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Stochastic Analysis for Long Term Capital Structures, Systems, and Components Refurbishment and Replacement

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Congjian Wang[1], Diego Mandelli[1], David Morton[2], Ivilina Popova[3], Stephen Hess[4], Shawn StGermain[1], Curtis Smith[1]

[1]*Idaho National Laboratory, 2525 N. Fremont Ave., Idaho Falls, ID 83415,*
{congjian.wang, diego.mandelli, shawn.stgermain, curtis.smith}@inl.gov
[2]*Northwestern University, Evanston, IL 60208, David.morton@northwestern.edu*
[3]*Texas State University, San Marcos, TX 78666, ivilina.popova@gmail.com*
[4]*Jensen Hughes, West Chester, PA 19380, shess@jensenhughes.com*

INTRODUCTION

As commercial Nuclear Power Plants (NPPs) pursue extended plant operation in the form of Second License Renewal (SLR), opportunities exist for these plants to provide capital investments to ensure long-term safe and economic performance. At the current time, several utilities have announced an intention to pursue extended operation for one or more of their NPPs via SLR [1]. The goal of this research is to develop a risk-informed approach to evaluate and prioritize plant capital investments made in preparation for, and during the period of, extended plant operations.

Since the capital investments are influenced by various factors, such as markets, safety and regulatory, the decision-making process of NPP operations should take into account relevant factors for balancing risks, costs and profits. The traditional method of capital budgeting is based on the priority list of candidate projects using economic measures such as benefit-investment ratio (BIR), net present value (NPV), and internal rate of return (IRR). In the literature, the problem of capital budgeting can be represented by an appropriate knapsack problem. The knapsack approach to capital budgeting takes as input the proposed investments, along with the cost and profit of each project. The objective of capital budgeting is to find the combination of the binary decisions for every investment such that the overall profit is as large as possible. The output is a collection of projects to be carried out, and we refer to this selected collection of projects as a project portfolio.

One limitation of traditional optimization models for capital budgeting is that they do not account for risk/uncertainty in profit and cost streams associated with individual projects nor do they account for risk in resource availability in future years [2-4]. Projects can incur cost over-runs, especially when projects are large, performed infrequently, and when there is risk regarding technical viability, external contractors, and/or suppliers of requisite parts and materials. Occasionally, projects are performed ahead of schedule with resultant cost savings. Planned budgets for capital improvements can be cut and key personnel may be lost. Or, there may be surprise windfalls in budgets for maintenance activities due to decreased costs for "unplanned" maintenance. In these cases, how should we resolve capital budgeting when we have risk forecasts for costs, profits and budgets? The approach we proposed in this summary is to re-solve the optimization models based on assumed statistical distributions of given parameters. If these distributions were not available, a two-stage stochastic optimization approach can be used to provide priority lists to decision-makers to support better risk-informed decisions [5, 6]. In this summary, we will only focus on the first approach.

Optimization Model Formulation

The basic knapsack problem for capital budgeting can be defined as follows: we are given an instance of the capital budgeting problem with investment set , consisting of investments with profit *, e.g. NPV, and cost , and the available budget*. Then the objective is to select a subset of such that the total profit of the selected investments is maximized, subject to the constraint that the total cost does not exceed . The knapsack problem can be formulated as a solution of the following linear programming formulation:

(1)

(2)

(3)

The constraint in Eq. (2) ensures that the cost of the project portfolio is within the budget. The binary variables *in Eq. (3) correspond to the selection in the binary decision (1 if project* is selected; 0 otherwise). In order to apply the knapsack problem to a nuclear generation station, with possible extension to a larger fleet of plants, we have extended the basic knapsack problem to a multi-dimensional multiple-choice knapsack problem that can extend over multiple years, i.e.

(4)

(5)

(6)

(7)

(8)

(9)

Indices and sets:

candidate projects

options for selecting project (e.g., initiate project in year or and in a standard (three year) or in an expedited (two year) manner)

"must-do" projects (e.g., due to safety reasons even if their NPV is negative) or projects include *do-nothing* option

option for project can be selected only if

option is selected for project , i.e.,

piggybacking

types of resources, e.g., capital funds, O&M funds, labor-hours, time during outage

time periods (years)

Data:

Net present value (NPV) of selecting project via option

available budget for a resource of type in year

consumption of resource of type in year if project is performed via option

Decision variables:

The decision variables, *, indicate whether we choose to do project* by means. Restated, if *, then we recommend doing project* via option , and taken together these decision variables produce both a portfolio of selected projects and a schedule for performing those projects over time. The set of available options, *, can explicitly include the "do-nothing" option, and the* first structural constraints in Eq. (6) and (7) ensure that we choose exactly one option from the available set for each project, including the possibility of selecting the do-nothing option. Even if we select the do-nothing option for a project, it induces an NPV, (which we note may be negative, representing growing O&M costs, losses in plant efficiency, etc.). The second structural constraint in Eq. (5) ensures that the budget of each resource is respected in each year . The third structural constraint in Eq. (8) captures piggybacking situations in which option

for project (which may have cheaper costs) may be selected only if project-option pair is also selected. The objective function includes the NPV for each project-option pair, *, and the correct NPV is selected by the 0-1 decision variable, .*

We note that sometimes there are projects that must be implemented, e.g., for safety and/or regulatory reasons. This can be handled within the mathematical formulation just given, without introducing additional constructs. The set *typically includes a do-nothing option* for each project, but when project must be done, we simply do not include the do-nothing option. Mathematically, an alternative is to *not* include an explicit do-nothing option, to replace the first structural constraint with an inequality, and to add an additional set of "must do" projects with an equality constraint. Both options are mathematically equivalent and simply represent a choice to be made by the analyst.

The optimization model can be repeatedly solved by changing the input values, *, , . This will allow for what-if sensitivity analysis to identify the crucial drivers behind the optimal project selection decision. Monte Carlo simulation permits a powerful variant of this approach in which we model , ,* as random variables, sample from their distributions, and perform a form of uncertainty quantification in terms of the resulting distributions governing the binary decisions selected, *,* and the overall NPV of the selected portfolio.

RESULTS

In order to show how the developed method can be applied to capital structures, systems, and components (SSCs) replacement scheduling, we have developed a test case. We consider a capital budgeting problem for a nuclear generation station, with possible extension to a larger fleet of nuclear plants. Due to limited resources, we can only select a subset from several candidate capital projects. Our goal is to maximize overall NPV. Example projects under consideration include upgrading high pressure feedwater heaters, improving emergency diesel generators, etc.. To understand the nature of the proposed methodologies, we consider a numerical example with 16 projects (see *Table 1*, *Table 2* and *Table 3*) each having liabilities in some or all of the next five years. These projects were selected because they constituted a set of projects that were close to the budget cutoff point, with some being funded and others not. Thus, the subset of projects identified in *Table 1* was selected to provide a useful validation of the applicability of the method proposed in the paper.

In this example, we only consider two sources of funding for these projects, i.e., capital and operation and maintenance (O&M) funds. We note that our optimization paradigm could be expanded to include additional types of resources such as labor-hours and time during an outage. The planning horizon for this set of projects is set to five

years although NPV is computed with a horizon of 20 years (detailed calculations can be found in report [6]). Plans A, B, and C represent different timing options for performance of the planned replacement. For this case study, some numerical values of the capital budget in *Table 2* are modified to incorporate uncertainty through uniform

distributions (indicated as as for a uniform distribution

between and); see Table 4 and Table 5

Table 1. List of candidate projects for the considered SLR plan

ID	Project name	Category	Options
1	HP feedwater heater upgrade	Optional	Plan A, B, don't do
2	Pressurizer replacement	Must do	Plan A, B, C
3	Improvement to emergency diesel generators	Optional	Plan A, B, don't do
4	Secondary system PHM system	Optional	Plan A, B, don't do
5	Replacement of two reactor coolant pumps	Must do	Plan A, B
6	Seismic modification, requalification, reinforcement, improvement	Optional	Plan A, B, C, don't do
7	Fire protection	Must do	Plan A, B
8	Service water system upgrade	Optional	Plan A, B, don't do
9	Batteries replacement	Optional	Plan A, don't do
10	Replace CCW piping, heat exchangers, valves	Must do	Plan A, B, C
11	Reactor vessel internals	Optional	Plan A, B, don't do
12	Reactor vessel upgrade (head included)	Must do	Plan A
13	Replace LP turbine	Optional	Plan A, B, don't do
14	Replace instrumentation and control cables	Must do	Plan A
15	Condenser retubing	Optional	Plan A, B, don't do
16	Replace moisture separator reheater	Optional	Plan A, B, C, don't do

Table 2. Available capital and O&M budget for each year

	Year 1	Year 2	Year 3	Year 4	Year 5
Capital budget [M$]	22.6	36.7	20.6	23.6	22.7
O&M budget [M$]	0.08	0.17	0.05	0.15	0.14

Table 3. Costs and NPVs of project-option pairs

Project-option	Capital costs [M$]					O&M costs [M$]					Total NPV [M$]
	Y1	Y2	Y3	Y4	Y5	Y1	Y2	Y3	Y4	Y5	
1: PlanA	12.99	1.30				0.02	0.01				27.98
1: PlanB		12.99	1.30				0.02	0.01			27.17
2: PlanA	9.15	0.92				0.04	0.01				-10.07
2: PlanB		9.15	0.92				0.04	0.01			-9.78
2: PlanC				9.15	0.92				0.04	0.01	-9.22
3: PlanA				10.08	1.10				0.01	0.01	20.23
3: PlanB			10.08	1.10				0.01	0.01		20.84
4: PlanA		4.50	0.30	0.20			0.01	0.01	0.01		35.00
4: PlanB			4.50	0.30	0.20			0.01	0.01	0.01	33.98
5: PlanA		18.60					0.03				-18.60
5: PlanB					18.60					0.03	-17.02
6: PlanA		2.24					0.20				9.48
6: PlanB				2.24					0.20		8.94
6: PlanC					2.24					0.20	8.68
7: PlanA	1.31	0.13				0.01	0.01				-1.44
7: PlanB				1.31	0.13				0.01	0.01	-1.32
8: PlanA	2.34					0.01					5.18
8: PlanB			2.34					0.01			4.88
9: PlanA	0.28					0.01					2.10
10: PlanA			4.57	0.46				0.01	0.01		-5.03
10: PlanB		4.57	0.46				0.01	0.01			-5.18
10: PlanC				4.57	0.46				0.01	0.01	-4.88
11: PlanA		19.82					0.03				41.14
11: PlanB					19.82					0.03	37.65
12: PlanA	5.25					0.02					-5.25
13: PlanA			18.77					0.02			167.94
13: PlanB				18.77					0.02		163.05
14: PlanA	5.92	0.60				0.02	0.01				-6.52
15: PlanA	5.24					0.02					16.72
15: PlanB			5.24					0.02			15.76
16: PlanA	3.16					0.01					8.26
16: PlanB				3.16					0.01		7.56
16: PlanC					3.16					0.01	7.34

Table 4. Capital budget uncertainties

Capital budget [M$]				
Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
U[20,23]	U[34,38]	U[17,22]	U[20,25]	U[18,24]

Table 5. Uncertainties related to component failure probabilities

ID	Project name	P_Failure
1	HP feedwater heater upgrade	U[0.05,0.15]
3	Improvement to emergency diesel generators	U[0.005,0.0.05]
6	Seismic modification, requalification, reinforcement, improvement	U[0.1,0.5]
8	Service water system upgrade	U[0.01,0.1]
11	Reactor vessel internals	U[0.01,0.1]
13	Replace LP turbine	U[0.01,0.05]
15	Condenser retubing	U[0.01,0.05]
16	Replace moisture separator reheater	U[0.01,0.05]

Table 6. Initial data for NPV calculations

Project-option	Soft savings [M$]				Hard savings [M$]	Total NPV [M$]
	P_failure	T_shutdown [days]	Repl. cost	NPV		
1: Plan A	0.10	20.00	25.98	27.98		27.98
1: Plan B						27.17
2: Plan A				-10.07		-10.07
2: Plan B						-9.78
2: Plan C						-9.22
3: Plan A	0.01	7.00	20.16	20.23		20.23
3: Plan B						20.84
4: Plan A					35.00	35.00
4: Plan B						33.98
5: Plan A				-18.60		-18.60
5: Plan B						-17.02
6: Plan A	0.50	10.00	4.48	9.48		9.48
6: Plan B						8.94
6: Plan C						8.68
7: Plan A				-1.44		-1.44
7: Plan B						-1.32
8: Plan A	0.05	10.00	4.68	5.18		5.18
8: Plan B						4.88
9: Plan A				2.10		2.10
10: Plan A				-5.03		-5.03
10: Plan B						-5.18
10: Plan C						-4.88
11: Plan A	0.05	30.00	39.64	41.14		41.14
11: Plan B						37.65
12: Plan A				-5.25		-5.25
13: Plan A	0.02	20.00	37.54	37.94	130.00	167.94
13: Plan B						163.05
14: Plan A				-6.52		-6.52
15: Plan A	0.04	25.00	15.72	16.72		16.72
15: Plan B						15.76
16: Plan A	0.03	12.00	7.90	8.26		8.26
16: Plan B						7.56
16: Plan C						7.34

Table 6 shows the corresponding input data that are used to compute the NPVs assuming the given failure probabilities; the discount rate is set to 3% for all situations. In this case study, a simple model is proposed to compute the NPV of project-option pairs:

(10)

where

- : candidate projects
- *: options for selecting project*
- : probability of item failure
- : number of days plant is off-line if a shutdown occurs
- *: cost of shutdown per day*
- *: cost of unplanned replacement*
- *: project hard* dollar savings
- : discount rate
- *: the starting year of plan A for project*
- *: the starting year of option* for project

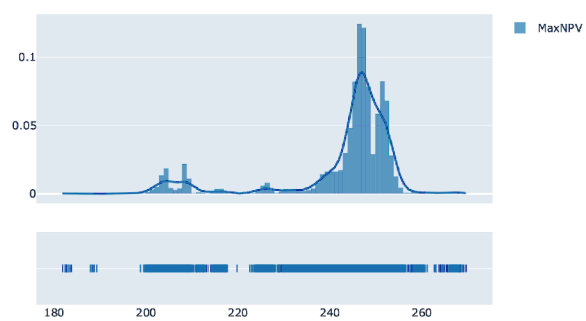

Figure 1. MaxNPV distribution ($ million) for selected portfolios

Table 7. Statistical analysis of MaxNPV

ID	Average	Minimum	Maximum	σ	5-percentile	95-percentile
MaxNPV	242.94	181.83	269.66	13.03	207.39	252.92

Table 8. Priority lists from scenario analysis

ID	Project name	Category	Options	Priorities	Probabilities	Risks (1-Probabilities)
1	HP feedwater heater upgrade	Optional	Plan A	43	0.00E+00	1.00E+00
			Plan B	31	7.76E-02	9.22E-01
			Don't Do	5	9.22E-01	7.76E-02
2	Presurizer replacement	Must do	Plan A	36	8.90E-03	9.91E-01
			Plan B	9	8.00E-01	2.00E-01
			Plan C	25	1.91E-01	8.09E-01
3	Improvement to emergency diesel generators	Optional	Plan A	20	2.96E-01	7.04E-01
			Plan B	13	6.29E-01	3.71E-01
			Don't Do	32	7.51E-02	9.25E-01
4	Secondary system PHM system	Optional	Plan A	6	9.14E-01	8.64E-02
			Plan B	29	8.64E-02	9.14E-01
			Don't Do	42	0.00E+00	1.00E+00
5	Replacement of two reactor coolant	Must do	Plan A	27	1.59E-01	8.41E-01
			Plan B	7	8.41E-01	1.59E-01
6	Seismic modification, requalification, reinforcement,	Optional	Plan A	41	0.00E+00	1.00E+00
			Plan B	40	0.00E+00	1.00E+00
			Plan C	39	0.00E+00	1.00E+00
			Don't Do	3	1.00E+00	0.00E+00
7	Fire protection	Must do	Plan A	21	2.85E-01	7.15E-01
			Plan B	11	7.15E-01	2.85E-01
8	Service water system upgrade	Optional	Plan A	15	5.21E-01	4.79E-01
			Plan B	17	3.96E-01	6.04E-01
			Don't Do	30	8.25E-02	9.18E-01
9	Batteries replacement	Optional	Plan A	10	7.62E-01	2.38E-01
			Don't Do	23	2.38E-01	7.62E-01
10	Replace CCW piping, heat exchangers, valves	Must do	Plan A	14	5.37E-01	4.63E-01
			Plan B	24	2.21E-01	7.79E-01
			Plan C	22	2.42E-01	7.58E-01
11	Reactor vessel internals	Optional	Plan A	8	8.32E-01	1.68E-01
			Plan B	33	6.13E-02	9.39E-01
			Don't Do	28	1.07E-01	8.93E-01
12	Reactor vessel upgrade (head included)	Must do	Plan A	2	1.00E+00	0.00E+00
13	Replace LP turbine	Optional	Plan A	18	3.55E-01	6.45E-01
			Plan B	12	6.45E-01	3.55E-01
			Don't Do	38	0.00E+00	1.00E+00
14	Replace instrumentation and control cables	Must do	Plan A	1	1.00E+00	0.00E+00
15	Condenser retubing	Optional	Plan A	4	9.64E-01	3.55E-02
			Plan B	35	2.93E-02	9.71E-01
			Don't Do	37	6.25E-03	9.94E-01
16	Replace moisture separator reheater	Optional	Plan A	16	4.68E-01	5.33E-01
			Plan B	19	3.10E-01	6.90E-01
			Plan C	26	1.84E-01	8.16E-01
			Don't Do	34	3.77E-02	9.62E-01

In this case study, the failure probabilities for projects 1, 3, 6, 8, 11, 13, 15, 16 and the capital budgets for years 1, 2, 3, 4, 5 are drawn randomly from their corresponding distributions. The corresponding NPVs are generated using the proposed simple equation, i.e. Eq. (10). The whole calculation is conducted via the RAVEN [7] software, and Monte Carlo sampling is used to calculate the output distributions or risk profiles of probable NPV of each project with a limit of 20,000 samples. Considering all the input uncertainties, the distribution of the selected project portfolios' best NPV, i.e. MaxNPV, is shown in Figure 1, and the statistical moments of best NPV are shown in Table 7. In this study, the expected NPV is $242.94M under 20,000 random scenarios, and the optimal priority list under all scenarios is given by Table 8.

CONCLUSIONS

This summary focuses on risk-informed capital investment decisions related to SSCs replacement plans. We employ the stochastic method to compute the priority lists for replacement/refurbishment expenditures of plant capital assets under different scenarios as well to generate statistical distribution of maximum NPV that can be used to support risk-informed decisions in NPP operations.

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