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Choice of optimum combination of construction machinery using modified advanced programmatic risk analysis and management model

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Abstract. Since the proper use of construction machinery in infrastructure projects is important, it is essential to employ an optimum selection of machinery in these projects. Advanced Programmatic Risk Analysis and Management model (APRAM) is one of the recently developed methods that can be used for risk analysis and management purposes considering schedule, cost, and quality, simultaneously. In this paper, the APRAM method is first introduced and then modified in order to consider environmental risks. This method can consider potential risks that might occur over the entire life cycle of the project, and can be employed as an efficient decision-support tool for construction managers selecting machinery for an infrastructure project where various alternatives might be technically feasible. A case study of 3 possible combinations of excavation machines is then discussed. All project risks related to cost, time, quality, and environment are identified considering the capital costs which should be spent on each combination. Finally, some graphs, which are derived from the method, are taken into account in order to decrease the risks of each combination and optimize the selection of excavating machinery. The outcomes highlight the efficiency of the APRAM model for the optimal selection of machinery in construction projects.

1. Introduction

Construction machinery plays a significant role in the choice of construction style, and in the overall cost and time of a project. Hence, an optimum selection of machinery is a matter of great importance. Construction machines bear several risks and it is essential to apply risk management techniques for their optimized selection. Taking into account the various conditions of a construction project, such as economic issues, managing policies, etc., and investigating the plausible risks (which are mostly a matter of time, costs, and quality) are of fundamental importance. Therefore, having an appropriate technique for risk analysis and management that can cover different combinations of risks in construction, while simultaneously minimizing the risks of project failure, is quite necessary considering cost, time, and quality. There are a variety of methods available for use in the analysis and management of risks in the construction industry [1-3]. However, most of these techniques address either those risks relating only to cost, schedule, and structural reliability individually, or those relating to a combination of cost and schedule risks [4]. Table 1 summarizes various methods that have been developed for use in the risk management of construction.

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Table 1. Some risk analysis methods and addressed risks.

Risk analysis methods	Addresses time risks	Addresses cost risks	Addresses quality risks
Judgmental Risk Analysis Process (JRAP)	Yes	No	No
Schedule risk system	Yes	No	No
Estimating project & activity duration using network analysis	Yes	No	No
Utility-function engineering performance assessment	No	No	Yes
Estimating using Risk Analysis (ERA)	No	Yes	No
Program Evaluation & Review Technique (PERT)	Yes	No	No
Failure Modes & Effect Analysis (FMEA)	Yes	Yes	Yes
Computer Aided Simulation for Project Appraisal and Review (CASPAR)	Yes	Yes	No
Data-driven analysis of corporate risk using historical cost-control data	No	Yes	No
Advanced Programmatic Risk Analysis and Management Model (APRAM)	Yes	Yes	Yes

As stipulated in the table, these methods are limited to addressing risks relating only to cost, time, or technical performance individually or, at best, a combination of cost and time risks; the exception is FMEA, which addresses cost, time, and quality together. However, it should be mentioned that FMEA is based on ordinal, rather than cardinal, scales. That is, the different possible failure events are ranked, but the differences between the rankings for any two possible failure events are not proportional to their risks. For example, the risk due to a potential failure event given an FMEA score of 10 (on the standard 1-10 scale) is not necessarily twice as high as the risk from a potential failure event given a score of 5. Without a cardinal scale, that is a scale in which scores are proportional to risk, FMEA does not provide a sound basis for allocating resources to manage risk [4].

The construction machinery required for any project carries several different risks, including cost, schedule, quality, and environmental issues. The Advanced Programmatic Risk Analysis and Management model (APRAM) is an example of a decision-support framework that can be useful for the risk analysis and management of a project. APRAM can address cost, schedule, and quality failure risks, simultaneously [5,6]. While the original APRAM takes into account only those risks that occur over the design and construction phases of the project's life cycle, the modified APRAM employed in this paper addresses the project's failure risks over the whole life cycle of the project, including the operation and maintenance phases [7]. However, this method still needs further improvement as it does not cover environmental risks. Hence, this study first develops the APRAM model in order to address the environmental failure risks. This developed model is then applied to an optimal combination of machines in construction projects. For the purpose of conducting a case study, 3 combinations of machines, which have been used in excavation and digging projects in one of Isfahan's subway stations, are investigated (Isfahan Subway Organization, 2013-14).

2. Construction machinery risks

Four types of risks can generally be identified in the construction machinery. The first type of risks is related to cost, and can simply be described in terms of a project exceeding its budget. Rydeen [8] mentions overlooked budget items, poor management, unforeseen site conditions, and inaccurate cost estimates as some of the factors that contribute to budget overruns in construction projects. The second type of risk deals with time, that is, the inability to complete the project within a specified duration. Mulholland and Christian [9] in their study on risk assessment in construction schedules mentioned excessive change orders, poor communication between disciplines, poor planning, incompetent management, and poor management controls as some of the causes of schedule overrun. The third risk is design related, that is, risk related to the technical characteristics of the project. The technical characteristics depend on the construction type and execution time, as well as the construction environment [10]. This leads to a different risk management scenario for each project. The fourth type of risk is the one related to environmental damage caused by machines. The growing significance of environmental issues in the current industrial world urges the need for investigating this type of issues. This risk manifests external expenses, harm to people's health, damage to the ecosystem, issues of handling materials, and effects on agricultural products. Generally, the machinery risks affect the project's aims and may cause setbacks in the project's timely completion [11].

3. Advanced Programmatic Risk Analysis and Management model (APRAM)

APRAM can be used by project managers to identify 3 sequential optimization steps [12]. The first step is to identify all feasible alternatives, considering the budgets that can be spent on the project, in order to minimize the technical Probability of Failure (PF) for each alternative. The minimum cost set for each technical design alternative and its appropriate residual budget are then identified. The residual budget refers to the difference between the total project budget and the minimum cost of each alternative. In the second step, managerial risks over the available range of the potential reserve budget should be identified and then minimized for each alternative by using appropriate optimization strategies.

The final step is the determination of the optimum technical design alternative, considering technical, managerial, and environmental risks. Each technical design alternative may need a different portion of the residual budget, through trade-offs between technical, managerial, and environmental failure risks based on the preferences of the decision maker(s). Finally, project managers need to choose the alternative that offers the best value, considering the probabilities of various failures of the project and the associated failure costs. If this is not satisfactory, the allocated resource should be increased until the selected alternative meets the threshold of acceptability. Figure 1 shows the steps and sub-steps involved in the implementation of APRAM.

4. Total budget of project

The entrepreneur(s) or the organization manager(s) determine the project budget before it is launched. One of the important parts of a construction project, which has a significant role in the project's budget, is the implementation of machinery and equipment. In this research study, for the purpose of conducting a case study, 3 combinations of construction machineries used in excavation and digging projects in one of Isfahan's subway stations are investigated. The total budget allocated for the project is shown in Table 2. The information is extracted from the annual reports of the municipal Isfahan Subway Organization (ISO) (Isfahan Subway Organization, 2013-14).

Table 2. Summary of total budget.

Type	Cost ($)	Details
Direct cost	200000	Lease, fuel, etc.
Maintenance cost	30000	—
Other cost	30000	Ramp, authorizations, etc.
Total cost	260000	

5. Implementation of APRAM

5.1. Identification of possible alternatives

The first step in a planned risk analysis is to select all machinery combinations that are technically suitable for the target project. Each machine is designed for a special operation and should be chosen according to the project. Lack of harmony between the machine and the operation would lead to sub-optimal efficiency, and could damage the machines in addition to causing additional expense. Hence, regarding the limitations and requirements of the project, the project's budget, schedule, and location, several construction machinery combinations would ordinarily be investigated before one of them is chosen.

In this study, 3 potential combinations for the excavation and digging of the subway projects are identified by the experts and engineers taking part in

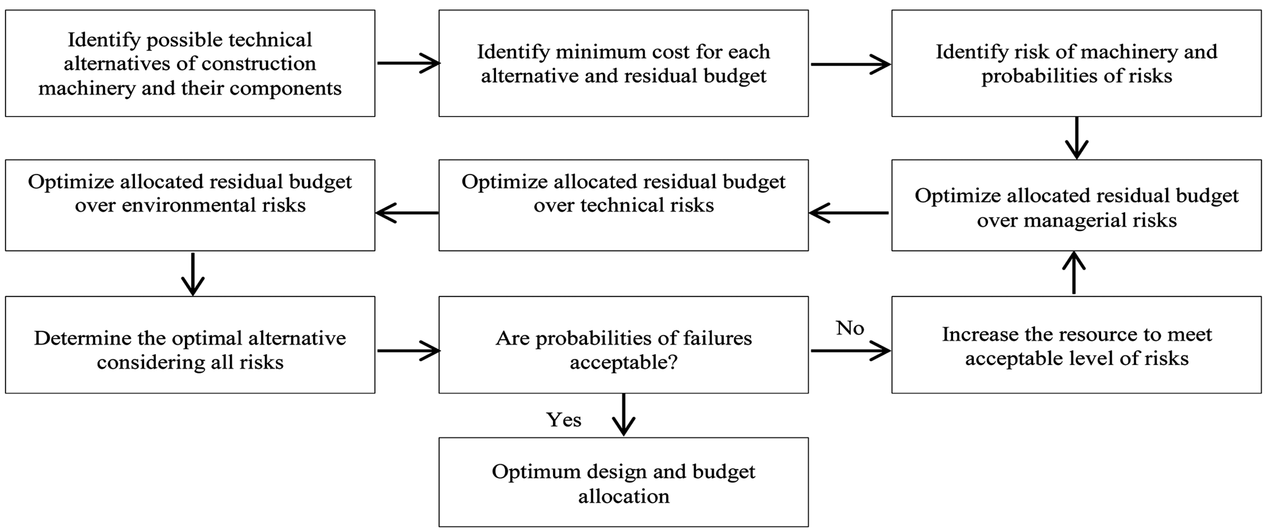

Figure 1. The modified APRAM process.

Table 3. Details of the machinery used in the possible alternatives.

Alternative	Machine	Model	Qty	Description
1 (ramp included)	Excavator (drill)	Komatsu PC220 LC-7 2006	1	With tracks
	Excavator (loading)	Komatsu PC220 LC-7 2006	1	With tracks
	Truck	Mercedes Benz 2000	6	Capacity 5 m3
	Loader	Volvo L90F 2010	1	—
2 (no ramp)	Excavator (drill)	Komatsu PC220 LC-7 2006	1	With tracks
	Excavator (loading)	Komatsu PC220 LC-7 2006	1	With tracks
	Truck	Mercedes Benz 2000	6	Capacity 5 m3
	Loader	Volvo L90F 2010	1	—
	Tower crane	Potain 46-6	1	Capacity 2 m3
3	Excavators (drill)	Komatsu PC220 LC-7 2006	1	With tracks
	Mini Loader (bobcat)	S250-h	1	—
	Truck	Mercedes Benz 2000	6	Capacity 5 m3
	Loader	Volvo L90F 2010	1	—
	Gantry Cranes	—	1	—

a Delphi method [13] survey. Also, the Delphi method is employed in order to identify all the plausible risks needed for assessing, optimizing, and selecting the optimal combination of machines. The Delphi method is a decision-making technique for collecting and classifying the knowledge possessed by a group of experts. This method is implemented through using questionnaires, controlled feedback of the received answers and ideas, and conducting repetitive surveys in several phases. In Alternative 1, the digging operations are performed by 2 excavators, and the soil is loaded into Trucks by a Loader. Then, the soil is carried out to the specified place. In this method, it is necessary to make an access ramp. To do so, digging and stabilizing operations are performed first, and then embarking (or blockage) is carried out. In Alternative 2, after digging operations, soil is carried out by a tower crane without a ramp. After disembarkation, the soil is loaded to the trucks again by a loader and is carried to the given place. In Alternative 3, the digging operations and soil moving are completed with an excavator and a Bobcat mini-loader. In this case, there is no need to make a ramp. Soil transfer is performed in 2 phases via a gantry crane, a loader, and a truck. Table 3 shows details of the machinery.

5.2. Identifying minimum cost and residual budget for each alternative

After assigning the potential machinery combination alternatives, the corresponding costs for each alternative are estimated by the machinery experts at ISO. This leads to the calculation of the total project cost, which is called the development cost of each alternative. The Residual Budget (RB) for each alternative is then evaluated by calculating the difference between the initial Total project Budget (TB) and the total cost of construction development (DevCost). Table 4 illustrates these features.

6. Risk of construction machinery

As mentioned earlier, the Delphi method was employed, incorporating 12 experts, mainly in 3 groups, including 7 engineers, 3 directors of ISO, and 2 machinery experts. The minimum educational degree of each group was BSc, MSc, and technical diploma, respectively; also, the average professional experiences of the groups were 14, 21, and 23 years, respectively. It is necessary to mention that all managerial risks, which refer to time and costs, and technical and environmental risks during the design and operation

Table 4. Alternatives' DevCosts, TB, and RB (in US Dollars).

Alternative	Cost			DevCost	TB	RB
	Lease	Fuel	Other			
1	153141	18309	74473	245923	260000	14077
2	206289	26309	6666	239265	260000	20735
3	207639	24529	6666	238835	260000	21165

phases, are identified and their probabilities of failure are evaluated using the Delphi method as well.

For this purpose, first, a questionnaire was answered anonymously and individually by each expert. Then, the answers were summarized and sent back to all members along with the next questionnaire. This time, the respondents were asked to give each failure event a validity score from 0 to 10. Next, graphs summarizing the results were again sent back to the respondents. They were asked to reassess their previous answers and the same questions were asked. After that, summaries of the answers were sent to all group members showing the mean and standard deviation. The respondents were asked to re-evaluate all new assumptions revealed in round two as well as the assumptions in round one that had a large standard deviation, and to assign a validity score, again. In the next step, the final failure risk events were finalized based on the results. The same process was performed in order to calculate the associated probabilities of failures. After 3 iterations, the final values for probabilities of failures had a good agreement among the whole group with a standard deviation of less than 20%. As an example, the risks of Alternative 1 are presented in Table 5.

It is worth noting that all risks can be categorized as partial or total risks. Total risks are those failures which happen in machinery and which cause failure in the whole project. Indeed, if partial risks become actual events, the machinery can remain active and the project continues, but at a degraded level of functionality. The managerial risks include the probabilities that the project cannot be completed within the assigned budget and provided timetable. Current evidence suggests that construction machinery projects are usually accomplished, even though there are often considerable cost and time overruns. Therefore, no Total Managerial Failures (TMF) are considered in this study and all identified managerial failure risks are categorized as Partial Managerial Failures (PMF). The same has been assumed for environmental failure events, which are considered Partial Environmental Failures (PEF), since it is expected that these failures would not affect the overall performance of the project.

Appropriate trade-offs between these failure risks are essential for achieving the optimum performance of the building. For example, spending more time and money on design to reduce the technical failure risks may increase the probability of management failure by cost and time overruns. The project risks are illustrated in Figure 2.

The risk probabilities of total failure and of partial technical, managerial, and environmental failure are calculated based on the fault-tree models using Eq. (1) [14], assuming that all basic identified risk events are independent. Appropriate trade-offs between these failure risks are essential to achieve the optimum performance of the construction machinery project:

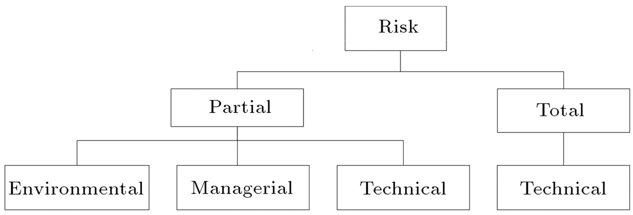

Figure 2. Construction machinery risks.

Table 5. Potential risks and probability of failure risks for Alternative 1.

	Type of risk	Risks related to:	Probability		Type of risk	Risks related to:	Probability
Truck	Managerial	Ramp	10.84		Managerial	Change in maps and routes	7.50
		Machinery downtime	10.42			Price change	29.30
		Taking certificate	18.00	Excavators (drill)	Technical	Excavation border error	10.00
	Technical	Control system	21.00			Control system	9.17
		Tyres	15.50			Breaking system	10.00
		Engine	9.58			Pump and selector	13.00
		Hydraulic system	10.00			Engine	13.50
		Overload issues	16.50			Hydraulic system	12.50
	Environmental	Pollution	26.25		Environmental	Pollution	10.83
Loader	Technical	Control system	11.50	Excavators (loading)	Technical	Control system	11.25
		Tyres	14.00			Excavator bucket	10.83
		Pump and selector	12.50			Pump and selector	11.70
		Engine	13.90			Engine	12.50
		Hydraulic system	10.00			Hydraulic system	10.80
	Environmental	Pollution	8.20		Environmental	Pollution	10.00

$$p(T)=\sum_{i=0}^{n}p(F_i)-\sum_{i=1}^{n}\sum_{j=i+1}^{n}p(F_iF_j)+\sum_{i=1}^{n}\sum_{j=i+1}^{n}\sum_{k=j+1}^{n}p(F_iF_jF_k)-.... \quad (1)$$

As the next step, the decreasing probability of existing risks, based on the spent residual budget, will be determined through Eqs. (2) to (4) [15]:

$$p(F_i|\text{Tech}_{\text{rein}})=p_0(F_i|\text{Tech}_{\text{rein}})\times \text{Exp}[-K_s\alpha], \quad (2)$$

$$p(F_i|\text{Mgmt}_{\text{rein}})=p_0(F_i|\text{Mgmt}_{\text{rein}})\times \text{Exp}[-K_s\alpha], \quad (3)$$

$$p(F_i|\text{Enmt}_{\text{rein}})=p_0(F_i|\text{Enmt}_{\text{rein}})\times \text{Exp}[-K_s\alpha], \quad (4)$$

where α is the portion of the residual budget that can be used as investment to improve the probability of failure for risk event, F_i, and is always between 0 and 1; and K_s is assessable constant. Using the equations, the risks would be eliminated by spending α percent of the residual budget. As an example, Table 6 and Figure 3 illustrate the effects of investments on risk reductions for managerial probabilities of failure events of Alternative 1. The risks' exponential functions are derived using Excel software. This is based on data that were obtained by interviews with experts at ISO. Based on the graph, one can interpolate the requested information.

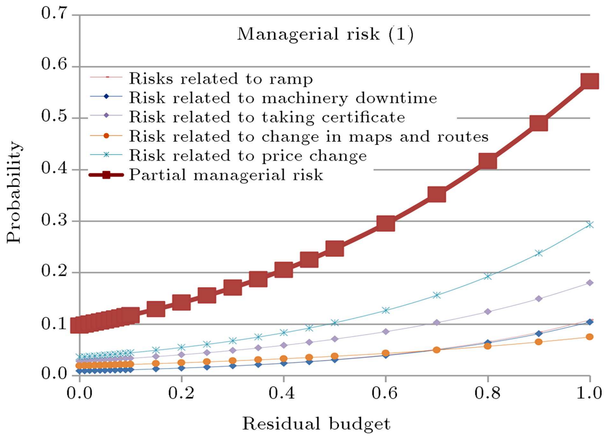

Figure 3. Probabilities of different managerial failures versus fractions of RB for Alternative 1.

Table 6. Effects of investment on managerial PF in Alternative 1.

Risks related to:	$p_0(F_i\|\text{Mgmt}_{\text{rein}})$
Ramp	$0.108\times\text{Exp}(-2.285\times\alpha)$
Machinery downtime	$0.104\times\text{Exp}(-2.447\times\alpha)$
Taking certificate	$0.18\times\text{Exp}(-1.861\times\alpha)$
Change in maps and routes	$0.075\times\text{Exp}(-1.373\times\alpha)$
Price change	$0.293\times\text{Exp}(-2.097\times\alpha)$

7. Cost of construction machinery risks

7.1. Cost of technical and managerial risks

In this section, the costs of all technical and managerial risks for 3 alternatives are evaluated utilizing questionnaires, which were filled out by machinery project experts. The results are shown in Table 7.

7.2. Cost of environmental risks

In this section, the amount of external costs of pollution emanating from construction machinery is evaluated. Generally, there are 2 views, top-to-bottom and bottom-to-top, for estimating the dissemination of pollution [16]. In this study, the latter is used, meaning that the pollution factors rates are evaluated first, and associated final emission factors will be calculated later. Finally, the corresponding fuel consumption and costs are estimated, based on the evaluated emission factors and provided tables in (EPA, 2010).

The pollution factors rates of Compression Ignition (CI) machinery can be derived from the reports of Environmental Protection Agency (EPA, 2010) using Eq. (5). To avoid complexity, no further detailed formulations are presented here. More details can be found in EPA (2010):

$$\text{EF}_{\text{adj}}=\text{EF}_{\text{ss}}\times\text{TAF}\times\text{DF}\times S_{\text{PMadj}}, \quad (5)$$

where EF_{adj} is final emission factor after adjustments to account for transient operation and deterioration (g/hp-hr); EF_{ss} is zero-hour, steady-state emission factor (g/hp-hr); TAF is Transient Adjustment Factor (unitless); DF is Deterioration Factor (unitless); and S_{PMadj} is Adjustment to PM emission factor to account for variations in fuel sulfur content (g/hp-hr).

The zero-hour, steady-state emission factors (EF_{ss}) are mainly a function of model year and horsepower category, which defines the technology type. The Transient Adjustment Factors (TAFs) vary by equipment type. The Deterioration Factor (DF) is a function of the technology type and age of the engine. As an example, exhaust emission factors for Alternative 1 are presented in Table 8.

Table 7. Cost of technical and managerial risks (in US Dollar).

Item	**Type**	**Symbol**	**Alternative 1**	**Alternative 2**	**Alternative 3**
Cost of technical risks	Total technical failure	TTF	82166	104066	109066
Cost of managerial risks	Partial technical failure	PMF	42000	50333	50333

Table 8. Exhaust emission factors for Alternative 1.

Machine	Fuel consumption (liter/hour)	Operation time (hour)	Amount of pollution (Ton)			
			PM	NO_x	CO	SO_2
Excavators (drill)	3	2443	0.032	0.408	0.152	0.085
Excavators	3	1960	0.025	0.328	0.122	0.068
Truck	5	12000	0.371	4.616	1.071	0.697
Loader	2	1700	0.024	0.147	0.107	0.046

Table 9. External costs of pollution factors.

Pollution factors	PM	CO	SO_2	NO_x
Cost ($/Ton)	1146.6	50	486.6	160

Table 10. Costs of environmental risks.

Alternative	Cost of pollution ($)
1	1906
2	1906
3	1832

Table 11. Costs of environmental risks.

Alternative	Cost of pollution ($)
1	7496
2	7496
3	7206

Based on local prices in 2002, the external costs of pollution factors and environmental destruction resulting from using vehicles working with fossil fuel energy are presented in Table 9 and Table 10, respectively.

It is necessary to mention that based on Table 10, the final cost of pollution for both Alternatives 1 and 2 is $1906 because the associated exhausted pollution for the electrical Tower Crane, which is employed in Alternative 2, is considered to be zero. Since the calculated costs are based on 2002 prices, the Cost Plus method [17] is employed in order to evaluate the costs based on present-time (2014) prices (World Bank website) in the target area. The outcomes are shown in Table 11:

$$ExCt_{2014} = ExCt_{2002} \times \frac{\$\text{Rate}_{2014}}{\$\text{Rate}_{2002}}, \quad (6)$$

where $ExCt_n$ and $Rate are the evaluated cost and the average dollar value on year n, respectively.

8. Choice of optimum alternative and corresponding residual budget

The final step is to determine the optimum alternative, considering technical, managerial, and environmental failure risks, and investigating the fraction of the residual budget that maximizes the owner's utility, which is defined as the minimum expected cost of failures. The order of failure occurrences, including technical, managerial, and environmental failures, over the whole life cycle of a construction machinery project is shown as an event tree in Figure 4. Managerial failures occur before technical and environmental failures because a technical and environmental occurrence can happen only after the design phase has been completed.

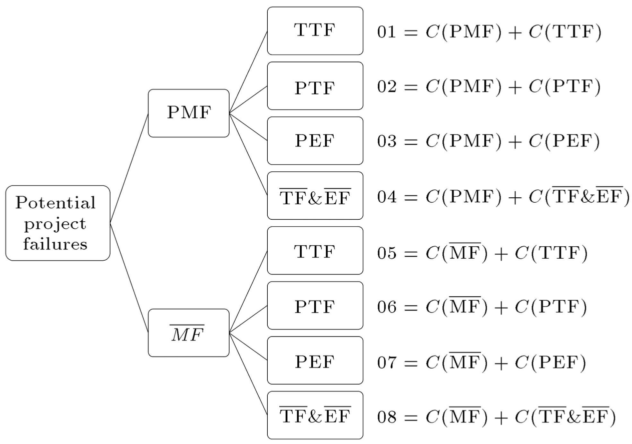

Figure 4. Potential project failures.

The minimum expected failure costs for each allocation of the residual budgets to technical, managerial, and environmental reserves is evaluated using Eq. (7):

$$\begin{aligned} E = & P(\text{PMF})P(\text{TTF})01 + P(\text{PMF})P(\text{PTF})02 \\ & + P(\text{PMF})P(\text{PEF})03 \\ & + P(\text{PMF})P(\overline{\text{TF}}\&\overline{\text{EF}})04 \\ & + P(\overline{\text{MF}})P(\text{TTF})05 + P(\overline{\text{MF}})P(\text{PTF})06 \\ & + P(\overline{\text{MF}})P(\text{PEF})07 + P(\overline{\text{MF}})P(\overline{\text{TF}}\&\overline{\text{EF}})08, \end{aligned} \quad (7)$$

where PMF means Partial Managerial Failure; TTF means Total Technical Failure; PTF means Partial Technical Failure; PEF means Partial Environmental Failure; $\overline{\text{MF}}$ means no Managerial Failure; and $\overline{\text{TF}}$&$\overline{\text{EF}}$ means no Technical and Environmental Failure. Moreover, $C(X)$ are costs of events Xs and $Xs = \text{PMF}, \text{TTF}, \text{PTF}, \text{PEF}, \overline{\text{MF}}, \overline{\text{TF}}$, and $\overline{\text{EF}}$.

Figures 5 to 7 and Table 12 show the summarized outcomes of the overall optimizations for all 3 alternatives, including technical, managerial, and environmental failure risks; the probability of overall project failure; and the estimated costs of failures over the whole life cycle of the construction machinery project. Table 12 shows that the cost of failure and the probabilities of failure risks for Alternative 1 are lower than those for the other alternatives. Therefore, it can be clearly concluded from comparison of the alternatives that utilizing Alternative 1 for the construction machinery used for Isfahan's subway stations is more economical. This case study evidently shows the usefulness and the efficiency of implementation of the modified APRAM method, which helps project managers to select the optimum technical alternative considering all failure modes over the entire machinery project life cycle.

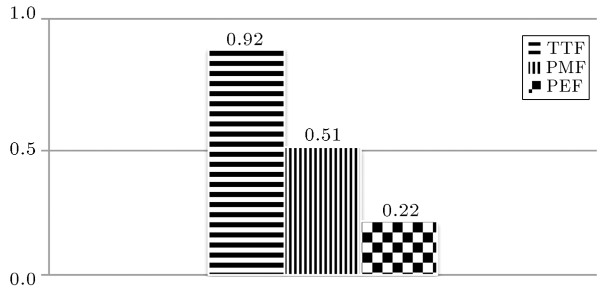

Figure 5. Probabilities of failures - Alternative 1.

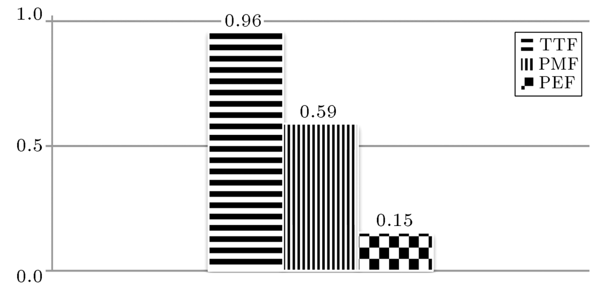

Figure 6. Probabilities of failures - Alternative 2.

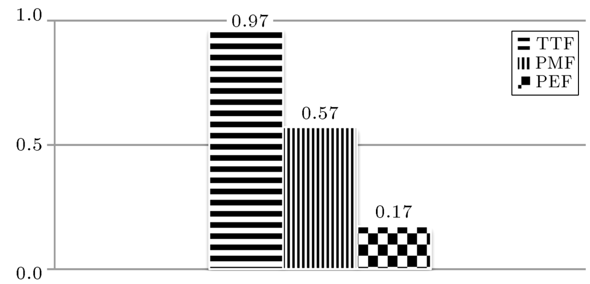

Figure 7. Probabilities of failures - Alternative 3.

Table 12. Costs of overall failure risks.

	Costs of overall failure risks (based on 2014) ($)		
α	**Alternative 1**	**Alternative 2**	**Alternative 3**
0%	114145	150901	155059
50%	106744	139505	144901
100%	102636	135420	140346

It should be emphasized that the modified APRAM model presented here contains a general risk/cost function for modeling systems, assuming that the probabilities of failures in a system diminish exponentially as the residual budget is spent to increase the robustness and performance of the system. The reliability of this assumption needs to be evaluated in further studies using historical data on similar or related projects.

9. Summary and conclusion

Machinery is one of the basic and central means for achieving the predetermined goals in construction and infrastructure projects. The different types of construction machinery usually bear different risks. This paper has presented the *modified* Advanced Programmatic Risk Analysis and Management Model as an appropriate decision-support tool for construction managers, which can address cost, time, quality, and environmental failure risks, simultaneously. This method would help project directors to minimize the plausible risks of a machinery project and to select the optimal combination of machines. Besides developing the APRAM model for covering environmental risks in addition to the technical and managerial risks, this study has investigated 3 alternative combinations of machinery in the excavation and digging project of Isfahan's subway. The optimal diagrams of all alternatives were drawn according to the identified risks and their initial costs. These diagrams were presented for each alternative, separately, considering environmental, technical, and managerial risks. Thus, one can compare them with each other and choose the optimum combination. Analyzing the optimal diagrams sets the ground for making appropriate decisions about choosing contractors and implementation methods. The APRAM model technique is suggested here as a method for the optimal selection of machinery in construction projects. Also, it should be mentioned that although the APRAM method considers all managerial, technical, and environmental risks, simultaneously, as the next step, it is suggested to develop the model for taking into account the other potential projects' risks, which might occur in the construction projects, e.g., human resource risks, transportation and traffic risks, and sound pollution risks.

Nomenclature

APRAM	Advanced Programmatic Risk Analysis and Management Model
CI	Compression Ignition
DevCost	Development Cost
DF	Deterioration Factors
$\mathrm{EF}_{\mathrm{adj}}$	Final Emission Factor after adjustments to account for transient operation and deterioration (g/hp-hr)
$\mathrm{EF}_{\mathrm{ss}}$	Zero-hour, steady-state Emission Factor (g/hp-hr)
$\overline{\mathrm{EF}}$	No Environment Failures
EPA	Environmental Protection Agency
$\overline{\mathrm{MF}}$	No Managerial Failures
NOx	Oxides of Nitrogen
PEF	Partial Environment Failures
PF	Partial Failure
PM	Particulate Matter
PMF	Partial Managerial Failures
PTF	Partial Technical Failures
RB	Residual Budgets
S_{PMadj}	Adjustment to PM emission factor to account for variations in fuel sulfur content (g/hp-hr)
TAF	Transient Adjustment Factor
TB	Total Budget
TF	Total Failure
$\overline{\mathrm{TF}}$	No Technical Failure
TTF	Total Technical Failure

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