics, vol. 96, pp. 175-187, 2005.

[8] S. Danka, “Robust resource constrained project scheduling with uncertain-but-bounded activity duration and cash flows,” International Journal of Optimization in Civil Engineering, vol. 3, no. 4, pp. 527-542, 2013.

[9] W. Herroelen, R. Leus, “The construction of stable baseline schedules,” European Journal of Operational Research, vol. 156, pp. 550– 565, 2004.

[10] S. Van de Vonder, E. Demeulemeester, W. Herroelen, R. Leus, “The trade-off between stability and makespan in resource constrained project scheduling,” International Journal of Production Research, vol. 44, no. 2, pp. 215-236, 2006.

[11] S. Van de Vonder, E. Demeulemeester, W. Herroelen, “Proactive heuristic procedures for robust project scheduling: An experimental analysis,” European Journal of Operational Research, vol. 189, no. 3, pp. 723-733, 2008.

[12] O. Lambrechts, E. Demeulemeester, W. Herroelen, “Proactive and reactive strategies for resource constrained project scheduling with uncertain resource availabilities,” Journal of scheduling, vol. 11, no. 2, pp. 121-136, 2008.

[13] O. Lambrechts, E. Demeulemeester, W. Herroelen, “Time slack-based techniques for robust project scheduling subject to resource uncertainty,” Annals of Operations Research, vol. 186, no. 1, pp. 443-464, 2010.

[14] W. Herroelen, B. De Reyck, E. Demeulemeester, “A note on the paper ‘Resource-constrained project scheduling: notation, classification, models and methods’ by Brucker et al,” European Journal of Operational Research, vol. 128, pp. 679–688, 2001.

[15] A. Sprecher, R. Kolisch, A. Drexl, “Semi-active, active, and non-delay schedules for the resource-constrained project scheduling problem,” European Journal of Operational Research, vol. 80, pp. 94–102, 1995.

[16] V. Valls, F. Ballestin, S. Quintanilla, “A hybrid genetic algorithm for the resource-constrained project scheduling problem,” European Journal of Operational Research, vol. 185, pp. 495–508, 2008.

[17] J. L. Ringuest, Multi objective optimization: Behavioral and Computational Considerations, Kluwer Academic publishers, 1992.

[18] M. Vanhoucke, J. Coelho, D. Debels, B. Maenhout, L. V. Tavares, “An evaluation of the adequacy of project network generators with systematically sampled networks,” European Journal of Operational Research, vol. 187, pp. 511-524, 2008.