EXPLAINING LARGE OBSERVED VARIATION IN CONSTRUCTION COST OF NUCLEAR POWER PLANTS THROUGH CORRELATED RANDOM VARIABLES

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EXPLAINING LARGE OBSERVED VARIATION IN CONSTRUCTION COST OF NUCLEAR POWER PLANTS THROUGH CORRELATED RANDOM VARIABLES

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To the memory of my uncle Walter

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LIST OF SYMBOLS AND 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
SMR	Small Modular Reactor
TCIC	Total Capital Investment Cost
TMI	Three Mile Island
USD	United States Dollar
WBS	Work Breakdown Structure
WEC	Westinghouse Electric Company

SUMMARY

The high overnight capital cost (OCC), as well as the large delays and cost escalation during construction, make nuclear reactors unattractive for investors. The history of nuclear power plants construction in the US shows the necessity to properly estimate construction costs and cost uncertainty and contingency. Uncertainties during construction can be classified as “known unknowns” and “unknown unknowns”. Project managers use tools to describe “known unknowns”, while “unknown unknowns”, due to their inherent nature, are not knowable. In this work, the cost trends in the various countries with nuclear power plants are analyzed. For the US data, the costs and the construction schedule of a four-loop PWR (PWR12) are also described in detail. A deterministic methodology, called EVAL, was developed to describe the construction of a nuclear power and then applied to the Westinghouse SMR. EVAL is based on a methodological approach that can evaluate construction cost for an entire Nuclear Power Plant (NPP). EVAL was applied to assess and compare different construction strategies for the Westinghouse Small Modular Reactor (WEC-SMR) nuclear island and was used to demonstrate and quantify the benefits of modularization. For this NPP design, modularization allows a 42% decrease in TCIC as compared to standard construction techniques (stick-built construction). EVAL was used to evaluate the effect of several decision variables on TCIC through sensitivity analyses. Specifically, the effect on construction costs of the discount rate, the size of the on-site assembly area, the use of different welding technologies, and testing was evaluated for the nuclear island of the WEC-SMR.

A methodology to perform stochastic analyses through Iman-Conover method to account for correlation between costs and activities is also presented. A probabilistic assessment is then performed for the construction of a fully-modularized SMR and a stick-built PWR12. The results show an improved prediction capability of TCIC uncertainty as correlations between variables are taken into account. The inputs of the model are then modified to be consistent with the cost history in the US for PWR12. The trend in the US before 1979 is used to adjust the model inputs to describe a stable nuclear era. The trend after 1979 is used to quantify, *a posteriori,* the impact of "unknown unknowns", representing regulatory changes during construction, resulting in cost and cost uncertainty increase.

With the inputs derived from the pre-1979 data, the TCIC mean value for the PWR12-BE is \$2.5 B, with a contingency of \$995.5 M, which corresponds to 39.8% of the TCIC mean. Similar results were obtained for the SMR, where cost contingency is 42.0% of the TCIC expected value. Regarding the project duration, the SMR relative standard deviation is 9.5%, 10% lower than that of the PWR12-BE. If the unknown unknowns are taken into account, the PWR12-BE cost contingency is 128% of the TCIC mean derived for the pre-1979 case. For the SMR, the cost contingency relative to the TCIC mean is 5.1%, higher than that of the PWR12-BE. However, the construction time relative standard deviation for the SMR is 11.5%, about half than that of the PWR12-BE (23.2%).

The analysis shows that the adoption of modular construction does not decrease OCC uncertainty with respect to stick-built construction, while it has a positive impact on the construction time uncertainty.

1 INTRODUCTION

Different studies identified nuclear power as a key technology in reducing carbon emissions (Intergovernmental Panel on Climate Change, 2014; International Energy Agency, 2014). Electricity generation from nuclear power is cost competitive with other sources of electricity generation, except where there is direct access to low-cost fossil fuels. Levelized Cost Of Electricity (LCOE) for Nuclear Power is heavily driven by capital costs. Locatelli et al. (2015) estimate Total Capital Investment Cost (TCIC) to contribute for 50-70% to LCOE, followed by operation and maintenance (O&M) and fuel cost. For Advanced Nuclear Power Plants (NPPs) entering service in 2022, studies estimate that capital cost will make up 75% of LCOE (International Energy Agency, 2010).

The nuclear industry is facing many challenges as capital costs of Nuclear Power Plants (NPPs) have increased considerably over time. Many studies investigated the NPP cost escalation, raising doubts about the future feasibility of Nuclear Power. The Energy Information Administration (1986) identified an Overnight Capital Cost (OCC) escalation from about $800 /kW in the early 1970s to about $2,500 /kW in the mid 1980s. Cooper (2010) determined an increase of OCC from $1,000 /kW for NPPs built in the early 1970s to $5,000 /kW - $6,000 /kW (all in 2008 USD) for NPPs built in the early 1990s. Different academic studies applied models to this set to predict a 2008-2009 cost escalation as high as $10,000 /kW (Cooper, 2010). The increase of NPP capital cost over time is mainly due to two reasons:

- Increasing safety concerns due to the Three Mile Island (TMI), Chernobyl, Three Mile Island (TMI), Fukushima-Daiichi accidents caused designs to become more complex, and the standardization of components becoming difficult to achieve (Cooper, 2010);

- Larger reactors were built to achieve economies of scale; however, as the size of a project increases, construction tends to be delayed offsetting and frequently overrunning the expected savings of larger sizes (Cooper, 2010).

The purpose of this work is to study the large variation and cost escalation observed in the construction of NPPs in the US, starting from the construction schedule (in terms of activity costs and durations) of the NPP. A similar methodology was not found in literature. First, a construction model was developed to describe the construction of the Westinghouse Small Modular Reactor (WEC-SMR) and to perform a set of deterministic analysis on TCIC decision parameters. 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. The same approach was also used to model the construction of a Westinghouse 4-loop "mainstream" PWR (PWR12), and the results were compared to the historical construction data in the US. Data for the best estimate "standard" PWR (PWR12-BE) were developed by the Department of Energy (DOE) Energy Economic Data Base (EEDB).

For the WEC-SMR, this study focuses only on the construction of the nuclear island (NI), as it represents the main contributor to TCIC. For example, for PWR12-BE, nuclear components and structures (that make up the nuclear island) contribute to about 40% of the total direct cost (US DOE, 1988). For a smaller integral design, this percentage is expected to be higher, 50% or more. The indirect cost may be assumed roughly proportional to the associated direct cost, and thus the impact on direct cost will reasonably well represent the impact on the total cost. Moreover, the construction of the nuclear island is the main cause of costs overrun and construction delays and, therefore, only the nuclear island portion of TCIC was considered in our analysis. It is likely that construction modularization is feasible and will reduce costs for non-nuclear-island components, in particular of SMR.

The work is organized as follows. Chapter 2 summarizes previous studies, the basic cost definitions that were used in the cost evaluation, and the historical NPP cost trends for several countries. In Chapter 3 the objectives and approach of this work are described. Chapter 4 describes the deterministic methodology (EVAL) that was applied to the WEC-SMR. Chapter 5 describes the method used in the stochastic analysis to perform Monte Carlo simulations. Chapter 6 contains the deterministic results obtained through EVAL. The results of the stochastic analysis are shown in Chapter 7.

2 BACKGROUND AND PREVIOUS STUDIES

2.1 Definitions 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 (Figure 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. Owners costs include the owners' 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 owners' capital investment and service costs. Financial costs include escalation, interest during construction (IDC) and fees. Fore costs, escalation costs, IDC and fees define TCIC.

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

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

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

Figure 1 – TCIC breakdown according to IAEA code of accounts (1999)

2.1.1 Direct and indirect cost

Direct costs are the main contributor to TCIC. They include direct construction cost plus pre-construction cost (site preparation) (Economic Modeling Working Group, 2007; Rothwell and Ganda, 2014). They include the cost of equipment, material and labor needed for the construction of the NPP. The value of direct costs (DC) is calculated summing the cash flow during construction as:

$$DC = \sum_{t=0}^{LT} C_t \tag{1}$$

where C_t represent the cash flow associated with an expenditure related to equipment, material or labor, t the time period and LT the number of time periods (project duration). Eq. 1 is based on the assumption that a construction schedule is available. A construction schedule relies upon a Part Breakdown Structure (PBS) and a Work Breakdown Structure (WBS), which often are not available at early stages of a reactor development. Indirect costs (IC) can be expressed as a percentage (in) of direct costs, as:

$$IC = in \cdot DC \tag{2}$$

For SMRs, Rothwell and Ganda (2014) sets the coefficient in to 10%. Cost estimates of other reactor designs use higher percentages of indirect cost over direct cost (Holcomb et al., 2011). Base cost, expressed as the sum of direct and indirect costs is then:

$$BC = DC \cdot (1 + in) \tag{3}$$

2.1.2 *Supplementary and Owner Costs*

Supplementary cost includes transportation and shipping costs, spare parts and supplies as well as costs for the core first loading. These costs are often neglected in the cost estimates (Holcomb et al., 2011).

Owner's cost includes costs that are owner's responsibility, such as capitalized operations, capitalized supplementary costs, and capitalized financing costs. For SMRs, Rothwell and Ganda (2014) estimate owner's cost as \$200 M plus 5% of the direct cost. Owner's costs (OC) and overnight capital cost (OCC) can be then calculated as:

$$OC = BC \cdot 0.05 + 200M \tag{4}$$

$$OCC = BC \cdot (1 + 0.05) + 200M \tag{5}$$

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:

$$OCC = DC \cdot (1 + oc) \tag{6}$$

where *oc* indicates the percentage of owner's cost over base cost. For an SMR with a base cost of \$1 B, Eq. 6 becomes

$$OCC = DC \cdot (1 + 0.35) \tag{7}$$

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 (Economic Modeling Working Group, 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. Under the assumption that the length of the project is known a priori, *IDC* can be calculated as (Economic Modeling Working Group, 2007):

$$IDC = \sum_{t=-LT}^{1} C_t \left[\frac{1}{(1+r)^t} - 1\right] \quad (8)$$

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 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" (Economic Modeling Working Group, 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.

$$C_t = C_{t,DC} + C_{t,IC,OC} \quad (9)$$

Direct costs have a cash flow profile that is determined by the construction schedule, while indirect costs and owner's costs are assumed to be uniformly distributed during the construction period. Under this assumption, the cash flow associated to indirect and owner's cost in each period is calculated as:

$$C_{t,IC,OC} = \frac{0.05 \cdot BC + 200M}{LT} \quad (10)$$

The calculation of IDC through Eq. 8 assumes that the cash flows and the lead time LT are known a priori at the beginning of the project. However, at the beginning of construction, both these quantities are unknown. Changing the subscripts, Eq. 8 becomes:

$$\begin{aligned} IDC &= IDC_{DC} + IDC_{IC,OC} = \\ &= \sum_{t=1}^{LT} [C_T, DC(1+r)^t - 1] + \sum_{t=1}^{LT} \left[C_{T,IC,OC}, (1+r)^t - 1\right] \end{aligned} \quad (11)$$

where the first term represents the *IDC* due to cash flows associated to direct costs, and the second term the *IDC* associated to indirect and owner's costs. Assuming that $C_{T,IC,OC}$ is uniformly distributed such that $C_{T,IC,OC} = (IC + OC)/LT$ the second term of Eq. 11 ($C_{T,IC,OC} = (IC + OC)/LT$) becomes:

$$IDC_{IC,OC} = \frac{IC + OC}{LT} \left[\sum_{t=1}^{LT} (1+r)^t - LT \right] \quad (12)$$

The exponential expression can be approximated with a second-order expansion:

$$\sum_{t=1}^{LT}(1+r)^t = \frac{[(1+r)^{LT}-1]}{r} \tag{13}$$

And the exponential expression can be approximated with a second order expansion, as:

$$(1+r)^{LT} \approx 1 + LT \cdot r + LT(LT-1)(r^2/2) + \ \ldots \tag{14}$$

Substituting Eq. 15 into Eq. 14, we obtain:

$$\sum_{t=1}^{LT}(1+r)^t \approx LT + LT(LT-1)(r/2) \tag{15}$$

Using Eq 16. in Eq.13 and simplifying:

$$IDC_{IC,OC} \cong (IC+OC)\left[\frac{(LT-1)r}{2}\right] \cong LT \cdot (IC+OC) \cdot (r/2) \tag{16}$$

Applying the same methodology to IDC_{DC}, it can be shown that:

$$IDC_{DC} \cong LT \cdot (DC) \cdot (r/2) \tag{17}$$

Therefore, Eq. 11 becomes:

$$IDC \cong LT \cdot (DC + IC + OC) \cdot (r/2) = LT \cdot (OCC) \cdot (r/2) \tag{18}$$

Substituting the expression for OCC expressed by Eq. 7 into Eq. 18, we obtain:

$$IDC \cong LT \cdot [DC \cdot (1 + 0.35)] \cdot (r/2) \tag{19}$$

Eq. 19 shows that IDC is directly proportional to OCC, and it highlights the importance of DC over the other cost items. However, Eq. 19 is obtained assuming that the cash flows associated to the direct cost, indirect cost, and owner cost are constant during the construction period. A more accurate calculation of IDC is obtained utilizing the real direct cost cash flow during construction. Assuming a constant cash flow for IC and OC and substituting Eq. 16 into Eq. 11, IDC is then:

$$IDC = \sum_{t=1}^{LT} \left[C_{T,DC}(1 + r)^t - 1\right] + LT \cdot (IC + OC) \cdot (r/2) \tag{20}$$

TCIC is calculated summing OCC (Eq. 5) and interests during construction (Eq. 11), as:

$$TCIC = OCC + IDC \tag{21}$$

2.2 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), proposed as evaluation tool by C.R. Hudson (Hudson, 1986), and further popularized in the guidelines for economic evaluation of bids, by the International Atomic Energy Agency (IAEA) (IAEA, 1999). The code of accounts allows to break down main costs (Total Capital Investment Cost, Fuel

Cycle Cost, Operation and Maintenance) to individual systems and items. Accounts are assigned a numeric sequence and increasing levels of detail are tracked by adding digits to the code.

The PWR12-BE represents a traditional four-loop PWR plant, with a core thermal power of 3417 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, averaging actual cost incurred in the construction of several nuclear power plants (NPPs), itemized with a great level of detail according to the Code of Accounts. For each account, the cost of equipment, site labor and site material is provided. 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). The cost data from Holcomb et al. (2011) was extracted, and industry experts at Westinghouse Electric Company performed a "sanity check" of the cost items (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 1. Unfortunately, the cost of the NSSS is not provided in the EEDB analysis. as a single line item as "procurement costs", and it is a substantial fraction of the total direct cost of NPPs.

Table 2 shows the main PWR12-BE accounts, with a cost breakdown into factory equipment, site labor and site material costs (in 1987 USD).

Table 1 – 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 2 – PWR12-BE accounts (1987 USD) (US DOE, 1987a)

		Factory equipment	Site Labor	Site Material	Total
21	Structures and Improvements	22,529,313	113,513,274	64,701,510	200,744,097
22	Reactor Plant Equipment	312,545,773	48,997,016	14,422,059	375,964,848
23	Turbine Plant Equipment	173,515,672	41,962,684	8,300,008	223,778,365
24	Electric Plant equipment	32,713,418	34,725,090	13,884,216	81,322,724
25	Miscellaneous plant equipment subtotal	18,655,809	22,672,386	5,373,702	46,701,898
26	Main Condenser heat rejection system	30,642,472	15,280,100	3,058,393	48,980,965
	Total direct cost	590,602,457	277,150,551	109,739,890	977,492,898

Account 22 costs, adjusted by WEC experts, are shown in Table 3. 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 4), which corresponds to 67.0% of the direct cost. Therefore, for the PWR12-BE *in* is equal to 0.67, and Eq. 3 becomes:

$$BC = DC \cdot (1 + 0.67) \qquad (22)$$

Table 3 – 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

The owner's cost breakdown is shown in Table 5. 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:

$$OC = BC \cdot 0.078 \quad (23)$$

The resulting OCC is $4.68 B and can be calculated through Eq. 24.

$$OCC = DC \cdot (1 + 0.67) \cdot (1 + 0.078) \quad (24)$$

The PWR12-BE construction schedule was derived by US DOE (1987c) and is presented in Figure 2 and the project duration is 7.56 years. IDC is calculated through Eq. 12 using a cost of capital of 10%. The resulting TCIC is $6.74 B.

Table 4 – 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 5 – 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

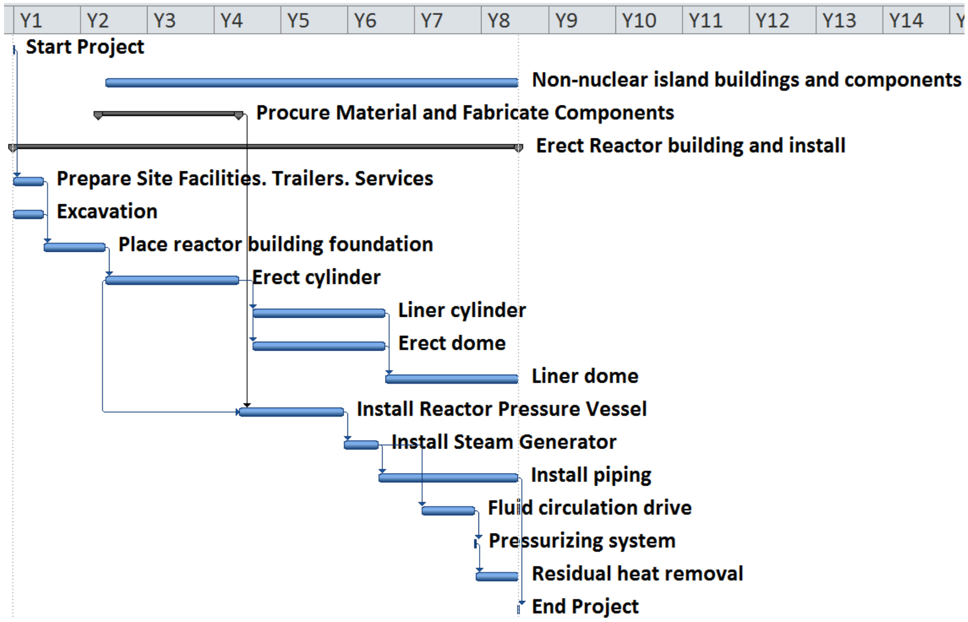


Figure 2 – PWR12-BE construction schedule (derived from US DOE (1987c))

2.3 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 NSSS design of each plant were taken from US NRC (2018). The collected data include, among other things: 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). The analysis of the historical data shows a cost escalation over the years. The goal of this work is to analyze the historical information on completed plants, not only to understand what has occurred but also to improve the ability to evaluate the economics and construction risks of future plants.

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). Data on total estimated construction costs was submitted quarterly by utilities, and both the actual and estimated cost data were reported in the dollar amount of the year the funds were expended. As the data is not uniform and therefore not comparable, financing costs were removed by the costs, and all costs were expressed in constant dollars (mid 1982 USD), using the regional Handy-Whitman index. The methodology to convert "as expended" dollars to "constant dollars" of a given year, is presented in detail in the reference. The OCC was then converted to 2017 USD using CPI. The OCC of the 101 reactors is shown in Figure 3 as a function of the NPP power load, while the power-specific OCC ($/kW) as a function of the NPP power load is shown in Figure 4.

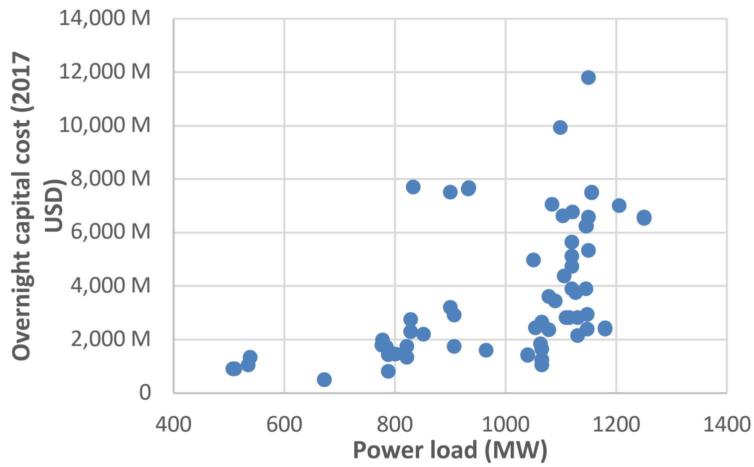


Figure 3 – OCC of US power plants as a function of power load

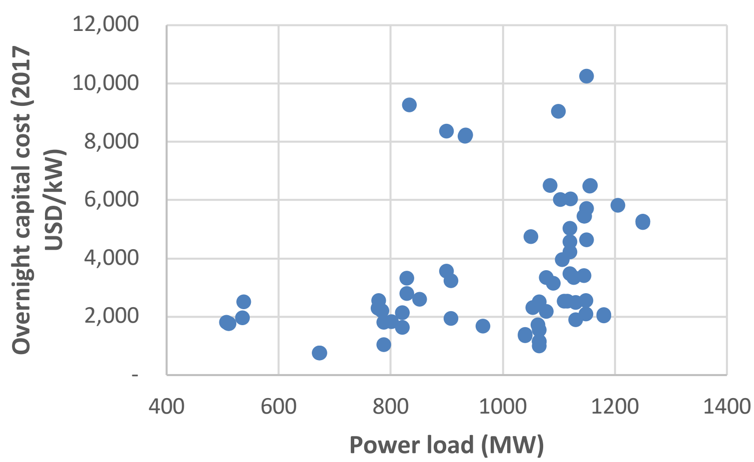


Figure 4 – OCC per unit power of US nuclear power plants as a function of power load

Figure 5 shows the NPP OCC as a function of the year of construction end. The data reveals an observable cost escalation for the reactors completed in the timeframe, especially after the Three Mile Island accident of March 1979. Nuclear reactors completed before 1979 have a OCC mean of $1,606.1 /kW (2017 USD), 2.5 times lower than the ones of reactors completed after 1979, which is $5,945.6/kW (Table 6). 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 $2,400 /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 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.

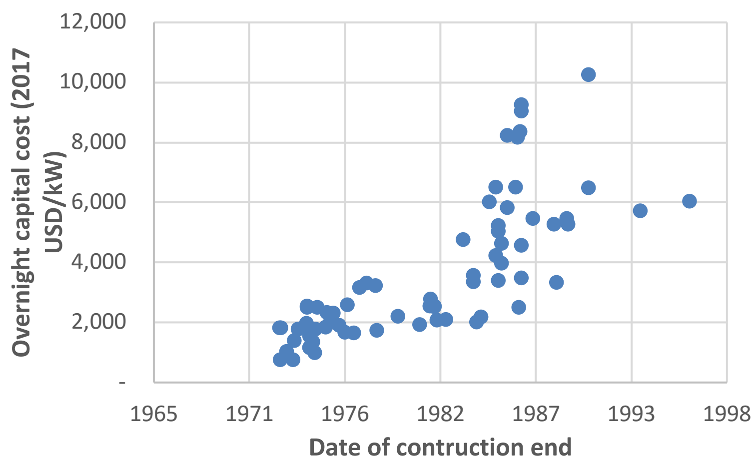


Figure 5 – OCC of US power plants by construction end date

Figure 6 shows the historical OCC as a function of the construction duration. The data indicates a positive correlation between the project cost and the time required for completion. It is important to note that the OCC does not include the financing cost, but it is only the sum of all cash flows during the project, expressed in the same year. In other words, the OCC represents the cost of the NPP if the project is completed “overnight”. The positive correlation between project "real" cost and time indicates the effect of time related managerial difficulties and regulatory changes over the construction period on cost.

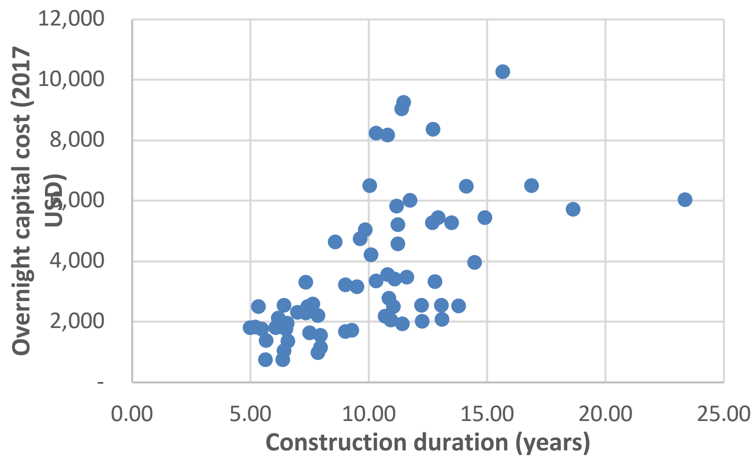


Figure 6 – OCC of US power plants as a function of construction duration

Figure 7 shows the construction duration of the 116 US power plants as a function of time. Regarding the project duration, reactors completed in the pre-1979 phase have a mean of 7.8 years and a relative standard deviation of 51.9%, while reactors completed after 1979 have a mean project duration of 10.6 years (1.4 times higher) and a relative standard deviation 23.3%.

Table 6 – OCC and construction duration of US power plants

		Pre-1979	Post-1979
OCC ($/kW)	μ	1,606.1	3,945.6
	σ/μ	36.0%	51.1%
Duration (years)	μ	7.8	10.6
	σ/μ	51.9%	23.3%

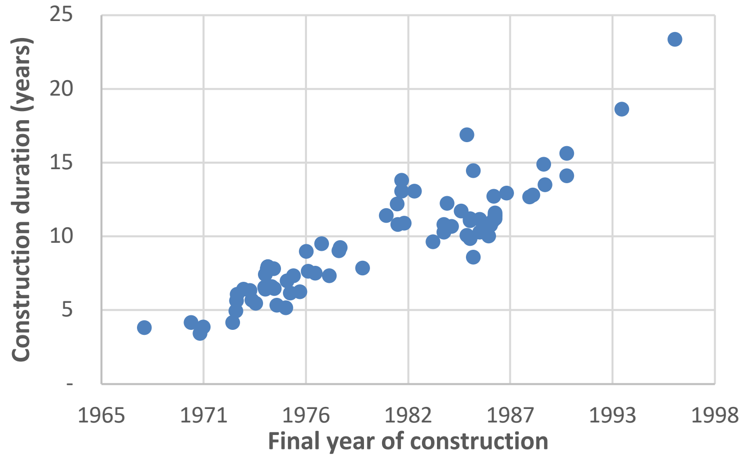


Figure 7 – Construction duration by construction end date

Figure 8 and Figure 9 respectively show the OCC and project duration of PWR12 completed in the US between 1973 and 1996, as a function by the final year of construction. For the plants completed before 1979, the OCC mean is $1,934.1 /kW, with a relative standard deviation of 30.2%, while the plants completed after 1979 have an OCC mean of $4,478.2 /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 7.

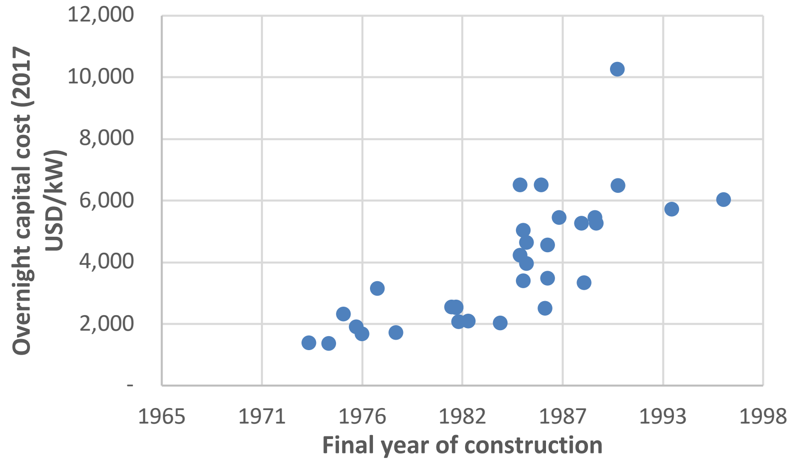


Figure 8 – OCC of US PWR12 by construction end date

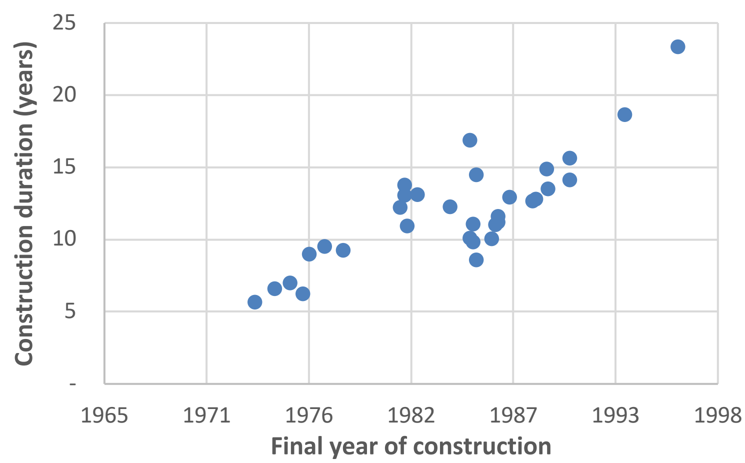


Figure 9 – Construction duration of US PWR12 by construction end date

Table 7 – OCC and construction duration of US PWR12

Historical		Pre-1979	Post-1979
OCC ($/kW)	μ	1,934.1	4,478.2
	σ/μ	30.2%	42.3%
Duration (years)	μ	7.6	13.2
	σ/μ	19.5%	23.2%

In Energy Information Administration (1986), the authors found a positive correlation between the utilities real project cost and construction time. The average estimated and realized overnight cost and construction times of NPP are shown in Table 8 and

Table 9, 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 underestimate the OCCs and construction times, even at times approaching the project completion.

Table 8 – 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)						
		0%	25%	50%	75%	90%	Realized	Increase
1966-1967	11	298	378	414	558	583	623	109.1%
1968-1969	26	361	484	552	778	877	1,062	194.2%
1970-1971	12	404	554	683	982	1,105	1,407	248.3%
1972-1973	7	594	631	824	1,496	1,773	1,891	218.4%
1974-1975	14	615	958	1,132	1,731	2,160	2,346	281.5%
1976-1977	5	794	914	1,065	1,748	1,937	2,132	168.5%
Average								215.6%

Table 9 –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)						
		0%	25%	50%	75%	90%	Realized	Increase
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%

The reports show that the correlation between actual costs and actual construction times was, in part, the result of events and regulatory changes that occurred after the cost estimates were prepared. This fact is more likely to be true especially for those estimates that were prepared early in the construction period. Thus, the lack of any correlation between estimated construction time and estimated costs was partly due to the inability to foresee future events and regulatory changes.

In the report, the authors also analyzed the effect of learning on the NPPs construction, both considering the cumulative industry experience and the of the construction firm. Regarding the experience of the constructor, the authors found that the experience of the external constructor did not considerably affect either the construction times or the costs. the analysis also shows that, with all other factors held constant, utilities that built their own plants experienced costs that were 35% less than the costs experienced by utilities that used outside contractor managers. The meaning of this finding is that utilities that managed their own projects were better able to control costs than those that did not. However, for utilities acting as their own construction manager, the authors did not find any noticeable construction time reduction. This result indicates that, for this case, although utilities may have been able to gain some cost benefits from a better understanding of the construction process, they did not gain the same benefits by building the plants faster than their nonutility constructor counterparts. The report points out two counter acting causes contributing to the non-reduction in the project construction times. First, utilities that manage their own construction are believed to be better able to monitor and control costs and "construction times”, which should result in shorter construction times. However, a utility that manages its own construction has access to information about the value of the plant (i.e., demand) that an external constructor would not have or would ignore in making decisions, resulting in longer construction times.

Zimmerman (1982) gives a further explanation on the causes of the cost reduction in case the construction management is held by the utility. For non-utility constructors, the author argued that more experienced constructors are able to charge the same price as less experienced ones and keep the cost savings as profits. On the other hand, utilities that do their own construction must pass the cost savings resulting from greater experience on to ratepayers in the form of a lower cost plant, since regulation prevents them from keeping the savings as profit, resulting therefore in lower actual construction costs.

The causes of the cost escalation in the United States can be found in the adoption of different designs, poor standardization of components, and changes in regulations after the Three Mile Island accident. 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). At this date, two two-units NPPs are under construction in the U.S., in Georgia (Vogtle, units 3 and 4), while the construction of the units in South Carolina (V.C. Summer, units 2 and 3) was abandoned. The units for both sites are Westinghouse AP1000, a large pressurized water reactor design being constructed through modularization. As of January 2016, the completion of the units in Vogtle is 39 months delayed, and the project estimated cost for the two units is about $21 B, 49 percent higher than the certified initial cost of $14.1 B (Georgia Power Service Commission, 2013). Before being canceled in July 2017, the VC Summer plant was delayed and the cost was projected to be $16 B, 78% higher than the initial estimate of $9 B (Downey, 2017). The main issue initially lied in the construction of the basic foundation, not in the modules manufacturing, and the delays in construction were mainly due the laying of concrete and rebar. One of the main construction companies (CB&Is Stone and Webster, earlier acquired by Shaw Group), did not have any experience building nuclear plants or with modularization. As Shellenberger (2017) states, "Vogtle builders struggled to create the special materials required for the plant as well as with documentation to meet NRCs stringent standards". In addition to a poor management, construction inexperience, and over regulation, the causes for the cost increase also lie in the "deliberate foot-dragging to raise costs by US plant builders and module manufacturers both in the US and China" (Shellenberger, 2017). The most recent status (as of March 2017) reveals that even higher cost overrun may be related to modular construction; however, the issue is not necessarily in the concept itself but in the inexperience of the manufacturer. Moreover, after 9/11, NRC introduced new design requirements after the plant design had been completed, which led to redesign and cost increase (Hals and Flitter, 2017).

2.4 Historical capital cost trend in France

France has the second largest fleet worldwide (58 reactors) and, until the recent construction of the EPR, it was identified as a success (Grubler, 2010; Rangel and Leveque, 2012). The construction cost of the French nuclear power plants was released in 2012, due to a request from the Prime Minister to the national audit agency Cour de Comptes. In the same year, the agency released a report that collected all the data concerning the actual construction of the 29 twin-units reactors installed in France (Cour des Comptes, 2012). Before the release of this report, historical construction costs of nuclear plants in France were estimated by Grubler (2010), who indirectly examined the EDF financial data released in the period from 1972 to 1998. Both data sets were analyzed and compared by Rangel and Leveque (2012), which also reports the Cour des Comptes costs. The French reactors are of different design types: the CP0, CP, CP2, P4, P'4 and N4. In the Cour de Comptes analysis, the reactors are divided into three *paliers* (levels), based on the reactor power load. The first *palier* includes reactors with power load between 917 and 954 MW (CP0, CP1 and CP2), for a total of 34 reactors. Although these reactors have similar capacity, they slightly differ in the conception of their intermediary cooling systems. In the second *palier*, there are the reactors with power load between 1362 and 1382 MW (P4 and P'4 type), for a total of 20 reactors. These reactors differ in the layout if the structure that contains the fuel rods and the circuitry. In the last palier, there are the reactors having a power load between 1560 and 1561 MW, which belong to only one type (N4), for a total of 4 reactors. This design differs both in capacity and in the conception of the steam generators, primary pumps and command room. A detailed description of the *paliers* and reactors types can be found in Autorité de Sûreté Nucléaire (2010). Types CP0, CP1, CP2 and P4 are Westinghouse licensed designs.

The Cour des Comptes (2012), reports the construction costs converted and escalated from the French Franc (FF) to the value of 2010 EUR. For illustration, the costs in 2010 EUR, extracted from Cour des Comptes (2012), were escalated to 2017 EUR using the Harmonised Index of Consumer Prices (HICP) for the euro area (European Central Bank, 2017). The costs were then converted to 2017 USD using the average yearly euro-dollar exchange rate in the period from December 2001 to December 2016, calculated from the yearly exchange rates taken from OFX (2018). The resulting early average exchange rate is 1.24 USD/EUR. The data obtained through this method has to be interpreted with caution, as the multiple currency conversions (FF to EUR to USD) and cost escalations are a source of uncertainty. However, useful insights can be learned. The absolute and power-specific OCCs are shown in Figure 10 and Figure 11, respectively. In both plots, the three *paliers* form three separate clusters.

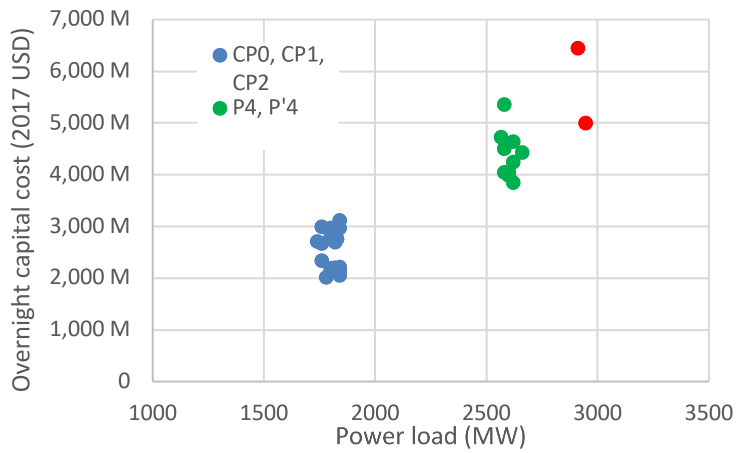


Figure 10 – OCC of French power plants as a function of power load (twin units)

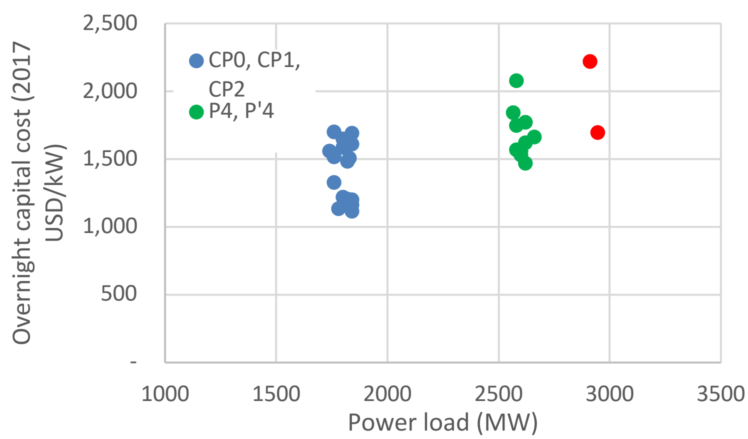


Figure 11 – OCC per unit power for French power plants as a function of power load (twin units)

The OCC, as a function of the year of construction end, is shown in Figure 12.

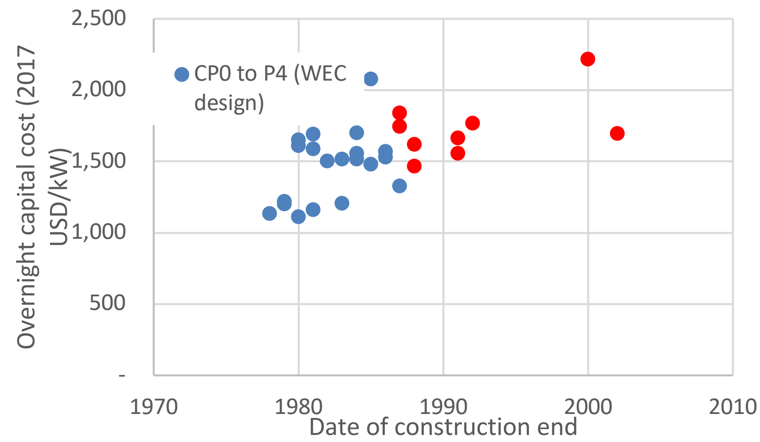


Figure 12 – OCC per unit power for French power plants by construction end date (twin units)

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). The source of the success of the can be found in a particular political/technocratic framework that, despite may not be replicated elsewhere, it is worth investigating. The authors 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 small number of institutions involved, allowed them to act in a well-coordinated way (Ganda et al., 2015; Grubler, 2010). Finon and Staropoli (2001) identify five key factors of the success of the French program:

1. A strong political support;
2. A state-owned electricity monopoly (EDF) endowed with engineering resources;
3. A highly concentrated electromechanical manufacturing industry;
4. An influential R&D public agency (CEA);

5. A high regulatory stability and efficient co-ordination resulting from long-term organizational arrangements.

A sign of the success of the French nuclear program can also be seen in the construction time, which is much shorter than the US case (Figure 13)

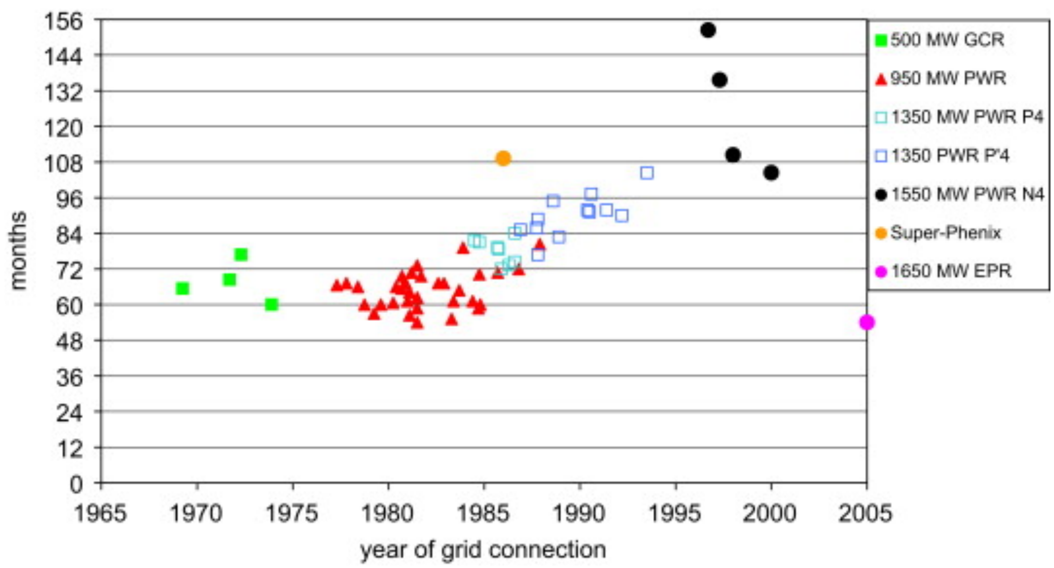


Figure 13 – Construction time of French reactors as a function of the year of grid connection (Grubler, 2010)

The mean construction time is 76 months, much lower than the mean of 114 months in the US reactor sampled size shown in Section 2.3. Grubler (2010) finds the main drivers of the French shorter construction schedules in the standardization of reactor designs and the rigorous quality and cost control performed by EDF. Standardization requires continued and dedicated efforts to produce positive effects in the long term that, in France, was guaranteed by the particular environment. As Rangel and Leveque (2012) argue, the learning effect that in France is present for same reactor types is rooted in the idea of standardization. In fact, as Ganda et al. (2015) explains, “standardization helps reducing the modifications during the construction phase, induced both by the regulatory turbulence and engineering instability.”

However, as the EDF determination to standardize started decreasing over time, together with the interruption of the nuclear program, costs and schedules started to increase, as the construction of the new EPR designs shows. Currently, four EPRs are under construction: one in Finland (Olkiluoto 3), one in France (Flamanville 3), and two in China (Taishan 1 and 2). In Finland, the project started in 2003 and was scheduled to be completed in 2010 (Areva, 2003). The project was delayed multiple times and, in 2017, the project is scheduled to be completed in 2019 (Reuters, 2017). The original fixed-price contract for the Olkiluoto EPR was for €3 B in 2003, which corresponds to a cost prevision of 2,356 €/kW (in 2017 EUR). The costs were revised multiple times, and the last estimates (released in 2012) are for €8 B (Nuclear-news, 2012), which corresponds to a cost of 5,195 €/kW (in 2017 EUR).

Similarly, the Flamanville EPR started construction in 2007 and was scheduled to begin operation in 2012 (World Nuclear News, 2007). The final construction schedule was released in July 2017 by EDF, which plans to complete the project in November 2019 (World Nuclear News, 2017). The initial cost of the reactor increased from the expected €3.3 B (in 2007 EUR), equivalent to 2,377 €/kW (in 2017 EUR), to €10.5 B in 2015, equivalent to 6,696 €/kW (in 2017 EUR) (World Nuclear News, 2017). This construction cost is almost four times the 1,697 €/kW of the last N4 nuclear reactor built in France (Civaux, Figure 12).

2.5 Historical capital cost trends in other countries

Lovering et al. (2016) carried out an extensive analysis of nuclear reactor capital cost trends in several countries. However, the data sources referenced in the paper for Japan, Korea, Canada and West Germany were not retrievable. As a consequence, the plotted OCC plots in Lovering et al. (2016) were digitalized and the capital costs as a function of the construction start date were extracted to calculate cost means and standard deviations.

The nuclear reactors capital cost trend in Japan is shown Figure 14, and it is made of three phases (Lovering et al., 2016). In the first construction phase, from 1960 to 1969, reactors were imported from American and British companies. The Japanese nuclear history started with 10 MW boiling water reactor and a 159 MW gas-cooled reactor. In the first 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 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%. Considering only the last era of the Japanese nuclear industry (Figure 15), the OCCs averaged ¥313,488 /kW (2010 JPN), with a relative standard deviation of 23.1%.

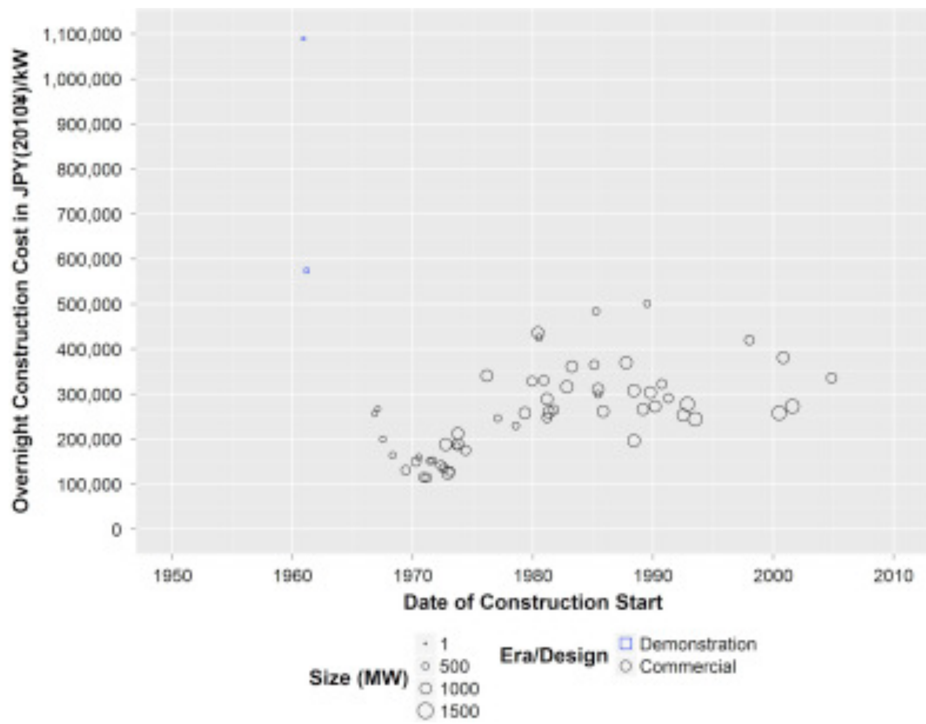


Figure 14 – OCC of Japanese nuclear reactors by construction start date (Lovering et al., 2016)

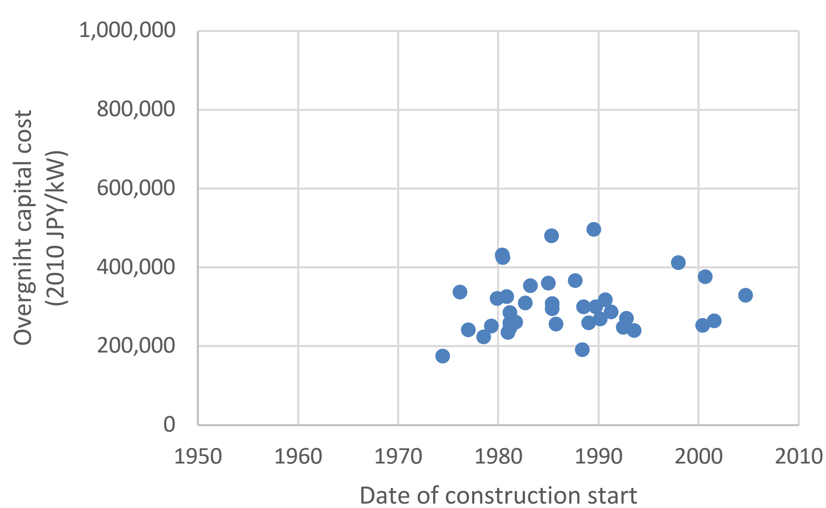


Figure 15 – OCC of third phase Japanese nuclear reactors by construction end date (extracted from Lovering et al. (2016)

The Canadian cost trend is shown in Figure 16. The data shows a sharply declining cost in a first phase and then relatively mild cost escalation. The relatively stable cost trend can be due to consistency in builders and manufacturers, the smaller reactor sizes, or that reactors were almost always built in pairs close in time (Lovering et al., 2016). The calculated mean and relative standard deviation of this data are $2,950.7 /kW (2010 CAN) and 21.3%, respectively.

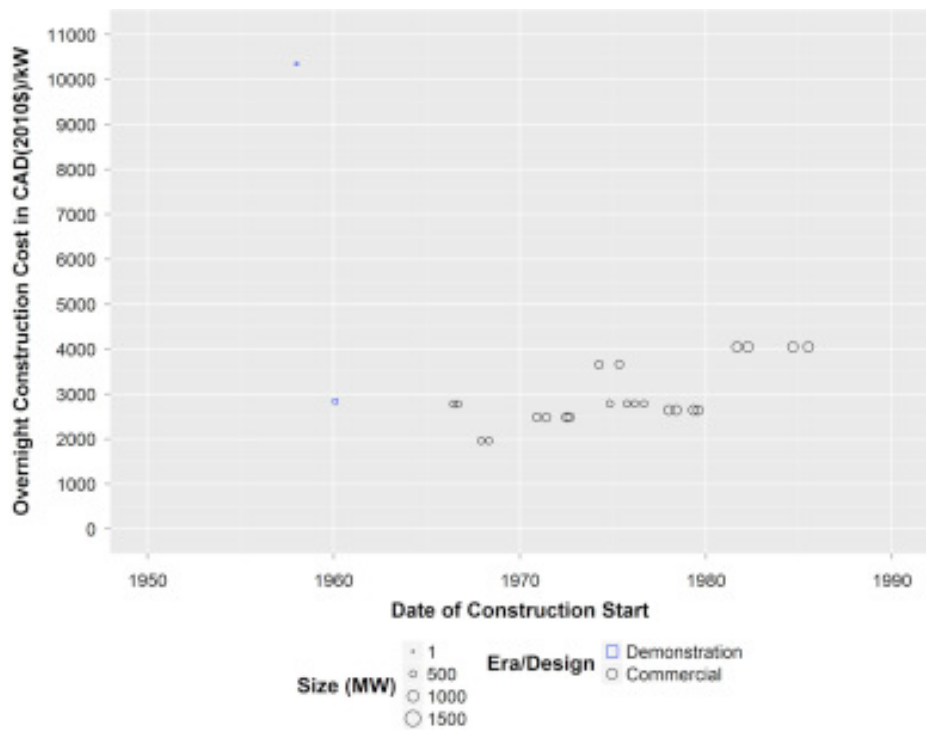


Figure 16 – OCC of Canadian nuclear reactors by construction start date (Lovering et al., 2016)

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 63% (6% annualized). In the following phase, between 1973 and 1983, costs by 200%, or a 12% annually. West Germany reactors have an estimated OCC mean of €1,772.7 /kW (2010 EUR) and a relative standard deviation of 43.2%.

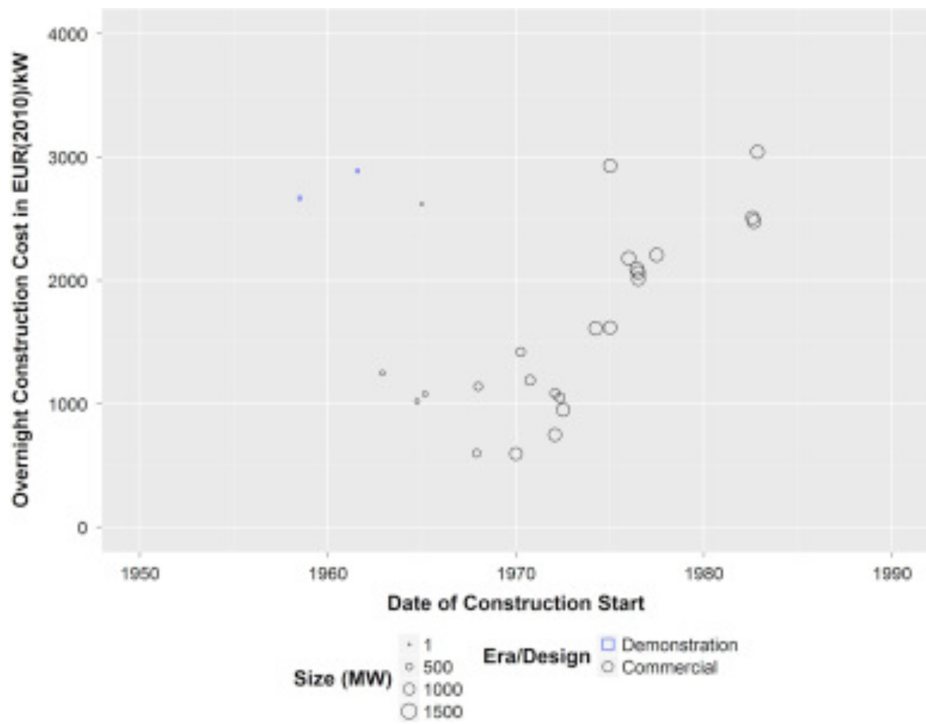


Figure 17 – Overnight Construction Cost of West Germany nuclear reactors by construction start date (Lovering et al., 2016)

The cost data of the Republic of Korea, shown in Figure 18, 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. South Korea went straight to importing a large commercial reactor, a 558 MW Westinghouse design, which began construction in 1972. Then, South Korea continued to import several reactor designs from American, French, and Canadian companies, building 9 reactors between 1972 and 1993. In this era, costs fell approximately 25% (2% annualized). Korea also started to domestically develop nuclear reactor design, the Korean Standard Nuclear Power Plant (KSNP), based on designs from Westinghouse, Framatome and Combustion Engineering, and it was 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 data, extracted from Figure 18, has a mean of ₩2,823,773.6/kW (2010 KRW) and a relative standard deviation of 25.4% 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).

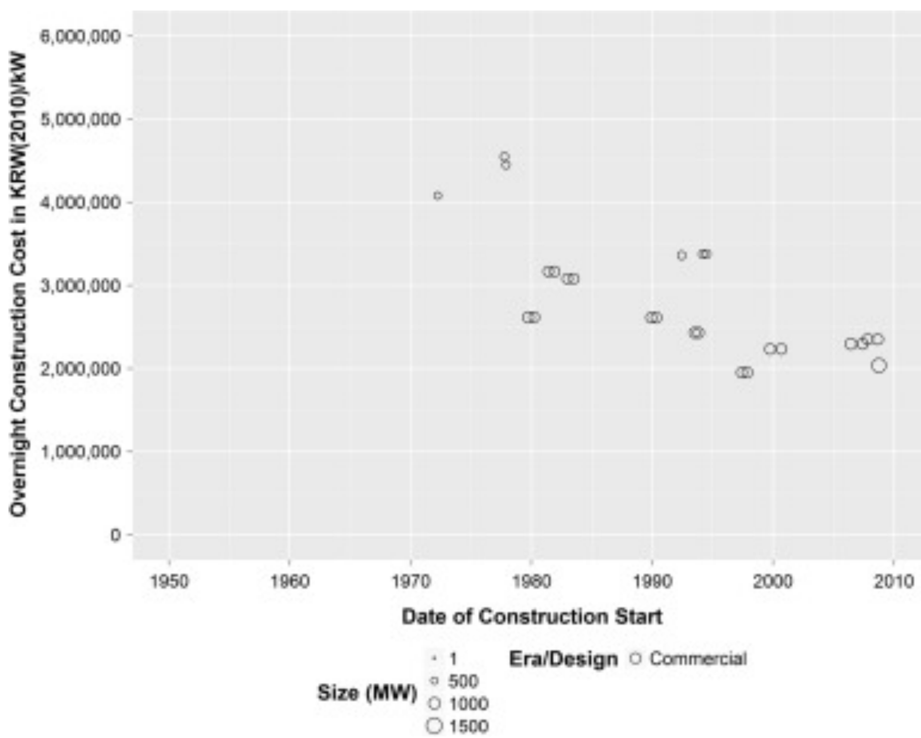


Figure 18 – OCC of Korean nuclear reactors by construction start date (Lovering et al., 2016)

3 OBJECIVES, SCOPE AND PROPOSED APPROACH

To the issue of NPP capital cost escalation over time, the industry and the scientific community proposed a range of solutions. One solution consists on the use of modularization as a construction technique, which is intended to improve construction efficiency as well as standardization of components (Barry, 2009; Lapp and Golay, 1997; N. Town, 2015; Nuclear Energy Agency, 2000; US Government Accountability Office, 2010). Another solution lies in the adoption of reactor of lower power level, such as of Small Modular Reactors (SMRs) that, together with the adoption of modularization, are associated with lower capital risks and are less likely to be delayed as being characterized by a smaller size and simpler design (2015; Gollier et al., 2005; Kuznetsov and Lokhov, 2011; Locatelli et al., 2014). In this chapter, a literature review of both proposed solutions is presented.

3.1 Modularization and off-site learning

Modularization is a construction technique that allows a better standardization of components, shortening of construction time and lower labor costs. Modularization consists of the decomposition of the whole plant into a number of standardized modules that allow factory fabrication. In the nuclear industry, modularization consists of moving the activities that are part of the NPP construction from the on-site construction location (reactor hole) to a different location, which can be on-site (assembly area) or off-site (factory). A schematic of the process is shown in Figure 19.

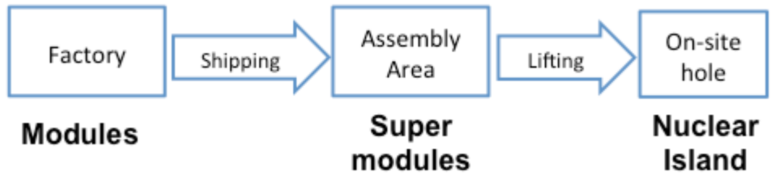


Figure 19 – Modular construction process

The benefits of this process can be described through the 1-3-8 rule of thumb that was developed in the shipbuilding industry (Barry, 2009; US Government Accountability Office, 2010) based on actual observed data. The 1-3-8 rule describes the labor time reduction due to a different performance site, as 1, 3 and 8 represent the required labor time to perform the same task in the factory, in the on-site assembly area and in the on-site hole, respectively. The shorter times are due to environment conditions (e.g., temperature controlled, sufficient space availability) that allow activities to be performed more efficiently. As tasks are performed in a shorter time, the amount of labor required to perform the tasks is also lower, with a subsequent reduction in cost. Modularization has an effect on the construction activities as well as on the testing activities. Through modularization, functional testing and system testing can be shifted from the installation stage (end of construction) to the fabrication and assembly stage, with time and cost savings that can be estimated through the 1-3-8 rule. These testing activities can be performed at the end of the fabrication process and once the modules have been assembled into a super module. This process also allows a higher degree of parallelism, as these activities can be performed in parallel during the construction process. Despite the 1-3-8 rule of thumb was derived by the shipbuilding industry, it can be applied to the nuclear industry. Ship construction and nuclear construction are characterized by similar environments (with lower availability of space) and components (large high-tech modules). Despite the similarities in the two industries, the factors 1, 3 and 8 that describe the ship modular construction might be different for NPP construction but will be used in this study as the best available values and to demonstrate the methodology.

If the entire nuclear island is built according to the modular construction technique, TCIC is expected to be lower than if built using the standard construction techniques (e.g. stick-built construction). Another advantage that is a direct effect of the module fabrication in a factory is that quality has been proved to be higher compared to the quality achieved at the construction site (Barry, 2009; US Government Accountability Office, 2010). Improved quality improves worker safety, schedule and cost, in addition to having a positive impact on maintenance costs, since it reduces the probability of failure of components. The reason for improved quality includes specialization of workers, earlier detection of weld defects and better welding due to improved environmental conditions.

Moreover, factory manufacturing and standardization of components are believed to increase the effect of learning. For factory fabrication of standardized components, the improvements in the manufacturing processes are retained by the manufacturer. As a consequence, the learning rate is higher and NOAK plants are reached earlier as compared to stick-built construction. The benefit of learning may be questioned, since in the United States costs of stick-built reactors have risen during the year, as shown in Section 2.3.

3.2 SMRs

The International Atomic Energy Agency (IAEA) uses the acronym to denote small and medium-sized reactors. IAEA defines as small those reactors with an electrical output less than 300 MWe and medium with an electrical output less than 700 MWe. According to this designation, 139 of the 442 commercial reactors operating in 2009 worldwide are SMRs (Ingersoll, 2009). However, most of these reactors are scaled-down versions of large reactors. In the United States and in other parts of the world, on the other hand, the acronym stands for small modular reactors, and is used to describe deliberately small reactors, built according to modularization of components. In 2014 there were more than 45 SMR designs under development in 13 countries (IAEA, 2014). Because of the assumed validity of the economies of scales principle, historically the unit power of reactors designed and built has been increasing, from a few hundred MWe to 1500 MWe and more. The capital cost per unit power of a nuclear reactor is expected to decrease with power, due to the rate reduction of unique set-up costs in investment activities and the more efficient use of raw materials and the exploitation of higher performances characterizing larger equipment (Carelli et al., 2010). However, the economy of scale applies only if the reactors are very similar in design, as it has been the case in the past but not today, where small modular reactors have different designs and characteristics than those of large reactors. (Carelli et al., 2005). Applying the economy of scale principle to derive SMRs capital costs from those of large reactors, is equivalent to assuming that SMRs are the same as large reactors except from size, which can be misleading. In fact, due to their smaller size, SMRs exhibit several benefits that can be hardly replicated by large reactors. These benefits have been largely reviewed in literature (Hayns and Shepherd., 1999; Miller, 2005; Schock et al., 2001). Carelli et al. (2007b) and Petrovic et al. (2012) compared capital costs of a pack of four 335 MWe SMRs to a monolithic 1340 MWe reactor. In case the only economy of scale is considered, the OCC per unit power ($/kWe) of the SMR would be 70% higher than the large plant. Once other factors are considered (multiple units at a single site, learning, construction time, match to supply and demand, and simplification in design), the pack of four SMRs has a capital cost only 5% higher than the large reactor. Other studies suggest that SMRs can "effectively compete in future electricity markets if their capital costs are controlled, favorable financing is obtained, and reactor capacity factors match those of current light water reactors" (Shropshire, 2011). Despite the benefits associated with SMRs, some experts predict higher costs per kW of capacity than currently operating reactors (Abdulla et al., 2013; Anadón et al., 2012). However, since no SMRs have been manufactured, it is not possible to reliably evaluate these arguments (Ramana and Mian, 2014a). As a consequence, work has to be done by stakeholders and policy makers to focus on developing the supply chain and addressing licensing issues (Locatelli et al., 2014; Ramana and Mian, 2014a; Sainati et al., 2015). However, other authors point out that cost is not the only issue that needs to be addressed by nuclear power. Safety, waste, and proliferation are key problems that need to be faced, and the adoption of SMRs to reduce cost may not address the other issues, or even make one or more of the other problems worse (Ramana and Mian, 2014b).

In the following sections, we analyze the factors that contribute to the capital costs of SMRs, giving particular emphasis to the comparison of capital costs of SMRs to the capital costs associated with conventional large reactors.

3.2.1 Fabrication in factory and modularization

Modularization, which has been extensively covered in Section 2.1, is applicable to both small reactors and large reactors. Mitenkov et al. (2007) show that 30-35% cost savings were achieved in the construction of a nuclear propulsion system with unified equipment and largely factory-made structures delivered to site. However, the design of SMRs embodies technical specifications (e.g. the integral layout, size reduction) which are not applicable to large reactors and allow a higher number of modularized equipment (Locatelli et al., 2014) (Carelli et al., 2010). As a consequence, benefits of modularization are believed to be higher for SMRs than for large reactors.

3.2.2 Simplification of design

SMRs are characterized by a simpler design, which is enhanced through the use of intrinsic and passive safety characteristics, resulting in a reduced number of components, especially active. An important effect of design simplification on capital costs is related to the amounts of required commodities (such as steel or concrete) during fabrication. In fact, as a consequence of their compactness, SMRs have a commodities index (m^3/kW) comparable and in some cases lower than that of large plants (Bari et al., 2015). The simplification of the design has the effect to lower the operation and maintenance costs (Carelli et al., 2007a). Because of the simplification of the design and smaller size, authors believe that engineering additions required to enhance security may be intrinsically less expensive in SMRs (Carelli et al., 2007a).

3.2.3 More units on site and on-site learning

The possible deployment of multiple SMR units at a single site must be taken into consideration, as sharing infrastructure, systems and services may result in a decrease of some fixed costs. Another factor that has to be taken into consideration is learning, for which a 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. M. D.

Carelli (Carelli et al., 2007a) estimated that learning is reached after 5-7 units. Therefore, considering a 350 MWe SMR plant, the NOAK is reached after 2100 MWe, while for a 1400 MWe large plant it is reached after 8400 MWe. This has the effect that reaching the NOAK point earlier, 18 more SMR units can take advantage of learning before the fleet of large plants is built. The number of reactors that have to be constructed in order that the benefit from learning would compensate for the economies of scale may need to be large, depending on the learning factor (Ramana et al., 2013).

3.2.4 Construction time

Another parameter that has an important impact on total capital investment cost is construction time. In particular, an increase in time schedule affects the following:

- Labor costs;
- Rent fees for building infrastructures (e.g. special cranes);
- Cost Escalation;
- Interest during construction.

The intrinsic characteristics of SMRs such as their smaller size, simpler design, increased modularization and the higher degree of factory fabrication allow achieving a shorter construction time, with subsequent lower construction costs (Berthelemy et al., 2016). Furthermore, the lower construction time lowers the pre-completion risk (Rosner and Goldberg, 2011). With respect to SMRs, Kuznetsov and Lokhov (2011) showed that, for example, if the construction duration for a small plant is three years instead of six years for a large plant, the savings due to lower interest during construction will be 9% at a 5% discount rate and 20% at a 10% discount rate (Figure 20), assuming a flat spending profile.

Current target schedules for SMRs are typically three years for the FOAK with a subsequent reduction to two years for the NOAK (Carelli et al., 2007a).

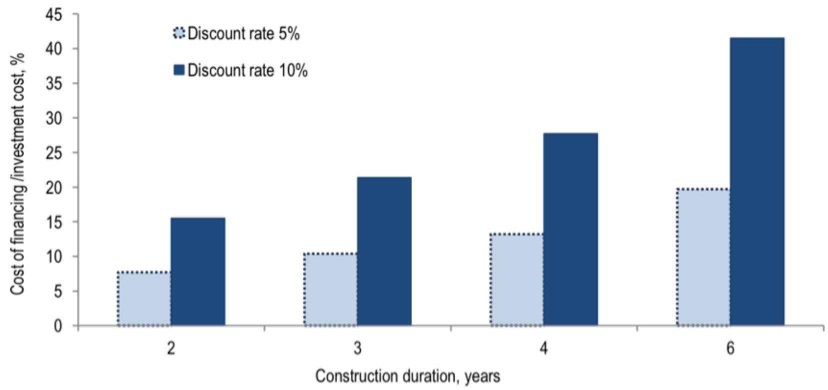


Figure 20 – Cost of financing as a function of construction duration and discount rate (Kuznetsov and Lokhov, 2011)

3.2.5 Capital outlay and capital at risk factor

Because of their lower design power, the total capital investment cost of an SMR is only a fraction of the cost of a large plant, with a subsequent lower front-end investment required. This aspect could be a critical factor especially for those countries or utilities with limited financing resources (Ramana and Ahmad, 2016). Another benefit of the smaller power of SMRs compared to large reactors is the lower market risk for the utility, as they produce less power that needs to be sold as compared to GWe-level plants, and are therefore less likely to depress prices in their own market. Furthermore, the combination of the reduced front-end investment and the shorter construction time makes it possible to minimize the capital at risk through a staggered construction/operation of multiple modules deployed in succession, as illustrated in Figure 21, where the maximum amount of capital at risk for a large reactor is about 65% higher than that for four SMRs of the same total power (Petrovic et al., 2012).

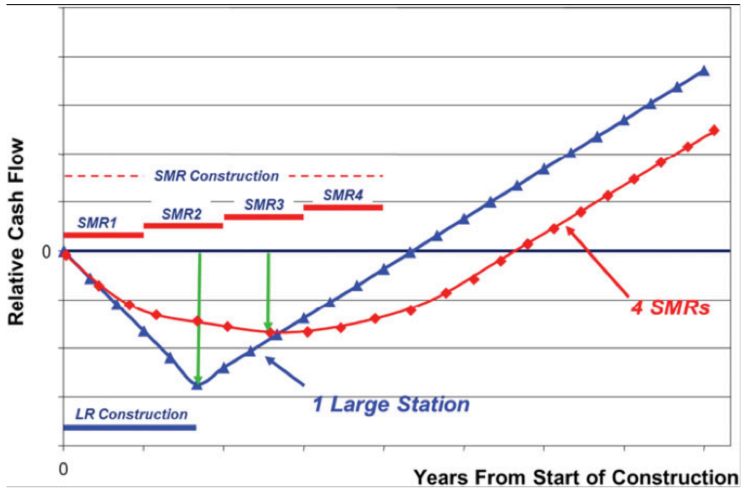


Figure 21 – Staggered modular build reduces maximum cash outlay and capital at risk (Petrovic et al., 2012)

3.3 Project risks estimates and unknown unknowns

In identifying contingencies, a proper project probabilistic cost and schedule risk model has to be developed. However, not all risks can be identified in advance. As Donald Rumsfeld, US Secretary of State for Defense, stated in February 2002, "There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know" (Rumsfeld, 2002).

Following this consideration, risks can be classified based on the level of knowledge about a risk event's occurrence (either known or unknown) and the level of knowledge about its impact (either known or unknown). This leads to four categories of risk (Cleden, 2009; Raydugin, 2010):

1. Known–knowns (knowledge);
2. Unknown–knowns (impact is unknown, but existence is known, i.e., untapped knowledge);

3. Known–unknowns (risks);
4. Unknown–unknowns (unfathomable uncertainty);
5. Biases (conscious or subconscious systematic errors occurring when identifying and quantifying general uncertainties and uncertain events.

In the nuclear industry, an example of known unknowns is the duration of an activity, which behaves as a stochastic process, whose value cannot be known with certainty. Unknown unknowns occur whenever information about uncertainties exists but is not accessible, or simply does not exist. In this case, the impact of these uncertainties cannot be evaluated in advance (Stoelsnesa, 2007). The reasons why some risks cannot be detected in advance are various (Hillson, 2005):

1. Risks are inherently unknowable;
2. Some risks are time-dependent;
3. Some risks are progress-dependent;
4. Some risks are response-dependent, i.e., secondary risks.

In the nuclear industry, an example of an unpredictable event having unpredictable consequences are the TMI accident that took place in March 1979, and or the 9/11 terroristic attack in New York City, which caused unpredictable changes in regulations by the Nuclear Regulatory Commission (NRC). In the US, all plants completed after 1979 began construction before the TMI event, and all experienced a cost escalation, as described in Section 2.3 (Figure 5). Following the 9/11 attack, NRC introduced new design requirements after the plant design had been completed, which led to redesign the shield buildings to be airplane crash proven. Westinghouse Electric Company had to revise the

AP1000 project with subsequent delays in the construction with a subsequent cost increase (Hals and Flitter, 2017). Several publications point to the importance of taking unknown unknowns into account in risk management (Chapman and Ward, 2003; Hubbard, 2009; Wideman, 1992). Missing or inadequately taken into account unknown unknowns lead to non-adequate contingencies.

There are different ways of managing unknown unknowns (projectmanager.com.au, 2016). A quantitative approach consists of analyzing historical data and trends as well as the established project parameters, costs and, limitations. A qualitative approach consists of estimating potential project restraints and failures through project management experience. Unknown unknowns can be converted to known unknowns, based on expert assessment/judgement, and different cases can be run through risk assessment tools. However, the very reason the unknowns are unknown to us in the first place is that they are hard to establish based on the past track records and predictable challenges. Also, the study of the type of industry may provide useful insights when evaluating unknown unknowns (Raydugin, 2010). The downside of this approach is potential for the managers to err in their estimations and assessments.

3.3.1 The four aspects of unknown unknowns

Raydugin (2010), identifies four aspects of unknown unknowns. First, unknown unknowns are higher for a unique and novel project. The development of a new technology, or the development in a new geography, increase the overall project risk exposure, including unknown unknowns. Second, the amount of standardization and repetitiveness adopted by an organization affects the occurrence of unknown unknowns. The organization experience, lesson learned and similarity with an already adopted technology can reduce unknown unknowns. The third aspect is related to the phase of a project development. A project at an earlier phase of development is inherently characterized by more unknown unknowns. The type of industry or projects inside a particular industry (for example, natural gas vs. nuclear vs. coal) can provide useful insights when assessing project unknown unknowns. The fourth relates to the level of bias of the project. As Raydugin (2010) points out, organizations tend to be "optimistic" in evaluating risks and consciously exclude some "factors such as hidden agendas, when some risks might be missed on purpose, to make a project more attractive, etc. This may be based on explainable desire to get project funding or support from key stakeholders" (Raydugin, 2010). There is no doubt that during construction of the four AP1000 units in the US (two in Vogtle and two in VC Summer), project managers have underestimated the impact of unknown unknowns. In these projects, omissions of unknown unknowns belonging to the categories described in this section can be found. The AP1000 design, despite being based on standard PWR technology, can be considered a new technology. The new design of the nuclear island structures, new nuclear components (reactor pressure vessel pumps, modules), new construction technique make the reactor a new technology. Modular construction of the NPPs had never been adopted before in the nuclear industry. Therefore, despite the intended higher standardization of components, the construction itself can be considered a novel approach, making the reactors 1st-of-a-kind plants. Moreover, project managers might have been too "optimistic" in evaluating the construction capabilities of WEC and the manufacturing capabilities of nuclear components by CB&Is Stone and Webster (earlier acquired by Shaw Group). The mistakes made in the concrete pouring at Vogtle, or the mistakes made by Shaw in the manufacturing of the RPV head might support this argument.

3.3.2 *Incorporating unknown unknowns in a risk management tool*

Unknown unknowns can be estimated analyzing the risk occurrence on previous projects, analyzing historical data. Based on the project managers experience, the risk evaluation can be modified to also include a qualitative risk assessment. Successively, unknown unknown allowances can be introduced in the probabilistic risk assessment models. Duration allowances can be introduced as an activity at the very end of the project schedule, which can be expressed as a percentage of the construction duration. Alternatively, an additional risk can be associated with the project completion milestone, assigning a probability to this risk. Considering a probability less than 100% reflects the possibility that some unknown unknowns are associated with activities outside the critical path and, therefore, have minimal or no impact on the project duration (Raydugin, 2010).

The effect of the TMI event on the construction of the nuclear reactors completed after 1979 was analyzed as a representative example of unknown unknown.

3.3.3 *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:

$$Cont = p_{TCIC} - Mo_{TCIC} \tag{25}$$

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:

$$Cont = p_{TCIC} - Mo_{TCIC} \tag{26}$$

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

4 COST ESTIMATE METHODS

The cost estimating process of a new generation reactor can take two different paths: top-down or bottom-up, depending on the stage of the project and the resources available to the design team.

Bottom-up cost estimating consists of collecting very detailed data on components and activities involved in the NPP construction, such as equipment, materials and labor quantities. Labor-hour rates, installation rates, commodities and unit prices are then applied to calculate costs of activities and components. This approach relies on the manufacturing assembly plan, the PBS and the WBS, that have to be available at the estimating stage.

For projects early in the development process, Bottom-up cost estimates are often not practical to use, as information on manufacturing and installation techniques of these systems is not available. For these projects, top-down cost estimating techniques are preferable. The first step consists of identifying a reference design to which estimating techniques can be applied. The estimating part consists of scaling up or down the costs of systems and components used in similar projects.

4.1 EVAL

EVAL is a methodology that was developed to calculate TCIC of an NPP. A schematic of the EVAL process is shown in Figure 22. The methodology was implemented in MS Project 2010 through the use of a series of Visual Basic for Applications (VBA) scripts. VBA scripts were made to automatically import data from inputs, contained in MS Excel spreadsheets, and automatically extract and calculate outputs into MS Excel spreadsheets. The methodology relies on a bottom-up approach that is based on the availability of a Part Breakdown Structure (PBS) or Work Breakdown Structure (WBS) of the NPP. Both the PBS and WBS contain information on components, activities and construction logic. The PBS is a list of components that make the NPP, where the construction logic and the activities are expressed as a function of the parts. The WBS is a list of the activities (work) needed for the NPP completion (AACE International, 2016), each associated with the parts needed for the activity and the logic with other activities. The construction process of an NPP can be either described by a PBS or a WBS, depending on the specific choice of the nuclear vendor under consideration. From the PBS or WBS, the construction schedule of the NPP is generated, associating attributes (activities and components construction times and costs) to every component and activity. An as-late-as-possible (ALAP) logic is used, as it allows a delayed (just-in-time) cash flow that lowers the value of TCIC. However, delaying activities in order to make activities end-dates coincide with start-date of subsequent activities, increases the project possible delays and project risk. The analysis shown in this paper was conducted to evaluate the impact of key parameters assuming a deterministic construction schedule and deterministic inputs (costs and durations). Duration of activities, cost of equipment, cost of materials, labor rates were provided by the vendor, but typical labor rates and material unit costs are publicly available in literature (Economic Modeling Working Group, 2007). Ongoing work is addressing the probabilistic aspect of the schedule and cost; it will allow assessing the risk associated with ALAP. Duration of activities, cost of equipment, cost of materials, labor rates were provided by the vendor, but typical labor rates and material unit costs are publicly available in literature (Economic Modeling Working Group, 2007). TCIC is calculated integrating the cash flow taking into account the time value of capital.

Figure 22 – EVAL process

In summary, the methodology implemented in MS Excel and MS Project consists of the following steps:

1. Create PBS/WBS (parts needed from factory, activities, construction logic) in MS Excel (input 1);
2. Create MS Excel file (input 2) with supply chain data (fabrication construction times/costs, labor rates, activities durations/costs);
3. Import data through VBA script from inputs 1-2 to MS Project file to model construction process;
4. Calculate and export to MS Excel output file through VBA scripts the following: direct costs; indirect costs; IDC; TCIC; cash flow profile; project duration.

As EVAL is based on a bottom-up methodology, it can be used for a NPP of any size and reactor as long as very detailed data on the design was developed. A baseline design, with number of components, and layout diagrams for all major systems, commodity quantity estimates, labor rates, activity durations, unit material costs, have to be available.

As a consequence, EVAL can be applied only to reactors at a mature design stage and cannot be applied to reactors at a pre-conceptual or conceptual stage of development.

Construction of a modular NPP proceeds in three different stages: fabrication, assembly and installation. In the fabrication stage, components (modules) are manufactured according to shippable constraints. The transportation constraints are defined by standard rail shippable limits, which are 12x12x80 feet (approximately 3.7x3.7x24.4 meters) for a weight of 80 tons. The fabrication of a module is preceded by a construction time, which represents the time between ordering and fabrication. At the time of ordering, the cash flow associated with the equipment is assumed to take place. The cash flow associated with the labor and material required to the manufacturing process is distributed over the process duration. After the fabrication stage, modules are transported to the site. Schematic of the sequence between fabrication activities and cash flow is shown in Figure 23.

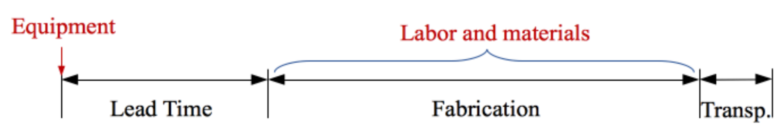


Figure 23 – Module fabrication cash flow representation

The WEC-SMR relies on a more compact site layout than that of the PWR12. As the NI performs the function of the PWR12 containment building, fuel storage building, administration and service building, and part of the radioactive waste (radwaste) building. In the PWR12-BE cost accounts, the components that are included in the WEC-SMR NI represent the 49.7% of the plant direct cost. The WEC NI is shown in Figure 24. The nuclear island of the WEC-SMR is made of different modules that can be categorized by the function they perform:

- Mechanical (safety)
- Mechanical (non-safety)
- Instrumentation and control (I&C) • Composite
- Structural

In EVAL, modules were categorized by module type, and typical fabrication costs and durations were used for each module type. On site, modules are assembled into super modules in the on-site assembly area. Super modules are designed according to the capacity of the crane available on site, as they need to be lifted and installed in the on-site hole to form the nuclear island (installation stage). Fabrication costs and construction times, and activities durations and costs were provided by the nuclear vendor. Cost of activities in the assembly and installation stages are distributed over the activities durations. The construction model of the WEC-SMR nuclear island is made of 1953 activities in the fabrication, assembly and installation stages. Testing follows the installation stage, and the cost was neglected. A breakdown of number of activities in each stage is shown in Table 10. EVAL was used to describe the construction of the WEC-SMR nuclear island, but it can be applied to a NPP of any size and design. However, since the methodology relies on a bottom-up approach, the nuclear reactor under consideration has to be at a late stage of development, as fairly detailed data (PBS/WBS, supply chain data), needs to be available.

Table 10 – WEC-SMR nuclear island, number of activities

	Number of activities
Equipment order	660
Fabrication	660
Assembly	359
Installation	274
Testing	4

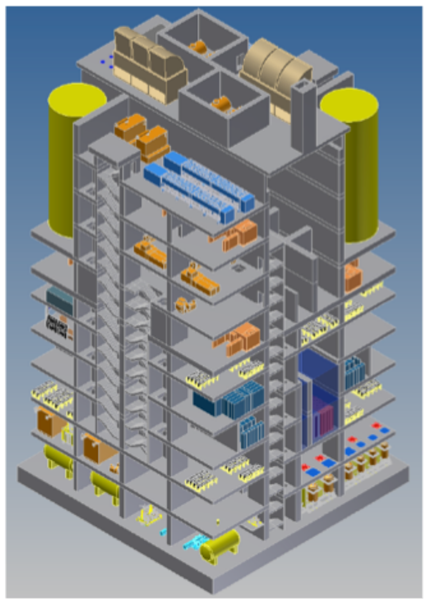


Figure 24 – WEC-SMR nuclear island (Bowser)

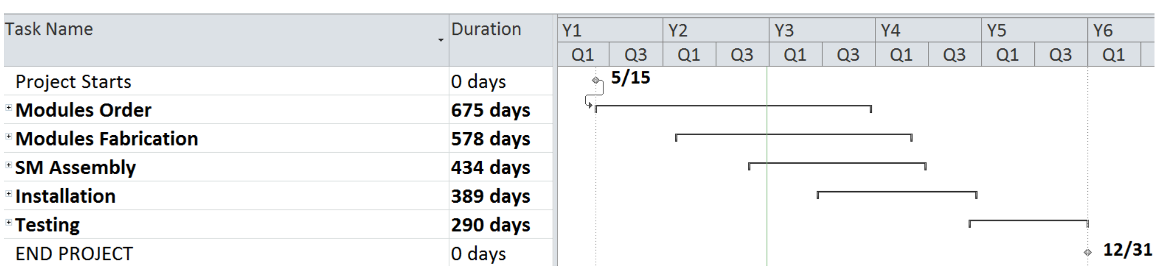


Figure 25 – WEC-SMR nuclear island constructions schedule

4.1.1 Modularization and TCIC

The benefits of modularization were calculated comparing three different strategies in the construction of the WEC-SMR nuclear island. The three construction strategies are shown in Fig. 9 and each one is characterized by a different degree of modularization.

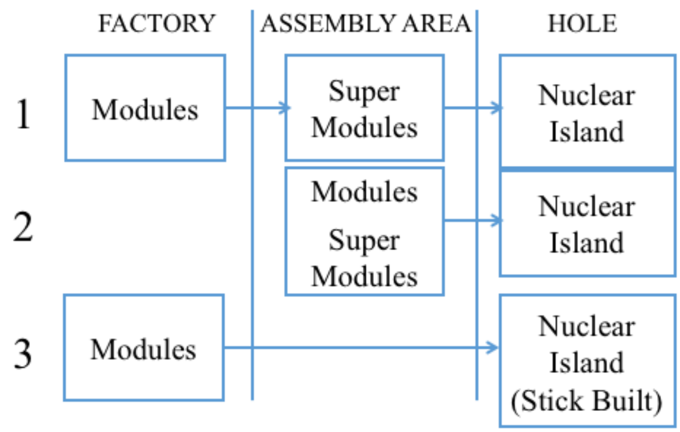


Figure 26 – Construction strategies schematic

The first construction strategy is defined as the complete modularization, as modules are fabricated in factory, assembled into super modules in the on-site assembly area and installed in the hole to create the nuclear island. The second construction strategy is characterized by a lesser degree of modularization as modules are fabricated in the on-site assembly area where they are assembled into super modules. The third construction strategy represents stick-built construction: modules are fabricated in factory, shipped to the site and installed in the hole, where the connections between modules are performed. Structural modules are not part of the stick-built construction, as the structures are built in the hole. No super modules are present in this construction strategy. The construction strategies were chosen to evaluate the impact of each construction location on TCIC. The comparison between strategy one and strategy two highlights the effect of off-site modular fabrication. The comparison between strategy one and strategy three shows the impact of the on-site modules assembly stage. It is important to note that NOAK cost inputs for modules and components were used. Under this assumption, the investment required to design and develop a supply chain for the SMR under consideration was not considered. As described in Sections 2.1 and 2.2, modular construction carries high investment costs in the supply chain that may increase the total risk of SMR deployment. The scope of this analysis is to quantify and estimate the benefits of modular construction on Total Capital Investment Cost of a NOAK single unit NPP, as compared to standard stick-built construction.

As the construction process of the WEC-SMR nuclear island is described in terms of the PBS, EVAL inputs for the first construction strategy are derived from the WEC-SMR part breakdown structure. Attributes of activities and components are taken from the industry experience in NPP construction. The assumption that no limitation is present in the offsite factories production capabilities was made. Factories were assumed to be capable of producing the exact number of modules needed on site at any time, i.e. there is no constraint on the degree of parallelism allowed in the fabrication stage. Inputs for strategy two are the same as those of strategy one. As fabrication is performed in the on-site assembly area, the level of parallelism allowed in this stage is lower and, therefore, the number of activities that can take place at the same time is lower In fact, as the availability of space in the assembly area is lower than in the factory, the assembly area is more congested,. The third construction strategy represents stick-built construction. The logic of connecting components in the third construction strategy is different than that of construction strategy one and two, as the installation stage is made of different activities.

Mechanical, I&C and structural modules are manufactured in factory and transported on site where they are installed level by level in the hole, as the construction of structures proceeds. The equipment needed for modules connections, which is part of composite modules in strategy one and two, is shipped to site and used to perform connections in the hole. Durations of installation activities were based on industry experience and on the use of the 1-3-8 rule.

4.1.2 TCIC sensitivities

Calculating TCIC of a NPP is fundamental to determine the economic competitiveness of its particular design. TCIC estimate is dependent on particular assumptions and cost models adopted. Sensitivity analyses on TCIC and direct costs obtained can show the impact of the assumptions. Furthermore, changing attribute values of key components and activities through sensitivity analyses can be used to improve the construction process and better inform the stakeholders decisions. Effect of the discount rate on TCIC was evaluated.

5 MODELING UNCERTAINTIES: METHODS AND APPROACH

In this chapter, the methods used to combine and describe uncertainties in the construction of an NPP are presented. As the construction of an NPP is dependent on different 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 TCIC and calculate cost contingency.

5.1 The effect of uncertainties

Whenever an activity is by its nature stochastic, its expected present value of cost is invariably greater than its present value if the activity is assumed to be deterministic. The demonstration compares an activity modeled as deterministic and an activity assumed to have a symmetric triangular distribution. The triangular distribution is a continuous probability distribution function described by three parameters: 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 project managers 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. The probability density function of an activity with a triangular distribution is shown in Figure 27.

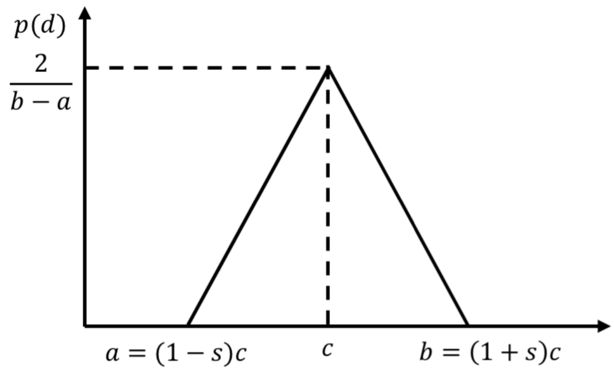


Figure 27 – Symmetric triangular probability density function

This probability density function is described functionally as

$$p(d) = \begin{cases} \dfrac{2(d-a)}{(b-a)(c-a)} & for \quad a \le d < c \\ \dfrac{2(b-d)}{(b-a)(c-a)} & for \quad c \le d < a \end{cases} \tag{27}$$

The cash flow of an activity of duration d_A, start time $T_{A,s}$ and end time $T_{A,e}$ is presented in Figure 28. We assume that the cost of the activity (C_A) is accrued in the middle of its duration ($d_A/2$). This is a simplification, as in reality the cash flow follows a particular distribution over time. Eq. 28 is used to calculate the present value of cost of the activity at the start time of the project ($T_{P,}$s):

$$v = \frac{C_A}{(1+r)^{T_{A,e}-d/2}} \tag{28}$$

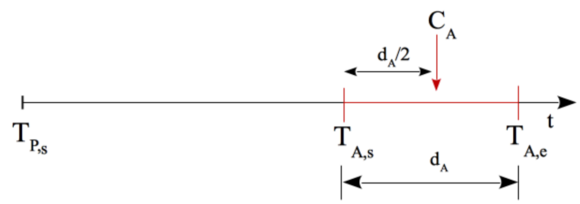


Figure 28 – Activity cash flow representation

Eq. 28 represents the present value of cost of an activity with a deterministic duration, under the assumption that the cost of the activity is accrued in the middle of its duration. The average expected present value of cost of the activity, assuming that the time at which cost accrued can be described using probability density function and calculated using Eq. 29:

$$E[v] = \int_{t_{c,\max}}^{t_{c,\min}} \frac{C_A}{(1+r)^{t_c}} p(t_c)\,dt_c \tag{29}$$

In case duration is expressed using a probability density function, the integral can be adjusted through a change of variables, as indicated in Eq. 30:

$$p(t_c) = p(T_{A,e} - d/2) = p(-d/2) = -1/2\,p(d) \tag{30}$$

and the integral becomes:

$$E[v] = \int_{t_{\min}}^{t_{\max}} \frac{C_A}{(1+r)^{t_c}} p(t_c)\,dt_c = -\frac{1}{2}\int_{t_{\min}}^{t_{\max}} \frac{C_A}{(1+r)^{t_c}} p(d)\,dt_c \tag{31}$$

In case we consider a symmetric triangular distribution, we can express the upper and lower bound as a function of the most probable value given in Eq. 32.

$$a = c(1 - s) \qquad and \qquad b = c(1 + s) \tag{32}$$

It can also be shown that for a symmetric triangular distribution, the most probable value corresponds to the expected value. The probability density function becomes:

$$p(t_c) = \begin{cases} \dfrac{2(2T_{A,e} - 2t_c - a)}{(b-a)(c-a)} & for \quad T_{A,e} - \dfrac{c}{2} \le t_c < T_{A,e} - \dfrac{a}{2} \\ \dfrac{2(b - 2T_{A,e} + 2t_c)}{(b-a)(c-a)} & for \quad T_{A,e} - \dfrac{b}{2} \le t_c < T_{A,e} - \dfrac{c}{2} \end{cases} \tag{33}$$

Substituting Eq. 33 in Eq. 31:

$$E[v] = \frac{C_A}{c^2 s^2}\left\{\int_{T_A - \frac{c+cs}{2}}^{T_{A,e} - \frac{c}{2}} \frac{1}{(1+r)^{t_c}}\left(c + cs - 2T_{A,e}\right) + \int_{T_A - \frac{c}{2}}^{T_{A,e} - \frac{c-cs}{2}} \frac{1}{(1+r)^{t_c}}\left(2T_{A,e} - 2t_c - c\right)\right\} \tag{34}$$

and solving the integrals, we obtain:

$$E[v] = \frac{C_A}{s^2 c^2}\left\{-\frac{1}{\ln(1+r)^2}\frac{1}{(1+r)^t}\left[1 + \ln(1+r)(c - 2T_{A,e} + 2t_c + cs)\right]\Big|_{T_{A,e} - \frac{c+cs}{2}}^{T_{A,e} - \frac{c}{2}} + \right.$$

$$\left. + \frac{1}{\ln(1+r)^2}\frac{1}{(1+r)^{t_c}}\left[1 - \frac{1}{2}\ln(1+r)(2T_{A,e} - c - 2t_c + cs)\right]\Bigg|_{T_{A,e} - \frac{c}{2}}^{T_{A,e} - \frac{c-cs}{2}}\right\} \tag{35}$$

Eq. 35 states the expected value of the cost CA is composed of the present value of cost of the deterministic activity multiplied by a term representing the probabilistic effects on the activity duration:

$$E[v] = \frac{C_A}{(1+r)^{T_{A,e}-c/2}} \frac{1}{s^2c^2 \ln(1+r)^2} \left[\frac{1}{(1+r)^{cs/2}} + (1+r)^{cs/2} - 2 \right] \tag{36}$$

Eq. 37 presents the ratio between the expected value of cost of the triangular symmetrically distributed activity and the present value of cost of the deterministic activity:

$$\frac{E[v]}{v} = \frac{1}{s^2c^2 \ln(1+r)^2} \left[\frac{1}{(1+r)^{cs/2}} + (1+r)^{cs/2} - 2 \right] \tag{37}$$

It can be shown that the ratio expressed in Eq. 37 is always greater than one, indicating that the expected value of the cost C_A (if d is a random variable with symmetric triangular distribution) is always greater than the present value of the cost C_A when d is deterministic. Eq. 37 as a function of s is plotted for different values of the discount rate r and the most probable duration c in Figure 29 and Figure 30.

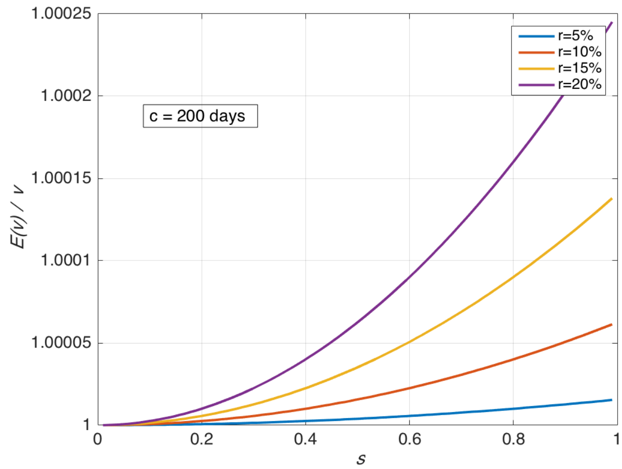


Figure 29 – Expected cost value as a function of the distribution dispersion for different discount rate values (c = 200 days)

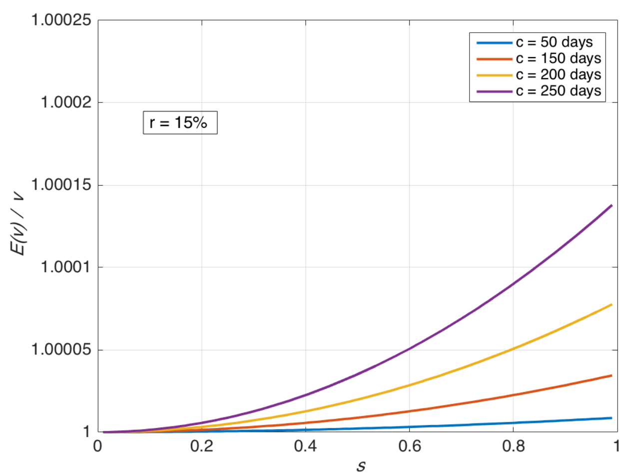


Figure 30 – Expected cost value as a function of the distribution dispersion for different activity durations (r = 15%)

Whenever a stochastic effect is introduced in the duration of a manufacturing process, the present value of cost of this process is always higher than the case when the process is deterministic (with duration equal to the average duration of the stochastic case). We also note that as *s* increases, the present value of cost increases and the differences between the average value and the lower and upper bounds increase. These facts support the need for an extensive study of the impact of randomness on the SMR construction process.

5.2 The Monte Carlo method

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 from 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. Considering a random variable x that takes values according to a specific probability distribution, its probability density function (PDF) and cumulative distribution function (CDF) are defined as $f(x)$ and $F(x)$, respectively. In every simulation, the value of the cumulative distribution function is sampled trough a random number generator. The random number generator generates random numbers ξ uniformly distributed between 0 and 1. The value that $F(x)$ takes in the simulation is then:

$$F(x) = \xi \tag{38}$$

To sample the value of the random variable x, the inversion has to be performed:

$$x = F(\xi)^{-1} \tag{39}$$

Sampling the variable x through this procedure for a number of times we obtain an estimate of its distribution. The inversion of the cumulative distribution function of x can be performed through different techniques. TCIC is calculated summing all the project costs that are stochastically sampled. Repeating this procedure for a large number of runs, we calculate the average value and variance of TCIC in the Monte Carlo simulation through Eq. 40 and 41:

$$\mu_{TCIC} = \frac{1}{N}\sum_{n=1}^{N} TCIC_n \tag{40}$$

$$S_{TCIC}^2 = \frac{1}{N-1}\sum_{n=1}^{N}(TCIC_n - \mu_{TCIC}) \approx \sigma_{TCIC}^2 \tag{41}$$

In the analysis shown in this paper, variances are labeled as σ.The Monte Carlo method was used to estimate the uncertainties in project duration, OCC, TCIC and estimate contingency for a general SMR design and for PWR12-BE.

5.3 Symmetric probability distributions

5.3.1 Symmetric triangular distribution sampling

Eq. 42 describes the triangular cumulative distribution function of x:

$$F(x) = \begin{cases} \dfrac{(x-a)^2}{(b-a)(c-a)} & 0 < \xi \leq \dfrac{c-a}{b-a} \\ 1 - \dfrac{(b-x)^2}{(b-a)(c-a)} & \dfrac{c-a}{b-a} < \xi < b \end{cases} \tag{42}$$

Equating the cumulative distribution function to ξ, where $0 < \xi < 1$, yields the inverse cumulative distribution function (Eq. 43):

$$\hat{x} = F(\xi)^{-1} = \begin{cases} a + \sqrt{(b-a)(c-a)\xi} & 0 < \xi \leq \frac{c-a}{b-a} \\ b - \sqrt{(b-a)(b-c)(1-\xi)} & \frac{c-a}{b-a} < \xi < b \end{cases} \tag{43}$$

Using a random number (between 0 and 1) generator, we can use Eq. 43 to compute the value of each random variable in every run. 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.

$$a = c(1-s) \tag{44}$$

$$b = c(1+s) \tag{45}$$

The parameter s is a dispersion indicator of the probability distribution. The triangular distribution variance is equal to its second moments given in Eq. 46:

$$\sigma^2 = \mu_2 = \frac{1}{18}(a^2 + b^2 + c^2 - ab - ac - bc) \tag{46}$$

from which, substituting Eq. 44 and Eq. 45, we can obtain an expression for the standard deviation:

$$\sigma = \frac{cs}{\sqrt{6}} \tag{47}$$

5.3.2 Normal distribution sampling

Eq. 48 and 49 present the probability density function and the cumulative density function of the normal (Gaussian) distribution function:

$$f(x) = \frac{1}{\sigma\sqrt{\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{48}$$

$$F(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \tag{49}$$

A random number ξ is generated and Eq. 49 is inverted to calculate the value of the random variable x. Every random variable is described by a mean value (equal to the deterministic value of the random variable) and a standard deviation. The standard deviation was expressed as a fraction of the mean value, as:

$$\sigma = t \cdot \mu \tag{50}$$

A normal distribution can be approximated by a symmetric triangular distribution, if the two distributions have the same mean value and standard deviation. Equating the value of the parameter t (Eq. 47) to the value of s (Eq. 50), since c and μ both represent the deterministic cost and duration of the activity, the relationship between t and s is:

$$t \cdot \mu = \frac{c \cdot s}{\sqrt{6}} \rightarrow t = \frac{s}{\sqrt{6}} \tag{51}$$

The values of t used in the simulations are shown in Table 11.

Table 11 – Equivalence between *s* and *t*

s	t
0	0
0.50	0.2041
1.00	0.4082
2.00	0.8165

5.4 Asymmetric probability distributions

Activity durations and costs are naturally described by asymmetric distributions; the probability that an activity will take longer (with a higher cost) than expected is more likely than the activity will take less time (with lower cost) than expected. Such situations are well represented by positive asymmetric distributions (skewed to the right).

5.4.1 Asymmetric Triangular distribution sampling

In the case where the triangular distribution is skewed to the right, the distance between c and b is higher than the distance between a and b (Figure 31).

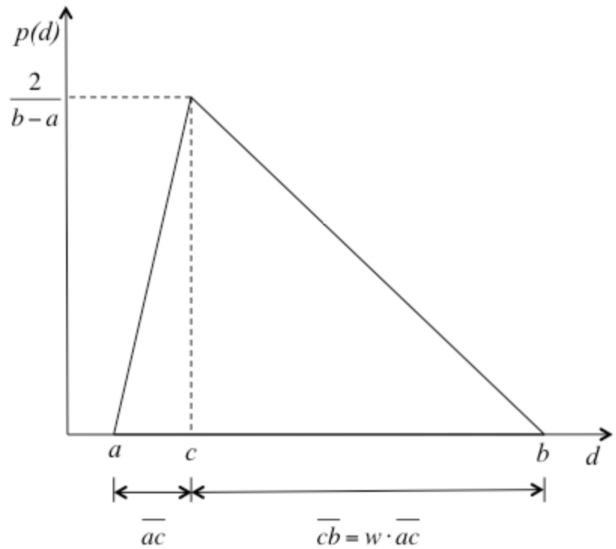


Figure 31 – Asymmetric triangular probability density function

The level of asymmetry can be expressed by the parameter *w*, defined as:

$$w = \frac{\overline{cb}}{\overline{ac}} \tag{52}$$

A value of *w* equal to 1 represents the case where the two sides of the triangle have the same length and the distribution reduces to a symmetric triangular distribution. The minimum value of the distribution *a* is expressed as a fraction of the most probable value *c*, while the maximum value of the distribution *b* is expressed through *w*:

$$a = c \cdot (1 - s) \tag{53}$$

$$b = c \cdot (1 + w \cdot s) \tag{54}$$

Each type of activity is characterized by different values of *s* and *w* (distribution skew). The parameter *s* represents the width of the distribution in case the probability distribution is symmetric. In other words, in case the probability distribution is skewed to the right, *s* represents the width of the left side of the distribution. Both parameters *s* and *w* 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).

However, for simplification, in each simulation, every activity was assumed have the same values of *s* and *w*. 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 function expressed by Eq. 42 is then inverted (Eq. 43) and the activities duration and cost are calculated. The value of TCIC for the project is then calculated based on the project schedule and cash flow. DC is then calculated summing the costs of all activities. For the SMR, OCC is calculated through Eq. 7, and for the PWR12-BE OCC is calculated through Eq. 24. For both plants, IDC is calculated through Eq. 20, and TCIC is calculated summing OCC and IDC (Eq. 21). In summary, the process is based on the following steps:

1. Sample random number ξ;

2. Calculate activity costs and durations, as:

$$x = F(\xi)^{-1} = \begin{cases} a + \sqrt{(b-a)(c-a)\xi} & 0 < \xi \leq \dfrac{c-a}{b-a} \\ b - \sqrt{(b-a)(b-c)(1-\xi)} & \dfrac{c-a}{b-a} < \xi < b \end{cases} \tag{55}$$

3. Calculate DC as the sum of all activity costs;

4. Calculate OCC as (see Eqs. 22-24):

$$OCC_{SMR} = DC \cdot (1 + 0.35) \tag{56}$$

$$OCC_{PWR} = DC \cdot (1 + 0.67) \cdot (1 + 0.078) \tag{57}$$

5.5 Correlated sampling through the Iman-Conover method

In the construction of a NPP, cost of components and duration of activities are not independent, but inter-correlated. For example, the cost of different components might depend on the price of the same commodities, such as steel and labor. 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. Iman and Conover developed the method while studying how radionuclides might escape a waste depository in bedded salt. While working on these models, they realized that the assumption of independence between input variables was not appropriate. For example, significant correlations were expected to exist between hydraulic properties in the vicinity of the disposal site and the time required for the circulating ground water to contact radioactive wastes. Similarly, subsets of variables in the construction of a NPP are expected to show a significant degree of correlation. 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).

Methods of sampling correlated normal distributed variables were well known at the time of the Iman and Conover work. In the case of normal distributions, a linear combination of independent random variables produces a multivariate normal input vector. Not so, however, for non-normal random variables. 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 presented 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:

$$\rho_{i,j} = \frac{cov(x_i, x_j)}{\sigma_i \sigma_j} \tag{58}$$

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*. A “score” matrix is introduced, as the simple multiplication of by to obtain a matrix with the proper correlation coefficients also would alter the values of the sampled distributions. 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_l be the *N*x*K* 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_l 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:

$$R = \sqrt{2}\,\mathrm{erf}^{-1}\left(2 \cdot \frac{R_i}{N+1} - 1\right) \tag{59}$$

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

$$R^* = RP' \tag{60}$$

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

5.6 Modeling the price of commodities and equipment

An example of known-unknown variable in the construction of a 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. The percentage of each cost type is shown in Table 12. 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 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. The price values were corrected for inflation, and they are shown in Appendix A, along with the CPI values over time (US Department of Labor, 2017a). 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 index 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 Figure 32 and Figure 33, along with their respective histograms and fitted triangular distributions. However, no historical data of nuclear equipment was available. For this purpose, the PWR12-BE breakdown of equipment costs was also used as a cost breakdown of the SMR components.

The correlation between variables was calculated using Eq. 58. The correlation matrix is represented in Figure 34, and the values of the correlation coefficients are reported in Appendix A. Figure 36 shows the absolute value of the correlation matrix in grayscale. 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 $(x_1,\dots,x_{18})$. At the end of each simulation, the total direct cost was calculated as the sum of all components, labor and materials. Through this process, the construction schedule is neglected and, therefore, TCIC is not calculated. As a high number of Monte Carlo simulations are performed, a OCC distribution is obtained, and its standard deviation can be calculated. This approach was applied to both the SMR and the PWR12-BE.

Table 12 – 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%

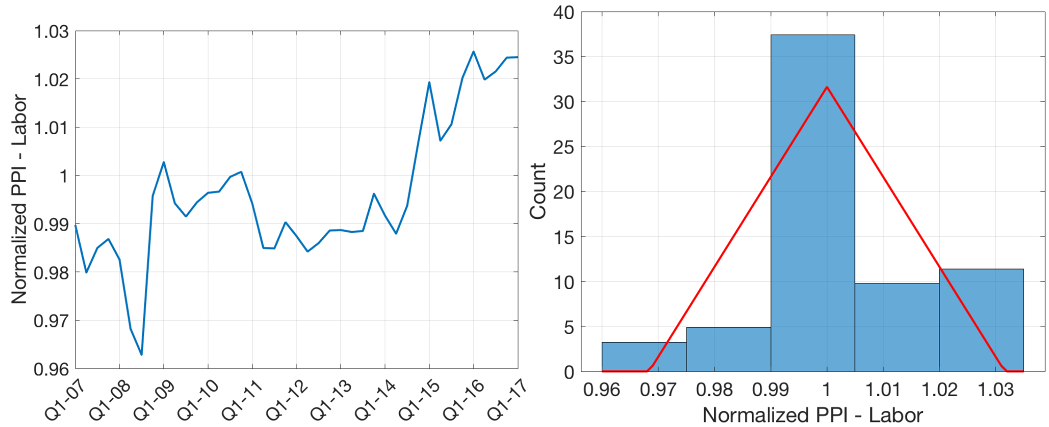


Figure 32 – Normalized PPI labor over time and frequency

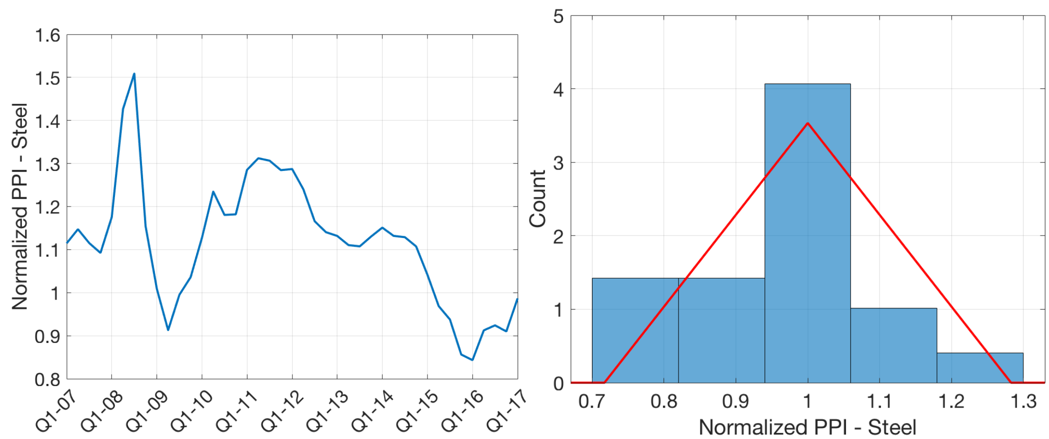


Figure 33 – Normalized PPI steel over time and frequency

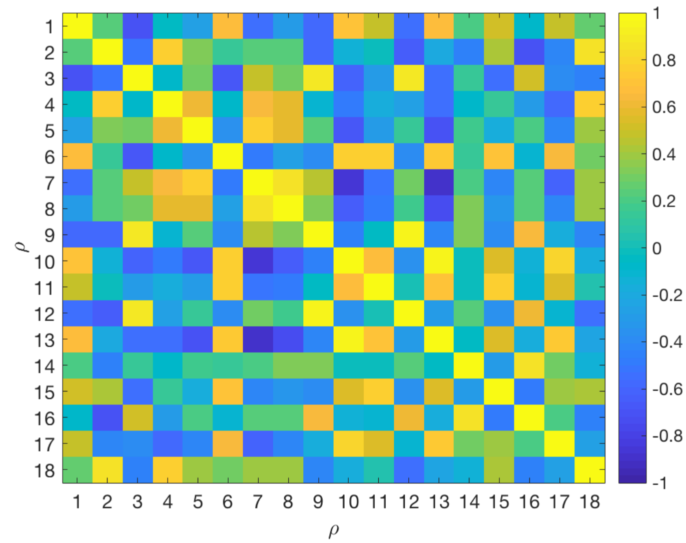


Figure 34 – Representation of the market prices correlation matrix

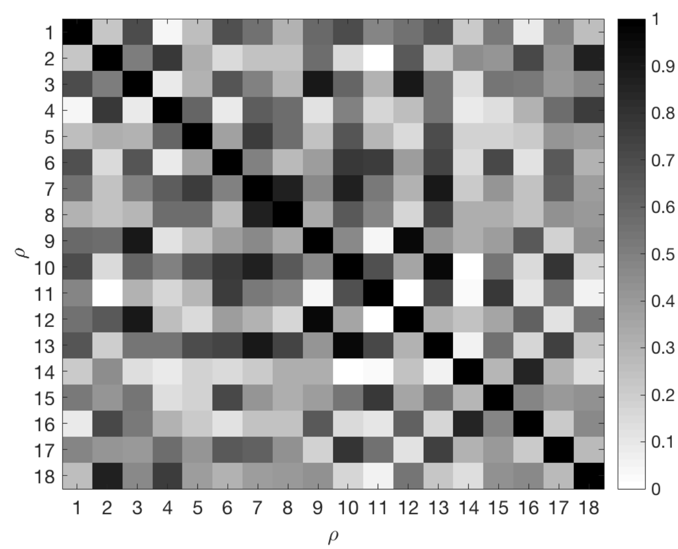


Figure 35 – Representation of the market prices correlation matrix (in grayscale)

5.7 Modifying the model parameters to fit the historical data

Once the SMR and PWR12-BE distributions of project durations, OCC and TCIC were obtained, their mean and standard deviation values were compared to the ones calculated from the historical data. In order to increase the output dispersion and obtain comparable results to the observed data in terms of OCC and project duration, the inputs of the model were then modified. With this goal, two approaches were identified:

1. Increase the correlation coefficients between commodities and equipment prices, and the correlation between activities of the same stage;
2. Increase the dispersion of the price and activity duration probability distributions.

Both approaches were explored, for pre-1979 data (case a) and post-1979 data (case b). Therefore, four sets of simulations were performed (Table 13).

Table 13 – Sets of simulations to fit the historical NPP cost and time data

	b. POST-1979
a. PRE-1979	1. Increase ρ
	2. Increase broadness

In the first approach, the correlation coefficients were simply increased to represent a market where all prices are more correlate while, in the second case, the prices dispersions were increased by broadening the triangular distributions. The distance between the minimum value and most probable value, and the distance between the maximum value and the most probable was increased. The values of the parameters a and b was calculated multiplying the values *(c-a)* and *(b-a)* by a coefficient d_2 (Eq. 43 and Eq. 44).

$$a = c - (c - a) \cdot d_2 \quad (61)$$

$$b = c + (c - b) \cdot d_2 \quad (62)$$

In the first approach, the following steps were followed (case 1a):

1. Increase d_1 until the relative standard deviation of the project duration was in the range 19.15% - 19.24%;
2. Increase d_2 until the relative standard deviation of the OCC was in the range 36.45% - 36.54%.

In the second approach, the following steps were followed (case 2a):

1. Manually set the correlation coefficient between activities of the same type to 0.99;
2. Increase d_1 until the relative standard deviation of the project duration was in the range 19.15% - 19.24%;
3. Set the correlation coefficient between activities of the same type to 0.99;
4. Increase d_2 until the relative standard deviation of the OCC was in the range 36.45% - 36.54%.

To simulate the cost escalation, the price modes (c) were increased using the parameter i_1, while to simulate the increase in project duration, the duration modes were increased through the use of the parameter i_2, as shown in (Eqs. 63,64):

$$c_{price,post79} = i_1 \cdot c_{price,pre79} \quad (63)$$

$$c_{dur,post79} = i_2 \cdot c_{dur,pre79} \tag{64}$$

To account for the cost and time increases after the TMI event, the first approach was modified as follow (case 1b):

1. Increase d_1 until the relative standard deviation of the project duration was in the range 22.75% - 22.84%;
2. Increase the value of i_1, until the project duration mean was increased of a factor in the range 1.75-1.84;
3. Increase d_2 until the relative standard deviation of the OCC was in the range 42.45% - 42.54%;
4. Increase the value of i_2, until the project duration mean was increased of a factor in the range 2.65-12.74.

The second approach was modified as follow (case 2b):

1. Set the correlation coefficient between activities of the same type to 0.99;
2. Increase d_1 until the relative standard deviation of the project duration was in the range 22.75% - 22.84%;
3. Increase the value of i_1, until the project duration mean was increased of a factor in the range 1.75-1.84;
4. Set the correlation coefficient between prices to 0.99;
5. Increase d_2 until the relative standard deviation of the OCC was in the range 42.45% - 42.54%;

6. Increase the value of i_2, until the project duration mean was increased of a factor in the range 2.65-12.74.

The two approaches previously presented differ as either the distribution dispersions (approach 1) or correlation coefficients (approach 2) are increased. However, the observed data can be described through a hybrid method (approach 3), where increasing both the distribution dispersions and the correlation coefficients. In regard to the activity durations, it is reasonable to assume that activities are highly correlated, but not close to 1.0. A case with almost 1.0 correlation implies that all activities are highly dependent on each other, and an event occurring in a single activity would most certainly (with a probability approaching 1) have an effect on all other activities. Therefore, the correlation coefficients for activity durations were not modified from the base case ($\rho_1 = 0.75$, $\rho_2 = 0$). Regarding the commodity and equipment prices, the correlation coefficients was set half-way between 0 and 0.99, that is 0.50. Approach 3a consists of the following steps:

1. Set the correlation coefficient between activities of the same type to 0.99;
2. Increase d_1 until the relative standard deviation of the project duration was in the range 19.15% - 19.24%;
3. Set the correlation coefficient between prices to 0.50;
4. Increase d_2 until the relative standard deviation of the OCC was in the range 36.45% - 36.54%.

Approach 3b consists of the following steps:

1. Increase d_1 until the relative standard deviation of the project duration is in the range 22.75% - 22.84%;

2. Increase the value of i_1, until the project duration mean is increased of a factor in the range 1.75-1.84;
3. Set the correlation coefficient between activities of the same type to 0.50;
4. Increase d_2 until the relative standard deviation of the OCC was in the range 42.45% - 42.54%;
5. Increase the value of i_2, until the project duration mean was increased of a factor in the range 2.65-12.74.

6 DETERMINISTIC RESULTS

EVAL produced construction schedules for the three construction strategies of the WEC-SMR (Maronati et al., 2016a; Maronati et al., 2016b). Project durations for the three construction strategies are shown in Table 14. Through strategy two, modules are fabricated in the assembly area, which allows a lower number of activities that can be performed in parallel as compared to an off-site factory. Under the assumptions that were made, the parallelism in the assembly area is such that the critical path of strategy one and two is the same, and only activities that are not on the critical path are affected. These activities need to start earlier in order to preserve the critical path, with a cash flow profile that takes place earlier in time. However, in strategy one modules need to be transported to the site, as they are fabricated in off-site locations. As a consequence, project duration according to construction strategy one is slightly longer than that of strategy two, as the critical path includes transportation of modules from off-site factories to site.

Table 14 – Project durations for the three construction strategies

	Duration
Strategy 1	1701 days
Strategy 2	1642 days
Strategy 3	2315 days

The absolute cash flows (not discounted) of direct costs for each strategy are presented in Figure 36. Base costs were calculating summing cash flows according to Eq. 1 and TCIC was calculated through Eq. 12. TCIC and cash flows were normalized to the TCIC of the third construction strategy, as it represents the reference methodology in NPP construction. The cash flow profile for strategy is shifted earlier in time as compared to that of strategy one, as the assembly area is more congested and fabrication activities have to start earlier. The difference in TCIC is mainly due to the different cash flow profile, which is delayed in time for strategy one. As cash flows occur later, the time value of money and the interest accrued during construction are lower, with lower value of TCIC. The cash flow of stick-built construction (strategy three) is more complex. As the assembly stage is not part of this construction methodology, the structures and the equipment required to connect modules are needed later in time in the installation stage. As a consequence, the cash flow peak representing the installation stage is delayed in time. However, as the installation stage is longer, mechanical and I&C modules have to be available earlier in time and the fabrication stage has to start earlier. This explains the first peak in the cash flow profile according to construction strategy three.

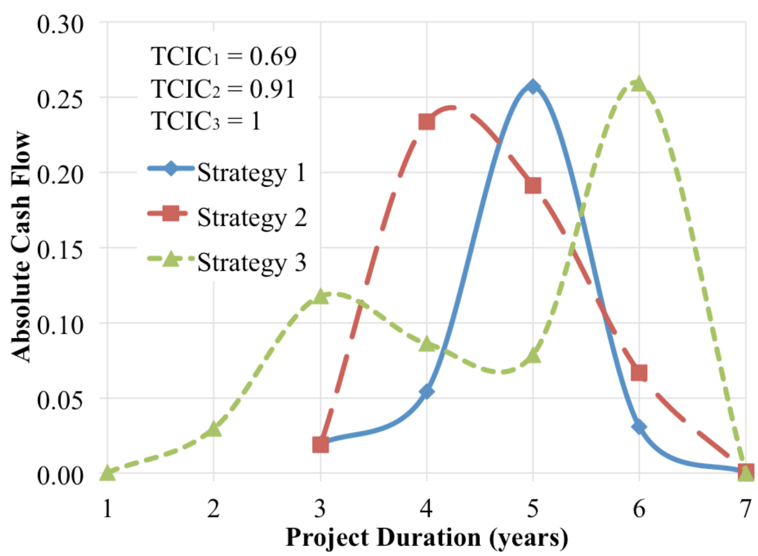


Figure 36 – Cash flow for the three construction strategies

TCICs breakdown into Base Costs and OCCs are presented in Table 4, calculated with a 5% (Table 15) and a 10% discount rate (Table 16) respectively. In this analysis, each value of TCIC is normalized to the TCIC of strategy three. Reduction in each cost item in respect to strategy three is shown in parentheses. Absolute values of base costs and OCCs are the same for the two cases, as they not dependent on the discount rate. Complete modularization of the nuclear island (represented by strategy one) allows a 36.74% savings in base costs. Once owner's costs are added to calculate OCC, savings decrease to 29.82%. OCC savings adopting strategy one and two are lower than the respective BC savings, as owner's cost are slightly dependent on the value of BC (Eq. 3). As owner's costs are added to calculate OCC, their weight on BC is higher for strategies with lower BC value (strategy one and two). As a consequence, the relative increase of OCC from BC due to the value of owner's costs is higher as BC is lower, and the OCC savings are lower. IDC values depend on the amount of OCC and the cash flow profile. As the cash flow profile is delayed in time, IDC is lower as the value of the cash flow at the end of the project (when revenue begins) is lower. Strategy three has a longer project duration than strategy one and two, and the cash flow profile has two peaks. The first peak occurs before projects according to strategies one and two begin, while the second peak is delayed in time with respect to the peak of the other two construction strategies. IDC due to the second peak of the strategy three cash flow profile is lower than IDC due to the peaks of strategies one and two. However, for strategy three IDC accrued to the cash flow that constitute the first peak cause the value of IDC to increase. These two opposite phenomena cause TCIC savings for strategy one and two to not considerably differ from OCC savings. For strategy one, calculated with a 10% discount rate, TCIC savings are slightly higher than OCC savings (in respect to strategy three) due to the lower OCC absolute value and the absence of the first cash flow peak. For strategy two calculated with a 10% discount rate, TCIC savings are slightly lower due to the higher IDC value calculated from the cash flow that occur earlier in time than the second peak of strategy three. Considering a 5% discount rate, TCIC savings are slightly lower than OCC savings for both strategies one and two. In fact, as a lower discount rate is considered, IDC value becomes less predominant for strategies having lower absolute values of OCCs.

Table 15 – TCIC breakdown for the three construction strategies (5% discount rate)

	Strategy 1	Strategy 2	Strategy 3
BC	0.50 (-36.74%)	0.70 (-10.61%)	0.78
OCC	0.68 (-29.82)	0.89 (-8.61%)	0.97
TCIC	0.71 (-29.46)	0.92 (-8.20%)	1.00

Table 16 – TCIC breakdown for the three construction strategies (10% discount rate)

	Strategy 1	Strategy 2	Strategy 3
BC	0.44 (-36.74%)	0.63 (-10.61%)	0.70
OCC	0.61 (-29.82)	0.79 (-8.61%)	0.87
TCIC	0.70 (-29.95)	0.91 (-8.26%)	1.00

From the TCIC values shown it is possible to calculate the TCIC difference between construction strategy one and two, which shows the impact of off-site modular fabrication. Considering a 10% real discount rate, adopting construction strategy one instead of strategy two, TCIC is 23.64% lower. The TCIC difference between construction strategy two and three shows the impact of the adoption of the on-site assembly area. This difference is equal to 8.26%. As the reactor is fully modularized, TCIC is 29.95% lower than if it is built adopting stick-built construction. This analysis was conducted considering that the cost of the nuclear island is the only contributor to TCIC. However, a NPP also includes components and structures outside the nuclear island, which may or may not be constructed through modularization. However, considering a proportionality between direct cost and

TCIC, under the assumption that components outside the nuclear island do not allow modularization, and that the nuclear island makes up 50% of direct cost, the savings on TCIC are about 15%. Through this type of analysis, EVAL can be used to identify the most cost effective construction strategy of a NPP, given the reactor design.

6.1 Sensitivity analyses

The impact of different factors on the results presented in the previous section was evaluated through sensitivity analysis (Maronati et al., 2015; Maronati et al., 2016a; Maronati et al., 2016b).

6.1.1 Discount rate

Values of TCIC as a function of the discount rate were calculated and are plotted in Figure 37. As previously, TCICs were normalized to the value of TCIC of strategy three. TCICs increase with the discount rate for each construction strategy, as the cost of financing (interest during construction) increases with the discount rate (Eq. 9). TCIC savings adopting full of partial modularization (strategy one and two) slightly increase with the discount rate (Figure 38).

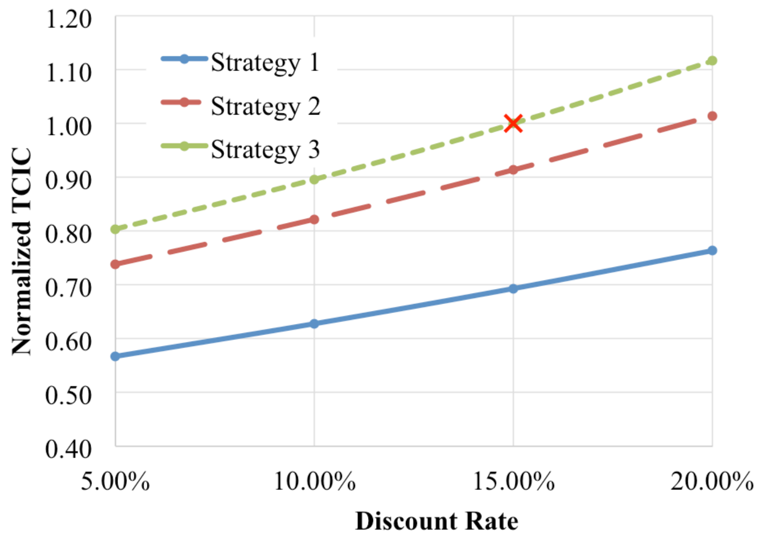


Figure 37 – TCIC as a function of the discount rate

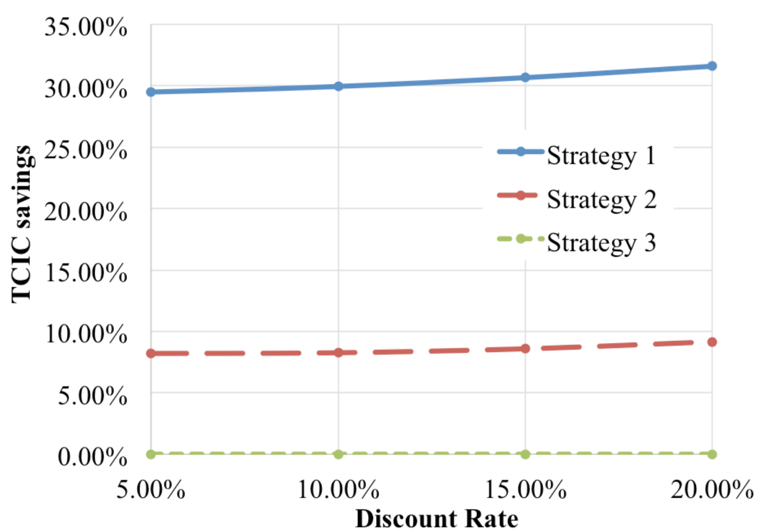


Figure 38 – TCIC savings as a function of the discount rate

6.1.2 1-3-8 rule

In standard modularization, the size of the modules is constrained to the capacity of rail-shippable limits. However, in case this constraint is relaxed, a higher degree of modularization is achievable. For instance, if the transportation by barge is available, the size of the modules could be increased so that the assembly stage is eliminated, and the super modules are fabricated in the factory. Then, instead of shipping by rail or road about 600 modules comprising a representative SMR nuclear island, up to 10 super modules would need to be shipped by barge. Moreover, if the NI is built through factory-made super modules, the total weight of the equipment that needs to be transported to the site is the same, or likely lower, as the number of composite modules is reduced, as shown in Section III. Furthermore, transportation by barge is more efficient than transportation by rail and, therefore, is likely cheaper. Alabama River Improvement Association (2017)Alabama River Improvement Association (2017)Alabama River Improvement Association (2017)Alabama River Improvement Association (shows that, for every gallon of fuel burned to move 1 ton, barge can reach a relative distance of 514 miles, almost nine times more than truck (59 miles), and over two and one half times more than rail (202 miles).

This section summarizes the findings presented in Maronati and Petrovic (2018). The same construction schedule of the WEC-SMR was used in this analysis, but the absolute values of costs were modified to represent a generic "reference" Small Modular Reactor having a NI direct cost of $500 M. The savings due to the assembly of the super modules in an off-site factory, as compared to the assembly in the on-site assembly area, was evaluated. As the assembly activities are moved to the factory, the activities are shortened, and the amount of labor needed for the super modules assembly is lower, resulting in a lower value of TCIC. The labor reduction was calculated assuming the validity of the 1-3-8 rule. Under this assumption, the amount of assembly labor is reduced to 1/3. All assembly activities are shortened by a factor 3, and the new construction schedule is calculated, calculating the new project duration. The SMR cost breakdown of the base case is shown in Table 17.

Table 17 – SMR nuclear island cost breakdown (reference case: 10% assembly labor)

	Cost (USD)	Cost percentage
NI installation labor	50,000,000	10.00%
SM assembly labor	50,000,000	10.00%
Big components	50,000,000	10.00%
Big components installation	10,000,000	2.00%
Small components	10,000,000	2.00%
Modules equipment cost	330,000,000	66.00%
NI direct cost	500,000,000	100.00%
Base cost	550,000,000	
OCC	775,000,000	
TCIC	918,277,683	

A sensitivity analysis was performed on the amount of assembly labor. For this purpose, the amount of all costs was left unchanged, while the assembly labor was changed to represent 5%, 15%, and 20% of the total nuclear island cost. For these cases, the same construction schedule of the reference case was used, and only the assembly stage labor was changed. The total nuclear island cost was increased accordingly. The cost breakdown for the different assembly labor percentages is shown in Table 18, Table 19 and Table 20. Table 20. A sensitivity analysis was conducted on the 3-to-1 factor of the 1-3-8 rule, evaluating labor-hours reduction factor in the range 2-4. The resulting rules are here referred to as 1-2-8 and 1-4-8 rule. For these cases, the durations of assembly stage activities were changed. From the reference case having super modules assembled on site, the assembly activities durations were reduced by a factor of 2 and 4, respectively.

Table 18 – SMR nuclear island cost breakdown (5% assembly labor)

	Cost (USD)	Cost percentage
NI installation labor	50,000,000	10.56%
SM assembly labor	23,684,211	5.00%
Big components	50,000,000	10.56%
Big components installation	10,000,000	2.11%
Small components	10,000,000	2.11%
Modules equipment cost	330,000,000	69.67%
NI direct cost	473,684,211	100.00%
Base cost	521,052,631	
OCC	744,736,842	
TCIC	882,419,641	

Table 19 – SMR nuclear island cost breakdown (15% assembly labor)

	Cost (USD)	Cost percentage
NI installation labor	50,000,000	9.44%
SM assembly labor	79,411,765	15.00%
Big components	50,000,000	9.44%
Big components installation	10,000,000	1.89%
Small components	10,000,000	1.89%
Modules equipment cost	330,000,000	62.33%
NI direct cost	529,411,765	100.00%
Base cost	578,766,246	
OCC	805,236,834	
TCIC	954,104,534	

Table 20 – SMR nuclear island cost breakdown (20% assembly labor)

	Cost (USD)	Cost percentage
NI installation labor	50,000,000	8.89%
SM assembly labor	112,500,000	20.00%
Big components	50,000,000	8.89%
Big components installation	10,000,000	1.78%
Small components	10,000,000	1.78%
Modules equipment cost	330,000,000	58.67%
NI direct cost	562,500,000	100.00%
Base cost	611,854,481	
OCC	839,979,481	
TCIC	$995,270,208	

This analysis was conducted considering that the same modules (in number and type) need to be fabricated, despite the assembly takes place in the assembly area or in the factory. However, as the super modules are fabricated in factory, the design of modules do not need to be optimized under the transportation constraint (Table 17). Modules can be designed so that a lesser number of connections need to be performed on the assembly stage. The savings due to the lower number of support connections, pipe connections, and cable connections was calculated. In all cases, the transportation cost of equipment (modules or super modules, depending on the construction strategy) from the factory to the site was not included. This is assumption is conservative, as barge transportation is more efficient than rail transportation. Therefore, building the nuclear island from barge transported super modules will be cheaper than building the nuclear island from rail transportable modules.

As before, the results are normalized to the base case TCIC. As super modules are fabricated in an off-site factory and the 1-3-8 rule is applied, TCIC is 94.16% of TCIC in case the super modules are assembled in the on-site assembly area, which corresponds to a

5.84% decrease in TCIC. If the additional transportation cost required for the super modules is lower than the TCIC saving, this construction methodology provides an overall cost benefit.

A sensitivity analysis was performed on both the fraction of assembly labor cost and on the 1-3-8 rule. The results of the sensitivity analysis are shown in Figure 39.

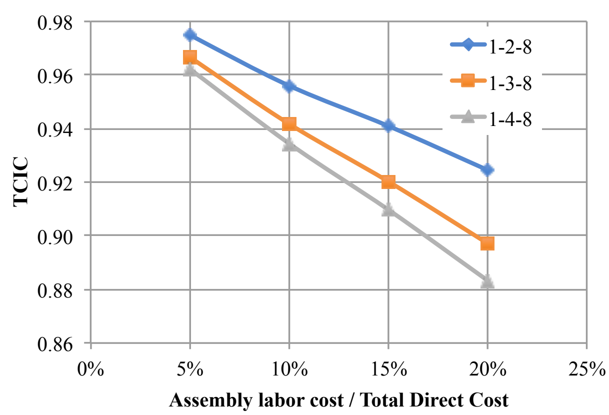


Figure 39 – 1-3-8 rule sensitivity analysis

If the 1-3-8 rule is valid, TCIC is reduced by 3-10%, i.e., it is in the range 90-97% of TCIC of the reference case. If the savings in moving the assembly stage to the factory is lower, and the 1-2-8 rule is used, TCIC is reduced less and is in the range 0.92-0.98. If, instead, the 1-4-8 rule is used, TCIC is reduced more and is in the range 0.88-0.96.

Since the super modules are fabricated in the factory, a lesser number of connections need to be performed in the assembly stage and the number of composite modules can be reduced. In this analysis, it was assumed that the number of composite modules is reduced by half. Therefore, both the equipment cost and the assembly labor cost associated with the composite modules are reduced by half. Under this assumption, for the reference case (where 1-3-8 rule applies), TCIC is further reduced by roughly 4% (Table 21), depending on the amount of assembly labor used. A sensitivity analysis was performed on the fraction of reduction of composite modules. The number of composite modules was also reduced by factors 3 and 4, and TCIC was calculated. In the most optimistic case in which the number of composite modules is reduced by a factor of 4, TCIC falls in the range 0.84-0.90 (Figure 40).

Table 21 – TCIC savings with half the number of composite modules

Labor	Savings
5%	4.51%
10%	4.45%
15%	4.39%
20%	4.31%

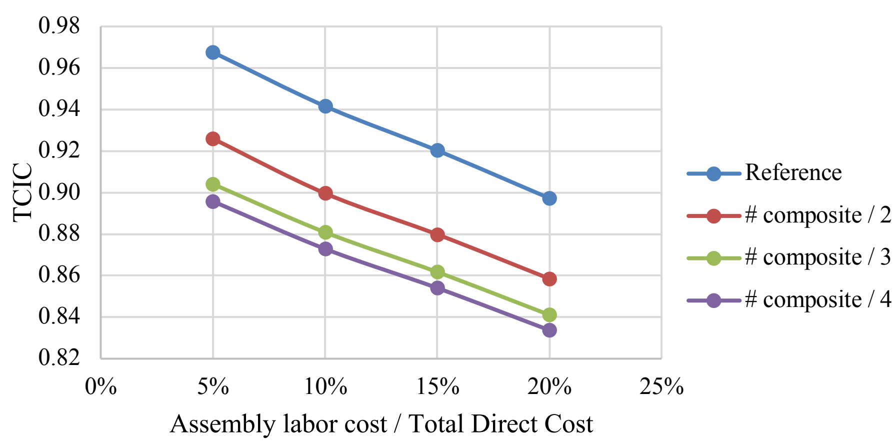


Figure 40 – Composite modules reduction sensitivity analysis

The most optimistic case is represented by a construction that allows a reduction in the number of composite modules by a factor of 4, in which the 1-4-8 rule is valid (Figure 41). For this case, considering an NI whose direct cost is made by 20% of assembly labor, TCIC is reduced by about 18%.

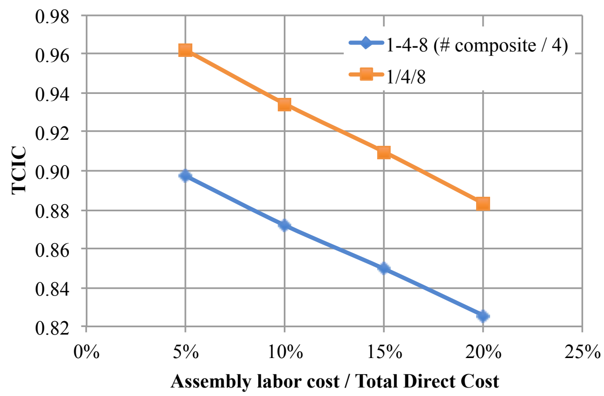


Figure 41 – TCIC with 1/4 composite modules (1-4-8 rule)

7 MONTE CARLO SIMULATIONS RESULTS

In this chapter, the results of the Monte Carlo simulations are described. For a Generic SMR, Section 7.1 reports the results of the simulation performed assuming uncorrelated variables, while Section 7.2 reports the results of the simulations where variables are assumed correlated. Section 7.3 describes the results obtained for PWR12-BE. In Section 7.4, the inputs of the PWR12-BE construction model were modified to fit the pre-1979 and post-1979 historical data. The updated inputs were then applied to the SMR case. All Monte Carlo simulations performed in this work are made of 10^5 runs. Million dollars are denoted as M-$, while billion dollars were denoted as B-$.

7.1 Uncorrelated variables

The first set of analyses assumes uncorrelated variables. For WEC-SMR, every cost item (equipment, material, labor) is treated as a random variable and is described through a probability distribution. As in Section 4.1.2, for this analysis cost values of the WEC-SMR were modified to represent a general reference SMR with an NI direct cost of $500 M, assuming that the labor cost of the assembly stage constitutes 10% of the NI direct cost. In any case, the absolute cost is arbitrary and does not negatively influence the results, as this study focuses on the uncertainties relative to the absolute value. The costs of this plant were artificially generated to represent two 300 MWe twin-units, for a total power level of the plant of 600 MWe. However, the analysis was extended to include non-NI components and buildings. As presented in Section 2.2, for the PWR12-BE, the components that are included in the WEC-SMR NI make up the 49.7% of the direct cost. In this analysis, it was assumed that the NI constitutes 50% of the cost of the plant. This assumption implies that the non-NI components and buildings have the same level of modularization as the nuclear island. The breakdown of the NI cost was presented in Table 17, while the cost breakdown of whole SMR plant is shown in Table 22. In the IDC calculation, a 10% cost of capital was assumed.

Table 22 – SMR cost breakdown

	Cost (USD)
NI direct cost	500,000,000
Non-NI direct cost	500,000,000
Direct cost	1,000,000,000
Base cost	1,100,000,000
OCC	1,350,000,000
TCIC	1,620,354,167

The cost of an activity is dependent on the duration of the activity. As the activity takes longer to be completed, the amount of total labor is higher. However, some delays do not lead to a higher amount of labor. For example, activities that are delayed due to the detection of a design problem are stopped until the issue is solved at the design level, and it does not increase the direct labor. The cost of an activity also depends on the cost of material, which is likely not to vary with the activity duration. Despite this might be true for the majority of cases, there are cases where a delay might cause a greater quantity of material to be used. Certain mistakes in tasks involving a high use of materials can be effectively fixed only by repeating part of or the whole activity, resulting in a higher use of the material. For this case, a fraction of each activity, representing the labor cost, was assumed directly dependent on the duration of the activity. A simplified construction model, consisting of 80 modules, was used. The fabrication stage consists of 80 activities, each one representing the fabrication of each module. It was assumed that the modules of the same type are fabricated in series, while modules of different types can be fabricated in parallel. The assembly stage and the installation stage of the simplified model consist respectively of 8 activities and 12 activities, for a total number of 100 activities for the whole construction model. The construction schedule of the I&C and mechanical modules is shown in Figure 42 and Figure 43, while the activities of the assembly and installation stages is shown in Figure 44. It was assumed that the activities of the fabrication, assembly, and installation of the non-NI components and buildings are never critical and take place in parallel with the construction of the NI.

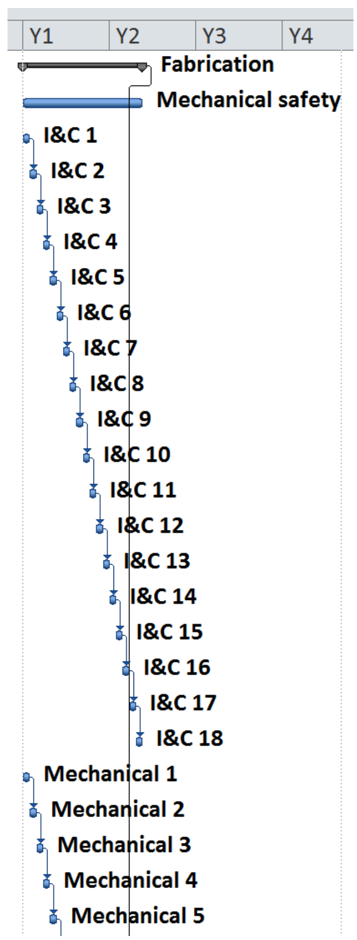


Figure 42 – SMR construction schedule (fabrication of I&C and mechanical modules)

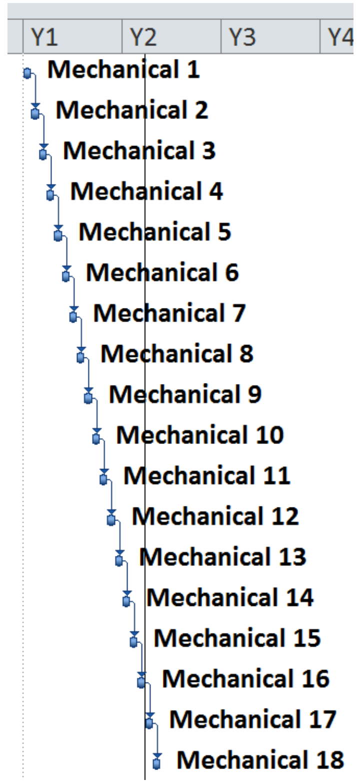


Figure 43 – SMR construction schedule (fabrication of mechanical modules)

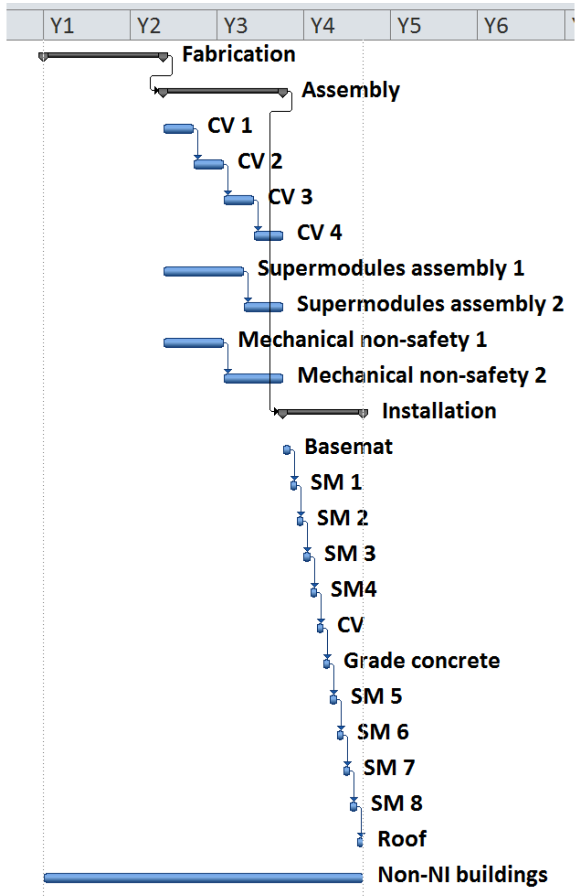


Figure 44 – SMR construction schedule (assembly and installation stage)

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%. The mean value and the TCIC standard deviation the simulations were also calculated, and the TCIC histogram is shown. For both triangular distributed and normally distributed activities, the TCIC dispersion increases with the standard deviation (relative to the mean) of the distributions (*s* and *t* for triangular and normal distribution respectively). Also, the TCIC mean value increases as a consequence of the time value of money.

7.1.1 *Symmetric Distributions*

7.1.1.1 Triangular Distributions

Monte Carlo simulations were performed varying the values of *s*. For simplicity, the value of *s* was fixed for all activities in the same simulation. This assumption is not realistic, as different types of activities are characterized by different relative standard deviations. However, the analysis so conducted is useful in order to understand the dispersion in TCIC as a function of the dispersion activities costs and durations. Figure 45, Figure 46 and Figure 47 show the project duration, OCC and TCIC distributions as a function of s. Cost contingency is calculated from the TCIC distribution as the difference between the TCIC 75th percentile and the TCIC mode, , as explained in Section 3.3.3. The results, including cost contingency, are presented in Table 23, Table 24 and Table 25, and show an increase in the relative standard deviations with *s*.

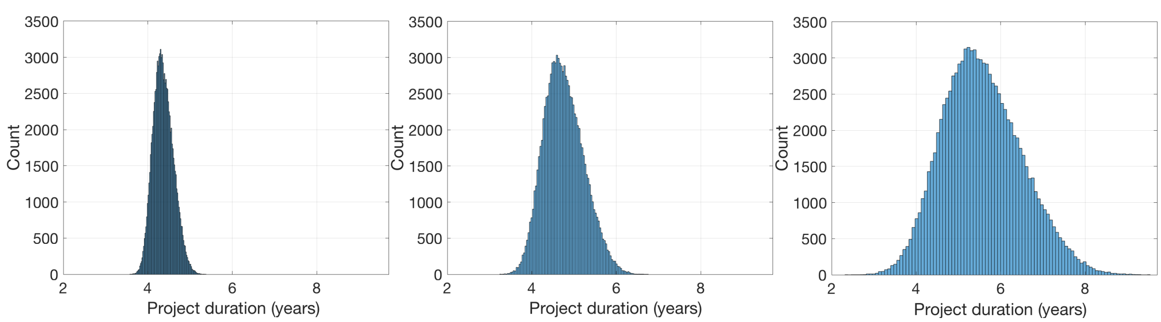


Figure 45 – Project duration distribution for s = 0.50, s = 1.00, s = 2.00

Table 23 – Project duration (symmetric triangular distributions)

s	μ_{dur} (years)	σ_{dur}/μ_{dur}
0	4.0	-
0.50	4.4	5.4%
1.00	4.8	9.9%
2.00	5.6	16.7%

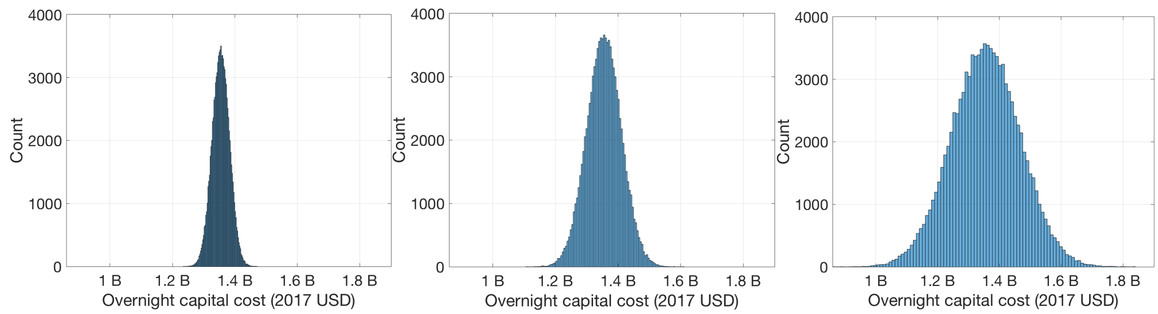


Figure 46 – OCC distribution for s = 0.50, s = 1.00, s = 2.00

Table 24 – OCC and OCC relative standard deviation (symmetric triangular distributions)

s	μ_{OCC}	σ_{OCC}/μ_{OCC}
0		
0.50	1.36 B	2.0%
1.00	1.35 B	4.1%
2.00	1.36 B	8.2%

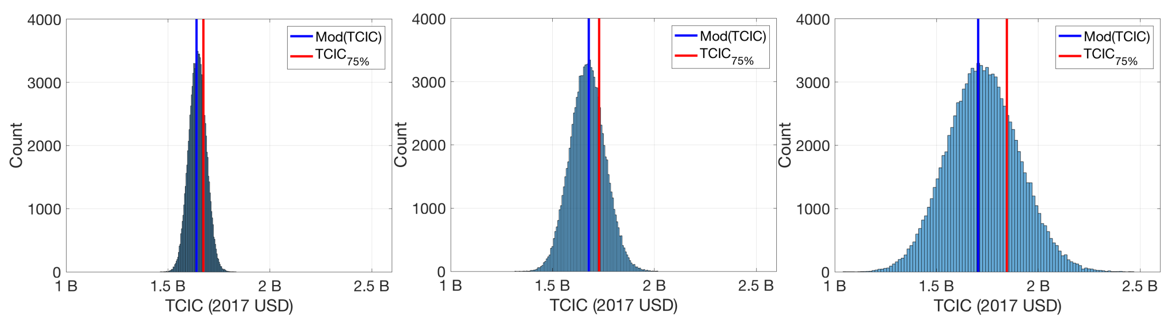


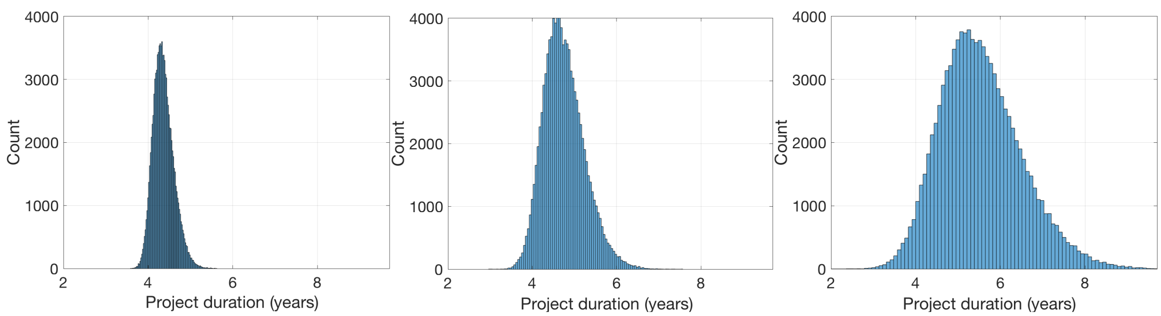
Figure 47 – TCIC distribution for s = 0.50, s = 1.00, s = 2.00

Table 25 – TCIC and TCIC standard deviation (symmetric triangular distributions)

s	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}	Mode	$TCIC_{75\%}$	Contingency
0	1.62 B	-			-
0.50	1.65 B	2.6%	1.64 B	1.67 B	37.75 M
1.00	1.67 B	5.1%	1.66 B	1.73 B	66.00 M
2.00	1.73 B	10.1%	1.75 B	1.85 B	100.08 M

7.1.1.2 <u>Normal distribution</u>

As for symmetric triangular distributed activities, in every simulation all activities were assumed to have the same fractional standard deviation (expressed as a linear function of the mean value). The ratio between the standard deviation and the mean value is expressed by the parameter *t* (Eq. 50). The values of *t* were chosen to correspond to the values used for the symmetric triangular distribution and were calculated from the *s* values through Eq. 51. The resulting distributions are shown in Figure 48, Figure 49 and Figure 50, and the results are presented in Table 26, Table 27 and Table 28. Relative standard deviations increase consistently with *t*, as well as with the mean TCIC value.

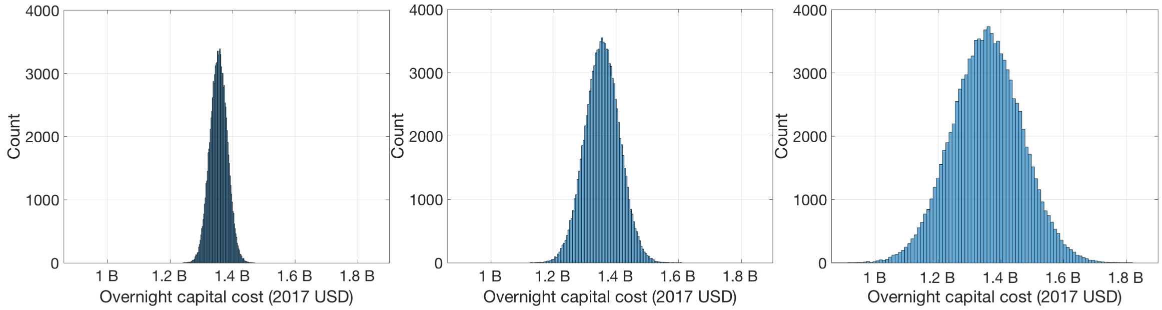


(a) **(b)** **(c)**

Figure 48 – Project duration distribution for t = 0.20 (a), t = 0.41 (b), t = 0.82 (c) (normal distributions)

Table 26 – Project duration (symmetric triangular distributions)

t	μ_{dur} (years)	σ_{dur}/μ_{dur}
	4.0	-
0.20	4.4	5.6%
0.41	4.7	10.2%
0.82	5.5	17.3%

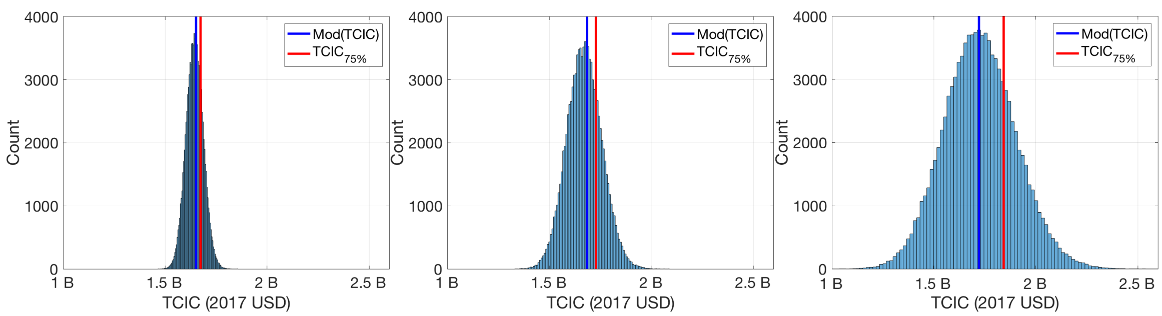


(a) **(b)** **(c)**

Figure 49 – OCC distribution for t = 0.20 (a), t = 0.41 (b), t = 0.82 (c)

Table 27 – OCC and OCC relative standard deviation (normal distributions)

t	μ_{OCC}	σ_{OCC}/μ_{OCC}
	1.36 B	-
0.20	1.35 B	2.0%
0.41	1.36 B	4.1%
0.82	1.35 B	8.2%



(a) **(b)** **(c)**

Figure 50 – TCIC distribution for t = 0.20 (a), t = 0.41 (b), t = 0.82 (c)

Table 28 – TCIC and TCIC standard deviation (normal distributions)

t	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}	Mode	$TCIC_{75\%}$	Contingency
	1.62 B	-		-	-
0.20	1.64 B	2.6%	1.65 B	1.67 B	21.8 M
0.41	1.67 B	5.12%	1.68 B	1.73 B	44.6 M
0.82	1.73 B	10.17%	1.72 B	1.84 B	121.0 B

7.1.1.3 Summary

TCIC mean values and standard deviations calculated from Monte Carlo simulations for triangular and normal distributed activities duration and cost are summarized in Table 29. The results show an accordance between the use of triangular and normal distributions. In the use of symmetric probability distributions, the differences in TCIC mean values and standard deviations obtained through triangular and normal distributions are very small, showing the equivalence between the two distributions in describing activities durations and costs.

Table 29 – TCIC and TCIC standard deviation (symmetric triangular and normal distributions)

		Triangular		Normal	
s	t	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}
0		1.62 B	-	1.62 B	-
0.50	0.2041	1.65 B	2.6%	1.64 B	2.6%
1.00	0.4082	1.67 B	5.1%	1.67 B	5.12%
2.00	0.8165	1.73 B	10.1%	1.73 B	10.17%

In fact, despite the use of quite dispersed probability distributions ($0 < \sigma/\mu < 0.82$), the numerical results indicate only a weak dependence of uncertainties in the construction process on TCIC. For the maximum value of *s* considered (where *b* and *a* are +/-200% of *c*), TCIC has a relatively low standard deviation (9% of TCIC). Figure 51 and Figure 52 respectively show the TCIC sensitivity of TCIC mean value and TCIC standard deviation with *t*.

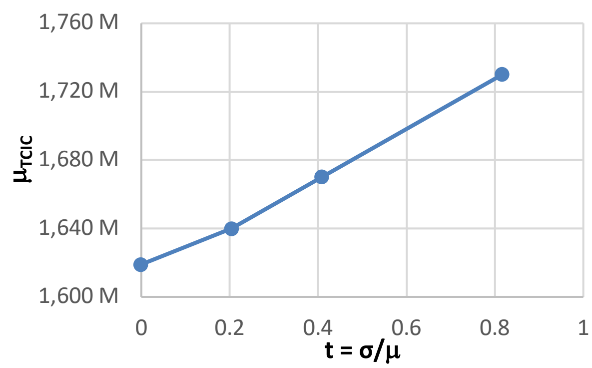


Figure 51 – TCIC as a function of the dispersion of normal distributed activities

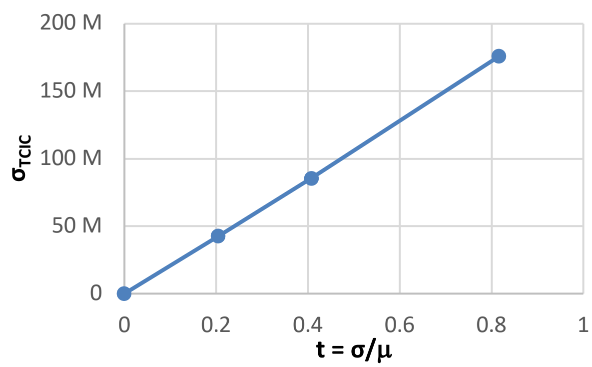


Figure 52 –TCIC standard deviation as a function of the dispersion of normal distributed activities

Comparing the results to the observed data, the TCIC relative standard deviation obtained through this analysis looks underestimated. This raises two possible concerns:

- The use of symmetric distributions to describe activities is not representative of the real SMR nuclear island construction. In reality, activities have a higher probability to be completed later rather than earlier. This concern was addressed through the use of asymmetric probabilistic distributions (skewed to the right);

- Activity duration and cost values cannot be treated as uncorrelated random variables. This concerned will be addressed through considering correlations between random variables.

7.1.2 Asymmetric triangular distributions

Asymmetric triangular distributions were described through the parameters *s* and *w* introduced in Section 5.4. Monte Carlo simulations were performed for different values of *s* and *w* to show the impact of these values on TCIC. For simplification, in every simulation the same value of *s* and *w* was used for all activities, computing the value of *a* and *b* of the distribution based on the most probable (deterministic) value, through Eq. 53 and Eq. 54. The same values of *s* that were considered for the symmetric case were used, and values of *w* between 1 and 10 were used. Numerical results of these simulations are shown in Table 30. TCIC mean and standard deviation as a function of *w* for fixed values of *s* are shown in Figure 53 and Figure 54, according to the data points shown in Table 30.

Table 30 – TCIC and TCIC standard deviation (asymmetric triangular distributions)

	w=1		w=2		w=5	
s	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}	μ_{TCIC}	σ_{TCIC}/μ_{TCIC}
0.50	1.65 B	2.6%	2.35 B	4.4%	3.15 B	5.8 %
1.00	1.67 B	5.1%	3.19 B	7.4%	5.04 B	9.0%
2.00	1.73 B	10.1%	5.16 B	11.4%	9.91 B	12.9 %

Figure 53 shows that TCIC suffers a significant increase with the asymmetry of the triangular distribution. The TCIC standard deviation as a percentage of TCIC mean value is shown in Figure 54. The simulations indicate that the TCIC standard deviation increases with the level of asymmetry, reaching 30% of the mean value for *w* equal to 10.

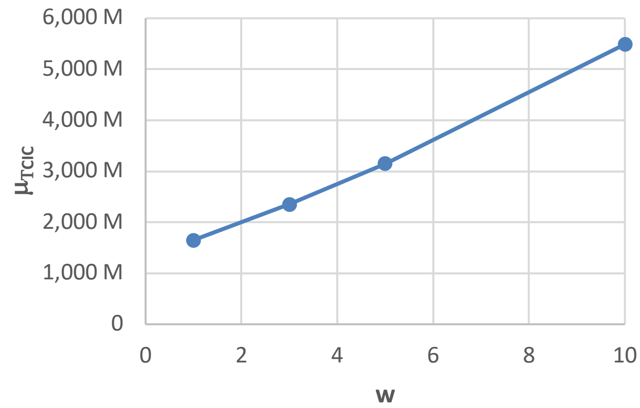


Figure 53 – TCIC as a function of the level of asymmetry (triangular distribution, *s*=0.50)

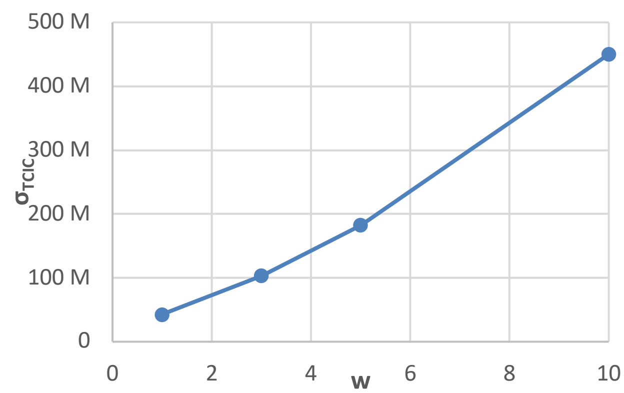


Figure 54 – TCIC standard deviation as a function of the level of asymmetry (triangular distribution, *s*=0.50)

7.1.3 Introducing more realistic distributions

More realistic probability distribution functions were introduced (Van-Wyk, 2016). 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 31. Activities of the same stage were modeled with the same probability distributions.

Table 31 – Activity durations minimum and maximum values (triangular distribution)

	Minimum	Maximum
Modules fabrication	-10%	+30%
Super modules assembly	-10%	+80%
Concrete pouring	-5%	+200%
NI installation	-10%	+80%

Under these assumptions, Monte Carlo simulations are performed and project duration, OCC and TCIC distributions are obtained. The project duration and OCC distributions are shown in Figure 55, while the results are summarized in Table 32. The project duration distribution has a mean value of 5.0 years with a relative standard deviation of 4.1%. The highest project duration is 6.0 years, 50% higher than the deterministic project duration. The OCC mean value is $1.51 B and a relative standard deviation of 1.86%. 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 $1.35 B (11.8% higher).

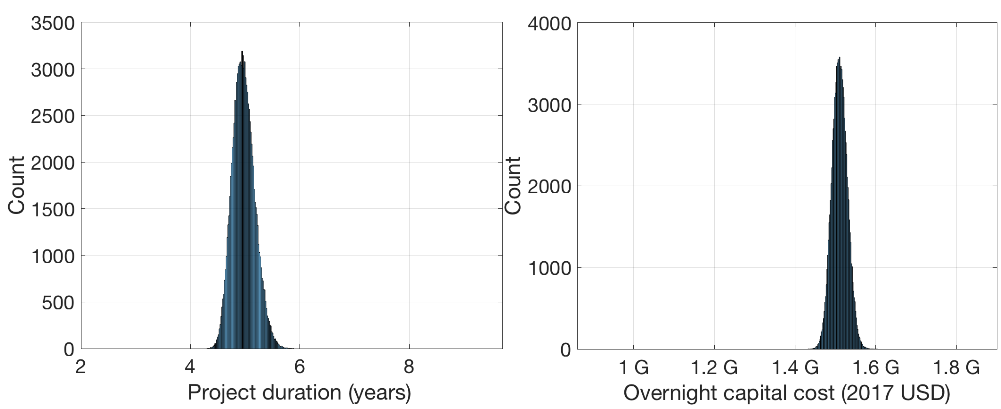


Figure 55 – Project duration and OCC distributions

Once the interest during construction is added to OCC, the TCIC distribution shown in Figure 56 is obtained. The average TCIC value is $1.87 B, with a relative standard deviation of 1.4%. The cost contingency is 28.77M, which corresponds to 1.5% of the TCIC mean value. The maximum TCIC value obtained in the simulation is \$1.99 B, 6.4% higher than the mean value.

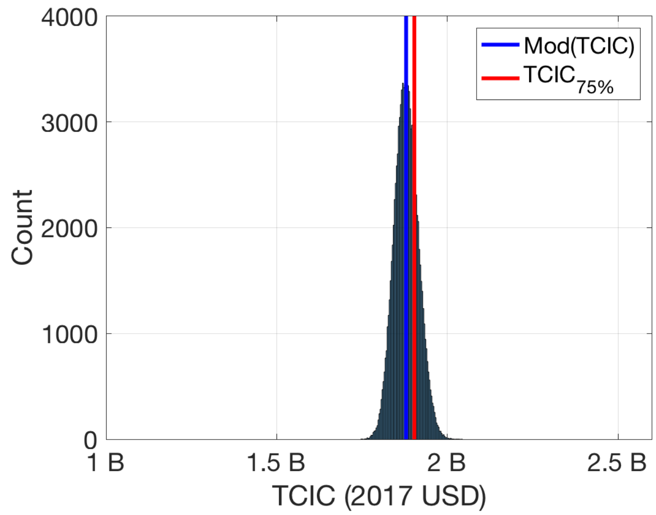


Figure 56 – TCIC distribution (r=10%)

Table 32 – TCIC distribution results, considering of activity durations uncertainties

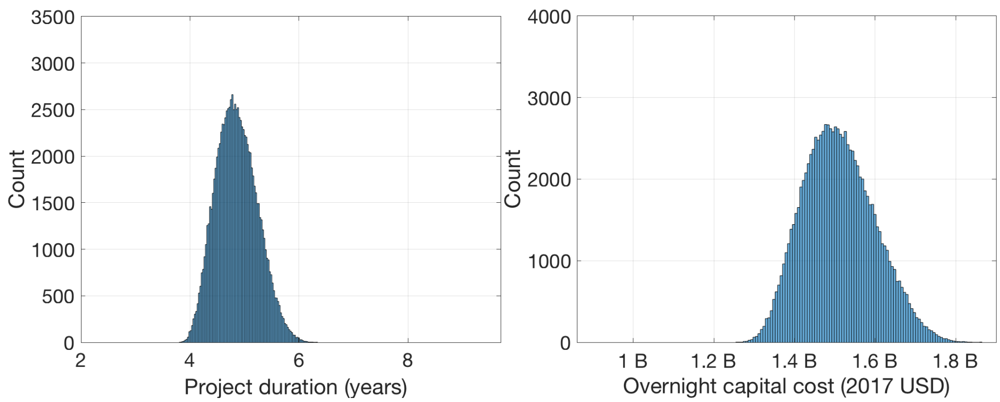
	Duration (years)	OCC (\$)	TCIC (\$)
μ	5.0	1.51 B	1.87 B
σ/μ	4.1%	1.26%	1.86%
Mode	5.0	1.51 B	1.88 B
75%			1.90 B
Contingency			28.77 M
Contingency/ μ_{TCIC}			1.5%

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 about 29 times lower than the one measured from the observed trend of NPP construction before 1979. The reason for this lies in the fact that all variables that were sampled in the previous 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 is the number of random variables used, the lower is the combined relative standard deviation. 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 dispersed.

7.2 Correlated variables

7.2.1 Correlated activities

Activity durations were described through triangular distributions, and activities taking place in the same stage were correlated with a higher correlation coefficient than activities taking place in different stages. These assumptions reflect the scenario where each construction stage shares a certain number of resources (equipment, material, special workers, management). As delays in 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. For example, as all the off-site fabricated equipment is provided by one manufacturer, in case design issues are identified in the fabrication process, all components fabricated by the manufacturer will be affected. This assumption reflects the scenario that took place in the construction of the AP-1000 units in the U.S., in Vogtle and VC Summer. For both projects, Shaw Group was responsible for the fabrication of all reactors modules and, as delays occur in the fabrication, the fabrication of all modules was delayed. 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 effect of these coefficient values on TCIC is later analyzed through sensitivity analysis. Under these assumptions, Monte Carlo simulations were performed and project duration, OCC and TCIC distributions were obtained. The project duration and OCC distributions are shown in Figure 57. The project duration has a mean of 4.9 years, with a mode of 4.7 years and a relative standard deviation of 7.8%. The highest project duration is 6.4 years, 36.1% higher than the mode. The OCC distribution has a mean of \$1.51 B and a relative standard deviation of 5.9%. As the probability distributions of activity durations are asymmetric (skewed to the right), the OCC distribution is also asymmetric, with an average sampled OCC value that is higher than the deterministic value of \$1.35 B (11.8% higher).



(a) **(b)**

Figure 57 – Project duration (a) and OCC (c) distributions

The TCIC distribution is shown in Figure 58. The average TCIC value is $1.87 B and the TCIC relative standard deviation is 7.0%, about 3.8 times higher than the one obtained in the uncorrelated case. The mode of the distribution is $1.85 B, and the maximum TCIC value obtained in the simulation is $2.36 B, 27.5 % higher than the mode. The results of the simulation are summarized in Table 33.

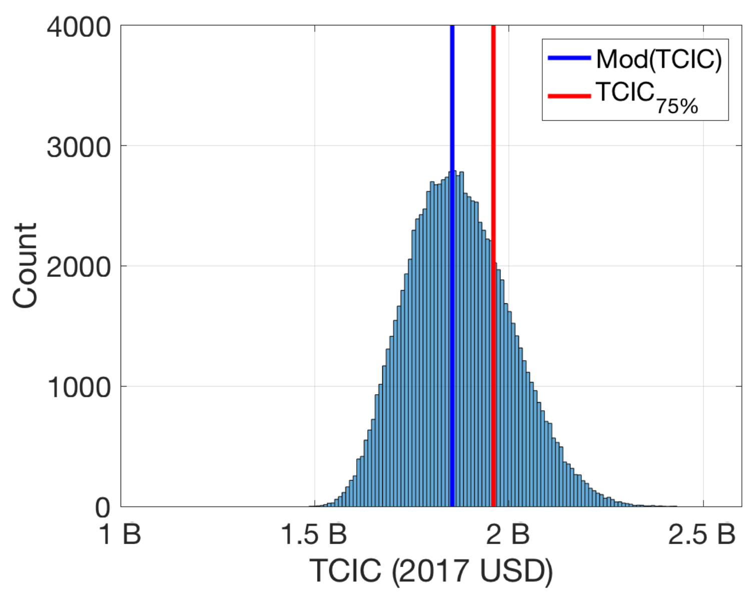


Figure 58 – TCIC distribution (r=10%)

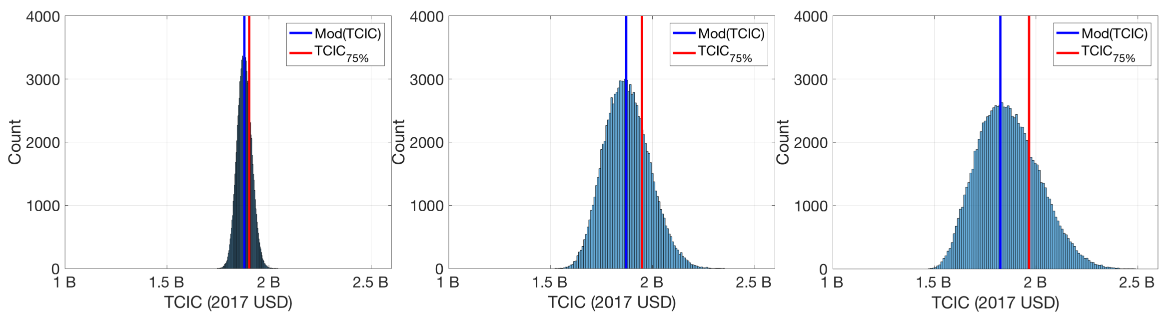
Table 33 – TCIC distribution results, considering activity durations uncertainties (ρ_1=0.75; ρ_1=0)

	Duration (years)	OCC ($)	TCIC ($)
μ	4.9	1.51 B	1.87 B
σ/μ	7.8%	5.9%	7.0%
Mode	4.7	1.54 B	1.85 B
75%			1.96 B
Contingency			106.0 M

7.2.1.1 Sensitivity analysis

A sensitivity analysis on the correlation coefficients was performed. For ρ_2 equal to zero, simulations were performed with ρ_1 in the range from 0 to 0.99. TCIC histogram plots for ρ_1 = 0, 0.25 and 0.99 are shown in Figure 59. The results of the sensitivity analysis on ρ_1 are shown in Table 34. The TCIC standard deviation and the project contingency increase with the value of ρ_1, which indicates an increase in both the TCIC dispersion and TCIC skewness with the correlation coefficient.

The project duration slightly decreases with the correlation coefficient. Despite this fact might seem counterintuitive, it is explainable by carefully analyzing the construction critical path. In a simulation, for parallel activities in the critical path having same duration, the overall project duration is determined by the sampled longest activity. For small correlation coefficients, the parallel durations are very slightly correlated, which implicates that their duration is independent one from the other. Then, the project duration of each simulation will always be high, as it is necessary that even only one activity is above the mode that the project duration will be above the mode. In this case, there is a high chance that the simulation will result in a project duration above the deterministic value. In case the activities are highly correlated, in the same simulation all activities will take either long durations (which determines a high project duration) or short durations (which determines a short project duration, shorter than the most probable value). Therefore, some simulations will result in a project duration shorter than the deterministic value and, combining all results, the average project duration will be shorter than if the activities are uncorrelated.



(a) **(b)** **(c)**

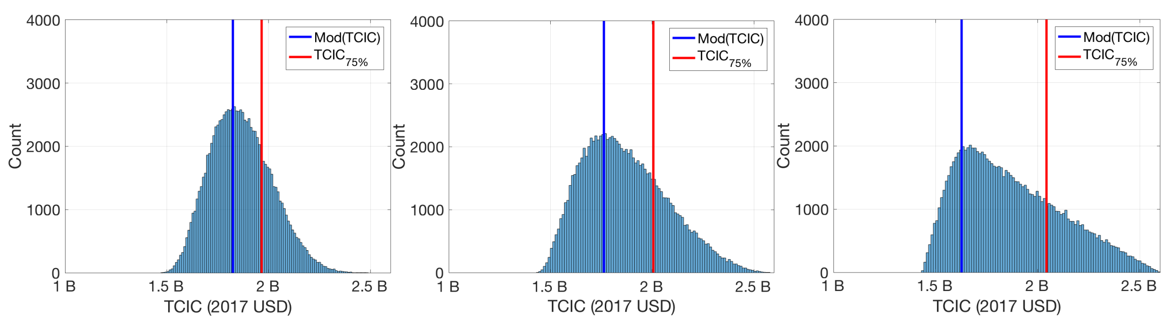
Figure 59 – TCIC distribution (r=10%, ρ_2=0); a) ρ_1=0; b) ρ_1=0.50; c) ρ_1=0.99;

Table 34 – ρ_1 sensitivity analysis results (r=10%, ρ_2 = 0)

ρ_1	μ_{dur} (years)	μ_{DC} (\$)	μ_{TCIC} (\$)	$(\sigma/\mu)_{TCIC}$	Mo_{TCIC} (\$)	$TCIC_{75\%}$ (\$)	Contingency (\$)
0	5.0	1.51 B	1.87 B	1.86%	1.88 B	1.90 B	28.8 B
0.25	4.9	1.51 B	1.88 B	4.32%	1.88 B	1.93 B	51.1 M
0.50	4.9	1.51 B	1.88 B	5.8%	1.86 B	1.95 B	84.7 M
0.75	4.9	1.51 B	1.87 B	7.0%	1.85 B	1.96 B	106.0 M
0.99	4.8	1.51 B	1.87 B	8.0%	1.82 B	1.97 B	141.2 M

A sensitivity analysis on the correlation coefficient between activities of different stages was performed, considering values of ρ_2 in the range between 0 and 0.99. The correlation coefficient ρ_1 was set equal to 0.99 and not 0.75 (nominal case). This is because the case if ρ_2 is higher than ρ_1, the correlation matrix of durations is non-positive semi definite, which is against the conditions that make the Iman-Conover method valid. Even intuitively, it is not realistic to have a case where the correlation coefficient between two activities of different stages is higher than the correlation coefficient of two activities of the same stage. For example, if both activities a_{f1} and a_{f2} in the fabrication stage have ρ_{12} = 0.99 with activity a_{a1} in the assembly stage, then both a_{f1} and a_{f2} must be correlated with a coefficient (at least) higher than 0.99.

TCIC histogram plots are shown in Figure 60 and the results of the simulations are summarized in Table 35. As in the ρ_1 sensitivity analysis, both TCIC standard deviation and project contingency increase with the correlation coefficient. In the worst case (complete correlations between activities in same and different stages), the contingency is \$415.8 M, about 14 times higher than the completely uncorrelated case (ρ_1 = 0, ρ_2 = 0, Table 32).



(a) **(b)** **(c)**

Figure 60 – TCIC distribution (r=10%, ρ_1=0.99; a) ρ_2=0; b) ρ_2=0.50; c) ρ_2=0.99)

Table 35 – ρ_2 sensitivity analysis results (r=10%, ρ_1 = 0.99)

ρ_2	μ_{dur} (years)	μ_{DC} ($)	μ_{TCIC} ($)	$(\sigma/\mu)_{TCIC}$	Mo_{TCIC} ($)	$TCIC_{75\%}$ ($)	Contingency ($)
0	4.8	1.51 B	1.87 B	8.0%	1.82 B	1.97 B	141.2 M
0.25	4.8	1.51 B	1.87 B	9.6%	1.79 B	1.99 B	189.6 M
0.50	4.8	1.51 B	1.87 B	11.0%	1.76 B	2.00 B	242.9 M
0.75	4.8	1.51 B	1.87 B	12.2%	1.70 B	2.02 B	329.4 M
0.99	4.8	1.51 B	1.87 B	13.4%	1.62 B	2.04 B	415.8 M

7.2.2 Market uncertainty

The study was further developed analyzing the cost of components and commodities. 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, equal to the one calculated based on historical data, and equal to one. Figure 61 and Figure 63 show some example of correlated samples 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).

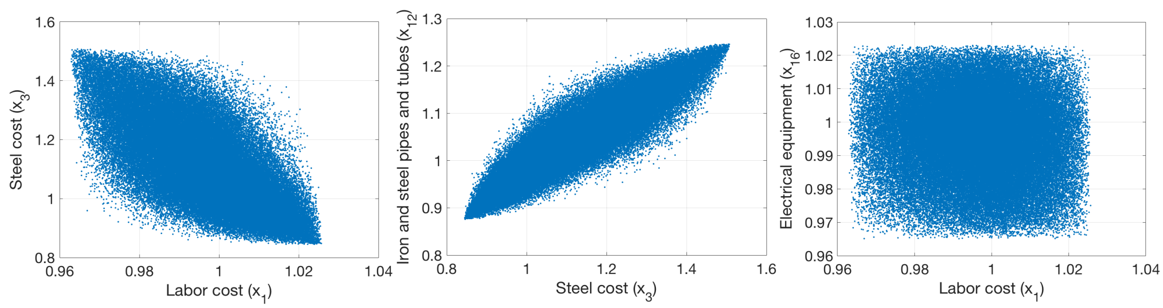


Figure 61 – Example of sampling correlated commodity prices

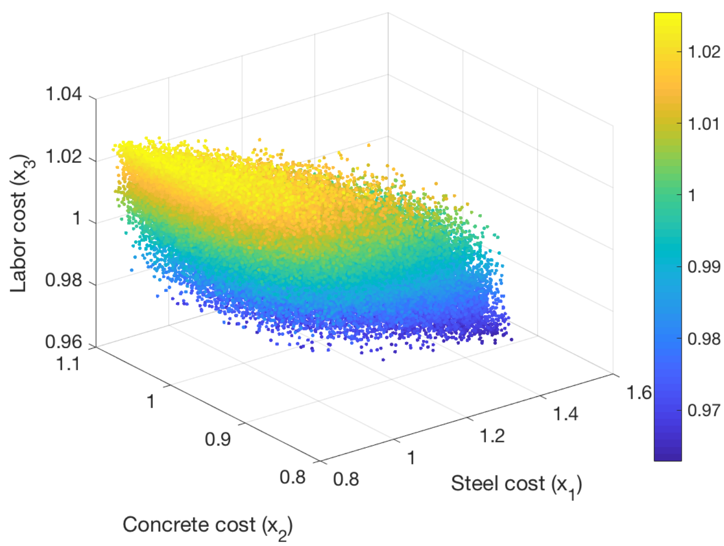


Figure 62 – Example of sampling three correlated commodity prices

Once the commodity costs were sampled, the total direct cost was calculated as the sum of all components, labor and materials. Results of the Monte Carlo simulation are shown in Table 36. Results show that the OCC relative standard deviation increases with the correlation coefficient. The direct cost histogram plot is shown in Figure 63. For a value of the correlation coefficients equal to the one calculated from the trend in commodity prices ($\rho_{ij} = \rho_{real}$) the OCC mean is \$1.40 B, and its relative standard deviation is 3.9%. The OCC mean is constant with the correlation factor (Table 36). The relative standard deviation of OCC is 3.4% for the case where all commodity and equipment prices are completely uncorrelated, and it is 5.5% for the case ρ_{ij} = 0.99 (Table 36). The relative standard deviation of the case where $\rho_{ij} = \rho_{real}$ is only 0.5% higher than the uncorrelated case, which suggests that most commodity and equipment are uncorrelated.

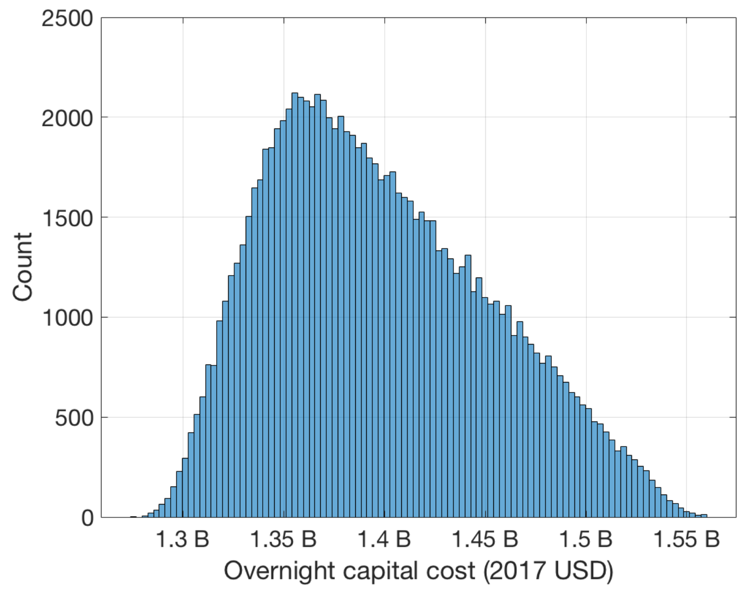


Figure 63 – Direct cost distribution, based on market uncertainty ($\rho = \rho_{real}$)

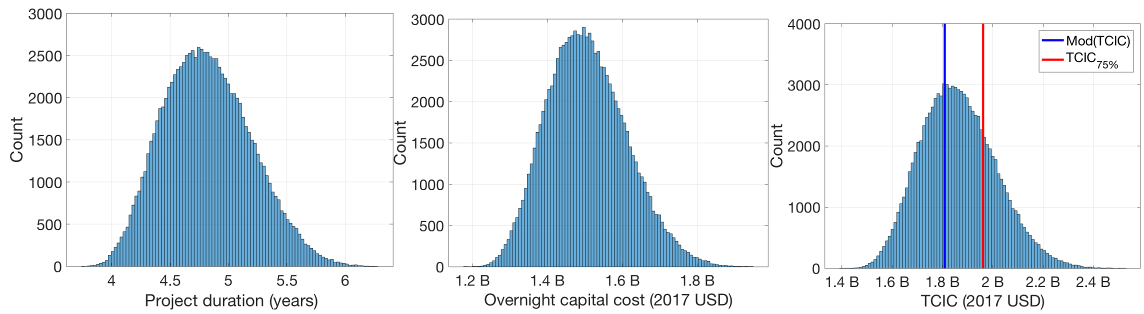
Table 36 – OCC uncertainty based on market uncertainty

	μ_{OCC} ($)	σ_{OCC}/μ_{OCC}
$\rho = 0$	1.4 B	3.4 %
$\rho = \rho_{real}$	1.4 B	3.9 %
$\rho = 0.99$	1.4 B	5.5%

The uncertainties in the market and in equipment prices can be 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. Regarding the project schedule, a coefficient of correlation of 0.75 was used for activities in the same stage (ρ_1 = 0.75), while activities in different stages were considered uncorrelated (ρ_2 = 0). As before, the effect of these coefficient values on TCIC is later analyzed through sensitivity analysis. The simulation consists of the following steps:

1. Sample the state of the market, based 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.

Under these assumptions, the TCIC mean value is \$1.9 B, and its relative standard deviation is 8.0%. The cost contingency is \$125.5 M, 6.6% of the TCIC mean. The mean project duration is 4.8 years, and its relative standard deviation is 7.8%. The resulting distributions of project duration, OCC and TCIC are shown in Figure 64. The results of the simulation are summarized in Table 37.



(a) **(b)** **(c)**

Figure 64 – SMR project duration (a), OCC (b), and TCIC (c) distributions (r=10%)

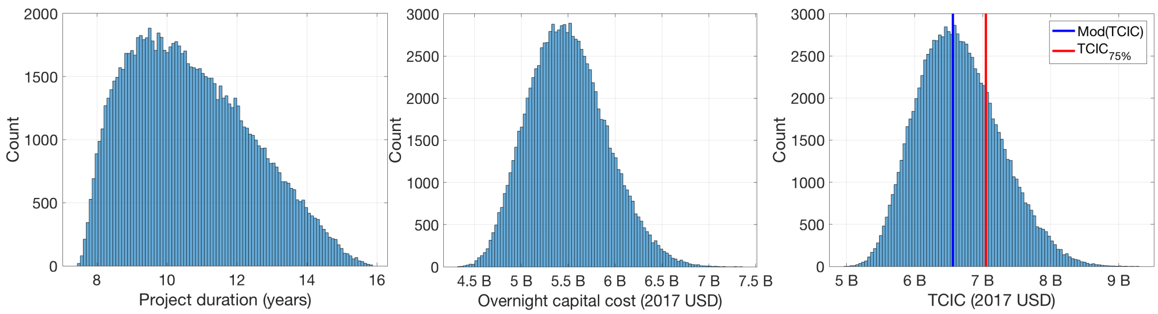
Table 37 –SMR results, considering market and durations uncertainties

	Duration (years)	OCC ($)	TCIC ($)
μ	4.8	1.5 B	1.9 B
σ/μ	7.8%	7.0%	8.0%
Mode	4.7	1.5 B	1.8 B
75%			2.0 B
Contingency			125.5 M
Contingency/ μ_{TCIC}			6.6%

7.3 PWR12-BE

The Monte Carlo simulations of PWR12-BE were run using the same approach used in Section 7.2.2. The prices of commodities and equipment (representing the "state" of the market) were sampled according to the correlations and distributions derived from the historical data. The activity durations were sampled according the distributions used for the SMR analysis (Section 7.1.3) and shown in Table 31.

The results for PWR12-BE are shown in Figure 65 and Table 38. The project duration has a mean of 10.7 years, with a relative standard deviation of 16.2%. OCC has a mean of $5.6 B and a relative standard deviation of 7.5%, and the TCIC mean and relative standard deviations are \$6.8 B and 9.0%. In respect to the SMR, the PWR12-BE project duration has a higher relative standard deviation (16% vs 7.8%, Table 38). The OCC and TCIC relative standard deviations have the same order of magnitude as the SMR, the OCC one being slightly higher (7.5% versus 5.9 %) and TCIC one being slightly higher (9.0% versus 7.0%). The project contingency is \$630.9 M, 9.3% of the TCIC expected value.



(a) **(b)** **(c)**

Figure 65 – PWR12-BE project duration (a), DC (b), and TCIC (c) distributions

Table 38 – PWR12-BE results

	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}			9.3%

7.4 Modifying the model parameters to fit the historical data

The historical data collected by the Energy Information Administration (1986) and presented in Section 2.3 shows that, before 1979, the NPP project durations and OCCs had a relative standard deviation of 19.3% and 36.5%, much higher than the ones obtained for the SMR and the PWR12-BE. However, the SMR results are not comparable to the observed data, as the SMR is a new design built according to a novel methodology (modularization), while the historical trend refers to stick-built nuclear power plants. For this reason, the project duration and OCC means and relative standard deviations were compared to the results obtained for PWR12-BE, and not for the SMR.

The relative standard deviation of the PWR12-BE project duration obtained through the Monte Carlo simulation is similar to the one calculated from historical data before the TMI event (pre-1979), which is 19.3%. However, the relative standard deviation of OCC is lower than the one observed in the same period, which is 36.5%. The reason of a lower OCC than that observed might lie in the unreliability of the commodity and equipment price trends that were used (the values of the correlation coefficients are reported in Appendix A). The data collected by the US Department of Labor shows very slight dispersions and correlations. However, this data includes prices collected from various industry, and most does not include data from the nuclear industry, as the production and sale of nuclear equipment in the US did not take place in the last decade. For this reason, the commodity and equipment prices data might not be reliable, and the recent construction of AP1000 units in the US might suggest that the actual prices (for nuclear components) are more dispersed and correlated than in other industries.

As discussed in Section 2.3, the project duration standard deviation for the nuclear reactors built after 1979 is 22.8%, with a mean increase of a factor 1.8 in respect to the pre-1979 phase. Regarding OCC, the observed data shows a relative standard deviation of 42.5%; with a mean increase of a factor 2.7. The causes of this increase can be identified in the change in regulation that took place after the 1979 Three Mile Island accident. This event is a good example of an unknown unknown that took place during the construction of plants completed after 1979 that, at the beginning and during construction, was not possible to forecast. The change in regulation caused an increase in commodity quantities and equipment prices that, if appropriately described today, can give insights on how to allocate allowances for unknown events.

7.4.1.1 Pre-1979 data fitting (Case 1a and case 2a)

Through the first approach, comparable OCC standard deviation to one observed before 1979 was obtained keeping the original correlation coefficients and modifying only the dispersion of the price and duration distributions. In this case, as variable are less correlated, the distributions need to be broadened using factors d_1 = 8.9 and d_2 = 1.28. Results are shown in Figure 66 and Table 39. In this case, the TCIC expected value is \$2.5 B, and the project contingency is \$1.0 B, which corresponds to 40.0% of the TCIC expected value. In absolute terms, this value is 1.72 times higher than the one obtained before modifying the inputs.

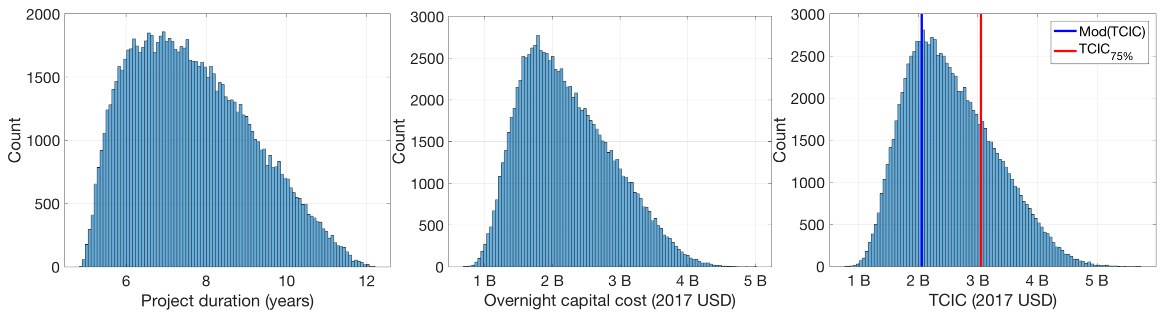


Figure 66 – PWR12-BE distributions, with pre-1979 modified inputs (case 1a)

Table 39 – PWR12-BE results, with pre-1979 modified inputs (case 1a)

	Duration (years)	OCC ($)	TCIC ($)
μ	7.6	2.2 B	2.5 B
σ/μ	19.5%	30.2%	29.0%
Mode	6.9	1.7 B	2.0 B
75%			3.0 B
Contingency			1.0 B
Contingency/ μ_{TCIC}			40.0%

Through the second approach, similar results were also obtained increasing the prices correlation coefficients to 0.99 and the activities correlation coefficients to 0.99. Values of d_1 and d2 were incrementally increased, and the historical data was matched using values d_1 = 5.44 and d_2 = 1.09. The results of this case are shown in Table 40, and the project duration, OCC and TCIC distributions are shown in Figure 67. The TCIC expected value is $2.5 B, and the project contingency is $729.7 M (29.2% of the TCIC expected value). In this case, the project contingency is 1.37 times higher than the one obtained before modifying the inputs.

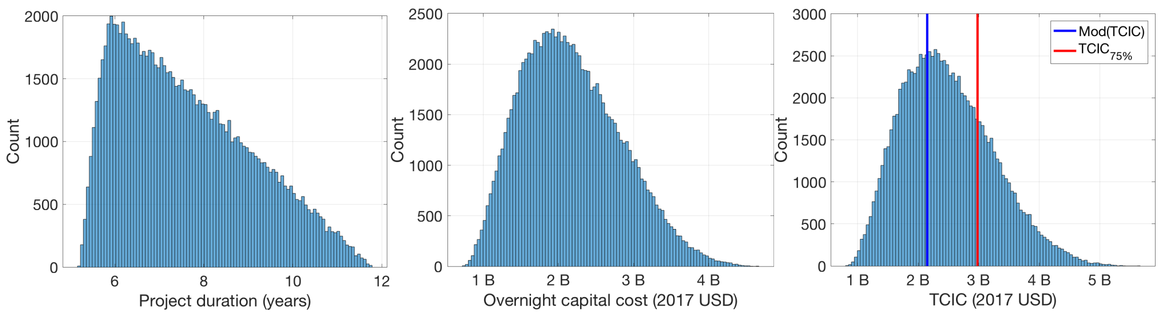


Figure 67 – PWR12-BE distributions with pre-modified inputs (case 2a)

Table 40 – PWR12-BE results with pre-1979 modified inputs (case 2a)

	Duration (years)	OCC ($)	TCIC ($)
μ	7.6	2.2 B	2.5 B
σ/μ	19.5%	30.2%	30.2%
Mode	5.9 B	1.9 B	2.3 B
75%			3.0 B
Contingency			729.7 M
Contingency/ μ_{TCIC}			29.2%

7.4.1.2 <u>Post-1979 data fitting (Case 1b and case 2b)</u>

To simulate the increase in cost and duration relative standard deviations, the parameters *a* and *b* were modified through the use of the parameter d_1 and d_2 (Eq. 43,44). Results comparable to the observed data were obtained for values of d_1 = 13.28 and d_2 = 1.65. The increase in the price and duration modes cause an increase in both project duration and OCC that, combined to the use of values i_1 = 2.23 and i_2 = 1.6, matches the observed increases in duration and OCC. The results of this case are reported in Table 41 and the distributions are shown in Figure 68.

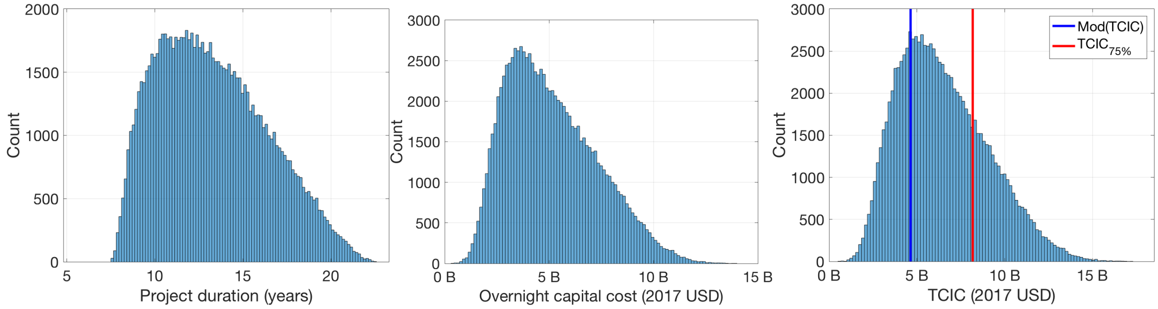


Figure 68 – PWR12-BE distributions, with post-1979 modified inputs (case 1b)

Table 41 – PWR12-BE results, with post-1979 modified inputs (case 1b*)*

	Duration (years)	OCC ($)	TCIC ($)
μ	13.2	5.1 B	6.5 B
σ/μ	23.2%	42.3%	39.3 %
Mode	11.8	3.8 B	5.1 B
75%			8.2 B
Contingency			3.1 B
Contingency/ μ_{TCIC}			47.0%

A scenario similar to the historical scenario was obtained by increasing the correlation coefficients between prices to $\rho = 0.99$. $d_1 = 8.1$, $i_1 = 2.29$. Regarding the project duration, values of $d_2 = 1.38$ $i_2 = 1.71$ were used. In this scenario, the project contingency is $9.3 B, 46.3% of the expected TCIC value of $20.2 B (Table 42). The high relative contingency is due to the higher skewness of the TCIC distribution. Under the assumption that the unknown unknown of a regulatory change during construction has the effects shown by the historical data, the expected TCIC is 3 times higher ($20.1 B vs $6.7 B) and is the project contingency is 4 times higher ($9.3 B versus $2.3 B) than expected.

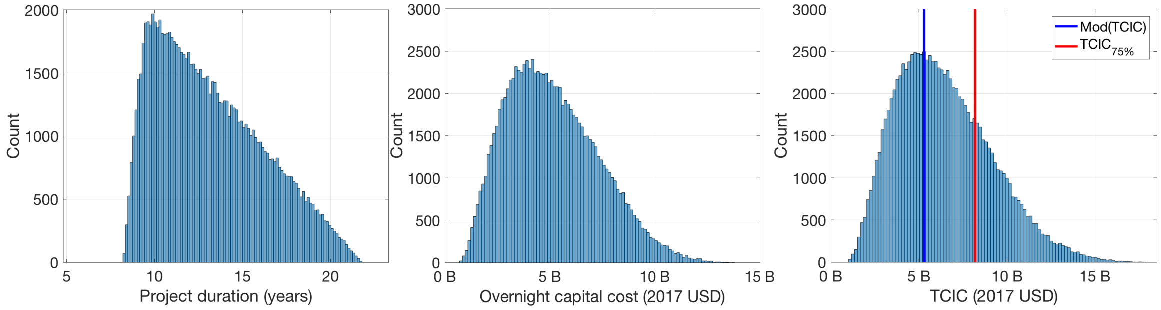


Figure 69 – PWR12-BE distributions, with post-1979 modified inputs (case 2b)

Table 42 – PWR12-BE results, with post-1979 modified inputs (case 2b)

μ	13.2	5.1 B	6.4 B
σ/μ	23.2%	42.3%	41.7 %
Mode	9.9	4.1 B	5.2 B
75%			8.2 B
Contingency			2.99 B
Contingency/ μ_{TCIC}			46.4%

7.4.1.3 Hybrid approach (case 3a and case 3b)

A more realistic approach consists of increasing the price correlation coefficients and distribution broadness, and increasing the duration distribution broadness, while keeping the activity duration correlations unchanged. This approach was denoted as "hybrid approach", and was used to calibrate the model inputs in order to fit the pre-1979 data (case 3a) and post-1979 data (case 3b). This case reflects the scenario where the activity durations given as input are more broad than expected, and the prices are more broad and more correlated than the ones extracted from US Department of Labor (2017b, 2017c). In fact, the historical prices data refers to the last 10 years and, therefore, and does not include nuclear data. For case 3a, acceptable results were obtained for d_1 = 6.98 and d_2 = 1.27. The results show a TCIC mean of $2.2 B and cost contingency of $995.5 M (Table 43), corresponding to 39.8% to the expected TCIC.

Table 43 – PWR12-BE results, with pre-1979 modified inputs (case 3a)

	Duration (years)	OCC ($)	TCIC ($)
μ	7.6	2.2 B	2.5 B
σ/μ	19.5%	30.2%	29.7%
Mode	6.7	1.9 B	2.1 B
75%			3.1 B
Contingency			995.5 M
Contingency/ μ_{TCIC}			39.8%

For case 3b, the observed data was described using $d_1 = 10.55$, $i_1 = 2.23$, $d_2 = 1.65$, $i_2 = 1.6$. The expected TCIC is $6.5 B, and the project contingency is $3.2 B, 49.2% of the expected TCIC (Table 46). The presence of unknown unknowns causes an increase in TCIC mean of a factor 2.6, which results in the need to allocate a project contingency 3.9 times higher than the base case without unknown unknowns. The probability distributions obtained through Monte Carlo simulations for case 3a and 3b are shown in Figure 70, Figure 71 and Figure 72.

Table 44 – PWR12-BE results, with post-1979 modified inputs (case 3b)

	Duration (years)	OCC ($)	TCIC ($)
μ	13.2	2.1 B	6.5 B
σ/μ	23.2%	42.3%	40.7%
Mode	6.8	3.9 B	5.1 B
75%			8.2 B
Contingency			3.2 B
Contingency/ μ_{TCIC}			49.2%

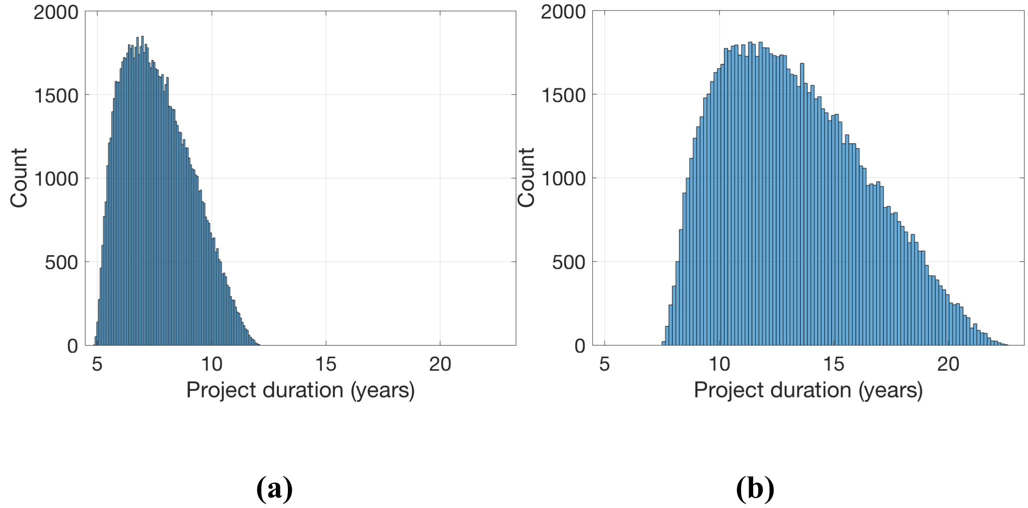


Figure 70 – Comparison between pre-1979 (a) and post-1979 (b) project duration distributions (case 3a and case 3b)

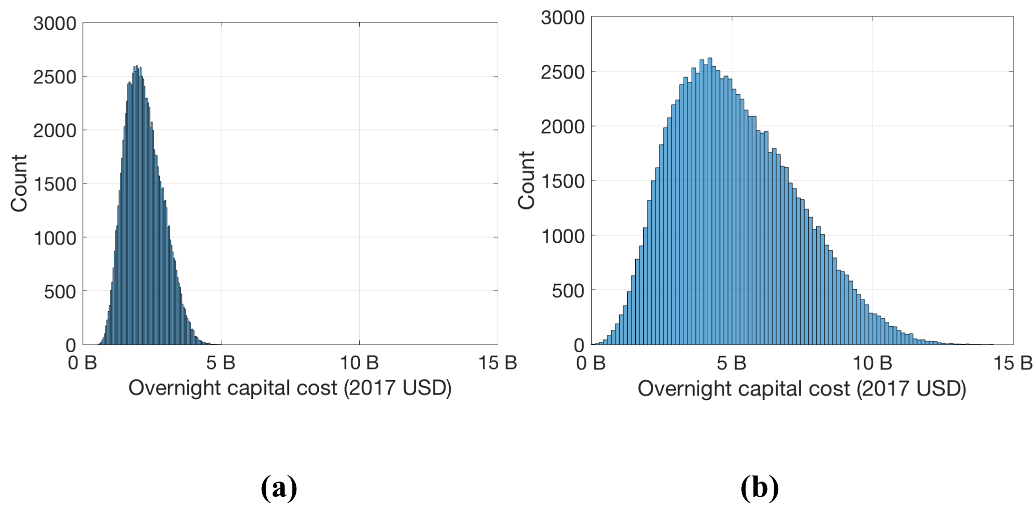
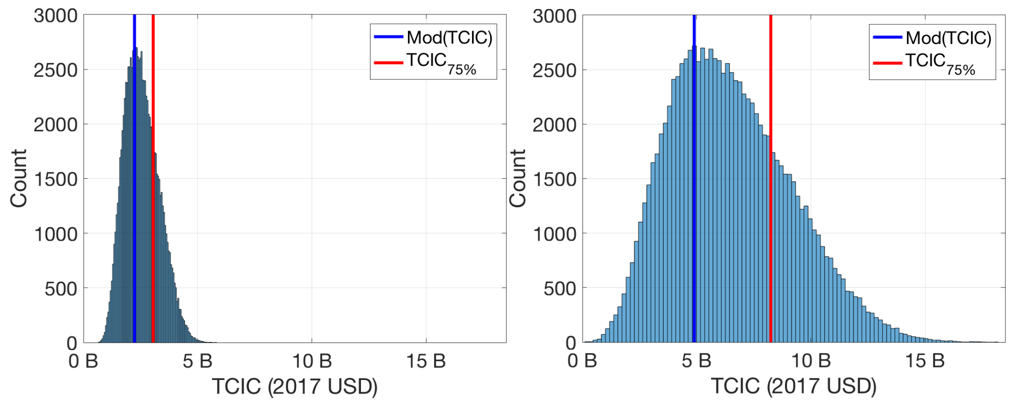


Figure 71 – Comparison between pre-1979 (a) and post-1979 (b) OCC distributions (case 3a and case 3b)



(a) **(b)**

Figure 72 – Comparison between pre-1979 (a) and post-1979 (b) TCIC distributions (case 3a and case 3b)

7.4.2 SMR

The SMR construction was further analyzed updating the model inputs, using the probability distributions and correlations derived through the comparison between the PWR12 and the US historical data. The scenario with only known unknowns was simulated under the assumptions of case 3, with the parameters obtained in matching the PWR12-BE results to the historical data (d_1 = 7.02, d_2 = 1.28). The results of this scenario are reported in Table 45. Under these assumptions, the TCIC expected value is \$1.9 B, with a contingency of \$798.5 M, representing 42.0% of the expected TCIC. As compared to the results obtained for PWR12-BE, for the SMR the TCIC relative contingency is higher (42.0% versus 39.9%). It is in regard to the construction time that the benefits of SMR modular construction are revealed. The SMR relative standard deviation of the construction duration is 10% lower than that of the PWR12-BE (9.5% versus 19.5%).

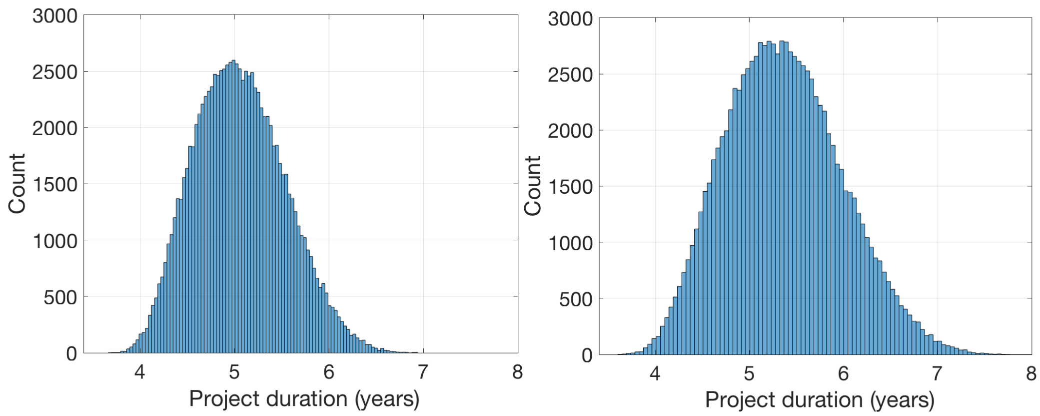
Table 45 – SMR results with pre-1979 modified inputs (case 3a)

	Duration (years)	OCC ($)	TCIC ($)
μ	5.1	1.5 B	1.9 B
σ/μ	9.5%	32.3%	32.7 %
Mode	5.0	1.3 B	1.6 B
75%			2.4 B
Contingency			798.5 M
Contingency/ μ_{TCIC}			42.0%

The scenario with the unknown unknown representing the change of regulation during construction was simulated d_1 = 10.55, i_1 = 2.23, d_2 = 1.65, i_2 = 1.6. The results show a TCIC mean of $4.5 B and cost contingency of $2.4 B (Table 46), corresponding to 53.3% of the expected TCIC. For the SMR, the cost contingency corresponds to 126% of the pre-1979 TCIC mean. As in case 3a, as compared to the PWR12-BE, the SMR TCIC relative standard deviation is 5.1% higher (45.8% against 40.7%), while the duration standard deviation is about half (11.5% against 23.2%). For the SMR, the increase in mean project duration is very small: from 5.1 years to 5.4, which corresponds to an increase of 5.9%, much lower than the one calculated from the historical data. The probability distributions obtained through Monte Carlo simulations for case 3a and 3b are shown in Figure 73, Figure 74 and Figure 75.

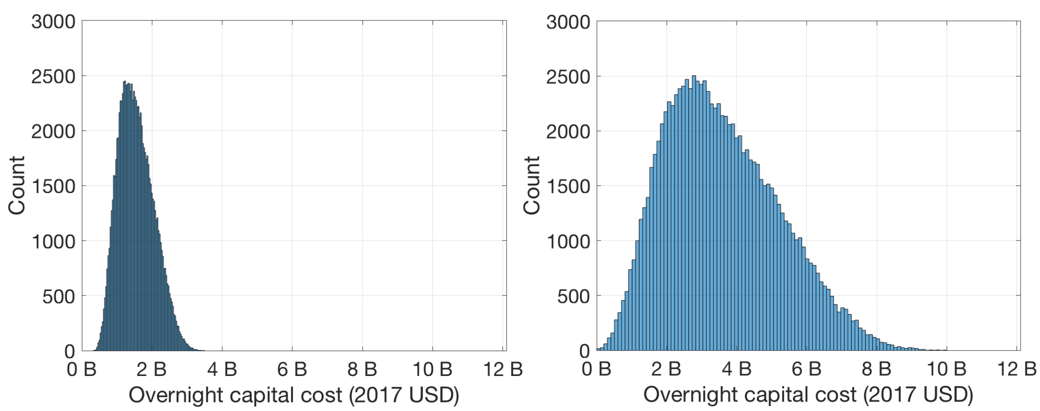
Table 46 – SMR results, with post-1979 modified inputs (case 3b)

	Duration (years)	OCC ($)	TCIC ($)
μ	5.4	3.6 B	4.5 B
σ/μ	11.5%	45.3%	45.8 %
Mode	5.3	2.8 B	3.5 B
75%			5.9 B
Contingency			2.4 B
Contingency/ μ_{TCIC}			53.3%



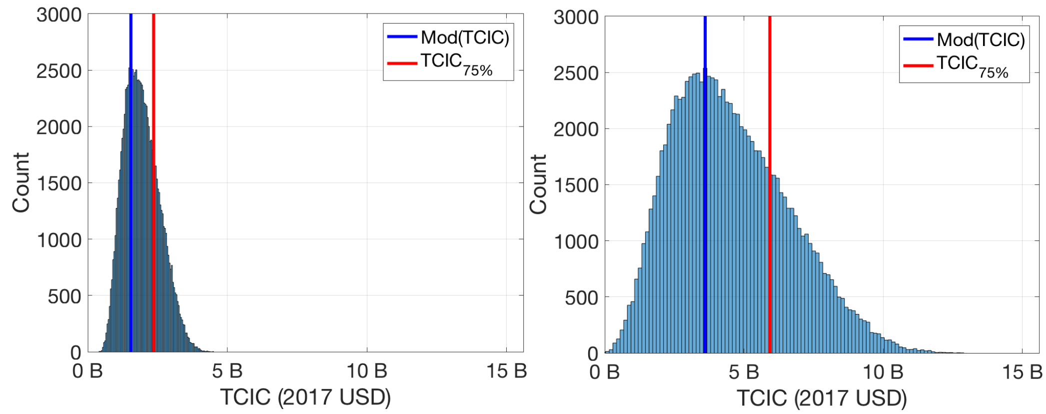
(a) **(b)**

Figure 73 – Comparison between TCIC distributions, without (a) and with (b) accounting for unknown-unknowns



(a) **(b)**

Figure 74 – Comparison between TCIC distributions, without (a) and with (b) accounting for unknown-unknowns



(a) **(b)**

Figure 75 – Comparison between TCIC distributions, without (a) and with (b) accounting for unknown-unknowns

The PWR12-BE and the SMR results obtained to fit the pre-1979 and post-1979 observed data are summarized in Table 47 and Table 48, respectively. The comparison between the SMR and PWR12-BE results suggests that modularization provides large benefits in the reduction of the uncertainty in the project duration. This fact might be in the diversification of stages in construction, since activities belonging to different stages are not correlated. However, regarding the predictability of TCIC and the cost contingency estimate, modularization does not lead to any improvements.

Table 47 – Comparison between PWR12-BE and SMR results (pre-1979)

		PWR12-BE	SMR
Duration (years)	μ	7.6	5.1
	σ/μ	19.5%	9.5%
TCIC ($)	μ	2.5 B	1.9 B
	σ/μ	29.7%	32.7 %
Contingency		995.5 M	798.5 M
Contingency/ μ_{TCIC}		39.8%	42.0%

Table 48 – Comparison between PWR12-BE and SMR results (post-1979)

		PWR12-BE	SMR
Duration (years)	μ	13.2	5.4
	σ/μ	23.2%	11.5%
TCIC ($)	μ	6.5 B	4.5 B
	σ/μ	40.7%	45.8 %
Contingency		3.2 B	2.4 B
Contingency/ μ_{TCIC}		49.2%	53.3%

7.4.3 Cost contingency of an NPP fleet

The results obtained from the cases without and with unknown unknowns can lead to a more accurate cost contingency estimate for the construction of a series of NPPs. In case a "nuclear renaissance" takes place in the US, a fleet of NPPs would be built, with reactors built at different times over a timeframe of decades. In this scenario, the realization of an unknown-unknown during construction wouldn't affect the whole fleet, but only the NPPs under construction whenever the unpredictable event takes place. In this case, the cost contingency of a single plant would be the cost contingency of the whole fleet divided by the number of plants. The contingency of the whole fleet is the summation of the cost contingency of each power plant, where the contingency of the NPPs completed before the unknown event is the one calculated without unknown unknowns (case 3a) and the contingency of the NPPS under construction at the time of the unknown event is calculated taking into account the unknown event (case 3b). Naming as p the fraction of NPPs affected by the unknown event, p also represents the probability of the unknown event to occur. Since the value of the parameter p is an unknown unknown, and not knowable *a priori*, the value of the parameter has to be decided by the decision maker. In this work, a sensitivity analysis of the overall cost contingency for the whole fleet was conducted as a function of *p*.

Cost contingency as a function of *p* was calculated for the case where the fleet under construction is made of PWR12 type plants only, and the case where the fleet is made of SMRs only. The trends are shown in Figure 76, and show a linear dependency of the cost contingency on *p*. The cost contingencies for *p* equal to 0% correspond to the one calculated in case 3a (without unknown unknowns) and the cost contingencies for *p* equal to 100% correspond to the one calculated in case 3b (with unknown unknowns). Therefore, the PWR12 contingency trend is higher and steeper than that of the SMR. As an example, considering *p=20%*, implying that unknown unknowns will affect 20% of the plants, the PWR12 contingency becomes \$1.4 B, and the SMR cost contingency becomes \$1.1 B.

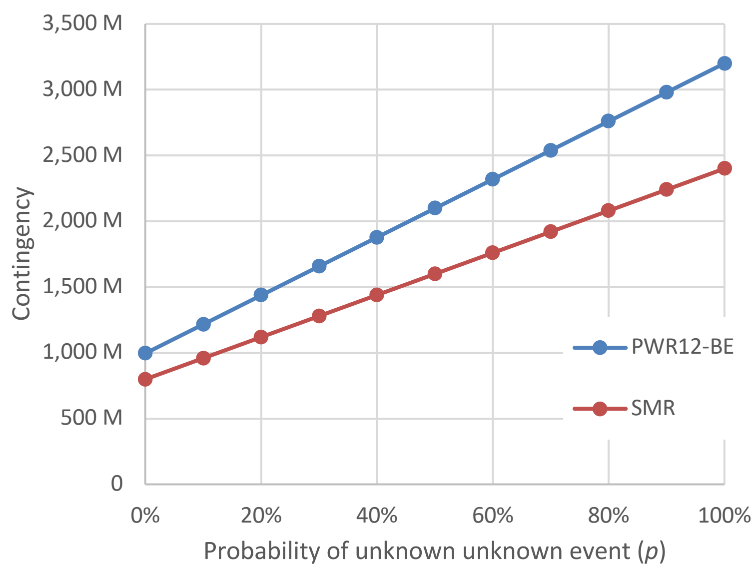


Figure 76 – PWR12 and SMR cost contingencies as a function of *p*

8 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. In the US, two trends can be identified. Nuclear reactors that were completed before the Three Mile Island 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. This phenomenon was mainly due to the change in regulation that took place after the 1979 event and affected the plants that were under construction.

The economics of a traditional four-loop Westinghouse PWR plant is described. Costs for that plant were prepared in 1978 by the Department of Energy (DOE) Energy Economics Data Base (EEDB), averaging actual cost incurred in the construction of several nuclear power plants (NPP), itemized with a great level of detail according to the Code of Accounts. This best estimate costs are denoted PWR12-BE. For each account, the costs of equipment, site labor and site material are provided. Industry experts at Westinghouse

Electric Company performed a "sanity check" of the cost items, adjusting the cost of several items to match the current market and supply chain data.

A deterministic methodology that produces a construction schedule and cash flow profile given a PBS of an NPP is presented. The methodology is based on a bottom-up approach and was used to calculate TCIC for the Westinghouse Small Modular Reactor. Construction is dependent on a number of variables, e.g. construction location, quantity and cost of labor and materials. The construction of the WEC-SMR nuclear island was described categorizing modules by the action they perform (type) and using typical labor rates, activities durations and costs for each module type. The model was applied to assess and compare different construction strategies for the Westinghouse Small Modular Reactor (WEC-SMR) nuclear island and was used to demonstrate and quantify the benefits of modularization. With a 10% discount rate, it was shown that the use of off-site factories to produce modules can reduce TCIC by 23.64%. Furthermore, EVAL showed that the adoption of an on-site assembly area to build super modules brings an additional 8.26% decrease in TCIC. Adopting full modularization, TCIC is 29.95% lower than if the nuclear island is built adopting stick-built construction. It was also shown how TCIC changes if higher discount rates are considered. Under the conservative assumption that manufacturing and construction of the portion of NPP other than nuclear island does not allow any type of modularization, the TCIC savings are about 15%. Under this methodology, the construction schedule of an NPP is generated from the NPP Part Breakdown Structure using an as-late-as-possible logic between activities, considering deterministic inputs (durations and costs of activities). Despite this logic provides a lower TCIC, due to the delaying of cash flows, it increases project risks, in case delays affect activities on the critical path. TCIC sensitivities on the discount rate and the 1-3-8 rule were analyzed. The analysis was extended to assess cost reduction if additional relocation of activities from the NPP construction site to off-site factories is feasible. The availability of barge transportation allows bigger pieces of equipment, which in the case of a modular reactor are called super modules, to be fabricated in a factory. Manufacturing super modules off-site allows labor to be moved from the site to the factory, with subsequent reduction in total labor required for the NPP to be built. This paper describes extending the EVAL methodology that allowed us to quantify the benefits of manufacturing super modules off-site. Based on the assumptions on the 1-3-8 rule and on the reduction of the number of composite modules, EVAL predicted a TCIC reduction up to 18% for the reference SMR. The deterministic analysis provides significant insights into the main contributors to the project costs and is able to support decisions in managing construction and reducing costs. However, the deterministic analyses highlighted the importance of extending the methodology to include stochastic capabilities through Monte Carlo simulations in order to estimate project risks, TCIC uncertainties, and costs escalation.

Costs were generated to represent an artificial standard SMR, consisting of two units, for a total power level of 600 MWe. A stochastic analysis through Monte Carlo simulations is performed for the generic SMR and PWR12-BE, with the objective of estimating uncertainties in project costs and time. Furthermore, accurate predictions in the TCIC distribution can provide a correct estimate of the cost contingency. The approach is based on the correlated sampling through the Iman-Conover method. A double-step approach was used, where correlations between main equipment and commodity prices were accounted based on historical data, as well as correlations between activities in the construction stage. The results show a more accurate estimate and an improved prediction of TCIC uncertainty as correlations between variables are taken into account. However, a comparison between the resulting OCC uncertainty for the PWR12-BE and the historical data on nuclear reactor constructions in the US shows that the model underestimates cost uncertainty. For this reason, the probability distributions and the correlation matrix were modified in order for the results to represent the observed data. The inputs were first modified for the PWR12-BE to represent the historical construction cost and project duration in the pre-1979 phase to represent the expected standard deviations in a stable era, with no regulatory changes and no unforecastable events taking place. The inputs were later modified for the PWR12-BE to describe the cost escalation and the increase in standard deviations of cost and project duration in the post-1979 phase. The difference in the inputs represents the contribution of the unknown unknown describing the unexpected regulatory change during construction (and possible other unexpected events). Updated inputs were then applied to the SMR construction to estimate project duration, OCC and TCIC distributions and calculate cost contingency. The comparison between the results obtained for the SMR and the PWR12-BE show the difference in time and cost distributions between stick construction and modularization. The results, with and without unknown unknowns, for both PWR12-BE and SMR are summarized in Table 49. With the inputs derived from the pre-1979 data, the TCIC mean value for the PWR12-BE is $2.5 B, with a contingency of $995.5 M, which corresponds to 39.8% of the TCIC mean. Similar results were obtained for the SMR, where cost contingency is 42.0% of the TCIC expected value. Regarding the project duration, the SMR relative standard deviation is 9.5%, 10% lower than that of the PWR12-BE. If the unknown unknowns are taken into account, the

PWR12-BE TCIC mean value increases to \$6.5 B, while the cost contingency increases to \$3.2 B, 49.2% of the TCIC expected value. The cost contingency is 128% of the TCIC mean derived for the pre-1979 case. For the SMR, TCIC increases to 4.5 B, while the cost contingency relative to the TCIC mean increases to \$2.4 B, which corresponds to 126% of the pre-1979 TCIC mean. However, the construction time relative standard deviation for the SMR is 11.5%, about half than that of the PWR12-BE (23.2%). As the results show, there is no substantial difference between the TCIC relative standard deviation resulting from stick construction and modularization. However, the adoption of modularization provides a significant reduction in the standard deviation of the project duration, reducing the uncertainty in the construction time.

Table 49 – PWR and SMR results summary (with and without unknown unknowns)

		w/o		w/	
		PWR	SMR	PWR	SMR
Duration (years)	μ	7.6	5.1	13.2	5.4
	σ/μ	19.5	9.5%	23.2	11.5%
TCIC (\$)	μ	2.5 B	1.9 B	6.5 B	4.5 B
	σ/μ	29.7%	32.7%	40.7%	45.8%
Contingency		995.5 M	798.5 M	3.2 B	2.4 B
Contingency/ μ_{TCIC}		39.8%	42.0%	49.2%	53.3%

The cost contingency of a NPPs being part of a fleet was calculated, simulating the case of a "nuclear renaissance". If the construction of a NPP fleet takes place in the US, the cost contingency of each plant will depend on the cost contingency of the other NPPs of the fleet, and therefore on the fraction of NPPs affected by the unknown unknown. In this case, the cost contingency of the plants was calculated as a function of the fraction of plants (p) affected by the unpredictable event, for both the PWR12 and the SMR. As compared to the SMR, the PWR12 presents a steeper cost contingency as a function of p.

For a fraction of plants affected by unknown unknowns equal to 20%, the cost contingencies for the PWR12 and the SMR are \$1.4 B and \$1.1 B, respectively.

APPENDIX A. HISTORICAL PRICES DATA

Table 50 – CPI (extracted from US Department of Labor (2017a))

	Q1	Q2	Q3	Q4
2007	203.7557	207.6623	208.2353	209.7163
2008	212.1003	216.7567	219.2777	213.0753
2009	212.015	214.263	215.718	216.152
2010	217.0197	218.0507	218.254	218.8977
2011	221.6663	225.5307	226.452	226.1077
2012	227.9067	229.7927	230.2967	230.3797
2013	231.7397	232.9933	233.874	233.2213
2014	234.9967	237.7717	238.0443	236.132
2015	234.8493	237.6807	238.305	237.233
2016	237.3863	240.1783	240.976	241.5047
2017	243.4143	244.6285		

Table 51 – Total compensation for Private industry workers in All industries and occupations, 3-month percent change (x_1, extracted from US Department of Labor (2017b))

	Q1	Q2	Q3	Q4
2007	1.19464	1.18271	1.18889	1.19112
2008	1.18598	1.16863	1.16212	1.20193
2009	1.21036	1.20005	1.19673	1.20029
2010	1.20267	1.20297	1.20665	1.20792
2011	1.19999	1.18886	1.18876	1.19533
2012	1.19183	1.18796	1.1901	1.19324
2013	1.19335	1.19287	1.19313	1.20245
2014	1.19695	1.19244	1.19941	1.21517
2015	1.23036	1.2157	1.21979	1.23143
2016	1.23802	1.23097	1.23303	1.23648
2017	1.2366			

Table 52 – Nonmetallic mineral products, hydraulic cement (x_2, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	246.002	246.241	245.673	244.598
2008	240.745	234.959	232.307	238.303
2009	239.739	237.832	231.188	227.501
2010	222.529	216.128	213.183	210.264
2011	205.488	203.435	203.5	198.547
2012	200.998	201.88	201.72	201.612
2013	206.824	208.069	207.528	208.421
2014	208.162	213.762	214.468	217.271
2015	226.454	229.956	229.179	230.045
2016	236.581	238.077	239.236	237.974
2017	241.728			

Table 53 – Metals and metal products (x_3, extracted fromUS Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	234.909	241.801	235.023	230.199
2008	247.736	300.636	318.009	243.315
2009	212.602	192.37	209.714	218.365
2010	237.583	260.23	248.788	249.089
2011	270.86	276.546	275.348	270.719
2012	271.259	261.299	245.691	240.34
2013	238.506	234.026	233.418	238.204
2014	242.583	238.547	237.897	233.372
2015	219.522	204.174	197.586	180.459
2016	177.722	192.297	194.763	191.755
2017	207.9			

Table 54 – Fabricated structural metal bar joists and concrete reinforcing bars (x_4, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	208.829	208.9902	209.9034	210.0171
2008	212.9528	225.3442	229.2818	231.0527
2009	223.2156	211.6261	203.7966	199.6489
2010	198.2111	194.8055	194.8859	194.3497
2011	195.6427	193.4817	193.5596	192.3734
2012	192.9648	194.5792	192.0275	192.4214
2013	191.2962	190.3306	190.1026	190.4598
2014	190.6167	191.3072	192.8716	194.5748
2015	195.4306	194.7101	195.5006	193.8065
2016	192.7535	196.1151	196.6871	196.864
2017	198.0001			

Table 55 – Sheet metal work mfg (x_5, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	136.7712	134.1165	133.746	132.8023
2008	132.3839	131.3167	130.2112	133.7103
2009	133.4137	130.4437	129.3337	129.3758
2010	129.0468	128.9974	133.2484	134.1259
2011	132.7865	130.7601	130.5164	130.4621
2012	128.8267	127.802	127.3471	127.1239
2013	127.6811	127.3072	126.7229	126.9026
2014	126.4309	125.6403	125.9764	127.2755
2015	130.4691	129.4313	128.303	128.643
2016	128.5943	127.0659	126.9827	127.1777
2017	126.4819			

Table 56 – HVAC and commercial refrigeration equipment (x_6, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	139.6508	138.4375	138.7994	139.2199
2008	138.5835	137.0321	139.6991	144.1688
2009	144.4851	141.7903	140.1871	139.981
2010	139.1589	138.5375	139.2309	138.933
2011	139.1128	138.3199	139.4148	140.4208
2012	140.8867	139.9074	139.1775	139.7313
2013	140.4914	140.367	140.0126	140.6144
2014	140.6639	140.0506	140.0613	141.6482
2015	143.0448	141.5477	141.4487	142.7418
2016	143.1297	141.6035	141.5058	141.5001
2017	141.6292			

Table 57 – Metal tanks and vessels, custom fabricated and field erected (x_7, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	249.2176	250.7907	250.098	247.2436
2008	251.337	255.3901	254.4322	259.2898
2009	260.4145	243.9231	236.7722	235.5032
2010	234.5625	233.4525	233.2351	229.3112
2011	220.3786	216.5954	215.03	213.9851
2012	212.2638	210.6244	208.1515	207.0798
2013	206.2182	203.497	201.8556	204.8705
2014	207.1788	206.985	207.0582	206.6295
2015	206.8943	203.2942	202.1082	201.8877
2016	201.0016	199.1066	199.191	199.2621
2017	199.6428			

Table 58 – Metal tank, heavy gauge, mfg (x_8, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	155.7028	155.6813	156.4288	156.5304
2008	157.4207	160.699	163.4722	168.8997
2009	168.3797	162.5069	159.3229	158.8136
2010	156.8636	157.5056	157.3964	156.6361
2011	153.9117	150.7998	151.518	152.9031
2012	152.3059	152.1913	153.1709	154.5325
2013	153.482	153.1822	150.93	152.5424
2014	153.8876	153.3968	153.6321	155.0519
2015	155.3099	152.3947	151.2734	150.6165
2016	150.3476	148.5656	148.5813	135.9265
2017	135.9324			

Table 59 – Steel product mfg from purchased steel (x_9, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	180.4518	179.254	178.0542	175.5139
2008	184.5161	214.1507	236.2446	227.0873
2009	193.518	173.4073	172.933	176.0234
2010	182.1164	192.86	192.7559	190.6603
2011	201.6446	210.5193	206.4923	205.4703
2012	205.5688	202.5651	196.5317	193.1635
2013	189.8527	186.6557	186.0899	186.8562
2014	186.1079	184.5834	184.818	185.7288
2015	181.8584	170.0062	165.7525	160.6202
2016	158.9389	162.7888	166.9298	163.9293
2017	171.6542			

Table 60 – Pump and compressor manufacturing (x_{10}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	139.4096	138.8692	139.1131	139.2203
2008	140.1559	138.2023	139.2904	144.6694
2009	146.5999	145.368	144.9142	144.7364
2010	144.6466	144.4487	144.9496	144.8958
2011	145.8127	144.4689	144.7817	145.4714
2012	146.3977	146.3334	146.2633	146.0673
2013	147.0395	147.4747	146.919	147.5752
2014	148.6142	147.29	147.7379	149.6979
2015	151.6263	150.2994	150.0069	150.995
2016	152.1345	150.1629	149.5968	149.5732
2017	149.6396			

Table 61 – Power boiler and heat exchanger mfg (x_{11}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	163.1948	162.3597	160.7772	160.3812
2008	160.7685	164.3189	170.6899	174.5166
2009	173.0367	163.5073	159.3601	158.474
2010	158.4423	163.1549	163.9747	163.8653
2011	164.3964	165.6994	167.728	167.8046
2012	167.0544	166.4623	166.4895	166.4997
2013	166.6125	166.9067	167.0452	167.3027
2014	166.1086	165.4742	165.4554	168.322
2015	171.6336	169.589	169.4509	172.4868
2016	171.276	170.8461	170.9241	170.7525
2017	169.7481			

Table 62 – Iron and steel pipes and tubes, purchased iron and steel (x_{12}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	284.2751	281.3158	277.2868	272.3369
2008	289.6048	338.5817	364.895	358.3475
2009	297.376	260.5366	260.1341	272.0748
2010	289.0867	315.5719	318.3806	317.2948
2011	342.7802	358.4258	348.7883	349.282
2012	352.8633	347.4412	333.1618	330.8097
2013	320.3619	311.4789	312.4982	313.0943
2014	311.259	307.9231	306.0311	308.3056
2015	302.1956	277.0332	268.3792	258.0034
2016	256.0216	264.6431	267.0374	259.9638
2017	277.3538			

Table 63 – Metal valve mfg (x_{13}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	149.2987	148.4528	150.1998	149.9563
2008	150.3479	148.9649	149.4454	155.1621
2009	157.4114	155.8765	154.9357	154.8888
2010	155.1341	155.1859	155.0788	155.1445
2011	155.7838	155.5732	156.7048	158.5682
2012	158.6422	158.475	158.7327	160.0913
2013	159.9608	159.5193	159.6155	160.7621
2014	161.3192	159.8476	159.8351	161.7548
2015	163.192	162.0719	162.2279	163.4086
2016	164.1611	162.9678	162.5286	162.6119
2017	161.9398			

Table 64 – Turbine and power transmission equipment mfg (x_{14}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	182.9707	180.474	178.9157	178.3527
2008	179.6513	179.7862	185.1604	196.4045
2009	201.2378	198.7463	199.2569	197.7623
2010	197.1233	195.5165	195.5959	195.3936
2011	194.837	193.1193	192.5141	192.9157
2012	191.3259	190.5676	190.6141	190.8981
2013	190.1326	189.8051	189.6483	190.7389
2014	189.7165	188.1528	188.245	190.4991
2015	191.85	190.0458	189.8191	190.781
2016	187.7024	185.0791	184.4655	184.1965
2017	183.2885			

Table 65 – Fabricated heat exchangers and steam condensers (except for nuclear applications) (x_{15}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	352.7336	350.0934	344.5114	344.5295
2008	343.8128	346.555	353.6152	357.1728
2009	357.6517	348.974	339.8597	337.4413
2010	337.0711	346.4753	343.5739	342.4144
2011	340.1719	336.1044	341.5416	348.8869
2012	347.3502	345.8468	346.2268	346.4551
2013	346.9543	346.5934	346.0544	347.8277
2014	345.7906	343.9518	343.7963	351.0556
2015	358.4487	354.2114	353.6224	364.7808
2016	364.7173	362.6525	362.0586	361.4684
2017	358.6334			

Table 66 – Electrical equipment mfg (x_{16}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	143.0522	141.7769	142.2467	142.4486
2008	143.3083	142.7923	144.3867	148.5989
2009	148.6385	147.2723	146.9935	147.8689
2010	148.5555	149.2002	149.8087	150.1133
2011	150.1162	149.3521	149.5373	149.5485
2012	149.4453	148.1437	147.1486	147.2011
2013	147.7116	146.9494	146.6747	147.5052
2014	146.9839	145.0604	145.1333	146.1732
2015	146.8677	144.7049	143.9478	144.1516
2016	143.8176	142.4522	142.3861	142.2769
2017	141.5965			

Table 67 – Mechanical power transmission equipment mfg (x_{17}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	230.0624	224.7864	227.2195	227.4026
2008	226.9291	225.8057	237.1733	248.6595
2009	255.9517	254.1857	252.503	252.2228
2010	252.4181	251.0363	251.6619	252.9717
2011	253.6075	250.5238	252.0258	255.9465
2012	255.7907	254.7878	254.517	254.2507
2013	256.1007	256.5051	255.3295	256.7786
2014	254.0786	251.3508	252.0558	254.7242
2015	258.0232	255.9786	256.1965	258.0431
2016	257.3958	253.8267	252.7133	252.3963
2017	252.4603			

Table 68 – Elevator and moving stairway mfg (x_{18}, extracted from US Department of Labor (2017c))

	Q1	Q2	Q3	Q4
2007	161.9116	160.2784	160.699	159.643
2008	158.1568	156.4168	160.9036	167.1757
2009	163.9936	161.1317	158.755	158.8893
2010	158.1804	155.9718	155.789	154.9959
2011	153.2448	154.525	153.8242	155.4292
2012	154.5969	154.1081	154.0559	154.1416
2013	154.0837	153.3916	154.348	156.0399
2014	155.3485	154.6322	155.106	157.1948
2015	158.7118	157.4378	157.1272	158.4927
2016	159.4196	157.6351	157.2136	157.41
2017	159.4258			

Table 69 – Market prices correlation matrix

1.00	0.22	-0.70	-0.03	-0.26	0.67	-0.55	-0.30	-0.58	0.70	0.48	-0.55	0.66	0.20	0.53	-0.08	0.48	0.25
0.22	1.00	-0.51	0.77	0.31	0.15	0.24	0.25	-0.57	-0.15	-0.01	-0.65	-0.20	-0.45	0.42	-0.71	-0.42	0.87
-0.70	-0.51	1.00	-0.09	0.30	-0.66	0.50	0.29	0.89	-0.60	-0.30	0.90	-0.55	0.13	-0.54	0.52	-0.39	-0.46
-0.03	0.77	-0.09	1.00	0.60	-0.08	0.63	0.56	-0.12	-0.50	-0.17	-0.25	-0.54	-0.09	0.13	-0.30	-0.57	0.76
-0.26	0.31	0.30	0.60	1.00	-0.37	0.76	0.57	0.24	-0.66	-0.30	0.14	-0.70	0.18	-0.17	0.20	-0.41	0.39
0.67	0.15	-0.66	-0.08	-0.37	1.00	-0.49	-0.28	-0.38	0.77	0.75	-0.38	0.72	0.14	0.72	-0.12	0.65	0.30
-0.55	0.24	0.50	0.63	0.76	-0.49	1.00	0.87	0.46	-0.87	-0.53	0.30	-0.90	0.21	-0.41	0.24	-0.62	0.37
-0.30	0.25	0.29	0.56	0.57	-0.28	0.87	1.00	0.33	-0.65	-0.48	0.17	-0.73	0.32	-0.32	0.24	-0.43	0.40
-0.58	-0.57	0.89	-0.12	0.24	-0.38	0.46	0.33	1.00	-0.46	-0.04	0.97	-0.41	0.33	-0.38	0.65	-0.17	-0.43
0.70	-0.15	-0.60	-0.50	-0.66	0.77	-0.87	-0.65	-0.46	1.00	0.68	-0.36	0.96	-0.01	0.54	-0.15	0.78	-0.17
0.48	-0.01	-0.30	-0.17	-0.30	0.75	-0.53	-0.48	-0.04	0.68	1.00	0.01	0.71	-0.02	0.78	-0.11	0.55	0.05
-0.55	-0.65	0.90	-0.25	0.14	-0.38	0.30	0.17	0.97	-0.36	0.01	1.00	-0.30	0.25	-0.35	0.62	-0.12	-0.53
0.66	-0.20	-0.55	-0.54	-0.70	0.72	-0.90	-0.73	-0.41	0.96	0.71	-0.30	1.00	-0.05	0.56	-0.16	0.74	-0.23
0.20	-0.45	0.13	-0.09	0.18	0.14	0.21	0.32	0.33	-0.01	-0.02	0.25	-0.05	1.00	-0.29	0.85	0.31	-0.13
0.53	0.42	-0.54	0.13	-0.17	0.72	-0.41	-0.32	-0.38	0.54	0.78	-0.35	0.56	-0.29	1.00	-0.48	0.39	0.43
-0.08	-0.71	0.52	-0.30	0.20	-0.12	0.24	0.24	0.65	-0.15	-0.11	0.62	-0.16	0.85	-0.48	1.00	0.22	-0.46
0.48	-0.42	-0.39	-0.57	-0.41	0.65	-0.62	-0.43	-0.17	0.78	0.55	-0.12	0.74	0.31	0.39	0.22	1.00	-0.27
0.25	0.87	-0.46	0.76	0.39	0.30	0.37	0.40	-0.43	-0.17	0.05	-0.53	-0.23	-0.13	0.43	-0.46	-0.27	1.00

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