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Estimating cost uncertainties in nuclear power plant construction through Monte Carlo sampled correlated random variables

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ABSTRACT

The high uncertainty in overnight capital cost (OCC), as well as the large delays and cost escalation during construction, make nuclear power plants (NPP) unattractive for investors. In the US, a significant increase in the cost trend was found in correspondence to the 1979 accident event at Three Mile Island. A methodology based on the Iman-Conover method was developed to perform stochastic analyses on the construction schedule and cost accounts through Monte Carlo simulations accounting for variable correlations. A probabilistic assessment was then performed for the construction cost and time of a representative NPP, PWR12-BE. The mean value of the Total Capital Investment Cost (TCIC) for the PWR12-BE is \$6.7 B, with a cost contingency of \$582.1 M, which corresponds to 8.7% of the TCIC mean. The project duration has a mean of 10.7 years, with a relative standard deviation of 16.2%. However, the simulation results show lower predicted standard deviations of cost and time than the ones historically observed. The analysis demonstrates the need to extend the methodology to account for all uncertainties, including unexpected events, in the construction process of nuclear power plants. This aspect will be analyzed in a follow up paper (Maronati and Petrovic, 2018).

1. Introduction

The purpose of this work is to study the large variation and cost escalation observed in the construction of Nuclear Power Plants (NPPs) in the US, starting from a representative NPP construction schedule (in terms of activity costs and durations). A methodology that includes all these aspects was not found in literature. First, a construction model was developed to describe the construction of a 4-loop "mainstream" stick-built PWR (PWR12) (US DOE, 1988). Then, the construction model was used to perform a probabilistic analysis to account for the stochastic nature of activities, to calculate the project contingency and to estimate the distributions of project duration, OCC, and TCIC. Data for the best estimate "standard" PWR (PWR12-BE) were developed by the Department of Energy (DOE) Energy Economic Data Base (EEDB) (US DOE, 1988).

2. Background and previous studies

2.1. Definition of terms as used

TCIC is the parameter that represents the cost of design, construction, and testing of the NPP up to commercial operation. Different methods are used to estimate TCIC. The IAEA provides a breakdown of TCIC to different factors (Fig. 1) (IAEA, 1999). Base costs include costs associated with the equipment, structures, installation and materials (direct costs), as well as the engineering, construction and management services (indirect costs). Supplementary costs include spare parts, contingencies, and insurance. Owner's costs include the owner's capital investment and services costs, escalation and related financing costs. The fore costs or overnight costs consist of the base costs, the supplementary costs and the owner's capital investment and service costs. Financial costs include escalation, interest during construction (IDC) and fees. Fore costs, escalation costs, IDC and fees define TCIC.

2.1.1. Direct and indirect costs

Direct costs are the main contributor to TCIC. They include direct construction cost plus pre-construction cost (site preparation) (EMWG, 2007; Rothwell and Ganda, 2014). The value of direct costs (DC) is calculated summing the cash flow during construction. Indirect costs (IC) can be expressed as a percentage (*in*) of direct costs, as:

$$IC = in \cdot DC \tag{1}$$

Base cost, expressed as the sum of direct and indirect costs is then:

$$BC = DC \cdot (1 + in) \tag{2}$$

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List of abbreviations

ALAP	As Late As Possible
BC	Base Cost
DC	Direct Cost
DOE	Department of Energy
ECI	Employment Cost Index
EEDB	Energy Economic Data Base
FOAK	First of a Kind
GIF	Generation-IV International Forum
IAEA	International Atomic Energy Agency
IC	Indirect Cost
IDC	Interest During Construction
LCOE	Levelized Cost of Electricity
LT	Lead Time
NI	Nuclear Island
NOAK	Nth of a Kind
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OCC	Overnight Capital Cost
O&M	Operation and Maintenance
PBS	Part Breakdown Structure
PPI	Producer Price Index
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SM	Super Module
TCIC	Total Capital Investment Cost
TMI	Three Mile Island
USD	United States Dollar
WBS	Work Breakdown Structure
WEC	Westinghouse Electric Company

2.1.2. Supplementary and owner's costs

Supplementary cost includes transportation and shipping costs, spare parts and supplies as well as costs for the core first loading.

Owner's cost includes costs that are owner's responsibility, such as capitalized operations, capitalized supplementary costs, and capitalized financing costs. Supplementary and owner's costs can be approximated as directly proportional to the base cost and, therefore, the direct cost. Under this approach, the overnight capital cost is:

$$OCC = DC \cdot (1 + oc) \tag{3}$$

where oc indicates the percentage of owner's cost over base cost.

2.1.3. Escalation costs and interests during construction

Escalation reflects the change of cost of equipment, labor and material over time during the construction of the NPP. The Generation-IV International Forum guidelines suggest setting it to zero, unless otherwise justified (EMWG, 2007). Interest during construction (IDC) is the cost of financing OCCs during the construction period. It is equal to the difference between value of the expenditures at the end of the project and the value of the expenditures at the beginning of the project. It represents the cost of capital needed to sustain expenses during construction. *IDC* can be calculated as (EMWG, 2007):

$$IDC = \sum_{t=1}^{LT} [C_t(1 + r)^t - 1] \tag{4}$$

where LT is the number of time periods (project duration), C_t is the expenditure in period t and r is the weighted average cost of capital (discount rate) over one period (e.g., month). The Generation IV

$$\text{Base costs} = \left\{ \begin{array}{c} \text{Direct costs} \\ + \\ \text{Indirect costs} \end{array} \right\}$$

$$\begin{array}{l}\text{Fore costs} \\ \text{(overnight costs)}\end{array} = \text{Base costs} + \left\{ \begin{array}{c} \text{Supplementary costs} \\ + \\ \text{Owner's capital investment} \\ \text{and services costs} \end{array} \right\}$$

$$\begin{array}{l}\text{Total capital} \\ \text{investment costs}\end{array} = \text{Fore costs} + \left\{ \begin{array}{c} \text{Escalation costs} \\ + \\ \text{Interest during} \\ \text{construction and fees} \end{array} \right\}$$

Fig. 1. TCIC breakdown according to IAEA code of accounts (IAEA, 1999).

International Forum guidelines state that the 5% cost of capital "*is appropriate for plants operating under the more traditional regulated utility model where revenues are guaranteed by captive markets*", while the 10% cost of capital "*would be more appropriate for a riskier deregulated or merchant plant environment where the plant must compete with other generation sources for revenues*" (EMWG, 2007). All cash flows (transactions) are assumed to take place at mid-periods. Cash flows (C_t) are made of expenditures associated to direct costs and expenditures associated with indirect and owner's costs. Eq. (4) represents a simplified calculation of total financing costs during construction. However, for the purpose of this study, we considered the calculation adequately valid.

TCIC is calculated summing OCC (Eq. (3)) and interests during construction (Eq. (4)), as:

$$TCIC = OCC + IDC \tag{5}$$

2.1.4. Uncertainties and cost contingency

AACE International (2016) defines contingency as "An amount added to an estimate to allow for items, conditions, or events for which the state, occurrence, or effect is uncertain and that experience shows will likely result, in aggregate, in additional costs". Cost contingency is typically estimated using statistical analysis or judgment based on past asset or project experience. In a project, the cost contingency is intended to provide compensation for "estimating accuracy based on quantities assumed or measured, unanticipated market conditions, scheduling delays and acceleration issues, lack of bidding competition, subcontractor defaults, and interfacing omissions between various work categories." (American Society of Professional Estimators, 2004). The cost contingency is calculated through a probabilistic analysis of the TCIC distribution, as:

$$Cont = p_{TCIC} - Mo_{TCIC} \tag{6}$$

Where $Cont$ is the cost contingency, p_{TCIC} is the desired percentile rank of the distribution, and Mo_{TCIC} is the mode of the TCIC distribution. Often used percentile ranks are the 75th or the 90th. In the nuclear industry, the 75th percentile is mostly used (Talabi, 2017). In this case, the cost contingency is:

$$Cont = p_{TCIC} - Mo_{TCIC} \tag{7}$$

where the 75th percentile rank corresponds to the third quartile of the distribution (Q_3).

2.2. Historical capital cost trend in the US

The Energy Information Administration (1986) collected the nuclear power plant construction costs (in 1982 USD) and construction times of 75 units that started construction in the 1966–1977 timeframe in the US. The data was extracted and integrated with information of additional 26 reactors from Koomey and Hultman (2007), which reports construction costs (in 2004 USD), to expand the data to 101 reactors in the US. The reactor type and Nuclear Steam Supply System (NSSS) design of each plant were taken from US NRC (2018). The collected data include: reactor name, reactor type, NSSS design, power load, overnight cost, construction start and end date. Koomey and Hultman (2007) report the reactor name and construction date of additional 15 reactors, for which only construction times were collected due to lack of cost data. The collected data includes cost and construction duration of 32 Westinghouse four-loop PWRs, of the same design as PWR12-BE, and the construction time (but not cost) of an additional Westinghouse four loop PWR (Indian Point 2). The costs from the two references were escalated to January 2017 USD using the Consumer Price Index (US Department of Labor, 2017a).

In Energy Information Administration (1986), as the data was not uniform and therefore not comparable, the authors removed financing costs, and expressed all costs in constant dollars (mid 1982 USD). The methodology to convert “as expended” dollars to “constant dollars” of a given year, is presented in detail in the reference (Energy Information Administration, 1986). We then escalated OCC to 2017 USD using CPI.

Fig. 2 shows OCC of the 101 NPPs as a function of the year of construction end. The data reveals an observable cost escalation for the reactors completed, especially after the Three Mile Island (TMI) accident of March 1979. Nuclear reactors completed before 1979 have an OCC mean of $1606.1/kW (2017 USD), 2.5 times lower than the ones of reactors completed after 1979, which is $5945.6/kW (Table 1). The OCC relative standard deviation is 36.0% for reactors built before 1979, and 51.1% for reactors whose construction ended after 1979. The Energy Information Administration (1986) estimated that approximately 75% of the $2400/kW (in 1982 USD) increase in real costs can be attributed to increases in the quantities of land, labor, material, and equipment. The authors found that, for both equipment and commodities, industry regulations were found to be major drivers of the cost increase. The stricter regulatory oversight increased cost overruns by increasing the labor costs through the extra requirements for supervision and compliance, and because of alterations requested changes after a design was completed or construction of a reactor has started (Ganda et al., 2015). The remaining 25% of the increase is due to increases in the real financing charges, escalation in the rate of increase in the real prices of land, labor, material, and equipment during the construction period, and increases in construction times.

The 61 reactors completed in the pre-1979 phase have a mean construction duration of 7.8 years and a relative standard deviation of 51.9%, while the 40 reactors completed after 1979 have a mean project duration of 10.6 years (1.4 times higher) and a relative standard deviation 23.3%.

The data presented in Fig. 2 is for NPPs of different designs, plant owner and architect-engineers. Furthermore, every plant historically went through its own regulatory safety review, which makes it hard to find common causes of the cost increase. Therefore, OCC trend over time was analyzed for all different groups of NPP designs. The OCC of Westinghouse 4-loop and 3-loop PWRs were extracted from the database and are shown in Fig. 3. The historical trends show a cost escalation over time for both designs. Theoretically, a positive learning rate is expected, under which an nth-of-a-kind (NOAK) plant has a lower cost with respect to a first-of-a-kind (FOAK) plant because of the lessons learned in the construction and deployment of earlier units. However, in the US the construction cost data shows a negative learning rate, both in the pre-1979 era and the post-1979 era.

Table 1
OCC and construction duration of US power plants (historical data).

		Pre-1979	Post-1979
OCC ($/kW)	μ	1606.1	3945.6
	σ/μ	36.0%	51.1%
Duration (years)	μ	7.8	10.6
	σ/μ	51.9%	23.3%

Fig. 4 shows the OCC and project duration of PWR12 completed in the US between 1973 and 1996, as a function of the final year of construction. For the plants completed before 1979, the OCC mean is $1934.1/kW, with a relative standard deviation of 30.2%, while the plants completed after 1979 have an OCC mean of $4478.2/kW and an OCC relative standard deviation of 42.3%. Regarding the construction duration, the pre-1979 plants have a mean of 7.6 years and a relative standard deviation of 19.5%, while the post-1979 plants have a mean of 13.2 years and a relative standard deviation of 23.2%. The means and relative standard deviations of OCC and project durations of pre-1979 and post 1979 PWR12 are summarized in Table 2.

The Energy Information Administration (1986) presented the cost and construction times estimates reported by utilities at the beginning of the projects and at different stages of completion (0%, 25%, 50%, 75%, 90%, 100% of completion). The average estimated and realized overnight cost and construction times of NPP are shown in Table 3 and Table 4, respectively. Over the construction process, on average the reactors analyzed in the timeframe were subjected to an OCC increase of 215.6% and a construction time increase of 93.7%. The paper suggests that utilities did not perceive that plants with longer construction times were more difficult to manage and build and were more highly affected by regulatory changes. The data reveals that, although the utilities did increase their construction times and cost estimates as work on the plants proceeded, they still tended to significantly underestimate the OCCs and construction times, even at times approaching the project completion.

2.3. Historical capital cost trend in other countries

While this paper focuses on the US, we will briefly review capital cost trends in other countries since the historical trends in the US are

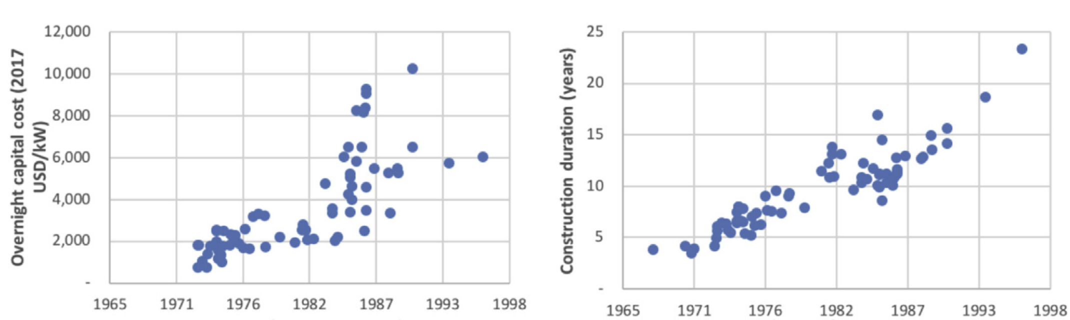

Fig. 2. OCC of 101 and construction duration of 116 US power plants by construction end date (based on data in Energy Information Administration (1986) and Koomey and Hultman (2007)).

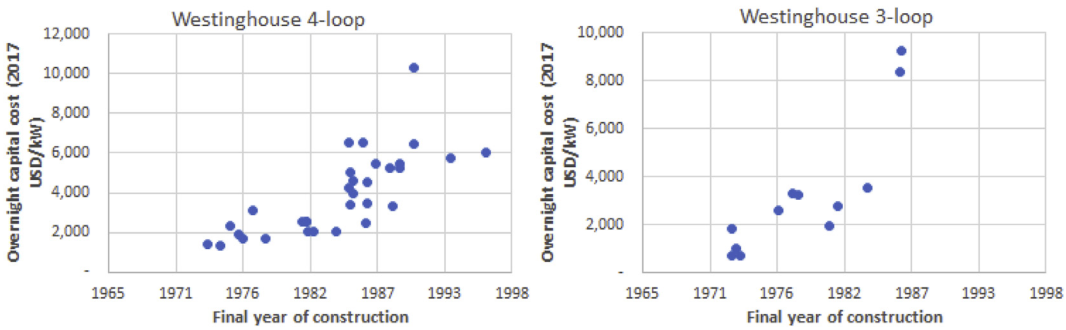

Fig. 3. OCC and of Westinghouse 4-loop (PWR12) and 3-loop PWRs by construction end date.

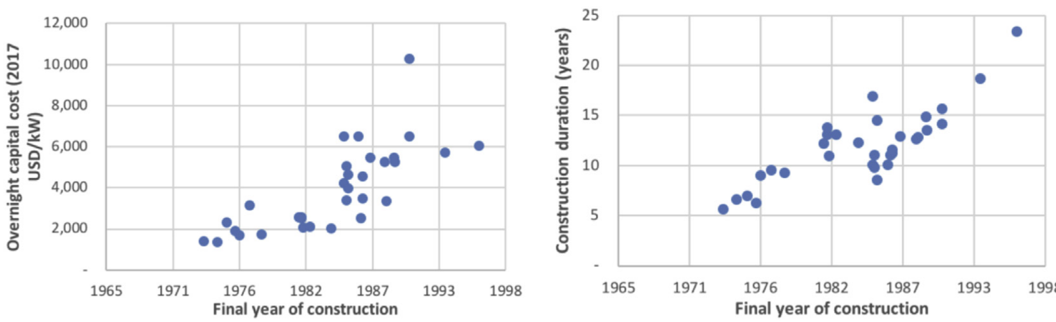

Fig. 4. OCC and construction duration of US PWR12 by construction end date.

Table 2
OCC and construction duration of US PWR12 (historical data).

Historical		Pre-1979	Post-1979
OCC ($/kW)	μ	1934.1	4478.2
	σ/μ	30.2%	42.3%
Duration (years)	μ	7.6	13.2
	σ/μ	19.5%	23.2%

not representative of the worldwide trends. Cost in France, Japan, UK, Canada, W. Germany and the Republic of Korea, collectively representing a significant fraction of the world's NPPs, exhibited much flatter trends with slight to moderate cost increase or decrease over time. France has the second largest fleet worldwide (58 reactors). The construction cost of the French nuclear power plants was released in 2012 (Cour des Comptes, 2012). The cost of NPPs over time shows a slight escalation, reason for which the French nuclear program is often taken as a good example by the nuclear industry (Ganda et al., 2015; Lovering et al., 2016). A sign of the success of the French nuclear program can also be seen in the construction time. The mean construction time is 76 months, much less than the US case. Ganda et al. (2015) and Lovering et al. (2016) found the key to the French success in the limited number of institutional actors: the government, the nationalized utility EDF, and the state nuclear R&D organization CEA. The

Table 4
Average estimated and realized construction times (months) of nuclear power plants by year (Energy Information Administration, 1986).

Year of construction start	Number of plants	Estimated times at different stages of completion (months)						Increase
		0%	25%	50%	75%	90%	Realized	
1966–1967	11	52	56	65	76	82	91	75.0%
1968–1969	26	55	63	72	83	91	107	94.5%
1970–1971	12	59	77	92	97	110	132	123.7%
1972–1973	7	65	87	96	107	115	131	101.5%
1974–1975	14	68	93	105	117	123	132	94.1%
1976–1977	5	74	92	95	97	100	112	51.4%
Average								93.7%

small number of institutions involved, allowed them to act in a well-coordinated way (Ganda et al., 2015; Grubler, 2010).

Lovering et al. (2016) carried out an extensive analysis of nuclear reactor capital cost trends in several countries. The nuclear reactors capital cost trend in Japan is made of three phases. In the first construction phase, from 1960 to 1969, reactors were imported from American and British companies. In this phase, the reactor size increased between 300 and 700 MW, causing a cost decline of 82% (16% annualized). In the second phase, from 1970 to 1980, the Japanese

Table 3
Average estimated and realized OCCs of nuclear power plants by year (1982 USD/kW) (Energy Information Administration, 1986).

Year of construction start	Number of plants	Estimated costs at different stages of completion ($/kW)						Increase
		0%	25%	50%	75%	90%	Realized	
1966–1967	11	298	378	414	558	583	623	109.1%
1968–1969	26	361	484	552	778	877	1062	194.2%
1970–1971	12	404	554	683	982	1105	1407	248.3%
1972–1973	7	594	631	824	1496	1773	1891	218.4%
1974–1975	14	615	958	1132	1731	2160	2346	281.5%
1976–1977	5	794	914	1065	1748	1937	2132	168.5%
Average							215.6%	

industries took over the construction and manufacturing of reactors, and reactor size also grew to an average of 950 MW. The overnight construction cost increased by 100% (8% annually). In the third phase of nuclear power construction in Japan, from 1980 to 2007, costs remained constant, with an annual change between −1% and 1%.

In Canada, costs of reactors fell by approximately 8% per year in the period from 1960 to 1974. Larger reactors were built between 1971 and 1986, which were subjected to a slight cost escalation (4% per year) (Lovering et al., 2016).

The cost experience in West Germany follows a similar pattern as the other Western countries (Lovering et al., 2016). In a first phase, Germany experienced a cost decline of 6% per year. In the following phase, between 1973 and 1983, costs increased by 12% annually.

The cost data of the Republic of Korea is different than for the other countries presented in this work. South Korea entered the nuclear market much later than US, France, Canada, Germany, or Japan, and skipped the early, small-scale demonstration phase. Korea also started to domestically develop nuclear reactor design, the Korean Standard Nuclear Power Plant (KSNP), later re-designated as the OPR-1000. Twelve reactors of this standard design began construction between 1989 and 2008, and their costs declined in a stable manner, with a 13% cost decline (1% annualized). Overall, from the first reactor built in 1971, costs fell by 50% (2% annually), in contrast to every other country presented. The main cause of surprising cost decline in the Korean nuclear reactors history can be identified in the adoption of a single, standardized design, a standard construction of plants, standard operation and standard regulation, which allowed small changes during the construction phase (Lovering et al., 2016; Shellenberger, 2017; World Nuclear Association, 2017).

3. Objectives, scope and proposed approach

3.1. The code of accounts and the PWR12-BE

The code of accounts was originally developed in the U.S. Department of Energy (DOE) EEDB Program Code of Accounts (US DOE, 1988). The code of accounts allows to break down main costs to individual systems and items.

The PWR12-BE represents a traditional four-loop stick-built PWR plant, with an electric power of 1144 MWth (US DOE, 1987c). In the US, a total of 33 Westinghouse four-loop PWRs were built (US NRC, 2018). Costs for the plant were prepared in 1978 by EEDB according to the Code of Accounts. The latest version of the account cost items were released in 1987 (US DOE, 1987a, 1987b; 1987c), and are summarized in Holcomb et al. (2011) along with the amounts converted to January 2011 US dollars (USD). Industry experts at Westinghouse Electric Company performed a “sanity check” of the cost items shown by Holcomb et al. (2011) (Mack, 2016). The equipment cost of account 222 (Main heat transfer transport system) was increased by $100 M (in 2011 USD) to match the current market and supply chain data. Similarly, the equipment cost of account 227 (Reactor instrumentation and control) was increased by $75 M (in 2011 USD) and construction supervision on site (from Holcomb et al. (2011)) was increased by $250 M (in 2011 USD). The accounts cost and their percent contributions to the total cost are shown in Table 5.

Account 22 costs, adjusted by WEC experts, are shown in Table 6. The NSSS costs were allocated to other subaccounts according to the percentages shown in Holcomb et al. (2011). The main component contributing to direct cost is the main heat transfer system (Account 222). The system includes main coolant pumps, pressurizer and steam generation system (primary heat exchangers, intermediate piping). Account 221 includes the Reactor Pressure Vessel (RPV). Safety systems are allocated to Account 223.

The PWR12-BE direct cost, with accounts modified by WEC experts, is $2.59 B, and the indirect cost is $1.47 B (Table 7), which corresponds to 67.0% of the direct cost. Therefore, for the PWR12-BE the *in* fraction is equal to 0.67, and Eq. (2) becomes:

$$BC = DC\cdot(1 + 0.67) \tag{8}$$

The owner's cost breakdown is shown in Table 8. The total direct cost contributes to OCC for a total of $338.92 M, which corresponds to 7.8% of the base cost. Under the assumption that the owner's cost is directly proportional to the base cost, it can be calculated as:

$$OC = BC\cdot 0.078 \tag{9}$$

The resulting OCC is $4.68 B and can be calculated through Eq. (10).

$$OCC = DC\cdot(1 + 0.67)\cdot(1 + 0.078) \tag{10}$$

The PWR12-BE construction schedule was derived by US DOE (1987c) and is presented in Fig. 5; the project duration is 7.56 years. IDC is calculated through Eq. (4) using a cost of capital of 10%, and a cash flow profile derived from the construction schedule. The resulting TCIC is $6.74 B.

3.2. Modeling uncertainties: the Monte Carlo method

As the construction of an NPP is dependent on several variables, uncertainties were combined through the use of a Monte Carlo method. Commodity and equipment costs, and activity durations were modeled through triangular distributions and sampled through the Monte Carlo method in order to estimate distributions of project durations, OCC and

Table 5
Accounts with differing cost basis and their percent contributions to the direct costs (Holcomb et al., 2011).

Account		Cost	% Cost
211	Yardwork	59,982,046	2.56%
212	Reactor Containment Building	155,606,497	6.63%
213	Turbine Room and Heater Bay	55,565,592	2.37%
214	Security Building	3,268,692	0.14%
215	Primary Auxiliary Building and Tunnels	44,333,149	1.89%
216	Waste Processing Building	34,481,564	1.47%
217	Fuel Storage Building	23,709,846	1.01%
218	Other Structures	104,838,447	4.47%
221	Reactor Equipment	197,406,910	8.41%
222	Main Heat transfer transport system	252,881,006	10.78%
223	Safety systems	94,361,424	4.02%
224	Radwaste Processing	50,261,777	2.14%
225	Fuel Handling and storage	29,121,984	1.24%
226	Other Reactor Plant Equipment	112,143,627	4.78%
227	Reactor Instrumentation and Control	148,253,449	6.32%
228	Reactor Plant Miscellaneous items	17,885,460	0.76%
231	Turbine Generator	321,562,255	13.71%
233	Condensing Systems	69,556,766	2.96%
234	Feedwater Heating system	56,613,122	2.41%
235	Other turbine plant equipment	53,575,665	2.28%
236	Instrumentation and control	16,450,109	0.70%
237	Turbine plant miscellaneous items	19,310,160	0.82%
241	Switchgear	28,671,080	1.22%
242	Station service equipment	48,392,131	2.06%
243	Switchboards	4,917,355	0.21%
244	Protective equipment	10,227,327	0.44%
245	Electric structure and wiring	53,524,039	2.28%
246	Power and Control wiring	49,442,606	2.11%
251	Transportation and Lifting equipment	14,385,192	0.61%
252	Air, water and steam service systems	107,155,789	4.57%
253	Communication equipment	15,396,111	0.66%
254	Furnishing and Fixtures	6,566,362	0.28%
255	Waste water treatment equipment	6,795,322	0.29%
261	Structures	10,398,528	0.44%
262	Mechanical Equipment	68,941,569	2.94%
	TOTAL	2,345,982,958	100.0%

Table 6
PWR12-BE account 22 subaccounts (1987 USD, from US DOE (1987a), adjusted by WEC experts, with NSSS allocation from Holcomb et al. (2011)).

		Factory equipment	Site Labor	Site Material	Total
220A	Nuclear Steam Supply (NSSS)	-	-	-	-
221	Reactor Equipment	72,574,428	3,763,592	5,914,859	82,252,878
222	Main Heat transfer transport system	98,369,396	6,367,615	630,075	105,367,086
223	Safeguards systems	33,159,421	5,480,770	677,069	39,317,260
224	Radwaste Processing	16,160,526	4,012,887	768,994	20,942,407
225	Fuel Handling and storage	11,170,495	857,891	105,774	12,134,160
226	Other Reactor Plant Equipment	27,720,415	16,534,002	2,472,094	46,726,511
227	Reactor Instrumentation and Control	53,391,092	7,707,179	673,999	61,772,270
228	Reactor Plant Miscellaneous items	-	4,273,080	3,179,195	7,452,275
	TOTAL	312,545,773	48,997,016	14,422,059	375,964,847

TCIC and calculate cost contingency.

The Monte Carlo method is used to evaluate the dispersion in the output of a system given a probability distributed input through statistical sampling. The entire system is simulated a large number of times where, in each simulation, each random variable assumes a value according to its probability distribution. The value of each random variable is sampled through a random number generator. The output of a single Monte Carlo simulation consists of a single value that depends on the values taken by all the random variables in the simulation. Outputs from different simulations are separate and independent, each representing a possible “state” of the system. Results from independent system realizations are then assembled to study the dispersion of the results. Assuming a random variable x that takes values according to a specific probability distribution, in every simulation the value of the cumulative distribution function is sampled trough a random number generator, that generates random numbers ξ uniformly distributed between 0 and 1. Sampling the variable x through this procedure for a number of times we obtain an estimate of its distribution. Repeating this procedure for a large number of runs, we calculate the average value and variance of the output in the Monte Carlo simulation through Eqs. (11) and (12):

$$\mu = \frac{1}{N}\sum_{n=1}^{N} TCIC_n \tag{11}$$

$$S^2 = \frac{1}{N-1}\sum_{n=1}^{N} (TCIC_n - \mu_{TCIC}) \approx \sigma^2_{TCIC} \tag{12}$$

In the analysis shown in this paper, variances are labeled as σ, since the difference between s and σ is negligible. The Monte Carlo method was used to estimate the uncertainties in project duration, OCC, TCIC and estimate contingency for PWR12-BE.

3.3. Probability distributions

The triangular distribution is a continuous probability distribution function described by three parameters (see Fig. 6): the most probable value (c), a lower limit (a) and an upper limit (b). In project management, durations and costs of activities are often described by a triangular distribution, as it allows to describe the stochastic nature of costs and durations through these three parameters. In fact, sufficient actual data to describe the probabilistic nature of costs and durations is typically not available. The triangular distributions facilitate the use of expert judgement to perform stochastic analysis, as it allows the experts to provide only the most probable, the minimum and maximum values instead of providing mean values and standard deviation (as it happens if a normal distribution is used). Moreover, distributions of activities and costs are often asymmetric, which reduces the number of probability distributions that can be used. Equating the cumulative distribution function to random generated number ξ, where $0 < \xi < 1$, yields the inverse cumulative distribution function (Eq. (13)).

$$\hat{x} = F(\xi)^{-1} = \begin{cases} a + \sqrt{(b-a)(c-a)\xi} & 0 < \xi \le \frac{c-a}{b-a} \\ b - \sqrt{(b-a)(b-c)(1-\xi)} & \frac{c-a}{b-a} < \xi < b \end{cases} \tag{13}$$

Example of random variables in the construction process are activity durations and costs of components. The lower and upper limits were expressed as a percentage of the most probable value c, through the parameter s. The most probable values of the distributions were chosen as the deterministic value of the random variable. For example, if the random variable expresses the cost of probability of a component, the most probable of the distribution (parameter c) was chosen as the deterministic value of the component cost.

The broadness and skewness of a triangular distributed activity may depend on various factors, as:

- Activity type;
- Activity location (factory, assembly area, hole);
- Site location (in which country the NPP is built);
- Learning, as the nth plant of its kind is characterized by sharper distributions with activity durations and costs closer to the most probable value (deterministic value).

When a project is simulated using a Monte Carlo simulation, every activity cost and duration are calculated through the generation of random numbers ξ. The triangular cumulative distribution functions for cost and durations are then inverted (Eq. (13)) calculating activity durations and costs. DC is calculated summing the costs of all activities. For PWR12-BE OCC is calculated through Eq. (11). IDC is calculated

Table 7
PWR12-BE Indirect cost accounts (2016 USD, from Holcomb et al. (2011)).

		Home office	Site labor	Site material	Total
31	Home Office Design services	533,953,685	–	–	533,953,685
32	PM/CM at home office	31,555,397	–	–	31,555,397
33	Design services at site	–	–	–	–
34	PM/CM at site	–	16,199,022	5,893,212	22,092,234
35	Construction Supervision	–	470,727,702	18,033,175	488,760,877
36	Field Indirect	165,318,277	241,268,139	228,811,851	635,398,267
37	Plant Commissioning	29,949,849	–	–	29,949,849
	Total Indirect Costs	**760,777,209**	**728,194,863**	**252,738,237**	**1,741,710,309**

Table 8
PWR12-BE preconstruction and operations cost accounts (2016 USD, from Holcomb et al. (2011)).

		Home office	Site labor	Site material	Total
11-19	Capitalized preconstruction cost	–	6,645,480	–	6,645,480
41-49	Capitalized operations cost	–	332,274,000	–	332,274,000
	Total owner's cost		338,919,480		338,919,480

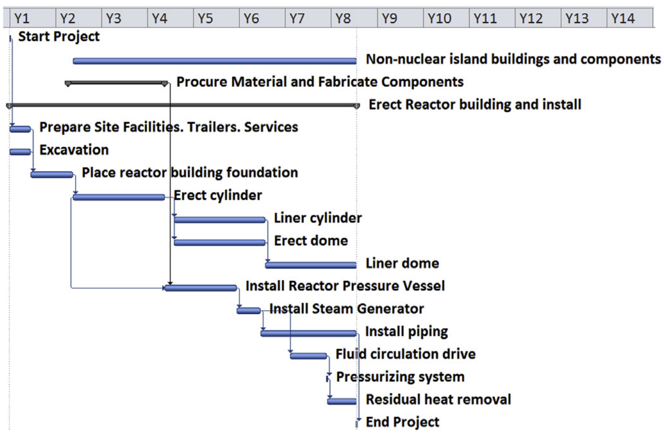

Fig. 5. PWR12-BE construction schedule (derived from US DOE (1987c)).

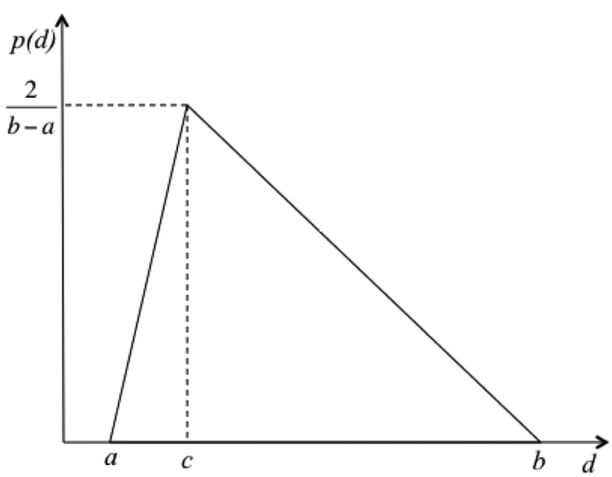

Fig. 6. Asymmetric triangular probability density function.

through Eq. (4), and TCIC is calculated summing OCC and IDC (Eq. (5)).

3.4. Correlated sampling through the Iman-Conover method

In the construction of an NPP, costs of components and durations of activities are not independent, but inter-correlated. For example, costs of different components are dependent on the price of the same commodities, or delays in construction durations are correlated for activities of the same type (e.g. welding, concrete pouring). Therefore, the correlation between variables was modeled. The method adopted here to account for partial correlations between input variables was originally developed in 1982 by Iman and Conover (1982), and then implemented in financial software such as "@Risk". The method was also used by Ganda et al. (2015) to sample correlated capital costs of different NPP designs. Similarly, subsets of variables in the construction of an NPP are expected to show a significant degree of correlation.

In their paper, Iman and Conover (1982) proposed a "distribution independent" method which preserves the original marginal distributions. The method, which is based on rank correlations, is summarized here. Assume a vector X of uncorrelated random variables. As the elements of X are uncorrelated, the correlation matrix of X will be the identity matrix I. C is the desired correlation matrix of a transformation of X. If the correlation matrix is calculated from a set of data, each item of the correlation matrix ($\rho_{i,j}$) is calculated. The components of the correlation matrix are defined as:

$$\rho_{i,j} = \frac{cov(x_i, x_j)}{\sigma_i \sigma_j} \tag{14}$$

Where $cov(x_i, x_j)$ represents the covariance between the elements x_i and x_j of X. As a correlation matrix, C is positive definite and symmetric and can be written as: $C = PP'$, where P is a lower triangular matrix. On this basis, the linear transformation XP' of X has the desired correlation matrix C. However, the simple multiplication of X by P' to obtain a matrix with the proper correlation coefficients also would alter the values of the sampled distributions. For this reason, a "score" matrix is introduced. The objective is for the rank correlation matrix M of the input vector to be as close as possible to the correlation matrix C, given as input, after the transformation by P. In this method, certain important properties of the input vector, such as marginal distributions, are preserved. Keeping the same notation as Iman and Conover (1982), let K be the number of variables (for example, the different correlated NPP equipment costs) and N be the sample size (number of simulations). Let R_I be the NxK matrix generated by the independent permutations of N integer numbers, generated by sampling from a uniform distribution. Then, it needs to be checked that the correlation matrix of R_I is "close to" I, to ensure that to the sampled vector is uncorrelated. Afterwards the rank matrix R is generated through the Van der Waerden scores as:

$$R = \sqrt{2}\,\mathrm{erf}^{-1}\left(2\cdot\frac{R_i}{N+1} - 1\right) \tag{15}$$

Subsequently, a rank matrix $R*$ having the correlation coefficients very close to the target value of C is generated by performing the transformation:

$$R^* = RP' \tag{16}$$

Afterwards, uncorrelated costs vectors can be sampled independently from the corresponding marginal distributions, generating the matrix k. Finally, the values in each column of the sampled matrix k are rearranged so that they will have the same ordering as the corresponding column of R^*, generating the final matrix K, in which the sampled values of k have the same ordering of R^*.

This method was used to sample variables in the construction of PWR12-BE, in order to estimate the uncertainties in project duration, OCC, TCIC and evaluate the cost contingency. Activities were modeled with triangular distributions, and activity durations were sampled assuming certain values of the correlation matrix components. Activities were grouped depending on the location where they are performed (factory, on-site assembly area, on-site construction hole). Activities in the same group were modeled with the same correlation coefficient, while activities in different groups with a different correlation coefficient.

3.5. Modeling the price of commodities and equipment

An example of known-unknown variable in the construction of an NPP is the price of commodities and equipment, which is not constant with time, and depends on the state of the market. The US Department of labor keeps a record of historical commodities and price of components. Labor cost is recorded through the Employment Cost Index (ECI). The index representing the total compensation for private industry workers in all industries and occupations was used (US Department of Labor, 2017b). In the PWR12-BE cost data, different cost types were identified. Price of commodities (concrete and steel) was taken from the Producer Price Index (PPI) commodity data (US Department of Labor, 2017c). Price of industrial components was taken from the PPI industry data (US Department of Labor, 2017c). The commodity and equipment costs were modeled with the following variables:

1. Labor (x_1)
2. Concrete (x_2)
3. Steel (x_3)
4. Fabricated structural metal bar joists and concrete reinforcing bars (x_4)
5. Sheet metal work manufacturing (x_5)
6. HVAC and commercial refrigeration equipment (x_6)
7. Metal tanks and vessels, custom fabricated and field erected (x_7)
8. Metal tank, heavy gauge, manufacturing (x_8)
9. Steel product manufacturing from purchased steel (x_9)
10. Pump and compressor manufacturing (x_{10})
11. Power boiler and heat exchanger manufacturing (x_{11})
12. Iron and steel pipes and tubes, purchased iron and steel (x_{12})
13. Metal valve manufacturing (x_{13})
14. Turbine and power transmission equipment manufacturing (x_{14})
15. Fabricated heat exchangers and steam condensers (except for nuclear applications) (x_{15})
16. Electrical equipment manufacturing (x_{16})
17. Mechanical power transmission equipment manufacturing (x_{17})
18. Elevators and moving stairways (x_{18})

The percentage of each cost type is shown in Table 9.

The 18 variables consist of one labor variable (x_1), two commodities variables (x_2 and x_3), and 15 equipment variables (x_4 through x_{18}). Historical prices in the period 2007–2017 were used. Each variable was modeled with triangular distributions using minimum, maximum and mode historical monthly recorded values (escalated to 2017 USD) in the period 2007–2017. Values of the indices were normalized by their mode, calculated for a histogram with five bins. The PPI distributions were then fitted to triangular distributions, taking the minimum value of the normalized index as *a* and maximum value of the normalized index as *b*. The value of the index for labor and steel are shown in Fig. 7 and Fig. 8, along with their respective histograms and fitted triangular distributions. However, no historical data of nuclear equipment was available.

The correlation between variables was calculated using Eq. (14). The correlation matrix is represented in Fig. 9. The correlation between variables describes how the market values of the commodities and components are correlated. Sampling each variable accounting for the correlation is equivalent to sample the "state" of the market, which drives the prices of commodities and components. The state of the market is then sampled through a Monte Carlo simulation, accounting for the correlation between variables *(x_1, …, x_{18})*.

4. Results

In each simulation, the duration and cost of every activity were described by a triangular distribution, with deterministic duration and cost as most probable values, and the resulting TCIC is calculated, using a cost of capital of 10%. For each simulation the resulting, project duration, OCC, and TCIC histograms are shown, along with the mean values, modes, and relative standard deviations. All activities were described through triangular distributions, and the same triangular distribution parameters were used for activities in each construction location (factory, on-site assembly area, on-site hole). Minimum, maximum, and most probable durations of each type of activity are shown in Table 10 (Van-Wyk, 2016).

First, the analysis was performed for uncorrelated variables. Second, the correlation between component and commodity prices was considered, sampling the prices of commodities and equipment (representing the "state" of the market) according to the correlations and distributions derived from the historical data. Third, correlations between activity durations are used.

All Monte Carlo simulations performed in this work are made of 10^5 runs. Million dollars are denoted as M-$, while billion dollars were denoted as B-$.

4.1. Uncorrelated variables

Under the assumption of uncorrelated costs and activities, the project duration, OCC, and TCIC distributions are obtained. The main parameters of the distributions are summarized in Table 11. The project duration distribution has a mean value of 10.92 years with a relative standard deviation of 7.6%. The highest project duration is 14.32 years, 1.31 times higher than the deterministic project duration. The OCC mean value is $5.50 B with a relative standard deviation of 1.89%. It is important to note that, because of the activity durations asymmetry (skewed to the right), the average sampled OCC value is higher than the deterministic value of $4.58 B (1.2 times higher).

Once the interest during construction is added to OCC, the TCIC distribution is obtained. The average TCIC value is $6.69 B, with a relative standard deviation of 2.76%. The cost contingency is $176.05 M, which corresponds to 2.63% of the TCIC mean value. The maximum TCIC value obtained in the simulation is $7.54 B, 1.12 times higher than the deterministic value of $6.74 B.

Despite the use of different probability distributions for different activities and the use of asymmetric probability distributions, the TCIC and OCC relative standard deviations are still underestimated, the OCC one being almost 30 times lower than the one measured from the observed trend of PWR12 construction before 1979. The reason for this lies in the fact that all variables that were sampled in these simulations were assumed to be uncorrelated. As they are uncorrelated, their variations largely cancel out and the combined relative uncertainty is reduced. Moreover, the higher the number of random variables used, the lower the combined relative standard deviation. The assumption of uncorrelated uncertainties clearly leads to unrealistic results. For this reason, a method to include correlations between variables and sample correlated random variables was developed. As correlations are introduced, correlated variables tend to take similar values in the same simulation and, subsequently, results for individual samples are more

Table 9
PWR12-BE cost percentage of each commodity and equipment cost.

Labor	28.35%
Concrete	0.95%
Steel	21.37%
Fabricated structural metal bar joists and concrete reinforcing bars	0.46%
Sheet metal work manufacturing	1.23%
HVAC and commercial refrigeration equipment	0.57%
Metal tanks and vessels, custom fabricated and field erected	0.83%
Metal tank, heavy gauge, manufacturing	5.53%
Steel product manufacturing from purchased steel	4.41%
Pump and compressor manufacturing	3.23%
Power boiler and heat exchanger manufacturing	3.81%
Iron and steel pipes and tubes, purchased iron and steel	3.08%
Metal valve manufacturing	0.00%
Turbine and power transmission equipment manufacturing	14.12%
Fabricated heat exchangers and steam condensers (except for nuclear applications)	3.63%
Electrical equipment manufacturing	3.35%
Mechanical power transmission equipment manufacturing	5.03%
Elevators and moving stairways	0.05%

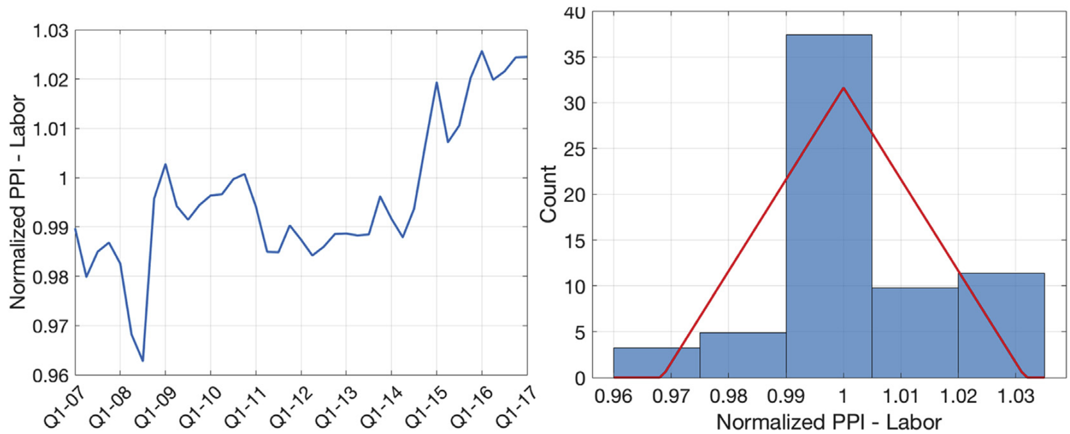

Fig. 7. Normalized PPI labor over time and frequency.

dispersed.

4.2. Correlated market prices

Market price correlations and probability distributions were calculated from historical price data as explained in Section 3.5. Each equipment and commodity cost was obtained multiplying the sampled normalized commodity or commodity cost (with most probable value of 1) by the respective deterministic cost given as input. Simulations were run for values of the correlation coefficients equal to zero, calculated based on historical data, and equal to one. Fig. 10 and Fig. 11 show examples of correlated sampling between different commodity costs. Labor and steel costs are negatively correlated, with a correlation coefficient of -0.6997, and to high values of one variable correspond low values of the other, and vice versa. The cost of steel and "iron and steel pipes and tubes" are very correlated, as their correlation coefficient is 0.9024. Labor and electrical equipment cost are an example of almost non-correlated variables (correlation coefficient equal to -0.0831).

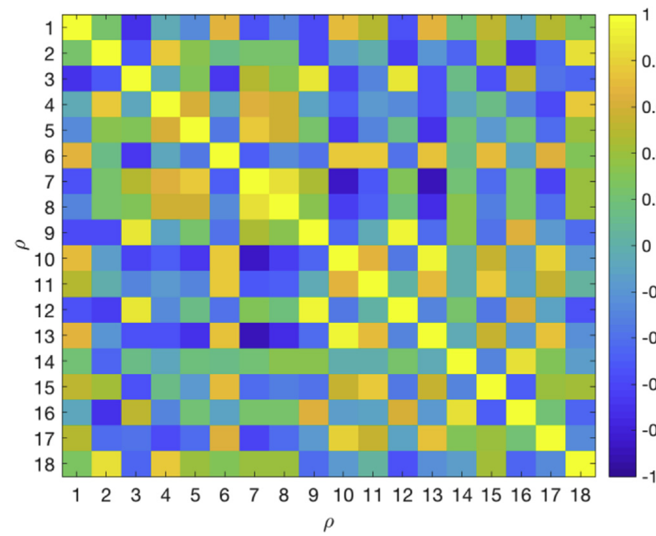

Fig. 9. Representation of the historical market prices correlation matrix.

4.3. Correlated activities

The uncertainties in the market and in equipment prices were combined with the uncertainties in the construction schedule. The causes of uncertainties in the component costs mainly lie in the uncertainty in the commodity prices and the uncertainty in the amount of labor needed to fabricate, assembly, or install the component. The analysis of the market variability informs about the uncertainty on the commodity prices, while the analysis of the stochastic nature construction activities gives information on the time and the amount of labor needed to have the component fabricated, assembled, or installed. The construction schedule provides information on the cash flow profile and project duration, which can be used in calculating the interest during construction and, subsequently TCIC.

Activities of the same stage were modeled with the same probability distributions, and activities taking place at the same stage were correlated with a higher correlation coefficient than activities taking place

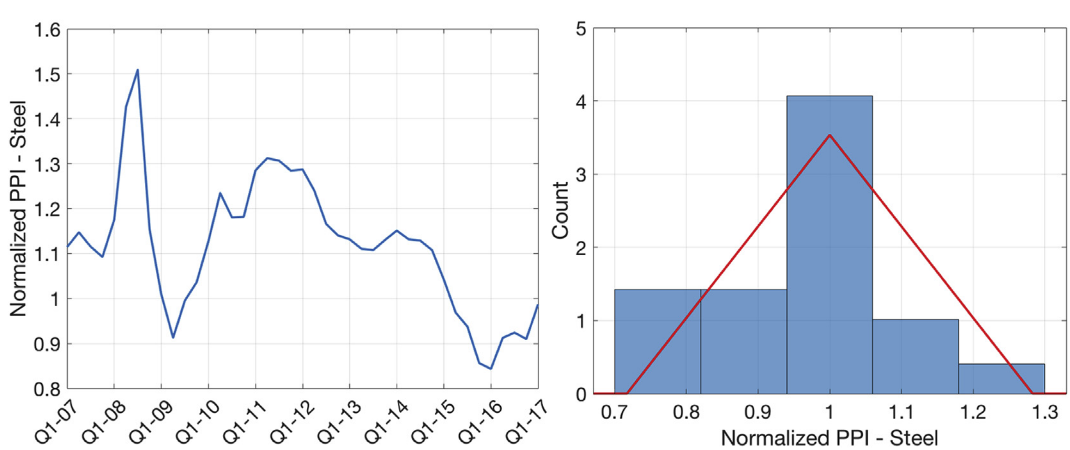

Fig. 8. Normalized PPI steel over time and frequency.

Table 10
Activity durations minimum and maximum values (triangular distribution) (Van-Wyk, 2016).

	Minimum	Maximum
Components fabrication	−10%	+30%
Concrete pouring	−5%	+200%
On-site construction	−10%	+80%

Table 11
Estimated OCC, TCIC, and construction duration for PWR12-BE, with uncertainties (MC simulations, uncorrelated variables).

	Duration (years)	OCC ($)	TCIC ($)
μ	10.92	5.50 B	6.69 B
σ/μ	7.64%	1.89%	2.76%
Mode	10.7	5.48 B	6.64 B
75%			6.82 B
Contingency			176.05 M
Contingency/μ_{TCIC}			2.63%

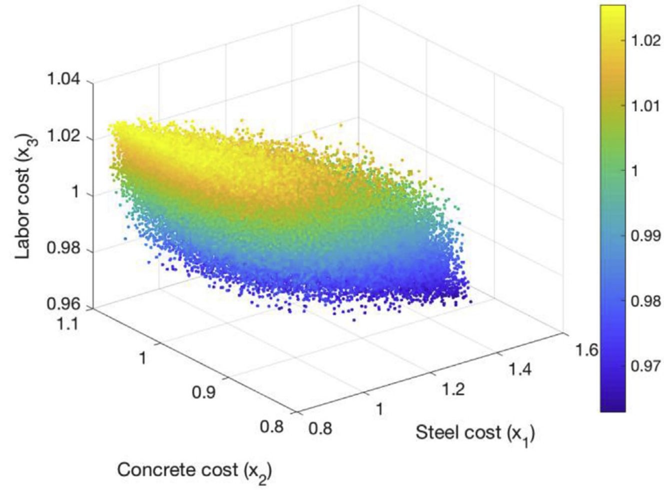

Fig. 11. Example of sampling three correlated commodity prices.

during different stages. These assumptions reflect the scenario where each construction stage shares a certain number of resources (equipment, material, special workers, and management). As delays during a certain stage take place due to the "failure" of a resource, it is most likely that all activities using the resource will be affected. Activity durations of the same stage were correlated with a correlation factor ρ_1 equal to 0.75. Activities of different stages were correlated with a correlation factor ρ_2 equal to 0. The values of these coefficients were chosen to represent a case where the activities taking place under the same environmental conditions are "somewhat" positively correlated, while activities taking place in different stages are not correlated. As an example, it can be intuitively seen that components fabricated in the same factory, or with the same manufacturing technologies, or that were designed by the same manufacturer, are exposed to the same causes of delays. If a design defect, or a manufacturing problem are found in the production line, it is most likely that most of the components fabricated under the same conditions will be affected.

The simulation consists of the following steps:

1. Sample the state of the market, based on commodity prices distributions and correlations (both calculated through historical data);
2. Sample activity durations, based on activity distributions and correlations between activities of same and different stages;
3. Calculate labor costs of each activity, multiplying the hourly labor cost for the activity duration;
4. Calculate project duration, OCC, TCIC.

The results for PWR12-BE are shown in Fig. 12 and Table 12. The project duration has a mean of 10.7 years, with a relative standard deviation of 16.2%. The mean project duration resulting from the model is 1.4 times higher than the historical pre-1979 average for PWR12, but 1.2 times lower than the post-1979 average; in either case, the relative standard deviation is underestimated, by about 15% and 30%, respectively. OCC has a mean of $5.6 B and a relative standard deviation of 7.5%. The OCC mean is equivalent to $4807.7/kW, 2.5 times higher than the observed $1934/kW pre-1979 average, but similar to the $4478.2/kW post-1979 average. The OCC relative standard deviation is significantly underestimated at 7.5% vs the observed 30.2% or 42.3%. The TCIC mean and relative standard deviations are $6.8 B and 9.0%. The project contingency is $630.9 M, 9.3% of the TCIC expected value.

The estimated relative standard deviation is significantly higher than in the uncorrelated uncertainties case and presents a change in the right direction, but it is still notably smaller than the observed one; this is due, as already discussed, to the unexpected event. This phenomenon will be addressed in a follow up paper.

5. Conclusions

This work describes the implementation of a methodological approach that was developed to evaluate uncertainties and risks in the construction of nuclear power plants.

The historical Overnight Capital Cost (OCC) trends in the US, France, Canada, West Germany, Japan, and South Korea were analyzed. The trends in costs have varied significantly by era, country, and experience. While the observed data shows an important cost escalation for countries such as the US and West Germany, a much milder cost escalation is present for France, Canada, and Japan. The Republic of Korea is the only good example of learning-by-doing, with a significant cost decline over time.

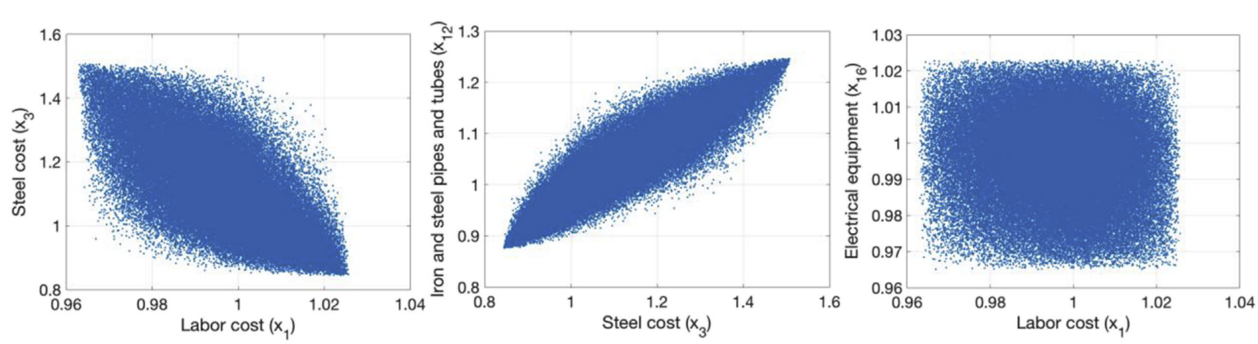

Fig. 10. Example of sampling correlated commodity prices.

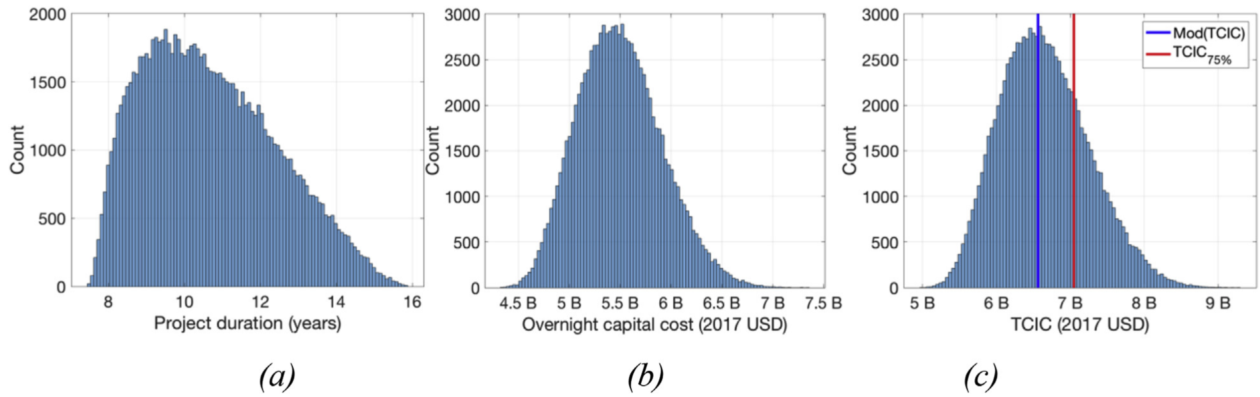

Fig. 12. PWR12-BE project duration (a), DC (b), and TCIC (c) distributions.

Table 12
Estimated OCC, TCIC, and construction duration for PWR12-BE, with uncertainties (MC simulations, correlated variables).

	Duration (years)	OCC ($)	TCIC ($)
μ	10.7	5.5 B	6.7 B
σ/μ	16.2%	7.5%	9.0%
Mode	9.5	5.4 B	6.5 B
75%			7.0 B
Contingency			582.1 M
Contingency/μ_{TCIC}			8.7%

In the US, two trends can be identified. Nuclear reactors that were completed before the TMI accident of March 1979 show a small standard deviation of OCC and project durations, with a relatively small cost escalation. The reactors that were under construction in 1979 and were completed after the accident, were subjected to an important cost and project duration escalations, with higher standard deviations. The causes of this phenomenon mainly lie in the change of regulations that took place after the 1979 event and affected the plants that were under construction. The high degree of regulatory oversight is a significant factor in construction delay and capital cost in the post-TMI period.

The cost of the best estimate traditional four-loop Westinghouse PWR plant (PWR12-BE) is presented. The cost for that plant were prepared in 1978 by the Department of Energy (DOE) Energy Economics Data Base (EEDB), according to the Code of Accounts. For each account, the costs of equipment, site labor and site material are provided. Industry experts at Westinghouse Electric Company adjusted the cost of several items to match the current market and supply chain data.

A methodology was developed to estimate cost uncertainty and cost overruns, and evaluate cost contingency for new reactor constructions. The methodology, based on the Iman-Conover method to account for correlation between variables, was applied to the construction of PWR12-BE, with the objective of estimating uncertainties in project costs and time. If costs and durations of all cost components (equipment, structures, materials, activities, etc.) are assumed uncorrelated, the project duration, OCC and TCIC standard deviations are very small. The low values of relative standard deviations despite the use of relatively large input standard deviations are obtained because, as variables are assumed uncorrelated, the combined uncertainty is reduced.

To account for cost and duration correlations a double-step approach was used, where correlations between main equipment and commodity costs were accounted based on historical data, as well as correlations between activities at each construction stage. Historical market price trend of nuclear commodity and equipment were extracted from US Department of Labor (2017b; 2017c) and analyzed to estimate correlation and probability distributions of costs in NPP construction. The methodology produced promising results, estimating a project duration mean of 10.7 years, with a relative standard deviation of 16.2%. However, a comparison between the results obtained for the PWR12-BE and the historical data on nuclear reactor constructions in the US shows that the model still underestimates cost uncertainty. The project duration mean is 1.4 times higher than the one observed for PWR12 completed before 1979, while its relative standard deviation is lower than that observed for PWR12 completed before 1979, which is 19.5%, or after 1979, which is 23.2%. Regarding OCC, the model without assumed correlations shows a relative standard deviation of 1.89%, substantially lower than that observed for plants completed before 1979 (23.2%), while producing an OCC mean value that is 2.5 times higher. Accounting for correlations between the variables increases the relative standard deviations to 7.5%, still to low but significantly closer to the observed one.

The historical review of NPP construction cost in the US is extremely valuable and can be used to support cost-estimates for future plants. Insights from this paper should be taken in order to help assure that in a future commitment to expanding nuclear energy in the U.S. the same mistakes are not made. In the follow-up companion paper, we will address how the model was modified to represent the pre-1979 data and the post-1979 data (Maronati and Petrovic, 2018) and account for unexpected events ("unknown unknowns").

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pnucene.2018.11.011.

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