Integrated Cost / Schedule Risk Analysis for Defence Acquisition Projects

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***Abstract*— Risk assessment is a crucial component in defence acquisition project management. It allows analysts to examine the impact of individual risks on the overall project cost and schedule. This paper suggests a new integrated cost/schedule risk assessment approach that combines cost risk and schedules risk analyses within a single mathematical model. Optimization and Monte Carlo simulation techniques are used to determine the expected cost and completion time of an acquisition project. A case study using a military aircraft replacement project for the Canadian Armed Forces is used to illustrate the approach.**

Keywords*— *Risk analysis; Schedule buffer; Cost contingency; Military; Aircraft.

I. Introduction

The quality of a project can be measured by three variables: time, cost, and performance. Time indicates how long the project takes. Cost indicates if the project is within budget. Performance indicates how well the project meets the requirements (Pinnell and Busch, 1993) [1]. Uncertainty in any of these variables leads to uncertainty in project cost estimates (Hulet, 2011) [2].

Integrated cost/schedule risk analysis focuses on resources required to execute the project activities. In this analysis, project schedule is constructed within the limited amount of resources available (Vanhoucke, 2012) [3]. These resources can be separated into two main categories: Time-dependent and time-independent resources.

- Time-dependent resource is the resource that will cost more if it works longer. Examples of such resource include labour and rented equipment.
- Time-independent resource is the resource that does not cost more if its activity takes longer. Examples of such resources include procured raw materials and some equipment (Hulett, 2011) [2].

Costs in an integrated cost/schedule risk analysis can be divided into two types: Fixed and variable costs.

- Fixed cost is a one-time cost assigned to a time-independent resource.
- Variable cost is a per time unit cost assigned to a time-dependent resource.

Assessing resource-constrained project scheduling implies the optimization of a certain scheduling objective. The problem can be formally stated by scheduling a set of project activities subject to the precedence relations and a set of resources within a minimal duration.

To rationalize financial management and business planning processes, the Department of National Defence (DND) has articulated the modernization of defence governance (Ghanmi et al., 2014) [4]. In 2014, Sokri and Ghanmi [4-6] standardized the assessment of cost risk for defence acquisition projects. They developed a novel schedule risk analysis approach for defence acquisition projects (Sokri and Ghanmi, 2016) [7]. In the same year, DND discussed potential research on cost and schedule risk assessment and reporting and highlighted the importance of integrating these two elements within the same framework.

This paper suggests a novel integrated cost/schedule risk assessment approach that combines cost risk and schedules risk analyses within a single mathematical model. The new approach combines optimization and Monte Carlo simulation techniques to determine the expected completion time and the corresponding cost of an acquisition project. A case study using a military aircraft replacement project for the Canadian Armed Forces is presented to illustrate the approach.

This paper is organized into five sections. Following the introduction, Section 2 provides a comprehensive review of literature on integrated cost and schedule risk analysis. Section 3 presents the key elements of the suggested methodology and highlights its mathematical background. Section 4 provides an illustrative example to portray the methodology. Section 5 provides some concluding remarks..

II. LITERATURE REVIEW

Different streams of research using various scheduling objectives have been adopted in the existing literature (Vanhoucke, 2012) [3]. These approaches can be classified along methodological lines into six main methods: (1) Time minimization (2) Net Present Value (NPV) maximization, (3) Resource leveling, (4) Resource availability cost problem, (5) Work continuity optimization, and (6) Time-cost trade-off problem (Brucker et al., 1999 [8], Herroelen et al., 1999 [9], Vanhoucke, 2012 [3]).

- The aim of *time minimization* is to minimize the entire project duration subject to the limited availability of resources. In this approach, a feasible schedule is constructed by minimizing the start time of the dummy end activity. In the basic formulation, activities are assumed to have a fixed duration and are not allowed to be pre-empted. Vanhoucke and Debels (2008) [10], for example, relaxed this assumption and investigated its impact on the total project lead time as well as on the efficiency of resource use. The authors analyzed three extended activity assumptions, i.e. the extension from fixed to variable activity durations, the presence of activity splitting (pre-emption) and the possibility of the parallel execution of subparts of activities (fast tracking). Results indicated that the extension to variable activity durations and/or fast tracking has a major effect on both the project lead time and the resource utilization. The additional effect of pre-emption is, however, negligible.

- In *the Net Present Value (NPV) maximization*, activity cash flows are discounted towards the beginning of the project using a discrete discount rate. This approach is used when financial aspects of project management are of interest. The Net Present Value (NPV) maximization was introduced by Russell (1970) [11] as a criterion of scheduling activities. In this approach, both positive and negative cash flows are associated with events. They are discounted towards the beginning of the project using a discrete discount rate (Mika et al., 2005) [12]. This scheduling problem has been studied by many scholars including Kazaz and Sepil (1996) [13], Dayanand and Padman (1997) [14], and Etgar et al. (1997) [15]. Kazaz and Sepil (1996) [13], for example, used a mixed-integer formulation of scheduling to maximize the present value of the cash flows. The authors defined and used activity profit curves to show how the net present value of cash flows associated with each activity changes with respect to activity finish times.

- *The resource-leveling problem* involves the scheduling of project activities to level the use of resources within a predefined project deadline. A survey conducted by Liberatore et al. (2001) [16] shows that 83% of professional project managers use project management software packages to solve the resource conflicts. Kastor and Sirakoulis (2009) [17] evaluated the effectiveness of resource levelling tools of three popular packages by comparing the results of two real case studies.

- *The resource availability cost problem* involves the scheduling of project activities within a predefined project deadline to minimize the total cost of the necessary resources. In this approach, the cost of a resource depends on its availability. Ranjbar et al. (2008) [18] considered a project scheduling problem with the objective of minimizing resource availability costs required to execute the activities by a given deadline. The authors developed and compared two metaheuristics to tackle this problem.

- The objective of *work continuity optimization* is to minimize idle time of resources. This approach minimizes the total work continuity cost of the project by minimizing the weighted time-span between the first and last tasks of similar activities. Hyari and El-Rayes (2006) [19], for example, present a multiobjective optimization model for the planning and scheduling of repetitive construction projects. The model enables planners to generate and evaluate optimal construction plans by simultaneously minimizing project duration and maximizing work continuity.

- *Time-cost trade-off problem* uses the technique of crashing to shorten the time required for performing a particular activity. The objective is to maximize the amount of time compression for the least incremental cost. Liberatore and Pollack-Johnson (2006) [20], for example, developed a model for reducing project completion time that considers crashing as well as the removal and modification of precedence relationships. To expedite projects, the authors suggested doing more tasks concurrently, or overlapping them, in addition to compressing task times.

The literature contains linear, nonlinear, and discrete formulations of the time–cost problem (Liberatore and Pollack-Johnson, 2006) [20]. Integrated cost/schedule risk analysis examines the risks to the project and specifies how they may affect the project cost and schedule. More specifically, this approach includes the impact of schedule risk on cost risk and cost contingency reserves (Hulett, 2011) [2]. The main contribution of this paper is to offer a comprehensive methodology that combines optimization and Monte Carlo simulation techniques to determine the expected project lead time. It takes into account not only time-dependent resources, but also time-independent resources in integrating cost and schedule risks.

III. THE MODEL

This section suggests a stochastic approach to conduct an integrated cost and schedule risk analysis for future projects. This approach uses simulation to investigate the behavior of the project duration and cost. Optimization is also used to identify the most likely critical path. This approach can be summarized by the following seven-step procedure:

Step 1 - List all activities required to complete the project. In this step, a work breakdown structure is used to present the causal dependencies between activities.

Step 2 - Assign costed resources to activities and distinguish between time-dependent and time-independent costs in the schedule (Hulett, 2011) [2]. Indexing each activity by *j*, the cost of activity *j* can be expressed as

$$c_j = a_j + b_j d_j, \tag{1}$$

Where d_j is the duration of activity j and the constants a_j and b_j are respectively the time independent cost and the cost

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per unit time of activity j. In this approach, the direction of influence is from schedule to cost.

Step 3 - Apply a probability distribution for the variables a_j, b_j, and d_j. A three-point estimate (minimum, most likely, and maximum) approach may be used to assess the likely fluctuation of each variable.

Step 4 - Run Monte Carlo simulation. Use Monte Carlo simulation to generate multiple schedules and costs. The project total cost is given by

$$C = \sum_{j=1}^{n} \left(a_j + b_j d_j\right), \tag{3}$$

where n is the total number of activities. For each iteration of the simulation, the potential critical paths are identified and ranked according to their total durations. A list of near-critical paths may be used to reduce the computation effort. A critical path can be ruled out if it is clearly dominated by another one in a pair-wise comparison (Sokri and Ghanmi, 2016) [7]. A critical path is said to be dominated if its maximal completion time is smaller than the minimal duration of another one (Alvarez-Benitez et al., 2005) [21].

Step 5 - Estimate the critical path ranking probabilities: The probability p_{ij} that path i ranks at position j is generated by dividing the number of times path i is ranked at a position j by the total number of simulation runs. A ranking probability matrix can be used to organize the potential critical path rankings from Monte Carlo simulation (Sokri and Ghanmi, 2016) [7].

Step 6 - Drive the risk-adjusted critical path. To drive the risk-adjusted critical path and its probability, let k be the number of potential critical paths and define the variable x_{ij} ($1 \le i, j \le k$) as (Sokri and Ghanmi, 2016) [7]:

$$x_{ij} = \begin{cases} 1, \text{if path } i \text{ is ranked at position } j \\ 0, \text{otherwise.} \end{cases} \tag{4}$$

The most probable rankings of potential paths and the corresponding ranking probabilities can therefore be determined by maximizing the following objective function

$$\max G = \sum_{i=1}^{k} \sum_{j=1}^{k} x_{ij}\, p_{ij} \tag{5}$$

subject to:

$$\sum_{j=1}^{k} x_{ij} \quad = \quad 1 \qquad 1 \le i \le k \tag{6}$$

The constraints in equation 3 state that each potential path is assigned to only one rank position. The overall duration of the project is given by the duration of the most probable critical path

$$D = \sum_{j \in CP} d_j. \tag{7}$$

Step 7 – Derive an integrated cost / schedule risk profile. The integrated cost / schedule risk profile can be derived by considering the impact of schedule risk on the cost risk. It can be presented using the cumulative distribution function (CDF) of the overall cost of the project considered as a random variable. The probability of not exceeding a given cost c is given by

$$F(c) = P(C \le c). \tag{8}$$

The end result should be a set amount of useful indicators about the expected cost contingency and schedule buffer. The buffer is the amount of spare time added to the estimate of total completion time to reduce the risk of not being able to complete a project on schedule.

IV. CASE STUDY

In this section, the integrated cost/schedule risk analysis method is applied to a military aircraft replacement project for the Canadian Armed Forces. The set of tasks and their interdependencies was identified by the project management officer. Typical tasks include, for example, the preparation of the procurement documents, requirement foundation documents, release of the request for proposal, in-service support contract documents etc. However, illustrative data were used in this paper to avoid issues with sensitive information. Table 1 provides the successor tasks as well as three point estimates of the task durations, time-dependent costs, and time-independent costs.

The integrated cost/schedule risk analysis method was applied to the aircraft replacement project dataset using 10,000 simulation runs. Figure 1 shows the cumulative distributions of just cost risk, just schedule risk, and integrated cost/schedule risk. This graph captures the impact of schedule risk on cost risk. It shows the value of integrating cost and schedule risk within the same model. It indicates that when the schedule risk is not taken into account, the cost risk is underestimated (Hulett, 2011) [2].

Considering the impact of schedule risk on the cost estimate risk in an integrated approach provides a more complete and accurate profile of cost risk. In this example, it's implicitly assumed that the time-cost trade-off problem has already been solved using an analytical model. It's also supposed that resources are assigned to each task and their respective time independent costs and their costs per unit time are known. The activity durations are also expected to be given. Any uncertainty in these knowns will have an impact on the cost estimate. Uncertainty is introduced via the probability distribution of each variable. A Program Evaluation and Review Technique (PERT) distribution is used. Like the Triangular distribution, PERT is comprehensible and very practical. It is, however, more adequate than the Triangular distribution when the distribution is skewed (Sokri and Solomon, 2013) [22].

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Table 1: Tasks, Costs, Durations, and Dependencies

Task	Successors	Duration (months) (d_j)			Time independent Cost (a_j)			Time dependent Cost (b_j)			Only Cost varies	Only Time varies	Cost & time vary
		Min	ML	Max	Min	ML	Max	Min	ML	Max			
T1	T2	0	0.5	1	99	101	103	0	0	0	101	101	101
T2	T3,T5	1	1.5	2	38	40	45	40.0	43	44.0	105	105	105
T3	T4	2.5	3	3.5	77	80	81	51.0	55	55.5	243	245	243
T4	T6	0.5	1	1.5	6	8	10	19.5	20	22.0	28	28	28
T5	T10	18	20	22	148	150	152	47.0	48	49.0	1110	1110	1110
T6	T7	6	7	8	0	0	0	73.5	75	76.0	524	525	524
T7	T10	6	7	8	100	102	104	44.0	45	46.0	417	417	417
T8	T10	0.5	1	1.5	48	50	52	0.0	0	0.0	50	50	50
T9	T10	1	2	3	37	40	42	37.0	38	38.5	116	116	116
T10	T11	0	0.5	1	4	5	6	49.0	51	52.0	30	31	30
T11	T12,T13	0.5	1	2	15	18	21	34.5	36	37.0	54	56	57
T12	T14	1	3	5	38	40	42	60.0	62	62.5	225	226	225
T13	T22	33	35	37	348	350	352	51.0	55	57.0	2263	2275	2263
T14	T15,T20	2	4	6	66	75	77	31.0	33	33.5	205	207	205
T15	T18	3	4	5	20	25	30	0.0	0	0.0	25	25	25
T16	T18	1	3	5	67	71	73	41.0	43	44.0	199	200	199
T17	T18	2	3.5	5	25	30	35	29.5	30	30.5	135	135	135
T18	T19	1	2	3	0	0	0	24.0	25	27.0	50	50	50
T19	T22	1	2	3	69	70	75	73.5	74	74.0	219	218	219
T20	T21	4	6	10	148	150	152	63.0	65	66.0	539	562	561
T21	T22	0.5	2	3.5	43	45	50	0.0	0	0.0	46	45	46
T22	T23	1	2	2.5	60	65	75	62.0	64	65.5	194	188	188

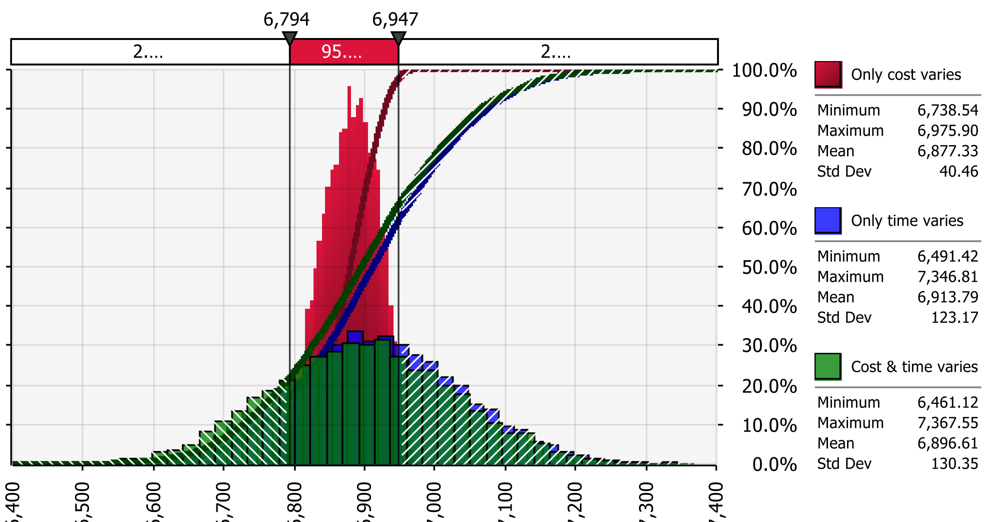

Figure 1: Distributions of the cost estimate

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V. CONCLUSION

Handling uncertainty in defence acquisition projects has been an ongoing challenge for military forces. The ability to accurately define a cost and a schedule for these projects is challenged by their large scale and uncertainties in their interrelated activities. This paper presents state-of-the-art methods for analyzing integrated cost and schedule risk. It suggests a seven-step risk analysis approach to analyze the expected cost and completion time of an acquisition project. A case study using a military aircraft replacement project for the Canadian Armed Forces is also presented to illustrate the approach.

The proposed approach captures the influence of schedule uncertainty on cost uncertainty by integrating project duration with time-dependent and time-independent resources. It provides more accurate project cost estimates and useful indicators about the potential critical activities, the expected cost contingency, and schedule buffer. This approach would enable decision makers to better handle common causal risks and minimize the consequences of adverse events in defence acquisition projects.

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