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1 Executive Summary

Affordable energy is a critical societal need. Capital construction cost is a significant portion of nuclear energy cost. By controlling and reducing cost, companies can build more competitive nuclear power plants and hence provide access to more affordable energy. Modular construction provides an opportunity to reduce the cost of construction, and as projects scale up in number, the cost of each unit can be further reduced.

The objective of this project was to advance design and construction methods for manufacturing Small Modular Reactors (SMRs), and in particular to improve modular construction techniques and develop best practices for designing and operating supply chains that take advantage of these techniques. The overarching objectives were to accelerate the construction schedule and reduce its variability, reduce the cost of construction, reduce interest costs accrued during construction (IDC), and thus enhance the economic attractiveness of SMRs. Our fundamental measure of merit was total capital investment cost (TCIC). To achieve these objectives, this project developed a decision support system, EVAL, to support identifying, addressing, and resolving or ameliorating challenges and deficiencies in the current modular construction approach. The results of this effort were consistent with the facts that the cost of a construction activity is often smallest when accomplished in the factory, greatest when accomplished at the construction site, and at an intermediate level when accomplished at an assembly area close to the construction site.

Further, EVAL can aid in providing insight into ways to reduce waste, improve quality, efficiency, and throughput and reflects the fact that the more done early in the construction process, i.e., in the factory, the more upfront funding is required and hence the more IDC will be accrued. The analysis has lead to a better understanding of circumstances under which modular construction performed mainly in the factory will result in lower expected total cost, relative to more traditional, on-site construction procedures. Further, we anticipate that EVAL can be used to gain insight regarding what role standardization can play in order for modularization to be most effectively defined. Such results would ultimately benefit all (small and large) new nuclear construction.

2 Comparison of the actual accomplishments with the goals and objectives of the project

The objective of this project was to advance methods for manufacturing Small Modular Reactors (SMRs), and in particular to improve modular construction techniques and develop best practices for designing and operating supply chains that take advantage of these techniques. The overarching goal is to accelerate the construction schedule and reduce its variability, reduce the cost of construction, reduce interest costs accrued during construction (IDC), and thus enhance the economic attractiveness of SMRs.

The scope of the proposed project was

- Evaluate the differences in stick build and modular construction for SMRs;
- Examine transportation limitations as they relate to modular construction;
- Investigate one-tier and two-tier modular construction options for SMRs;
- Analyze the impact of front-loaded fabrication cost.

The actual accomplishments successfully met the goals, objectives and scope of the project. Specifically:

The differences in stick build and modular construction for SMRs were evaluated. This was combined with investigation of one-tier and two-tier modular construction options, so that 3 different construction strategies were evaluated. Impact of transportation limitations was accounted through assumed viable size of the modules to be transported. In all cases the Total Capital Investment Cost (TCIC) was determined. TCIC accounts for the Interest During Construction (IDC) and thus accounts for the impact of front-loaded fabrication cost, in case of increased off-site fabrication. It also accounts for the increased efficiency in that case, which tends to overcome the front-cost issue and ultimately proves beneficial in most cases.

In addition to developing the methodology and applying it to performing the proposed scope, sensitivity studies were performed on key parameters, including the IDC, cost of land, level of parallelism in construction, impact of welding techniques, impact of off-site testing and so on. These studies provided insight on various construction decisions. Moreover, a method to account for uncertainties was developed and applied. This is important since the deterministic assumptions are difficult to justify and rarely represent the reality.

The overarching achievement is development of a methodology that was applied to evaluate different approaches to construction of SMRs and understand key factors under specific conditions. This methodology may be used to inform future SMR build. Overall, it can help to accelerate the construction schedule and reduce its variability, reduce the cost of construction, reduce interest costs accrued during construction (IDC), and thus enhance the economic attractiveness of SMRs.

Thus, it can be stated that the overall project goals and objectives were met, and in some aspects exceeded.

3 Overview of work performed to date

The project has produced a literature review, which is provided in Appendix A of the 31 January 2015 Semi-Annual Report [3]. We developed a model, EVAL, of nuclear island construction and an overview of factors and constraints that influence total capital investment cost (TCIC). The case study is described in the 30 June 2015 Annual Report [4]. and in the 31 December 2015 Semi-Annual Report [5] and produced three publications [6,7,8]. EVAL capabilities were extended to perform stochastic analysis through Monte Carlo simulations. In the 30 June 2016 annual report we presented the stochastic capabilities of EVAL [9]. In the last reporting period (July-December 2016), we extended EVAL capabilities to account for correlations between variables. Results show better predictions in TCIC uncertainty as correlation between variables are taken into account. EVAL deterministic analyses were submitted as a publication for Progress in Nuclear Energy [10].

4 Technical work

The project activities for the entire period of funding, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results are summarized in the appendix. Figures, analyses, and assumptions used during the life of the project to support the conclusions are also included.

5 Publications

In summary, through this project the team has produced the following publications:

1. G. Maronati, B. Petrović, J. W. Banner, C. C. White, M. H. Kelley, and J. V. Wyk, “Location sensitivity analysis of Small Modular Reactor construction cost,” in *Proceedings of the ANS Winter Meeting 2015*, (Washington, DC), American Nuclear Society, 2015 [6].
2. . Maronati, B. Petrović, J. W. Banner, C. C. White, M. H. Kelley, and J. V. Wyk, “Total capital investment cost evaluation of SMR modular construction designs,” in *Proceedings of ICAPP 2016*, (San Francisco, CA), American Nuclear Society, 2016 [7].
3. G. Maronati, B. Petrović, C. C. White, M. H. Kelley, and J. V. Wyk, “Impact of testing activities on Small Modular Reactor total capital investment cost,” in *Proceedings of ICONE24*, (Charlotte, NC), American Society of Mechanical Engineers, 2016 [8].
4. . Maronati, B. Petrović, Chelsea C. White III, Matthew H. Kelley, Jurie Van Wyk, “EVAL: a methodological approach to identify NPP Total Capital Investment Cost drivers and sensitivities”, Progress in Nuclear Energy (Accepted for publication with major revisions) [10].

6 Computer modeling details

6.1 Model description and key assumptions

The description of the model along with the key assumptions used for deterministic analysis is shown in Appendix A, Section 2. The description of the stochastic model is shown in Appendix A, Section 3.

6.2 Test results

Results of the deterministic model are explained in Appendix A, Section 2.4 and Section 2.5. Results of the stochastic model are shown in Appendix A, Section 4.

6.3 Theory behind the model, non-mathematical

The description of the deterministic model in a non-mathematical form is shown in Appendix A, Section 2.1. The description of the stochastic model in non-mathematical form is shown in Appendix A, introduction of Section 3.2.

6.4 Mathematics used

The description of the model in mathematical form is shown in Appendix A, Section 2.2. The description of the equations that constitutes the stochastic analyses performed by the model is shown in Sections 3.2.1, 3.2.2 and 3.3 of Appendix A.

The theory and the mathematical algorithms that constitute the model were not peer reviewed.

APPENDIX A

1 EVAL: an introduction

Modularization is a construction technique that allows a better standardization of components, shortening of construction time and lower labor costs. 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 1.

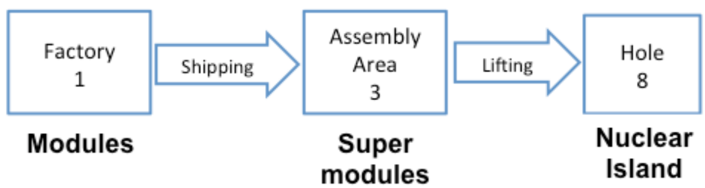


Figure 1 - Modular construction process

The benefits of this process can be described through the 1-3-8 rule of thumb that was developed in the shipbuilding industry [1,2]. The 1-3-8 rule describes the time shortening due to modularization, as 1, 3 and 8 represent the required labor time to perform the same task in the on-site hole, in the on-site assembly area and in the factory, 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. The 1-3-8 rule of thumb is derived by the shipbuilding industry and is often 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 ship modular construction might be different for NPP construction, but will be used in this study as the best available values.

As an entire nuclear island (NI) is built according to this construction technique, Total Capital Investment Cost (TCIC) is lower as compared to a NI built according to standard construction techniques (e.g. stick-built construction). The purpose of EVAL is to evaluate the benefits of modular construction and to highlight the key parameters that affect TCIC.

1.1 TCIC

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 break down of TCIC to different factors (Figure 2) [11]. Base costs include costs associated with the equipment, structures, installation and materials (direct costs), as well as the engineering, construction and management services (indirect costs). Supplementary costs include spare parts, contingencies and insurance. Owner's costs include the owner's capital investment and services costs, escalation and related financing costs. The 'fore costs' or 'overnight costs' consist of the base costs, the supplementary costs and the owner's capital investment and service costs. Financial costs include escalation, interest during construction (IDC) and fees. Fore costs, escalation costs and 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 2 - TCIC breakdown according to IAEA code of accounts [11]

1.1.1 Direct and Indirect costs

Direct costs are the main contributor to TCIC. They include direct construction cost plus pre-construction cost (site preparation) [13]. 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:

$$DC = \sum_{t=0}^{LT} C_t \qquad (1)$$

Where C_t represent the cash flow associated with an expenditure related to equipment, material or labor, r is the discount rate, t represents 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:

$$IC = in \cdot DC \qquad (2)$$

Ref. [12] sets the coefficient *in* to 10%. Other cost estimates suggest higher percentage markups [14]. Base cost, expressed as the sum of direct and indirect costs is then:

$$BC = BC(1 + in) \qquad (3)$$

1.1.2 Supplementary and Owner Costs

Supplementary costs include 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 [14]. Owner's costs include costs that are owner's responsibility, such as capitalized operations, capitalized supplementary costs, and capitalized financial costs. Ref. [12] and [13] estimates owner's costs as $200M plus 5% of direct costs. Owner's costs (*OC*) and overnight capital cost (*OCC*) can be then calculated as:

$$OC = BC \cdot 0.05 + 200M \qquad (4)$$

$$OCC = BC(1 + 0.05) + 200M \qquad (5)$$

1.1.3 Escalation costs and interests during construction contingency

Escalation reflects the change of cost of equipment, labor and material over time during the construction of the NPP. The Generation-IV International Forum (GIF) guidelines suggest setting it to zero, unless otherwise justified [13].

Interest during construction is the cost of financing overnight capital costs 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 know a priori, IDC can be calculated as:

$$IDC = \sum_{-0.5}^{-LT+0.5} C_t \left(\frac{1}{(1+r)^t} - 1 \right) \qquad (6)$$

Where LT is the number of time periods (project duration), C_t is the expenditure in period t and r is the cost of capital over one period (e.g., month). 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.

$$C_t = C_{t,DC} + C_{t,IC,OC} \qquad (7)$$

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:

$$C_{t,IC,OC} = \frac{0.05 \cdot BC + 200M}{LT} \qquad (8)$$

Under these assumptions, the expression for IDC becomes:

$$IDC = \sum_{-0.5}^{-LT+0.5} C_{t,DC} \left[\frac{1}{(1+r)^t} - 1 \right] + 0.05 \cdot BC + 200M \sum_{-0.5}^{-LT+0.5} \left[\frac{1}{LT(1+r)^t} - 1 \right] \qquad (9)$$

Where the first term represent the IDC due to cash flows associated to direct costs, and the second term the IDC associated to indirect and owner's costs. *TCIC* is calculated summing direct costs (Eq. 1), indirect costs (Eq. 2) overnight capital costs (Eq. 5) and interests during construction (Eq. 9), as:

$$TCIC = BC + OCC + IDC \qquad (10)$$

Assuming that $C_{t,DC}$ is also uniformly distributed such that C_t=DC/LT and C_t=OCC/LT, Eq. 9 becomes:

$$IDC = OCC\left[\sum_{-0.5}^{-LT+0.5} \frac{1}{LT(1+r)^t} - 1\right] \qquad (11)$$

IDC is proportional to OCC (and then direct costs). Using this expression for IDC and substituting Eq. 5 into Eq. 9, TCIC can be calculated as:

$$TCIC = [BC(1+0.05) + 200M]\left[\sum_{-0.5}^{-LT+0.5} \frac{1}{LT(1+r)^t} - 1\right] \qquad (12)$$

This expression shows that TCIC is directly dependent on direct costs. From this premise, the necessity to properly evaluate this cost item among the others arises.

2 Deterministic EVAL

2.1 Method

EVAL is a methodology that was developed to calculate TCIC of an NPP. A schematic of the EVAL process is shown in Figure 3. The methodology relies on a bottom-up approach that is based on the availability of a Part Breakdown Structure of the NPP, which contains information on components, activities and construction logic. From the PBS, the construction schedule of the NPP is generated, associating attributes 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. TCIC is calculated integrating the cash flow taking into account the time value of capital.

Figure 3 - EVAL Process

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 presented in Table 1 and represent the standard rail shippable limits. The fabrication of a module is preceded by a lead 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 4.

Dimension	12ft x 12ft x 80ft
Weight	80 tons

Table 1 - Module transportation limitations

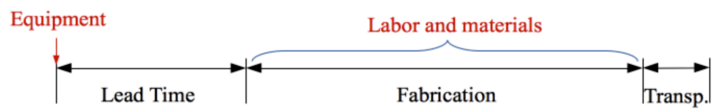


Figure 4 - Module fabrication cash flow representation

2.2 Model in mathematical form

The construction schedule model is described discretizing time by units (days, half days, hours) first. The construction schedule is described by a binary function $S_{l,i}(t)$ so that:

$$S_{l,j}(t) = \begin{cases} 1 & if \quad t_{s,l,j} \le t \le t_{e,l,j} \\ 0 & elsewhere \end{cases} \tag{13}$$

where j represents the activity identification number and l the activity level. Each component assembly task is described by an assembly start time and an assembly end time, which are related through Eq. 14. Eq. 14 also expresses the condition that, once an assembly activity has started, it cannot be interrupted before completion.

$$t_{s,l,j} = t_{e,l,j} - d_{l,j} \tag{14}$$

In Eq. 14 $t_{s,l,j}$, $t_{e,l,j}$ and $d_{l,j}$ represent the start time, the end time and the duration of activity j in level l. Predecessor-successor relationship between activities, if the parts assembly j and j' has to be performed in series, can be expressed through Eq. 15.

$$t_{s,l,j'} \ge t_{e,l,j} \tag{15}$$

During assembly activities, a certain number of resources (such as qualified workers, of specialized equipment, or assembly area) are needed in order to perform construction. The resources needed to assemble components are described by the variable $R_{i,l,j}$ which represents the percentage of resource i needed to assembly part j in level l. The resource constraint, for assembly activities j taking place at the same time, is expressed through Eq. 16.

$$\sum_{j=1}^{J} R_{i,l,j} S_{l,j}(t) \leq 1, \forall l \tag{16}$$

The resources are allocated according to the tasks priorities, expressed through the function p. p assumes integer values between 1 and 1000, where to a higher value correspond a higher priority. For both construction methods, direct module construction cost (C_{mod}) consists of the equipment cost (C_{eqp}), labor cost (C_{lab}) and other construction related cost (c_{other}, such as materials) (Eq. 17,18).

$$c^{site}{}_{\mathrm{mod}} = c_{eqp} + c^{site}{}_{lab} + C^{site}_{other} \tag{17}$$

$$c^{fact}{}_{\mathrm{mod}} = c_{eqp} + c^{fact}{}_{lab} + C^{site}_{other} \tag{18}$$

The construction cost for a module built through the two construction methods follows the profile represented in Figure 5, where the cash flows are highlighted in red.

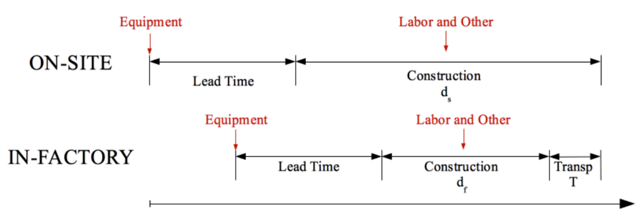


Figure 5 – Single module construction cash flow representation

The cash flow associated to the equipment cost is considered to take place at the time of the module ordering (lead-time start time), while the labor cost and other is distributed uniformly along the construction duration. The in-factory construction is followed by a transportation time required to transport the modules from factory to site. For this analysis the ordering lead-time for the two cases is considered to be the same. The in-factory construction duration is shorter than the on-site duration, as in-factory manufacturing allows parallel construction and is characterized by higher efficiencies. Under the previous assumptions, the in-factory is cheaper than the on-site method, as it is characterized by a payment delayed in time and a lower construction cost. Using the time schedule illustrated in Figure 5 it is possible to evaluate the savings due to the adoption of in-factory construction.

The construction schedule for the two construction methodologies is calculated using an *as late as possible* (ALAP) logic. In fact, given a fixed project end date, it is desirable to reduce the project present value of cost delaying every payment associated with the components purchasing and assembly. The construction schedule is determined through the following steps:

1. Calculate activity durations;
2. Starting from the fixed project end date, enumerate activities ($n=1,2,\dots,N$) in each level from the successors relationships, starting from the last one to the first one. If two activities have the same successor (meaning that the two activities can take place at the same time), assign a greater n to the one having a lower priority; if two activities have the same priority, assign a greater n to the one with a shorter duration. Calculate activities start times.
3. For each activity ($n=1,2,\dots,N$) in each level ($l=3,4,5$), check if the constraints are satisfied ($R<1$). If not, shift to earlier the activity characterized by a greater n by 1 unit of time until the conditions are satisfied.

The cash flows $c(t)$ in each time period t are then used to calculated TCIC according to Eq. 1-12.

2.3 Application of EVAL to the WEC-SMR

EVAL was used to model the construction of the WEC-SMR through the use of MS Project 2010. The use of EVAL allows a modeling simplification of the construction process, as it natively models the mathematical relationship between activities expressed by Equations 13-16. 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

The WEC-SMR nuclear island is shown in Figure 6. In EVAL, modules were categorized by module type and a simplification assumption was made, as typical fabrication costs and durations were used for each module type. On site, modules are assembled into super modules (SMs) in the on-site assembly area. SMs 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). Cost of activities in the assembly and installation stages are distributed over the activities durations. The WEC-SMR construction model 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 2.

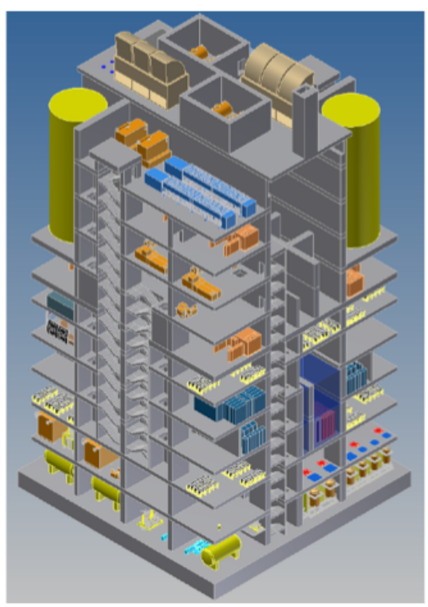


Figure 6 - WEC-SMR Nuclear Island

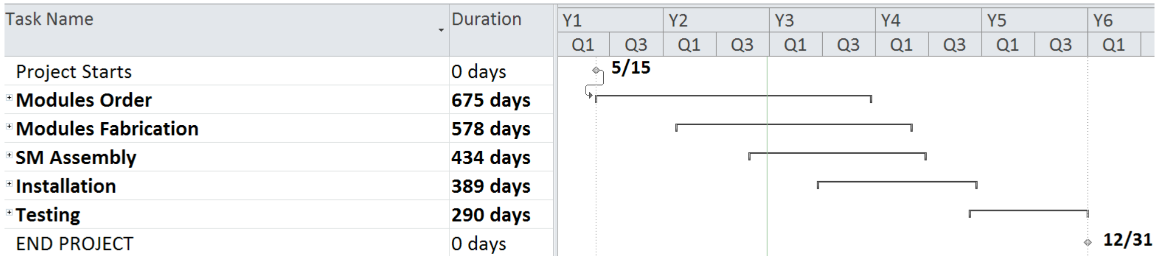


Figure 7 - WEC-SMR construction schedule

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

Table 2 – WEC-SMR number of activities

2.4 Modularization and TCIC: Results

The benefits of modularization were calculated comparing three different strategies in the construction of the WEC-SMR. The three construction strategies are shown in Figure 8 and each one is characterized by a different degree of modularization. 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.

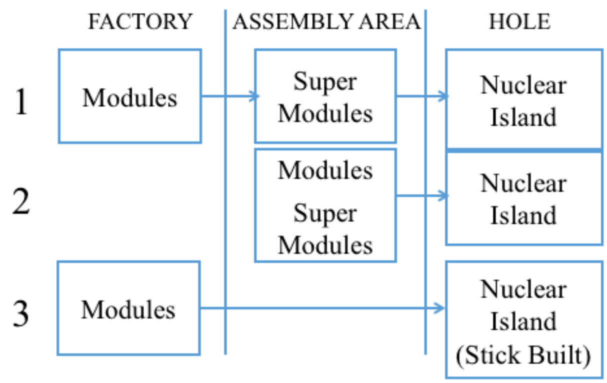


Figure 8 - Construction strategies schematic

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. In fact, as the assembly area is more congested, the availability of space in the assembly area is lower. 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.

EVAL produced construction schedules for the three strategies [6,7]. Project durations for the three construction strategies are shown in Table 3. 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 we 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 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.

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

Table 3 - Project durations for the three construction strategies

The absolute cash flows (not discounted) of direct costs for each strategy are presented in Figure 9. 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 is 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. Interest during construction was calculated with a 15% discount rate (corrected for inflation).

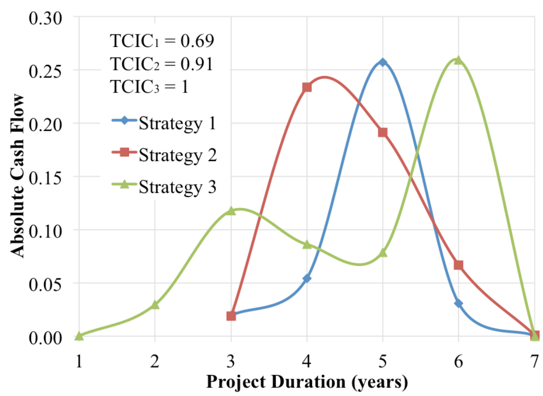


Figure 9 - Cash flow for the three construction strategies

TCICs breakdown into Base Costs and Overnight Capital Costs are presented in Table 4 and Table 5, calculated with a 15% and a 8% discount rate respectively. Each value 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 overnight capital costs are the same for the two cases, as they not dependent on the discount rate. Complete modularization (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 15% 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 15% 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 8% 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 overnight capital costs. 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. Adopting construction strategy one instead of strategy two, TCIC is 24.18% 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 8.58%. As the reactor is fully modularized, TCIC is 30.66% lower than if it is built adopting stick-built construction. Through this type of analysis, EVAL can be used to identify the most cost effective construction strategy of a NPP, given the reactor design.

	Strategy 1	Strategy 2	Strategy 3
BC	0.40 (-36.74%)	0.56 (-10.61%)	0.63
OCC	0.55 (-29.82%)	0.71 (-8.61%)	0.78
TCIC	0.69 (-30.66%)	0.91 (-8.58%)	1.00

Table 4 – TCIC breakdown for the three construction strategies (15% discout rate)

	Strategy 1	Strategy 2	Strategy 3
BC	0.46 (-36.74%)	0.66 (-10.61%)	0.73
OCC	0.64 (-29.82%)	0.83 (-8.61%)	0.91
TCIC	0.70 (-29.73%)	0.92 (-8.21%)	1.00

Table 5 – TCIC breakdown for the three construction strategies (8% discout rate)

2.5 Sensitivity Analyses

2.5.1 Discount Rate

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. Values of TCIC as a function of the discount rate were calculated, and are plotted in Figure 10. As previously, TCICs were normalized to the value of TCIC of strategy three. TCIC savings adopting full of partial modularization (strategy one and two) slightly increase with the discount rate (Figure 11).

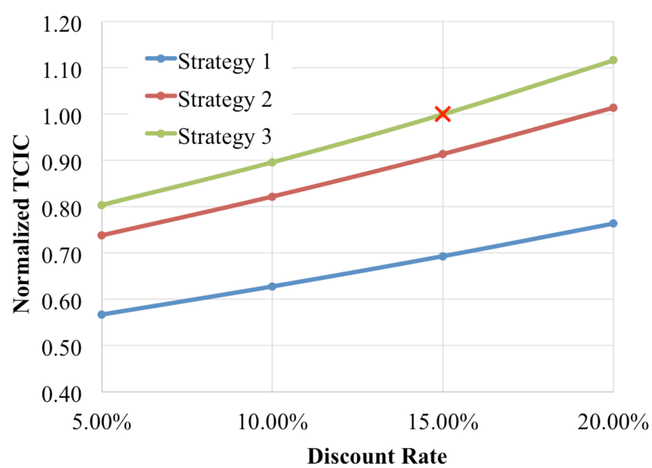


Figure 10 - Discount rate sensitivity analysis

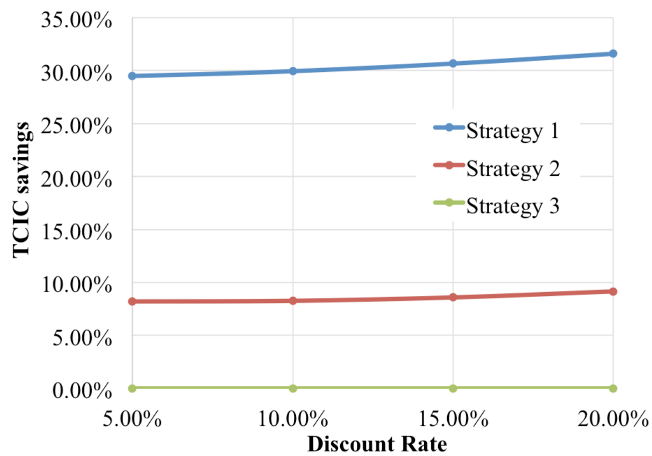


Figure 11- Discount rate sensitivity analysis (TCIC savings)

2.5.2 Assembly area size

In modeling construction strategy two, assumptions on the assembly area size were made. The space available for fabricating modules in the assembly area was assumed 25% in cross sectional area of that of off-site factories used to fabricate modules in strategy one. Different assembly area sizes were evaluated through sensitivity analysis. A different assembly area size impacts TCIC through:

- Cost of purchased land;
- Different level of parallelism allowed.

The additional cost of land due to the introduction of the on-site factory (in the assembly area) was calculated through historical data of the cost of land in the US. As prices of industrial land are characterized by a higher dispersion, they were estimated from historical prices of agricultural land. The US department of agriculture keeps statistical records of land sold every year for agricultural purposes [15]. The average value of cropland cost per state was used to compute an average cost of industrial land (in a developing location) per state multiplying the average value of cropland by a factor of 37.5 [16]. Higher, lower and average costs of land in the US were used to analyze the sensitivity of the site location on TCIC. Estimated maximum, minimum and average cost of industrial land in the US are shown in Table 6.

New Jersey (maximum)	506,250 $/acre
Montana (minimum)	37,388 $/acre
US (average)	154,875 $/acre

Table 6 - Estimated industrial land cost

A sensitivity analysis on the assembly area size for the construction strategy two was also performed. In construction strategy two, the on-site assembly area acts as an on-site fabrication facility, where modules are fabricated before being assembled into super modules. The on-site assembly area has a lower space availability than an off-site factory, with lower level of parallelism obtainable. The number of modules that can be fabricated at the same time is lower and the modules fabrication stage becomes longer. As a consequence, the fabrication stage has to start earlier in time, with an increase in TCIC caused by the discounting formula (Eq. 12). As the size of the assembly area is increased, the interest during construction reduced, but the cost of purchasing land for the assembly area is higher. These opposing phenomena lead to the presence of a minimum in TCIC as a function of assembly area size, which depends on the discount rate and the cost of land. The sensitivity of TCIC on assembly area size is shown in Figure 12. The analysis was performed for the US minimum, maximum and average cost values of industrial land. For the spectrum of the industrial land cost in the US, the optimum in assembly area size (expressed as cross sectional area), calculated with respect to the factory size, lies in a range between 47% and 79%. For a low cost of land, TCIC is only slightly dependent on the assembly area size. As long as the assembly area is bigger than a threshold value, the optimization of its size is not crucial. For the US minimum cost of industrial land, the DC minimum occurs for an assembly area that is 79% of the factory size. When higher costs of industrial land are considered, the TCIC minimum becomes more noticeable and DC values increase more rapidly with the cost of land. In these cases, the importance to optimize the assembly area size becomes more significant. For the US average cost of industrial land, the minimum TCIC occurs for an assembly area size that is 58% of the respective factory. For the US maximum value of industrial land cost, the TCIC minimum is reached for an assembly area that is 47% of the factory size.

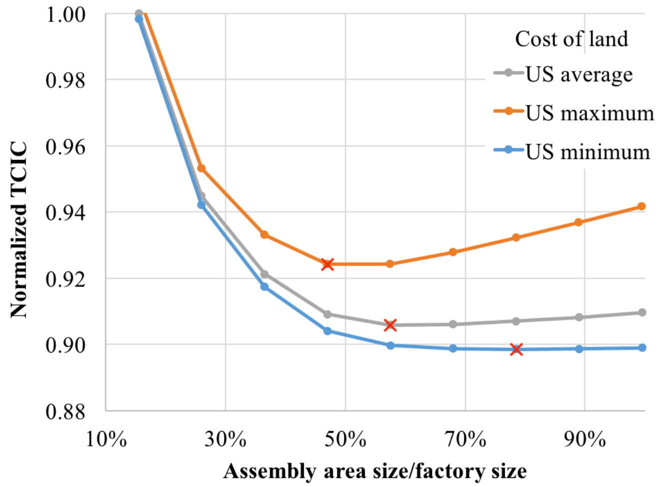


Figure 12 - Assembly area sensitivity analysis

2.5.3 Parallelism

Stick-built construction consists of erecting the structure in the hole, while installing modules and performing connections level by level. The installation of modules and connections can start once part of the previous level has been completed. The percentage of activities in the installation of the previous level that have to be completed is defined as level of parallelism in the installation stage. The level of parallelism is dependent on numerous factors, e.g. number of modules, size of the NPP, type of design. The level of parallelism is key and the sensitivity of TCIC on it can be analyzed through EVAL.

TCIC values as a function of the level of parallelism allowed in the installation stage is shown in Figure 13. The base case is represented with a 50% of parallelism, which was chosen as normalization value. The design of the SMR can be changed to allow a higher installation parallelism and lower TCIC. For example, as the design is improved and the parallelism is increased to 70%, TCIC would be lowered by 3.3%.

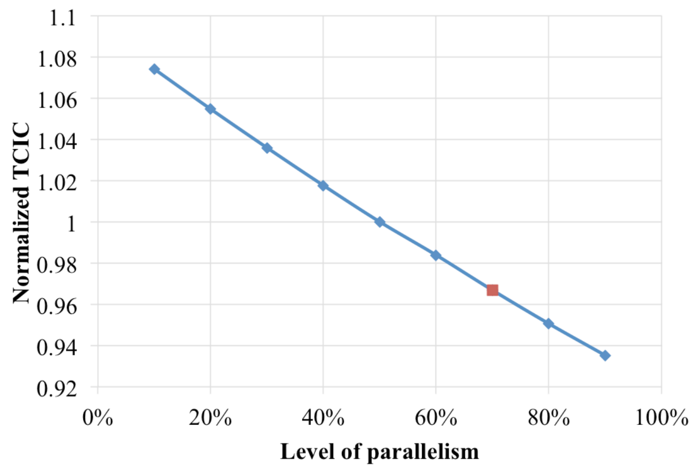


Figure 13 - Installation parallelism sensitivity analysis

2.5.4 Welding

As the construction model is a function of different activities types and unit costs, a study was performed to evaluate how TCIC can be improved by adopting innovative manufacturing technologies. A focus was placed on welding activities in the assembly stage. Innovative welding technologies allow higher deposition rates with subsequent reduction in welding activities durations. The standard quantities that were used and derived from the industry available data are referred to a general Manual cold wire Gas Tungsten Arc Welding (GTAW) technology. Different welding technologies were identified: hot wire GTAW, Shielded Metal Arc Welding (SMAW), Semi-automated track Gas Metal Arc Welding (GMAW) and Hot Wire Laser Welding (HWLW). Deposition rates and TCIC for each welding technology are shown in Figure 14.

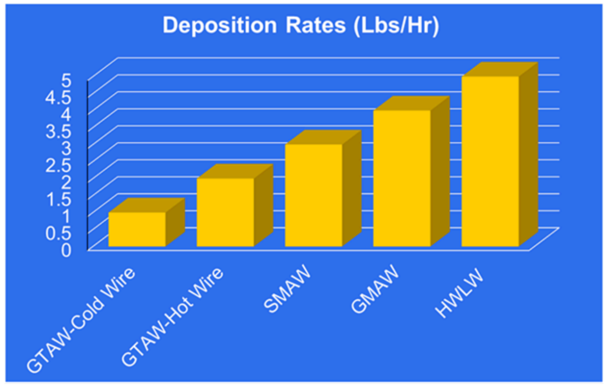


Figure 14 – Welding technologies deposition rates

Direct costs were calculated as a function of welding deposition rate. Deposition rates of different welding technologies were evaluated. The most promising technology, Hot Wire Laser Welding, allows a 1.8% decrease in TCIC. From the relative TCIC decrease, the total savings due to adoption of a certain welding technology in the assembly process can be calculated. Based on the number of Nuclear Power Plants the nuclear vendor is projecting to sell and build, EVAL may be used to evaluate the business case of developing a welding technology.

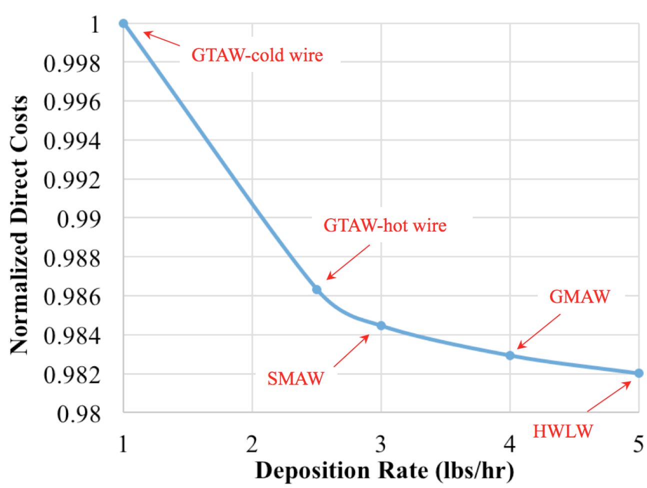


Figure 15 - TCIC for different welding technologies

2.5.5 Testing

Testing is believed to represent a considerable fraction of TCIC. However, for a new NPP design testing costs are affected by a high uncertainty and are not easy to predict.

The amount, duration and cost of testing activities are characterized by a high uncertainty for two reasons:

- Only a limited number of Nuclear Power Plants (NPP) were built in the recent years;
- The WEC-SMR is an innovative design still at an early stage of development.

Modularization allows cost savings due to the moving of activities from the installation stage to more efficient stages (fabrication as assembly), including benefits in testing activities durations and costs. In particular, functional and system testing can be performed once the modules have been fabricated and at the end of the super module assembly. This allows testing activities that can be performed in a shorter time (according to the 1-3-8 rule), with lower labor cost and with a higher level of parallelism, as activities are then removed from the critical path. The amount of system testing depends on the level of system integration that took place at that stage of integration. For example, if the super module has incorporated the completed system or set of systems, a complete system test can be performed on the single systems and on the combined systems that are integrated into that specific super module. However, as these activities are performed earlier in the process, the time value of cost is higher and might offset the benefits of modular testing.

EVAL was used to evaluate the impact of testing on direct costs for the WEC-SMR [8]. A set of data points representing testing costs expressed as a fraction of total labor costs was considered. Direct costs were calculated for values of testing costs in the interval 0-50% over the total labor costs, for the three construction strategies. Results of the sensitivity analysis are shown in Figure 16. Impact of modular testing on direct costs for different numbers of testing activities that are moved from the installation stage was evaluated for construction strategy one. Given a number of testing activities that are removed from the installation stage, half were assumed to take place during the fabrication stage while the other half during the assembly stage. Results of this analysis are shown in Figure 17. As an illustration, the data points shown as red triangles represents normalized direct costs, considering a testing cost of 40% over total labor cost. The data points are presented in Table 7.

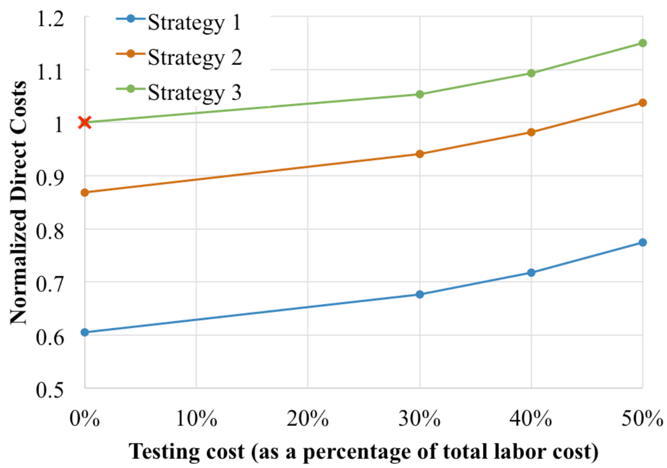


Figure 16 - TCIC as a function of testing cost

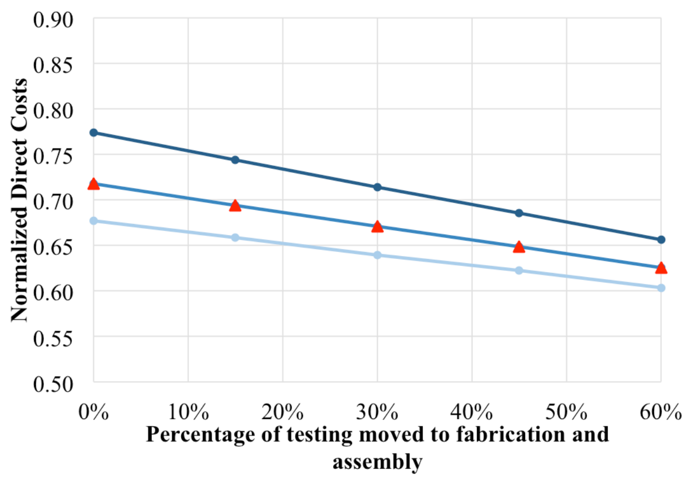


Figure 17 - DC as a function of percentage of testing moved

Testing moved from installation	DC
0%	0.717
15%	0.694 (-3.26%)
30%	0.671 (-6.51%)
45%	0.648 (-9.61%)
60%	0.625 (-12.81%)

Table 7 - Modular testing sensitivity analysis

The data can be well represented by a linear fit, with a R^2 value equal to *0.99992*. The line is expressed by Eq. 18, where t is the percentage of testing activities moved. The linear coefficient is *-0.1529*, which represent the percentage decrease of TCIC due to a 1% increase of the fraction of labor moved from the installation stage.

$$DC = 0.717 - 0.1529 \cdot t \qquad (19)$$

Linear coefficients and R^2 for different testing costs are shown in Table 8. Linear coefficients increase with the testing cost, as the savings due to the moving of a percentage unit of testing activities from the installation stage is greater. This can also be seen by analyzing the same data points shown in Figure 17 with a different normalization value. In Figure 18, DC values for each testing cost are normalized to the DC value for 0% of the testing moved from the installation stage. The lines represent the percentage of savings (on a relative scale) caused by moving a percentage unit of testing from the installation stage. DC as a function of the percentage of testing moved from the installation stage is steeper for higher testing costs, as the relative value of testing activities is greater.

Testing cost	Linear coefficient (strategy one)	R^2
30% of labor	-0.1224	0.99993
40% of labor	-0.1529	0.99992
50% of labor	-0.1958	0.99988

Table 8 - Linear coefficients (DC as a function of percentage of testing moved)

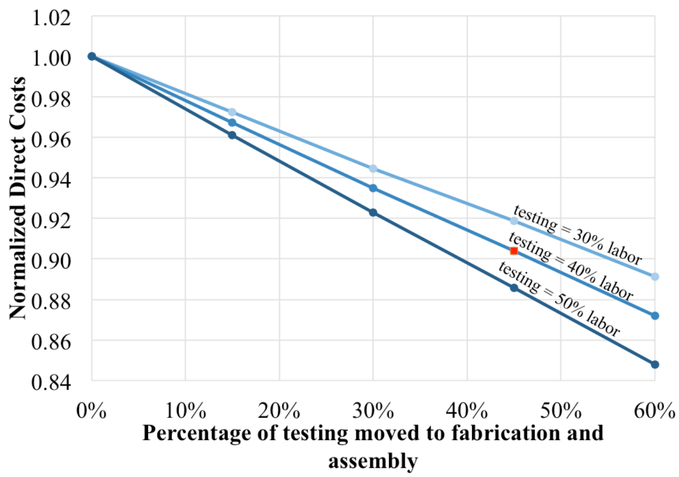


Figure 18 - DC as a function of percentage of testing moved (strategy one), normalized at 0% testing moved

DC increases with the number and costs of testing activities and DC savings increase with the capability of moving testing from the installation stage. Activities to perform functional and system testing can be moved to the fabrication and assembly stages. Considering a realistic testing cost equal to 40% of the total labor cost, and functional and system testing that represent 45% of total testing activities, modular testing allows a 9.61% savings in direct costs (Table 7, Figure 17, Figure 18).

3 Stochastic EVAL: Method

3.1 Triangular distributed activities and time value of money

In project management, durations and costs of activities are often described by a 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*). The probability density function of an activity with a triangular distribution is shown in Figure 19.

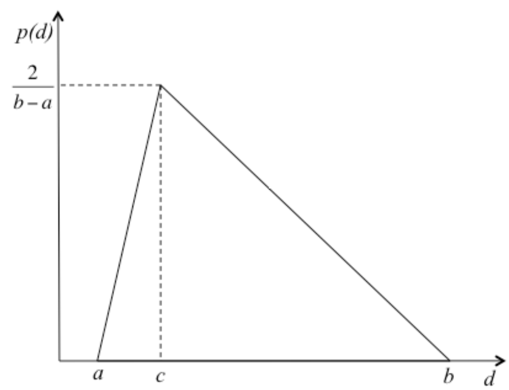


Figure 19 – Triangular probability density function

This probability density function is described functionally as

$$p(d) = \begin{cases} \dfrac{2(d-a)}{(b-a)(c-a)} & for \quad a \le d < c \\ \dfrac{2(b-d)}{(b-a)(c-a)} & for \quad c \le d < a \end{cases} \qquad (20)$$

We represent the cash flow of an activity of duration d_A, start time $T_{A,s}$ and end time $T_{A,e}$ in Figure 20. We assume that the cost of the activity (C_A) is accrued in the middle of its duration ($d_A/2$).

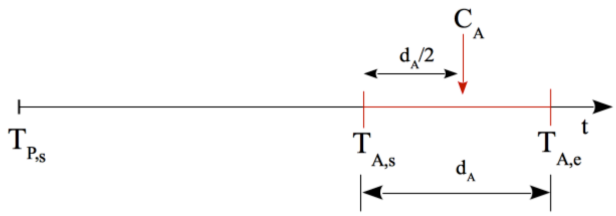


Figure 20 – Activity cash flow representation

We use Eq. 20 to calculate the present value of cost of the activity at the start time of the project ($T_{P,}$s):

$$v = \frac{C_A}{(1+r)^{T_{A,e} - d/2}} \qquad (21)$$

Eq. 20 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. 21:

$$E[v] = \int_{t_{c,\max}}^{t_{c,\min}} \frac{C_A}{(1+r)^{t_c}} p(t_c)\, dt_c \qquad (22)$$

In case duration is expressed using a probability density function, the integral can be adjusted through a change of variables, as indicated in Eq. 22.

$$p(t_c) = p(T_{A,e} - d/2) = p(-d/2) = -1/2p(d) \qquad (23)$$

The integral becomes:

$$E[v] = \int_{t_{min}}^{t_{max}} \frac{C_A}{(1+r)^{t_c}} p(t_c)\,dt_c = -\frac{1}{2}\int_{t_{min}}^{t_{max}} \frac{C_A}{(1+r)^{t_c}} p(d)\,dt_c \qquad (24)$$

In case we consider a symmetric triangular distribution (Figure 21), we can express the upper and lower bound as a function of the most probable value given in Eq. 24.

$$a = c(1-s) \quad and \quad b = c(1+s) \qquad (25)$$

It can also be shown that for a symmetric triangular distribution, the most probable value corresponds to the expected value.

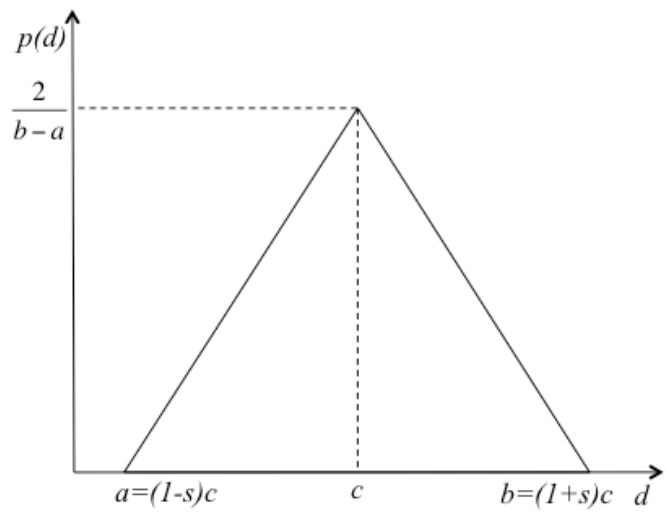


Figure 21 – Symmetric triangular probability density function

The probability density function becomes:

$$p(t_c) = \begin{cases} \dfrac{2(2T_{A,e} - 2t_c - a)}{(b-a)(c-a)} & for \quad T_{A,e} - \dfrac{c}{2} \le t_c < T_{A,e} - \dfrac{a}{2} \\ \dfrac{2(b - 2T_{A,e} + 2t_c)}{(b-a)(c-a)} & for \quad T_{A,e} - \dfrac{b}{2} \le t_c < T_{A,e} - \dfrac{c}{2} \end{cases} \qquad (26)$$

Substituting Eq. 25 in Eq. 23:

$$E[v]=\frac{C_A}{c^2s^2}\left\{\int_{T_{A,e}-\frac{c+cs}{2}}^{T_{A,e}-\frac{c}{2}}\frac{1}{(1+r)^{t_c}}(c+cs-2T_{A,e})+\int_{T_{A,e}-\frac{c}{2}}^{T_{A,e}-\frac{c-cs}{2}}\frac{1}{(1+r)^{t_c}}(2T_{A,e}-2t_c-c+cs)\right\} \quad (27)$$

Solving the integrals, we obtain:

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

$$\left.+\frac{1}{\ln(1+r)^2}\frac{1}{(1+r)^{t_c}}\left[1-\frac{1}{2}\ln(1+r)(2T_{A,e}-c-2t_c+cs)\right]\Bigg|_{T_{A,e}-\frac{c}{2}}^{T_{A,e}-\frac{c-cs}{2}}\right\} \quad (28)$$

Eq. 28 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:

$$E[v]=\frac{C_A}{(1+r)^{T_{A,e}-c/2}}\frac{1}{s^2c^2\ln(1+r)^2}\left[\frac{1}{(1+r)^{cs/2}}+(1+r)^{cs/2}-2\right] \quad (29)$$

Eq. 29 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:

$$\frac{E[v]}{v}=\frac{1}{s^2c^2\ln(1+r)^2}\left[\frac{1}{(1+r)^{cs/2}}+(1+r)^{cs/2}-2\right] \quad (30)$$

It can be shown that the ratio expressed in Eq. 29 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. 29 as a function of s is plotted for different values of the discount rate r and the most probable duration c in Figure 22 and Figure 23.

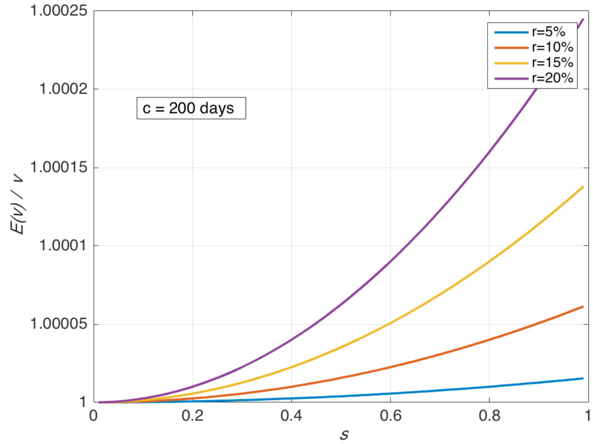


Figure 22 – Expected cost value as a function of the distribution dispersion for different discount rate values (c = 200 days)

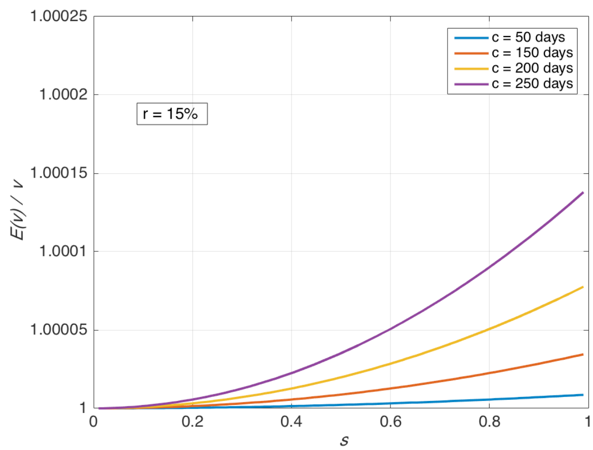


Figure 23 - Expected cost value as a function of the distribution dispersion for different activity durations (r = 15%)

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.

3.2 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. 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. Sampling method and the analysis of the results were described in the previous annual report.

Considering that an activity has duration *d* and cost *c* that are characterized by cumulative density functions *P(d)* and *P(c)*, respectively, duration and cost are sampled in an unbiased manner through the use of the uniformly distributed random numbers *u* and ξ:

$$P(d) = u, \qquad P(c) = \xi \tag{31}$$

The duration and cost are then calculated after the inversion as

$$d = P(u)^{-1}, \qquad c = P(\xi)^{-1} \tag{32}$$

After stochastically determining the duration and cost of all project activities, the project schedule of the run is calculated and TCIC is computed. Repeating this procedure for a large number of runs, we calculate the average value and standard deviation of TCIC in the Monte Carlo simulation through Eq. 32 and 33:

$$\overline{TCIC} = \frac{1}{N}\sum_{n=1}^{N} TCIC_n \qquad (33)$$

$$\sigma_{TCIC} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(TCIC_n - \overline{TCIC}\right)} \qquad (34)$$

3.2.1 Symmetrical probability distributions

1. Triangular distribution sampling

Eq. 34 describes the triangular cumulative distribution function:

$$P(d) = \begin{cases} \dfrac{(d-a)^2}{(b-a)(c-a)} & for \quad a \le d < c \\ 1 - \dfrac{(b-d)^2}{(b-a)(c-a)} & for \quad c \le d < a \end{cases} \qquad (35)$$

Equating the cumulative distribution function to *u*, where $0 < u < 1$, yields the inverse cumulative distribution function Eq. 35:

$$P(u)^{-1} = \begin{cases} a + \sqrt{(b-a)(c-a)u} & for \quad 0 \le u < \dfrac{c-a}{b-a} \\ b - \sqrt{(b-a)(b-c)(1-u)} & for \quad \dfrac{c-a}{b-a} \le u < 1 \end{cases} \qquad (36)$$

Using a random number (between 0 and 1) generator, we can use Eq. 31 to compute the duration of the activity in a run. The same procedure can be used for the activity cost. Once the random number *u* is generated, the number is used to calculate both the duration and the cost of the activity, as duration and cost are directly related. For example, an increase in the duration of the activity may affect the labor time dedicated to the activity and the use of materials during the activity. If the value of the generated random number is high (close to 1), the duration of the activity is close to the upper bound (*b*). The cost of the activity is then computed using the same value of *u* to compute through the cost inverse cumulative probability function the cost in the same run. In this case, the cost of the activity is guaranteed to be close to its upper bound.

In each simulation, duration and cost of every activity was described by a triangular distribution, with deterministic duration and cost as most probable values (Fig. 3). The lower and upper limits were expressed as a percentage of the most probable value *c*. The same *s* parameter was used for each activity cost and duration:

$$a = c(1-s) \quad and \quad b = c(1+s) \qquad (37)$$

The parameter s is a dispersion indicator of the probability distribution. The triangular distribution variance is equal to its second moments given in Eq. 37:

$$\sigma^2 = \mu_2 = \frac{1}{18}\left(a^2 + b^2 + c^2 - ab - ac - bc\right) \qquad (38)$$

from which, substituting Eq. 36, we can obtain an expression for the standard deviation:

$$\sigma = \frac{cs}{\sqrt{6}} \qquad (39)$$

In case *s* is larger than one, negative values of durations and costs can be sampled, leading to unrealistic values. To deal with this problem, the triangular distribution is modified so that, in case of negative sampling, durations and costs are set equal to 0. An example of a modified triangular distributed duration, with *c* and *s* equal to 35 days and 2.20 respectively, is shown in Figure 24.

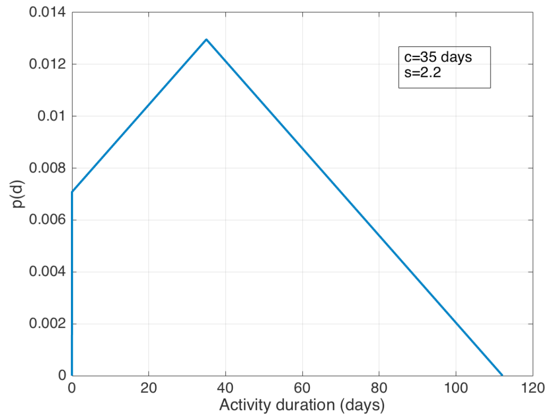


Figure 24 – Correction of triangular probability density function for positive durations

The data points that were used are shown in Table 9.

Table 9

s
0.2
0.5
0.8

2. Normal distribution sampling

Eq. 39 and 40 present the probability density function and the cumulative density function of the normal (Gaussian) distribution function:

$$p(d) = \frac{1}{\sigma\sqrt{\pi}} e^{-\frac{(d-\mu)^2}{2\sigma^2}} \qquad (40)$$

$$P(d)=\frac{1}{2}\left[1+erf\left(\frac{d-\mu}{\sigma\sqrt{2}}\right)\right] \qquad (41)$$

A random number u is generated and Eq. 40 is inverted to calculate the activity duration. As in the case of activities with triangular distributions, the activity cost was computed through the use of the same random number u.

Every activity cost and duration is described by a mean value (equal to the deterministic cost/duration) and a standard deviation. The standard deviation was expressed as a percentage of the mean value:

$$\sigma = t \cdot \mu \qquad (42)$$

In order for the results of simulations regarding triangular distributed and normal distributed activities to be comparable, we related the value of the parameter t to the value of s equating Eq. 38 and Eq. 41. Since c and μ both represent the deterministic cost and duration of the activity, we obtain:

$$t \cdot \mu = \frac{cs}{\sqrt{6}} \rightarrow t = \frac{s}{\sqrt{6}} \qquad (43)$$

Since normal distributions are unbounded (no lower and upper limits), negative durations and costs are mathematically feasible, especially in the presence of large values of standard deviations. As for triangular distributions, the normal distribution is truncated so that, in case a negative duration or cost is sampled, the value is set to zero. An example of a modified normally distributed activity duration having μ=35 days and σ=0.9μ is shown in Figure 25.

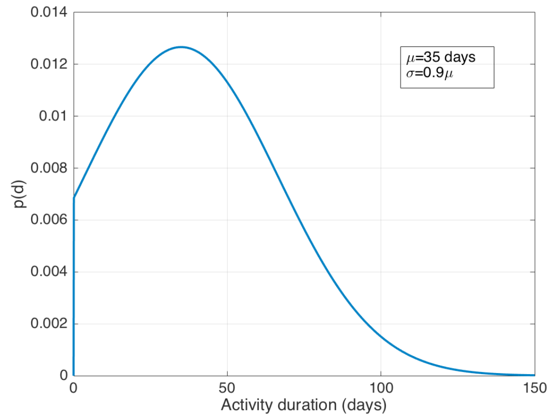


Figure 25 – Correction for normal probability density function for positive durations

The values of *t* used in the simulations are shown in Table 10.

Table 10

s	t
0.2	0.0817
0.5	0.2041
0.8	0.3266
2.2	0.90

3.2.2 Asymmetrical probability distributions

3. Triangular distribution

Activity durations and costs are naturally described by asymmetrical 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 asymmetrical distributions (skewed to the right). 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 26).

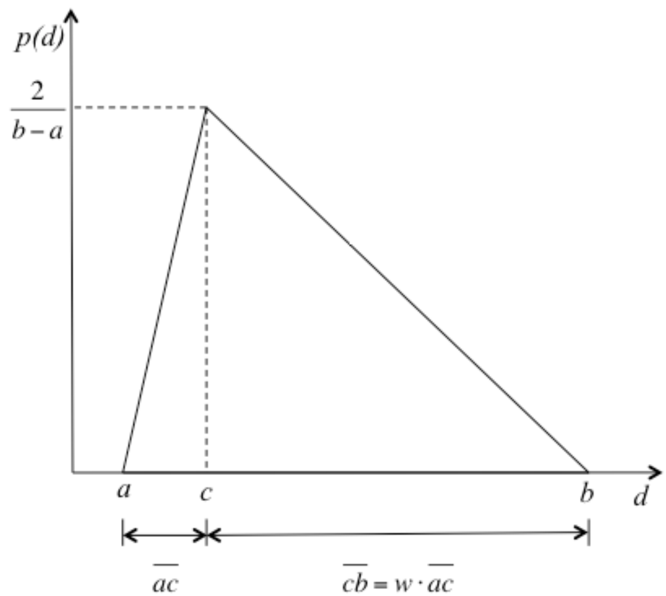


Figure 26 - Asymmetrical triangular probability density function

The level of asymmetry can be expressed by the parameter *w*, which we define as:

$$w = \frac{\overline{cb}}{\overline{ac}} \tag{44}$$

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 symmetrical triangular distribution (Figure 21). 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*:

$$a = c(1 - s) \tag{45}$$

$$b = c(1 + ws) \quad (46)$$

3.3 Correlated variables

In order to model the correlation between variables, we focused our study on the use of multivariate distributions. Multivariate distributions are a generalization of a one-dimensional probability distribution to higher dimensions. A multivariate probability density function *f(x)* of an n-dimensional random vector *x* can be described by a n-dimensional mean vector μ and a *n* x *n* covariance matrix Σ.

$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_{22} & & \\ \vdots & & \ddots & \\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_{nn} \end{bmatrix} \quad (47)$$

Each element of the covariance matrix Σ_{ij} expresses the correlation between variable *i* and variable *j* and is defined as:

$$\sigma_{ij} = E\left[\left(x_i - \mu_i\right)\left(x_j - \mu_j\right)\right] \quad (48)$$

Each element of the covariance matrix can be written as a function of the correlation coefficient ρ that is defined as:

$$\rho_{ij} = \frac{\sigma_{ij}^2}{\sigma_i \sigma_j} \quad (49)$$

The matrix of the correlation coefficients is then:

$$\rho = \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1n} \\ \rho_{21} & 1 & & \\ \vdots & & \ddots & \\ \rho_{n1} & \rho_{n2} & \cdots & 1 \end{bmatrix} \quad (50)$$

The correlation coefficient expresses the correlation between variables x_i and x_j and its absolute value is less or equal to 1. If ρ_{ij} is zero, variables x_i and x_j are not correlated; if it is one, variables x_i and x_j are completely correlated.

The normal probability density function is defined as:

$$f(x_1,...,x_n) = \frac{1}{\sqrt{2\pi|\Sigma|}} \exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu)\right\} \quad (51)$$

The marginal probability distribution of x_i can be obtained by integrating the expression for Eq. 50 in variables x_i in $(-\infty, +\infty)$. The marginal probability of x_i is normally distributed as:

$$f(x_i) = N(\mu_i, \sigma_{ii}^2) \quad (52)$$

Marginal probability distributions along with a bivariate normal distribution are represented in Figure 27.

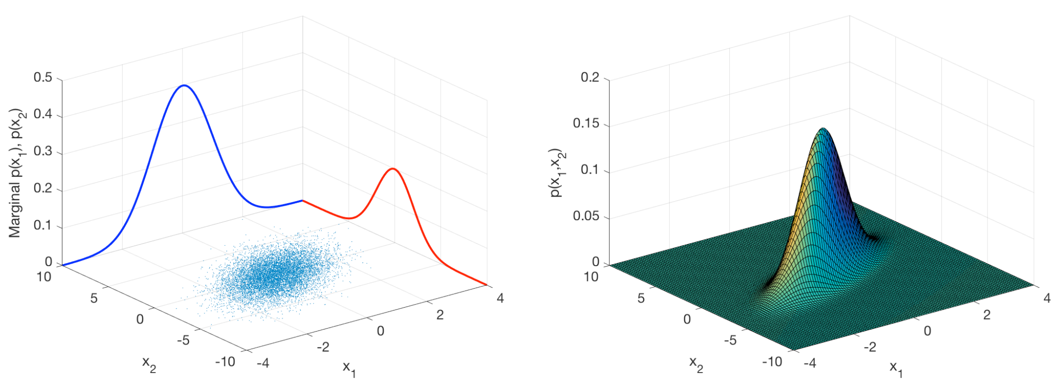


Figure 27 - Bivariate Normal distribution (*x_1 = N (0, 1)*; *x_2 = N (0, 2)*)

3.3.1 Multivariate sampling

For a multivariate distribution, the cumulative distribution function is not defined. Therefore, variables sampling through the Monte Carlo method is not possible. We developed a method to sample multivariate distributed variables that can be summarized by the steps shown in the following flow chart:

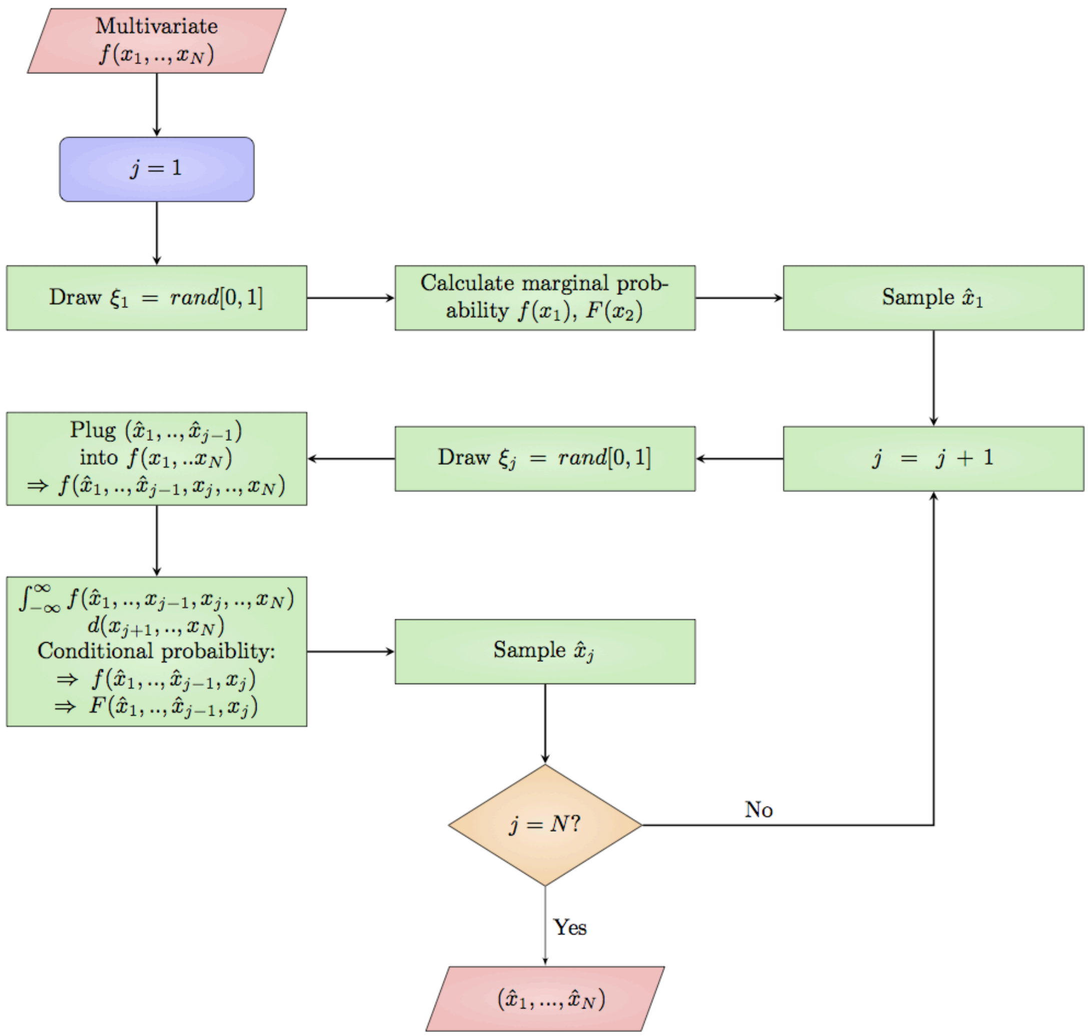


Figure 28 - Multivariate distribution sampling flow chart

Sampling through this method preserves the correlation between variables ($x_{i...}$ x_n).

4. Bivariate case

In the bivariate case, x_1 is sampled from its marginal probability density function. As x_1 is sampled, its value is plugged into the marginal probability density function $f(x_1, x_2)$. x_2 is then normal distributed with mean value and standard deviation that are function of the sampled value of x_1.

$$f(x_2 |_{x_1}) = N(\bar{x}_2, \bar{\sigma}_2^2) \quad (53)$$

Equations 48 and 49 show expressions for the mean value and standard deviation of Eq. 52. Probability density function of variable x_2 can be visualized by cutting the bivariate normal density function with a vertical plane parallel to axis x_2, intersecting axis x_1 at the sampled value of variable x_1 (Figure 29).

$$\bar{x}_2 = \mu_2 + \frac{\rho(\hat{x}_1 - \mu_1)}{\sigma_1} \quad (54)$$

$$\bar{\sigma}_2 = \sigma_2 \sqrt{1 - \rho_{12}^2} \quad (55)$$

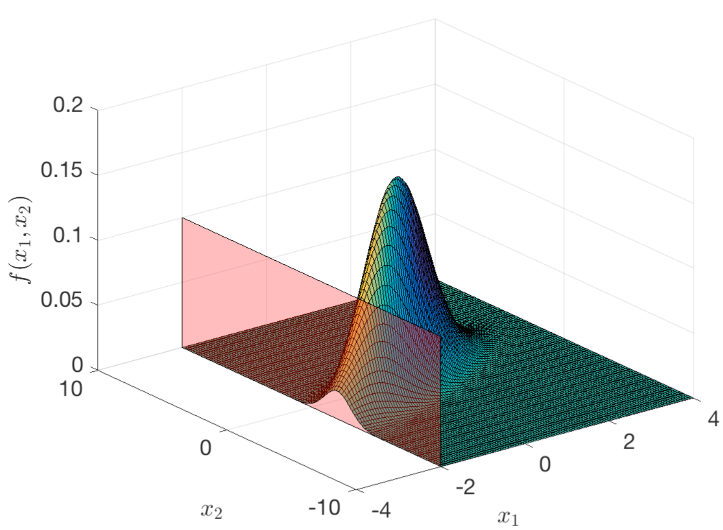
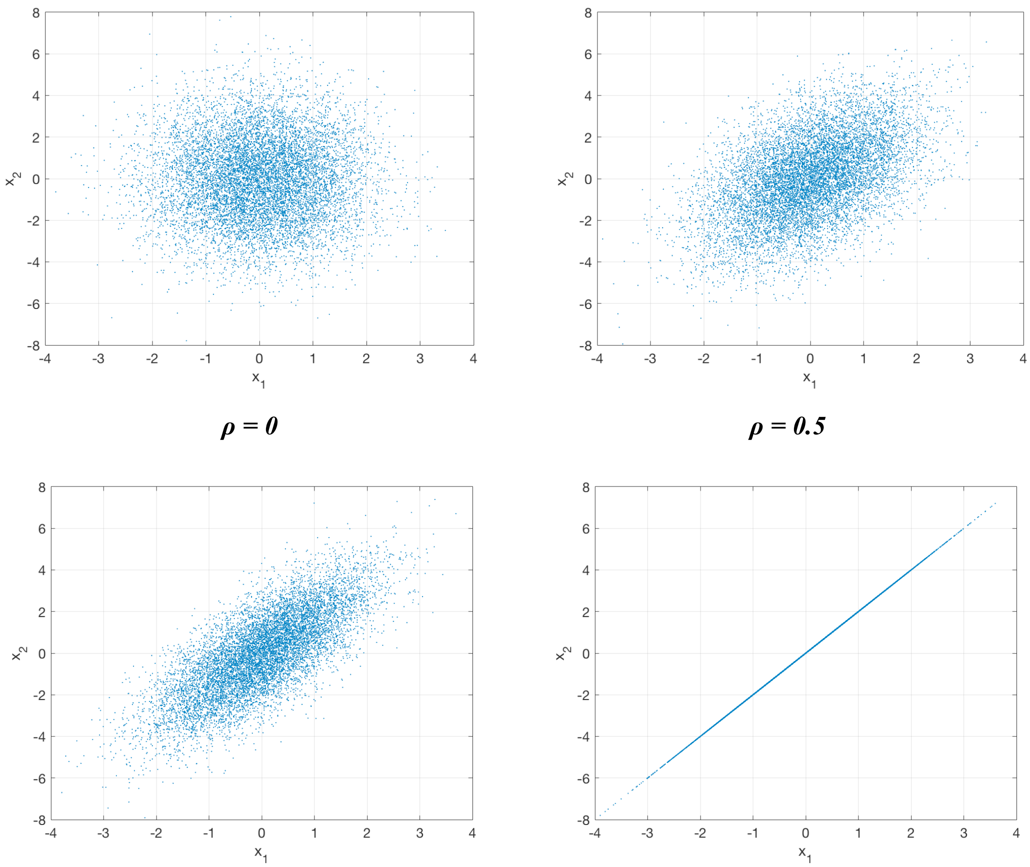


Figure 29 – Bivariate normal distribution sampling process

Monte Carlo sampling according through this method for different values of ρ is shown in Figure 30.



$\rho = 0$

$\rho = 0.5$

$\rho = 0.75$

$\rho = 0.99$

Figure 30 - Bivariate Normal Monte Carlo samples ($x_1 = N(0, 1)$; $x_2 = N(0, 2)$)

5. Trivariate case

For the trivariate case, variable x_1 is sampled from the conditional probability $f(x_1,x_2)$, calculated integrating the probability density function $f(x_1,x_2, x_3)$ in variable x_3. x_1 and x_2 are then bivariate normal distributed and sampled according to the process shown in Section 4. Once the values of sampled variables x_1 and x_2 are plugged into $f(x_1,x_2,x_3)$, variable x_3 is normal distributed with mean value and standard deviations that are dependent on the values of sampled x_1 and x_2. Equations 51 and 52 show the expressions for the mean value and standard deviation of Equation 50.

$$f(x_3 |_{x_1,x_2}) = N(\bar{x}_3, \bar{\sigma}_3^2) \tag{56}$$

$$\begin{aligned}\bar{x}_3 = \quad & -\frac{1}{\sigma_1\sigma_2(\rho_{12}^2 - 1)}[\hat{x}_1\sigma_2\sigma_3\left(\rho_{12}\rho_{23} - \rho_{13}\right) + \hat{x}_2\sigma_1\sigma_3\left(\rho_{12}\rho_{13} - \rho_{23}\right) \\ & -\mu_3\sigma_1\sigma_2 + \mu_1\rho_{13}\sigma_2\sigma_3 + \mu_2\rho_{23}\sigma_1\sigma_3 + \mu_3\rho_{12}^2\sigma_1\sigma_2 \\ & -\mu_2\rho_{12}\rho_{13}\sigma_1\sigma_3 - \mu_1\rho_{12}\rho_{23}\sigma_2\sigma_3]\end{aligned} \tag{57}$$

$$\bar{\sigma}_3 = \sigma_3\sqrt{\frac{\rho_{12}^2 + \rho_{13}^2\rho_{23}^2 - 2\rho_{12}\rho_{13}\rho_{23} - 1}{1 - \rho_{12}^2}} \tag{58}$$

4 Stochastic EVAL: results

4.1 Uncorrelated variables

TCIC is calculated at the start date of the project for every run. In order to compare TCIC determined from different runs, each value of TCIC has to be calculated based on the same point in time. Therefore, TCIC values were calculated with respect to the start date of the project for the deterministic case. TCIC values were then normalized based on the value of TCIC for the deterministic case. In every run, various cost and time values were treated as uncorrelated random variables.

For every case, the TCIC frequency diagram and the TCIC standard deviation as a function of the number of simulations are shown. The TCIC frequency represents the relative number of times that TCIC falls between different intervals, while the TCIC standard deviation is a measure of the dispersion of the TCIC values. The standard deviation of the TCIC standard deviation was also calculated and plotted for each simulation.

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 an effect of the time value of money (as demonstrated in Section 3.1).

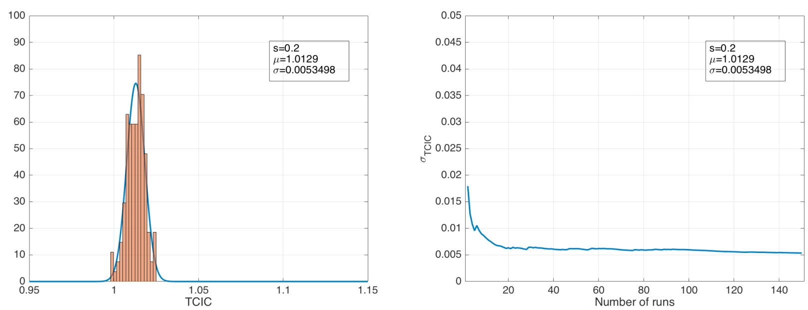
4.1.1 Symmetrical Distributions

For every simulation, TCIC values were fit to normal distributions and the mean value and standard deviation of the distributions are presented in Figure a of each set (Figures 30-32 and Figures 34-37). The standard deviation of the distribution reaches a stable value quickly (after about 30 runs) in every case (Figure b of each set). The standard deviation of the population standard deviation (Figure c of each set) decays with the square root of the inverse of the number of runs:

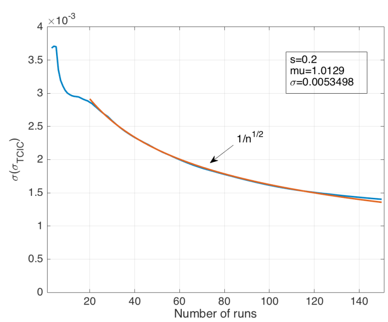
$$\sigma(\sigma_{TCIC}) \approx \frac{1}{\sqrt{n}} \tag{59}$$

6. *Triangular Distributions*

Monte Carlo simulations were performed for different 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 type of activities are characterized by different standard deviations, but it is quite useful in order to understand the dispersion in TCIC with the dispersion in cost and duration of the single activities.

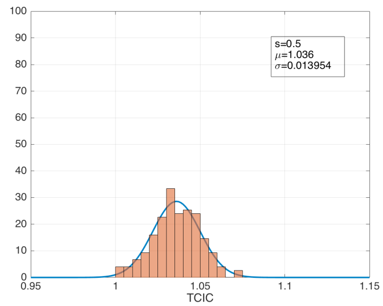


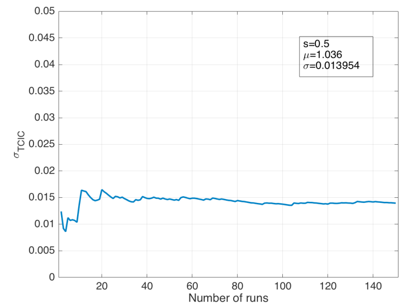
(a) **(b)**



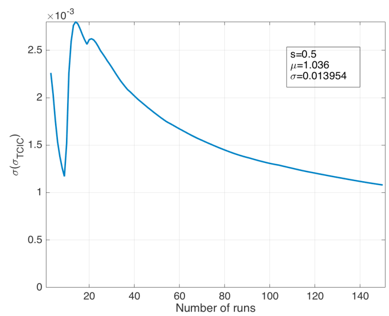
(c)

Figure 31 – Results for s=0.2



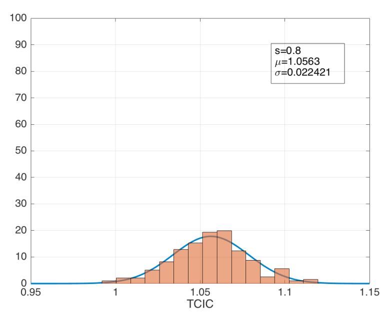


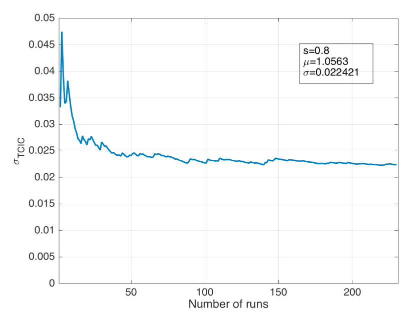
(a) **(b)**



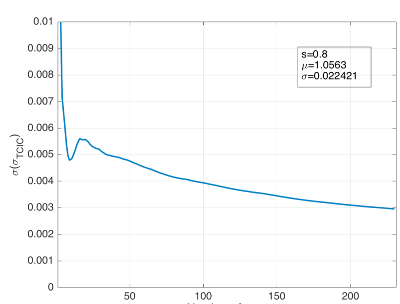
(c)

Figure 32 – Results for s=0.5





(a) **(b)**



(c)

Figure 33 – Results for s = 0.8

A summary of the results obtained with triangular distributed activities is shown in Table 11 and Figure 34. Values of TCIC increase with the value of *s* as cost and duration of activities become more dispersed and the time of value of money shown in Section 3.1 becomes more important. Also TCIC standard deviation increases with *s*.

Table 11

s	TCIC	σ_{TCIC}
0	1	0
0.2	1.01294	0.00534982
0.5	1.03602	0.0139543
0.8	1.05631	0.022421

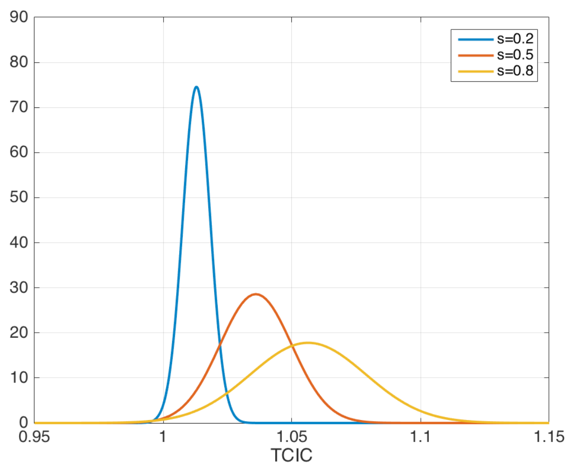
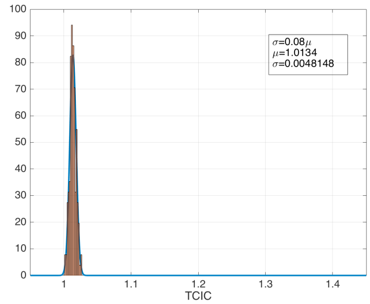


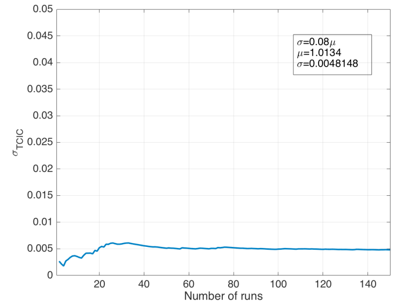
Figure 34 – TCIC fitted probability density functions

7. Normal distribution

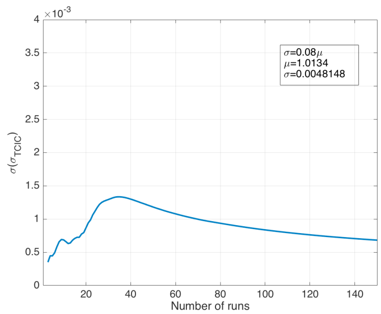
As for symmetrically triangular distributed activities, in every simulation all activities were assumed to have the same standard deviation (expressed as a linear function of the mean value). The ratio between the standard deviation and the mean value is expressed by the parameter *t*, which was chosen to correspond to the values used for the symmetrical triangular distribution. Equation 37 expresses the relationship between the parameters *s* and *t*.



(a)

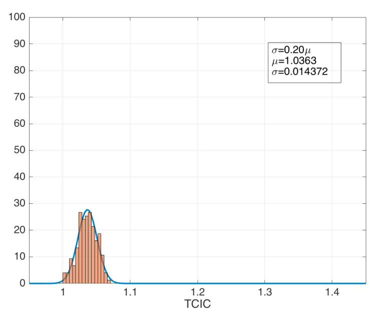


(b)

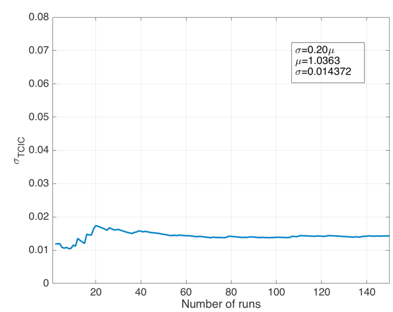


(c)

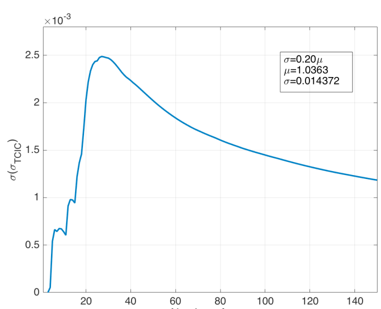
Figure 35 - Results for σ = 0.817 μ



(a)

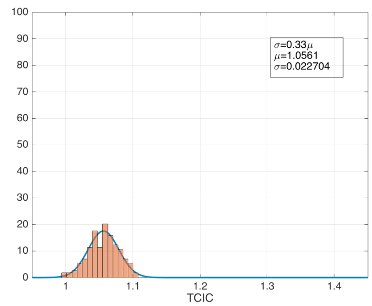


(b)

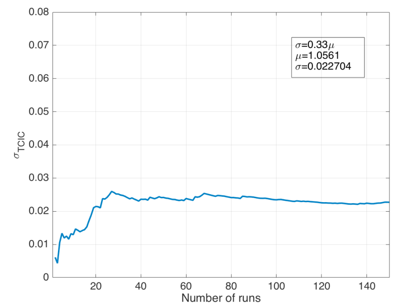


(c)

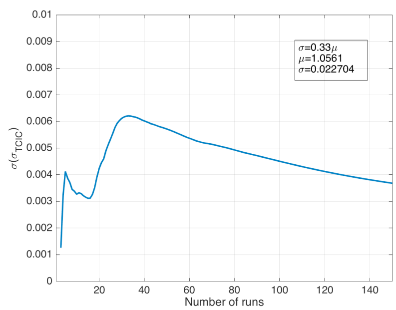
Figure 36 – σ = 0.2041 μ



(a)

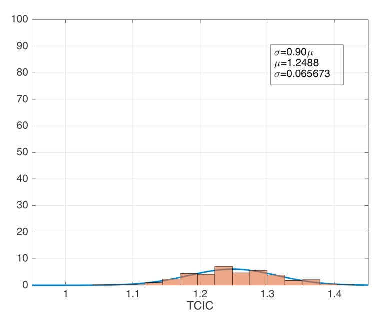


(b)

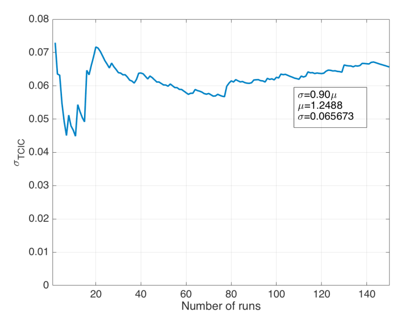


(c)

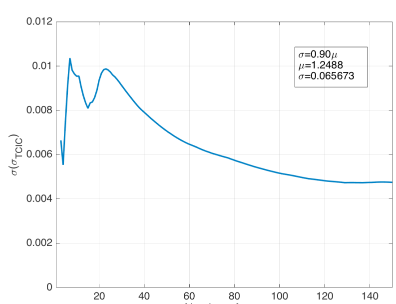
Figure 37 – Results for σ = 0.3266 μ



(a)



(b)



(c)

Figure 38 – Results for σ = 0.90 μ

Results of the simulations are shown in Table 12. Standard deviations increase consistently with *t*, as well as with the mean TCIC value.

Table 12

t	TCIC	σ_{TCIC}
0	1	0
0.0817	1.01339	0.00481476
0.2041	1.03602	0.01437234
0.3266	1.05539	0.0227043
0.90	1.24881	0.065673

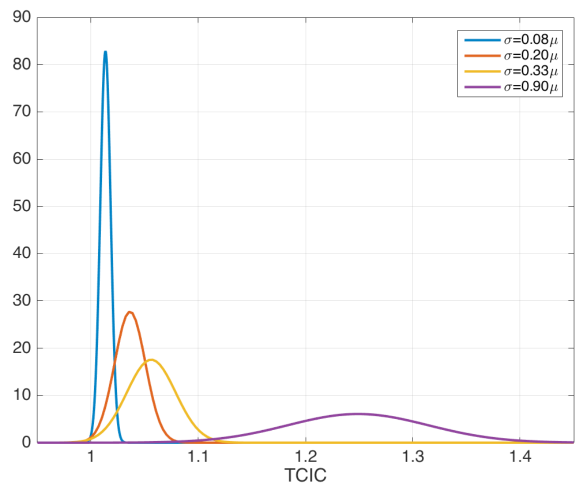


Figure 39 – TCIC fitted probability density functions

8. 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 13.

Table 13

		Triangular			Normal		
s	t	TCIC	σ_{TCIC}	σ/TCIC	TCIC	σ_{TCIC}	σ/TCIC
0.2	0.0817	1.013	0.0053498	0.53%	1.013	0.0048	0.47%
0.5	0.2041	1.036	0.0139543	1.35%	1.036	0.0144	1.39%
0.8	0.3266	1.056	0.022421	2.12%	1.055	0.0227	2.15%
2.2	0.89				1.249	0.0656	5.25%

Despite the use of quite dispersed probability distributions (0.08 < σ/μ < 0.89), the numerical results indicate a weak dependence of uncertainties in the construction process on TCIC. For the maximum value of *t* considered, TCIC is 25% higher than the deterministic case, with a low standard deviation (5.25% of TCIC).

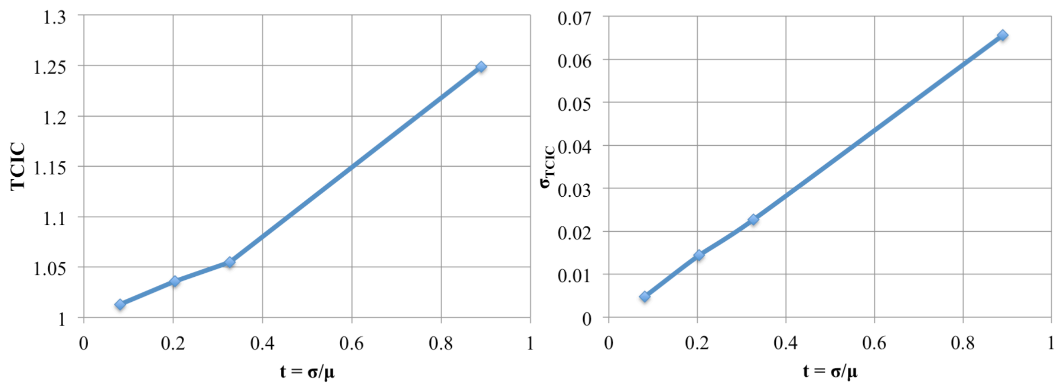


Figure 40 – TCIC and TCIC standard deviation as a function of the dispersion of normal distributed activities

The results suggest that the mean value and standard deviation of TCIC that we have obtained were underestimated, which raises two possible concerns:

- The use of symmetric distributions to describe activities is not representative of the real SMR construction situation. In reality, activities have a higher probability to be completed later rather then earlier. This concern was addressed through the use of asymmetrical probabilistic distributions (skewed to the right, Section 4.1.2)
- Activity duration and cost values cannot be treated as uncorrelated random variables.

4.1.2 Asymmetrical triangular distributions

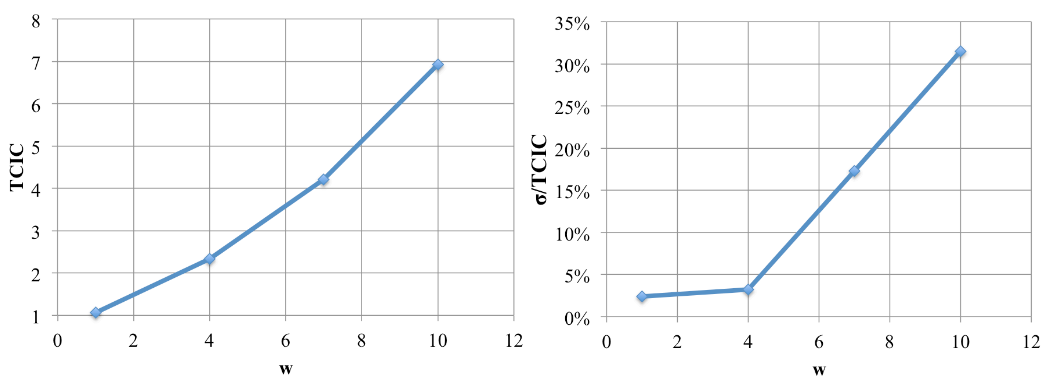
Asymmetrical triangular distributions were described through the parameters *s* and *w* introduced in Section 0. Monte Carlo simulations were performed for different values of *s* and *w*. to show the impact of these values on TCIC. This analysis showed how EVAL is capable of evaluating probabilistic effects. 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 Equations 24 and

25. The same values of *s* that were considered for the symmetrical case were used. Values of *w* between 1 and 10 were used.

Numerical results of these simulations are shown in Table 14. TCIC as a function of *w* for fixed values of *s* are shown in Figure 41, according to the data points shown in Table 14.

Table 14

	w=1		w=4		w=7		w=10	
	TCIC	σ/TCIC	TCIC	σ/TCIC	TCIC	σ/TCIC	TCIC	σ/TCIC
s=0.2	1.013	0.53%	1.269	1.16%	1.557	2.56%	1.892	2.04%
s=0.5	1.036	1.35%	1.750	2.45%	2.664	7.83%	3.865	12.89%
s=0.8	1.058	2.36%	2.333	3.19%	4.214	17.29%	6.933	31.50%



(a) (b)

Figure 41 – TCIC and TCIC standard deviation as a function of the level of asymmetry (triangular distribution)

Figure 41-a shows that TCIC suffers a significant increase with the asymmetry of the triangular distribution. TCIC increases to about 7 times the value of TCIC for the deterministic case if the level of asymmetry (*w*) equals 10. The TCIC standard deviation as a percentage of TCIC mean value is shown in Figure 41-b. The simulations indicates that the TCIC standard deviation increases with the level of asymmetry, reaching 30% of the mean value for *w* equal to 10.

4.2 Correlated variables

The construction cost of a NPP can be mainly divided into three categories: labor, raw material and equipment. Equipment consists of components that are "bought" from off- site locations and their cost consist mainly of raw material and labor. The cost of each activity is affected by the labor rate and the material cost related to the activity. To properly model the probability distribution of an activity cost, the probability distribution of the labor rates and the material costs needs to be analyzed. Each activity in the construction of the WEC-SMR was assumed to be dependent on labor rate or material cost. As a first approximation, material was assumed to be steel or concrete. Equipment cost was assumed to only depend on the cost of steel. Activities in the fabrication, assembly and installation stages were assumed to be dependent only on labor rates. As the WEC-SMR is built through modular construction, concrete is used only in the installation process and concrete-related activities in the installation stage were considered function of the concrete cost. Standard deviations of labor and material costs were estimated from historical rates based on the Producer Price Index in the period 2001-2016 [17, 18, 19]. Each value was corrected for inflation calculated through the Consumer Price Index (CPI, Ref. [20]), i.e. the inflation rate was subtracted. The cost of steel, labor and concrete over time, their frequency and the fitted normal density are shown in **Figure 42**. The trivariate normal distribution was used to model the correlation between steel cost (x_1), labor cost (x_2) and concrete cost (x_3). Sampled values of trivariate distributed steel, labor and concrete unit cost are shown in Figure 43. Costs sampled through this methodology give an indication of the possible values of cost escalation during the project duration.

Figure 42 - Steel, Labor and Concrete cost (2001-2016), corrected for inflation

Figure 44 shows the direct costs distribution (fitted to normal) of two sets of simulations. The first curve represents the DC distribution if activity durations are deterministic; the second curve shows the results with activity durations modeled as triangular distributed. Different activity types were represented with different distribution parameters, based on industry experience. In the case of triangular distributed durations, the costs of the activities dependent on labor cost were calculated as proportional to the duration of each activity. In case the labor cost per hour is constant, in case an activity is delayed, its cost increases proportionally with the activity duration. The maximum and minimum value as percentage increase in respect to the most probable value for each activity type is shown in Table 15.

	Max	Min
Fabrication	+30%	-10%
Assembly	+30%	-10%
Installation	+80%	-10%
Concrete Pouring (Installation)	+200%	-5%

Table 15 - Triangular distribution maximum and minimum values

For all simulations, DC values were calculated fixing the end date of the project and considering the start date of the longest simulation as first time period in Eq. 2.3. All results were normalized to the DC value calculated with deterministic durations and costs. The stochastic nature of activity durations cause direct costs to increase by 14% in respect to the deterministic case. A set of simulations was run setting the correlation coefficients ρ_{ij} (for $i \neq j$) to zero. A comparison between the results here obtained is shown in Table 4.5, with DC values normalized to DC calculated with deterministic costs and durations. Comparing correlated and uncorrelated cases, the difference in direct costs standard deviation is relatively small. This is due to two main reasons:

- The standard deviations of steel, labor and concrete costs are small;
- The correlation coefficients ρ_{ij} ($i \neq j$) is small.

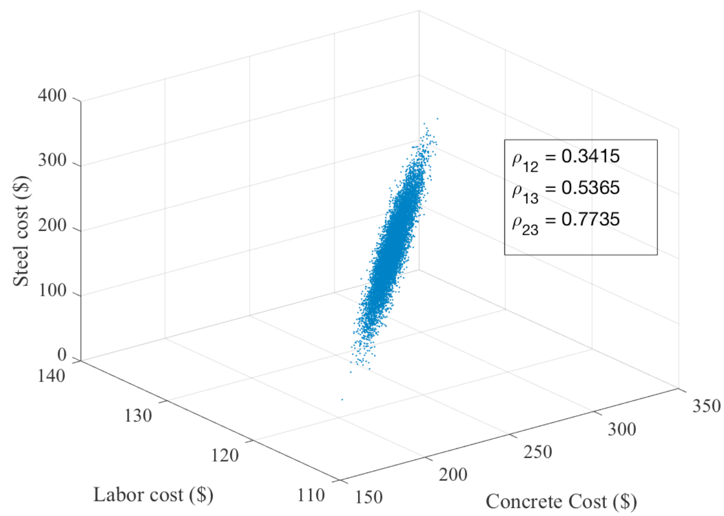


Figure 43 - Trivariate Monte Carlo cost samples

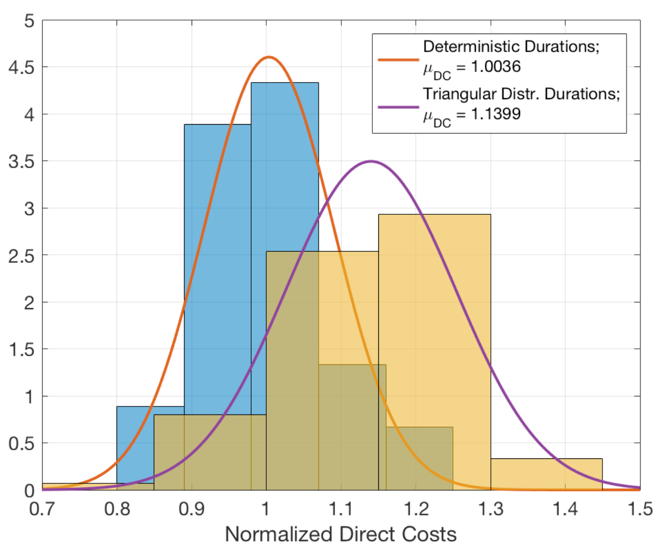


Figure 44 - Trivariate Monte Carlo results (100 runs per simulation)

This can be well understood by representing the construction of the WEC-SMR by a single activity, with 50% of the cost dependent on steel cost (x_1) and the remaining 50% dependent on labor cost (x_2). The cost of the activity represents TCIC. Steel cost and labor cost were modeled through bivariate normal distribution, with $\sigma_1 = \sigma_2$. Monte Carlo simulations were run to analyze the sensitivity of σ_{TCIC} on the values of σ_1, σ_2 and ρ. Results of the simulations are shown in Figure 45. All values of σ_{TCIC} were normalized to the case $\sigma = 0$, $\rho = 0$. This simplified case suggests that:

- σ_{TCIC} increases as the correlation (ρ) between the random variables x_1 and x_2 increases;
- The increase in σ_{TCIC} with ρ becomes more pronounced as the random variables x_1 and x_2 are more dispersed (for high values of σ1 and σ_2).

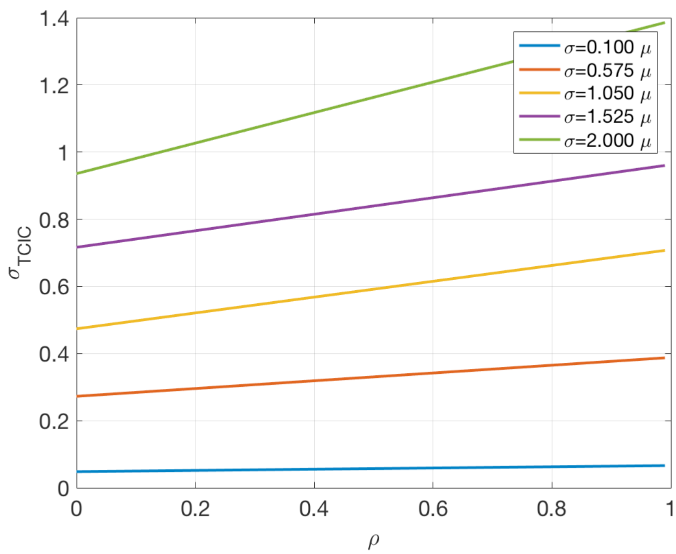


Figure 45 - σ_{TCIC} as a function of ρ

5 Conclusions

Modular construction is a construction innovation intended to reduce NPP TCIC. In modular construction, transportable modules (building blocks of the NPP) are manufactured in factories, assembled at the on-site assembly area into super modules, which are then lifted to the construction site and integrated with the other super modules to complete the Nuclear Island. Modular design reduces construction cost by exploiting the 1-3-8 Rule.

Through this work, a methodology that aims to evaluate and improve SMR construction was developed. This methodology, called EVAL, relies on MS Project 2010 to generate a construction schedule given the part breakdown structure of the NPP. From the construction schedule, values of project duration, cash flows and TCIC are extracted. TCIC is the figure of merit used in this work, which represents the costs of activities and components and the time value of money condensed in one parameter. EVAL was applied to the construction of the WEC-SMR and various types of analyses were conducted.

First, a case study was identified in order to assess the benefits of modularization in the construction of the SMR. Three construction strategies were evaluated, each characterized by a different degree of modularization. EVAL produced cash flows profiles and calculated TCIC for the three strategies. From the TCIC values, the benefit of adopting an off-site manufacturing facility (factory) and the improvements due to the adoption of the on-site assembly area were quantified.

TCIC is dependent on a various number of assumptions, such as labor rates, materials unit costs, location where activities are performed, space availability, type of technologies adopted. EVAL was developed in order to evaluate and quantify the impact of the different assumptions on TCIC through sensitivity analysis. Different sensitivity analyses were performed and the impact of discount rate, cost of land, assembly area size, level of parallelism, welding rates, and amount of modular testing were assessed. Through sensitivity analysis, EVAL can be used to inform the design team and stakeholders to optimize the design and make decisions minimizing cost given a location for the reactor.

EVAL was implemented with the capability of performing stochastic analysis through Monte Carlo simulations, in order to predict risks and evaluate TCIC uncertainties. Activities costs and durations were modeled with different types of probability distributions. The analysis showed that the TCIC dispersion is small, as activities are considered independent. A methodology to account for correlation between variables was also developed. All cash flows in the SMR construction were considered dependent on labor cost, steel cost and concrete cost. Multivariate distributions were used to describe correlations between steel cost, labor cost and concrete cost. Activity durations were modeled with triangular distributions. Monte Carlo simulations were performed to calculate expected value and ranges of TCIC. It was demonstrated that considering the correlation between unit costs of steel, labor and concrete and accounting for the dependence on unit costs of steel, labor and concrete leads to more accurate results.

In this study, some simplifying assumptions were made. Equipment costs were assumed to be entirely dependent on steel unit cost, while activities in the fabrication, assembly and installation stage were assumed to be entirely dependent on labor unit cost. Activities involving concrete pouring in the installation stage were assumed to be dependent on the concrete unit cost. Despite the official end date was December 31st, 2016, in the next year we intend to continue the work and better investigate the correlation effects in order to provide more accurate results. Also, we plan to model probability distributions and correlations of indirect, owner's costs and interest during construction.

A proper analysis of the TCIC distribution function can lead to many benefits. First, the expected project duration can be estimated and project delays can be prevented and late-end fees can be avoided. Second, once a proper TCIC range is provided, the expected value and confidence level of contingency can be estimated. Through EVAL, decision makers can account for the project risk and properly allocate contingency costs.

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