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Experience of Bohunice V1 NPP in risk management of decommissioning projects and application of Monte Carlo simulations for schedule analysis and cost estimation

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Site: BOHUNICE NPP

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Title	Experience of Bohunice V1 NPP in the risk management of decommissioning projects and application of Monte Carlo simulations for schedule analysis and cost estimation
Developed by	JAVYS
What is the goal?	This document aims at compiling the experience acquired by JAVYS company in the implementation of existing IAEA / NEA methodology and guidance in decommissioning risk management and use of MC simulations for cost estimates and schedule simulations of the V1 NPP Decommissioning Project. The goal is to facilitate the transfer of practical experience of JAVYS to organizations willing to perform similar analyses.
Who may benefit?	Decommissioning operators that want to set up the risk management procedures, want to quantify the cost of decommissioning including contingency, or want to simulate the decommissioning schedule using Monte Carlo method.
What will you learn?	Users of this product will get specific and practical examples of risk management methodology and applications of MC simulation, including examples of the V1 NPP site specific input data. The reader will also get the basic understanding of the MC simulation necessary for its application and will be guided on what assumptions and simplifications of the models were made, based on which they may set up their own model more smoothly.
About this knowledge product	This knowledge product is presented in the form of use cases, with a quick introduction to Monte Carlo Applications to provide context. The product is not meant to be a complete guideline for Monte Carlo simulation implementation, but rather, to present specific, comprehensive examples of real cases, compiling lessons learned, recommendations and tips.

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1. EXECUTIVE SUMMARY

Compiling lessons learned and sharing knowledge from the progress of European Nuclear facility decommissioning is of current interest. This document addresses the lessons learned acquired in the application of both qualitative and quantitative Risk Management of the V1 NPP Decommissioning Project and was developed based on Council Regulation (EURATOM) No. 2021/100. This document provides insights into acquired knowledge and specific tips on qualitative risk analysis (development of site-specific scales of risk impact and likelihood of occurrence, risk matrix, risk register, etc.), and on application of Monte Carlo (MC) simulation (qualitative risk management) of the decommissioning schedule and the Monte Carlo simulation of the decommissioning cost.

Primarily, the V1 NPP site-specific modifications of international recommendations in Qualitative Risk management in decommissioning are highlighted in this knowledge product. International recommendations are also compared to methodology applied in V1 NPP Decommissioning project, to give the reader an idea in which part the V1 NPP methodology is adjusted and why.

Monte Carlo (MC) simulation provides realistic estimates of project costs and completion dates by incorporating the possible effects of risk and uncertainty. It analyses a wide set of variables and complex dependencies in one simulation and is particularly useful when managing expectations of stakeholders and establishing contingencies. The result provides the insight on the range of potential outcomes for the entire project. Results obtained from MC simulation are considered objective and insightful for decision-making and allow project managers to create a more practical project schedule and cost plan. By analysing the results, the potential cost overruns, schedule overruns and project milestones may be assessed. The activities requiring the mitigation measures may be also identified via MC simulation.

The international methodology in the area of application of MC simulation in decommissioning cost estimates is developed in detail. However, more detailed information on the recommended uncertainty levels for cost estimate items would be an advantage (e.g., on ISDC III level).

The recommendations for application of MC simulation of the decommissioning schedule require further attention from the supra-national organizations. E.g., international recommendations on the level of uncertainty of the duration of specific decommissioning activities would be advantageous for the decommissioning projects.

The experience of V1 NPP decommissioning is that both earlier completion and completion with delay of partial decommissioning sub-projects may be viewed by the stakeholder as “bad project management” or “improper planning”. If the decommissioning schedule is viewed from the start as uncertain and subjected to risk occurrences, the completion with specific % of delay compared to the total decommissioning duration could also be viewed as successful completion. Any decommissioning project has several objectives, and the completion in compliance with a deterministic deadline is less important than safety or minimizing the burden for future generations by producing as little radioactive waste as possible.

The MC simulation of the V1 NPP decommissioning deadline was carried out with use of a high-level schedule, with the emphasis to properly include all strategic time related risks which had potential impact on the decommissioning deadline. However, in schedule modelling, there is significant room for improvement: simplifying activities and schedule, including operational level risks, and changing the methodology to model both uncertainty and risks separately. These improvements are currently examined by the JAVYS and PMU Consultant.

Through the development of this document, JAVYS Company provides to NDAP recipients, and other stakeholders of the European Union, a valuable tool in the field of nuclear decommissioning for the effective development of an analysis of the risks of project delays and of the compliance with defined budgets. The procedure used in this document is methodologically in accordance with other global projects.

2. INTRODUCTION

2.1. Background

This knowledge product "*Experience of Bohunice V1 NPP in the risk management of decommissioning projects and application of Monte Carlo simulations for schedule analysis and cost estimation*" is developed based on the Council Regulation (Euratom) 2021/100, of 25 January 2021, Article 5 – Dissemination of knowledge and ANNEX II.

2.2. Objective

The objective of this document is:

- to share the knowledge and lessons learned in Risk Management of the V1 NPP Decommissioning Project,
- to provide examples of Bohunice-site specific data used in applications of Monte Carlo (MC) simulation methods,
- to share examples of estimations of V1 NPP Decommissioning cost contingencies in a manner that facilitates the development of tailored models for end users,
- to provide examples of Monte Carlo simulations of V1 NPP Decommissioning schedule.

2.3. Scope

Risk management of the V1 NPP decommissioning is introduced firstly, as within this process the qualitative risk assessment (risk register, risk matrix, risk categorization, etc.) is being carried out at both the strategic and operational level. In Chapter 3 – "Risk Management of the V1 NPP Decommissioning Project" the recommended international methodology of risk management in decommissioning is introduced including the modifications applied in V1 NPP and their impact on the risk management process. Moreover, the concept of strategic and operational level management of risks in V1 NPP Decommissioning is explained. The interlinkages and communication between these two levels of management is crucial for the correct application of risk management in any decommissioning project.

Qualitative risk management (risk register, risk matrix, etc.) is needed to be developed before the quantitative risk management in which the Monte Carlo method is usually applied (there are other methods which may be applied in quantitative risk management – e.g., methods of decision theory). In chapters 5 and 6, two specific uses of Monte Carlo (MC) method in decommissioning (application in schedule modelling and in cost modelling) are introduced, summarized, and examples are provided on V1 NPP site-specific input data and in the development of the simulation models. These applications are introduced separately as there are differences in models, assumptions and expected results. In the area of decommissioning cost determination, the development, lessons learned and differences between respective simulated Monte Carlo cost models of V1 NPP for 2014, 2017 and 2021 are summarized.

The process of setting up the simulation model and results for the V1 NPP with respect to both cost and schedule occur in the following order:

- Assumptions of the model (incl. software, decommissioning schedule).
- Input data – selection of variables (uncertain decommissioning schedule activities).
- Input data – selection of the probability distribution of variables.
- Input data – determination of parameters of probabilistic distribution of variables.
- Simulation – definition of output cell and running of simulation.
- Interpretation of results.

3. RISK MANAGEMENT OF V1 NPP DECOMMISSIONING PROJECT

3.1. Methodology for Risk Management in Decommissioning

Risk management methodology applied in the V1 NPP decommissioning complies with international standard for risk management (ISO 31000:2018) and IAEA report on risk management in decommissioning - "Risk Management for Decommissioning" (Safety Reports Series No. 97, IAEA, Vienna, 2019). The "Management of Project Risks in Decommissioning" was available in JAVYS from early 2017, as the IAEA shared the report before issuance of the final report. This report is also referred to as DRiMa report in frame of this paper.

Check any relevant, past-issued documents from international organizations, but also their on-going works. This is because working papers and knowledge shared in these topics are usually available before the issuance of the final reports.

Safety Reports Series No. 97, IAEA, Vienna, 2019 is considered by JAVYS a sufficient resource for setting up the risk management process and qualitative risk assessment (not quantitative).

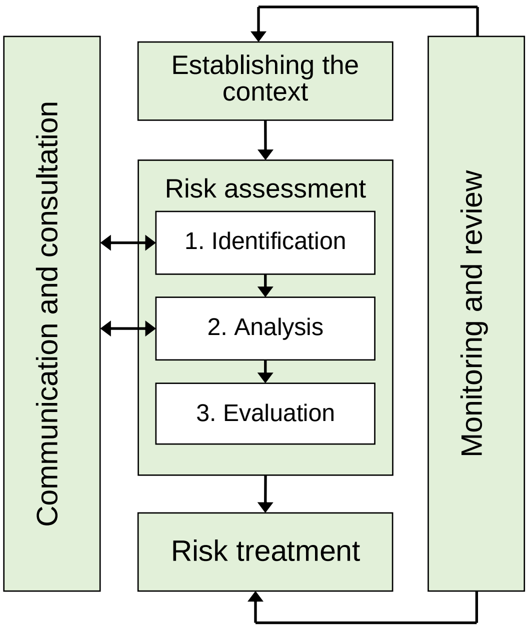


Figure 1: Risk Management Process (Safety Reports Series No. 97, IAEA, Vienna, 2019).

The IAEA report describes specifics of risk management in decommissioning. The cyclic risk management process (see Figure 1) and its steps in detail, provides a list of risk families specific to decommissioning. However, this report does not address the quantitative risk assessment (Monte Carlo simulation, decision trees, etc.). The report generally introduces the "*more quantitative risk assessment*", which basically means adding a new column to the assumptions register, which would include the "quantitative" estimate of the impact to better understand consequences.

The "*more quantitative risk assessment*" introduced by IAEA is not a synonym of quantitative risk assessment.

3.2. V1 NPP Strategic vs. Operational Level Risk Management

The risk management process of V1 NPP Decommissioning Project is a cyclic process, which is implemented on both strategic (top management, etc.) and operational (at sub-project level of the V1 NPP Decommissioning Project) levels.

Risk management on a strategic level represents the management of strategic risks and risks escalated from the operational level. Strategic risks are risks with potential impact on the total decommissioning cost or overall decommissioning completion.

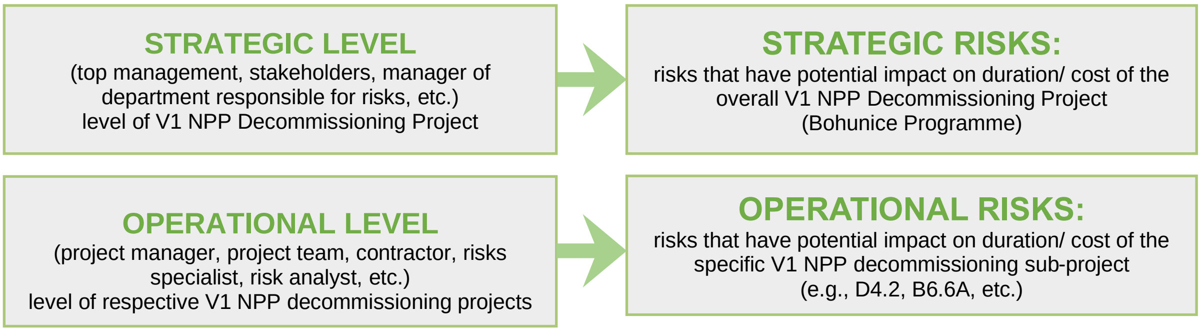


Figure 2: Two Levels of V1 NPP Decommissioning Risk Management.

*<u>Note</u>: **Stakeholders** – Ministry of Economy of the Slovak Republic, Slovak Innovation and Energy Agency, European Bank for Reconstruction and Development, European Commission, etc.; **D4.2** – "Dismantling of Reactor Coolant System Large Components"; **B6.6A** – "Decommissioning Support Surveys"*

Risk management at the operational level of the V1 NPP decommissioning project represents the risk management of respective sub-projects of the overall project, referred to as "V1 NPP decommissioning projects". Operational level risks are risks with potential impact of the cost or duration of specific V1 NPP decommissioning sub-projects (see Figure 2). Not every operational level risk is strategic risk. e.g., in terms of duration, operational level risks with impact on completion date/duration of specific V1 NPP decommissioning sub-projects may not automatically impact the overall V1 NPP Decommissioning Project deadline, as this specific project/activity (with risk of delay) may not be on the Critical Path (CP) of V1 NPP Decommissioning (or even close to getting on the CP).

There is continuous communication and overlapping of these two levels of risk management of V1 NPP Decommissioning (see Figure 3). **Bottom-up communication** (from operational level to top management) is used mainly in escalation of risks. In the case that the project manager identifies operational level risk(s) which may impact the overall V1 NPP Decommissioning Project, the risk(s) is/are escalated to top management.

Figure 3: Communication between Two Levels of V1 NPP Decommissioning Risk Management.

So far, every audit related to risk management (e.g., related to ISO 31000:2018 – "Risk management – Guidelines") carried out at the V1 NPP has directly or indirectly examined whether **escalation of risks is applied,** and if there are proper communication channels between operations and top management.

> Set up proper communication channels for escalation of risks from operational to strategic management in your processes/procedures.

There is also (not so often mentioned) **top-down communication** between management levels of decommissioning (see Figure 3). In the frame of top-down communication, a strategic risk may become also operational level risk. However, it <u>does not mean</u> that the risk is deescalated.

> Top-down communication is equally important as bottom-up communication for decommissioning.

3.3. Qualitative Risk Analysis Applied in V1 NPP vs. International Recommendations

In this chapter the scales of probability or risk occurrence, scales of risk impact, and the size of the risk matrix applied in V1 NPP decommissioning are compared to international recommendations. And we provide the example of how and why these may vary in specific decommissioning projects.

The left side of Table 1 below includes the **Scales of probability of risk occurrence** applied in V1 NPP Decommissioning on both operational and strategic level. The right side of the Table 1 includes the ″example" scales from the DRiMa report.

JAVYS's Scales of Probability of Risk Occurrence (on operational and strategic level)			
Value	Risk occurrence likelihood	Expressed in %	Likelihood description
5	Very high	***71 - 100***	Risk of very high likelihood – the likelihood that the risk will occur is very high
4	High	***41 - 70***	Risk of high likelihood – the likelihood that the risk will occur is high
3	Medium	***16 - 40***	Risk of medium likelihood – it is quite likely that the risk will occur
2	Low	***6 - 15***	Risk of rare likelihood – low likelihood that the risk will occur
1	Very low	***0 - 5***	Highly unlikely risk – the risk occurrence is practically not expected

Example of Scales from DRiMa Report			
Probability score	Probability in %	Scale	Sample definitions
5	***81-100***	Very High	It is almost certain to happen on this decommissioning project
4	***61-80***	High	It has typically happened on a similar decommissioning project.
3	***41-60***	Medium	It has happened before on a similar decommissioning project.
2	***21-40***	Low	Rare to happen but has happened before on a similar decommissioning project.
1	***0-20***	Very low	Very rare to happen or never heard on a similar decommissioning project.

Table 1: Scales - Probability of Risk Occurrence: V1 NPP vs. International Recommendations

If we compare the example scales of probability of risk occurrence from DRiMa Report, and scales of probability applied in V1 NPP decommissioning, JAVYS's scales of probability of risk occurrence are stricter. V1 NPP decommissioning scales define the high and very high probability of risk occurrence already from 41%, whereas the DRiMa report defines this region from 61%. This means that JAVYS Company puts greater emphasis on elimination/mitigation of decommissioning risks.

International recommendations for scales of probability of risk occurrence, scales of risk impact, for risk matrix, etc., serve as examples which may be followed, or the decommissioning operator may individualize them.

While it is natural to develop site-specific scales stricter than international recommendations, the application of scales which are more tolerant, may be a subject of stakeholder's approval and may be questioned by applied methodology reviewer (e.g., audit).

The left side of Table 2 below includes the **scales of risk impact** applied in the V1 NPP decommissioning on operational level. The right side of the Table 2 includes the scales from the DRiMa report.

JAVYS's Scales of Risk Impact on Operational Level				
Value	Risk impact	Impact description	Cost	Schedule
5	Very high	Has a very high impact on the project in significant manner. It is very likely that the project objective will not be met. The situation requires adopting the anti-risk measures. It is assumed that there will be a **major increase in price** or **major delay in the project Time schedule**.	***71-100 %*** of total budget	***71-100 %*** of total duration
4	High	Has a high impact on the project. The situation requires adopting the anti-risk measures. It is assumed that there will be a **significant increase in price** or **delay in the project Time schedule.**	***41-70 %*** of total budget	***41-70 %*** of total duration
3	Medium	Has an average impact on the project. The situation requires adopting the anti-risk measures. It is assumed that there will be a **slight increase in price** or **slight delay in the project Time schedule.**	***16-40 %*** of total budget	***16-40 %*** of total duration
2	Low	Has a low impact on the project. Only small problems/issues are expected regarding its impact. The situation may also require possible anti-risk measures. It is assumed that there will be **no increase in price** or **delay in the project Time schedule.**	***6-15 %*** of total budget	***6-15 %*** of total duration
1	Very low	Has a minimal impact on the project. Almost no problems/issues are expected regarding its impact. It is not required to adopt any anti-risk measures. It is assumed that there will be **no increase in price** or **delay in the project Time schedule.**	***0-5 %*** of total budget	***0-5 %*** of total duration

Example of Scales from DRiMa Report			
Impact score	Scale	Cost	Schedule
5	Very high	**>20%** of the remaining budget	**>20%** of the remaining duration
4	High	**11 to 20%** of the remaining budget	**11 to 20%** of the remaining duration
3	Medium	**6 to 10%** of the remaining budget	**6 to 10%** of the remaining duration
2	Low	**1 to 5%** of the remaining budget	**1 to 5%** of the remaining duration
1	Very low	**<1%** of the remaining budget	**<1%** of the remaining duration

Table 2: Scales - Risk Impact: V1 NPP (operational) vs. International Recommendations

If we compare the above scales of risk impact the main difference, is that DRiMa's scales consider the REMAINING cost/duration, while the scales of impact applied in V1 NPP capture the impact on total price or total duration of the V1 NPP decommissioning sub-project. Implementing the impact on remaining time/cost is considered for V1 NPP purposes as a weakness, as at the end of a specific sub-project even an insignificant impact (e.g., 10 days delay) may be interpreted as e.g., high impact (if compared against the remaining duration). By application of remaining cost/duration, more importance is assigned to risk impact at the end on the project.

When developing the scales of risk impact, it is necessary to consider:

- Are operational scales or strategic scales being developed?
- What is more important for your decommissioning project? The scope of the deviation from total cost and total duration, or the scope of the deviation from remaining cost and duration e.g., one year from completion?

Scales of risk impact on strategic level for the V1 NPP Decommissioning risk management are site-specific. They were developed in cooperation with all stakeholders (in case of V1 NPP the representatives of: European Commission, Ministry of Economy of the Slovak Republic, European Bank for reconstruction and Development, Slovak Innovation and Energy Agency, and Nuclear Regulatory Authority).

Risks for the V1 NPP are formally tracked in a risk register. There are operational level risk registers – of respective sub-projects of V1 NPP decommissioning (from these separate sub-project risk registers are developed, yet one overall operational level risk register is summarized), and a strategic risk register of overall V1 NPP Decommissioning Project. The main aim of the development of a risk register is to identify, analyse, and evaluate risks before they become an issue. A project risk register should also include mitigation measures.

In Table 3, the structure of a risk registers of a specific V1 NP decommissioning sub-project is presented. Sub-project staff monitor, and report risks continuously - updating their Risk Register monthly in the frame of a Monthly Progress Report. The left side of Risk Register is always the initial risk assessment from Inception Report. When a new risk is identified during the implementation of sub-project, it is added as new row. The right side – highlighted in green - is updated on monthly basis, as a revision of risks.

No.	Risk identification date	Type of risk	Name / Description of the risk	Consequences	Risk rating			Risk owner	Measure for risk elimination (Measure for risk impact elimination)	Occurrence Yes/No	Effectiveness / Ineffectivenes s of action	Revised risk rating					Risk expiration date
					Likelihood [L]	Impact [I]	Level of risk [LR=L x I]*					Likelihood [L]	Impact [I]	Level of risk [LR=L x I]	Date of revision	Reason for revision	
1																	
2																	
3																	

Table 3: JAVYS's Risk Register of Specific Sub-project on Operational Level

After the risk analysis, which determines for every identified risk the probability of its occurrence and impact should it occur, the risk evaluation follows (see Figure 1). Within the risk evaluation, which is the final step of the risk assessment process, identified risks are scored based on the analysis of the probability of occurrence and severity of the impact. The risk score is a correlation between both scores. A Correlation diagram (risk matrix) of the risk management methodology of V1 NPP decommissioning projects (on strategic and operational level) is provided in Table 4. The colouring in Risk matrix represents categorization of risks.

JAVYS's risk matrix has the dimension five x five. More important than the matrix size is how precisely the scales are defined and how accurately the person managing the risk can rank each risk's probability and impact within the defined ranges. Risk matrix sizing is a matter of preference; however, it can be detrimental to effective risk management. For example, in matrices with sizes smaller than 4x4, the uncertainty ranges become too vague, and in matrices with sizes larger than 5x5, the range of uncertainty becomes too constrained.

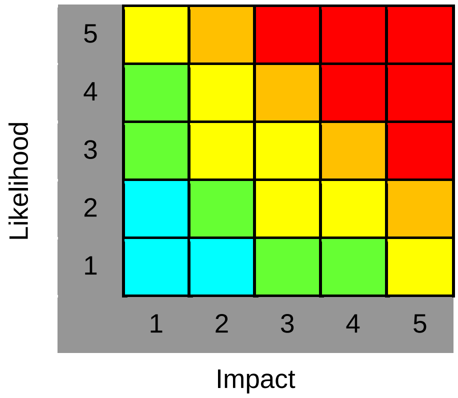


Table 5: Risk Matrix applied in JAVYS

Risk matrix with the dimension 5x5 is the mostly used in project management. However, Risk matrix sizing is a matter of preference.

3.4. Qualitative vs. Quantitative Risk Analysis

The previous subchapter addressed the qualitative risk analysis, which is always to be implemented on both strategic and operational level. It tends to be more subjective and focuses on identifying risks to measure both the likelihood of a specific risk occurrence and the impact it will have on the overall cost/schedule, should it occur. The overall goal is to determine **severity**. Therefore, the methods of qualitative risk analysis include the risk register, risk matrix and risk categorization (see Table 5).

Always develop a project risk management plan and specify in it **how the qualitative risk analysis will be performed**. Furthermore, decide whether you **will perform quantitative risk analysis or not**. Do the benefits of its application outweigh the costs/input?

Risk Analysis (RA)

Qualitative RA (QLRA)	Quantitative RA (QTRA)
• Risk Register	• Sensitivity Analysis
• Risk Matrix	• Decision Analysis (Decision Tree)
• Risk Categorization	• Scenario Analysis
	• Latin Hyper Cube Simulation
	• Monte Carlo Simulation

Table 6: Qualitative vs Quantitative Risk Analysis

Quantitative risk analysis is applied usually only on strategic level, to support the decision making, and is optional (see Table 7). A guide to the Project Management Body of knowledge (ANSI/PMI 99-001-2017) defines the quantitative risk analysis as the "*process of numerically analysing the combined effect of identified individual project risks and other sources of uncertainty on overall project objectives*". Quantitative risk analysis includes analytical methods such as Decision trees or Monte Carlo simulation. To perform such analysis, it is necessary to collect/estimate the input data, carry out complex calculations which require specific tools/software, and to dedicate significant periods of time amongst a group of experts. This group of experts shall include:

- personnel to estimate input data,
- experts to develop quantitative risk model,
- experts responsible for the development of decommissioning schedule (if the analysis addresses the schedule) or the experts responsible for elaboration of the decommissioning cost (if it addresses the cost of decommissioning),
- experts responsible for the elaboration of a prioritized lists of project risks,
- other experts from specific departments and last, but not least,
- a data analyst/statistician.

If the qualitative risk analysis is to be performed, it is unavoidable to have a statistician/data analyst within the organization structure. The added value of such personnel is higher if he/she is familiarized with your decommissioning project (involved in decommissioning from early stages).

Qualitative Risk Analysis (QLRA)	**Quantitative Risk Analysis (QTRA)**
• always to be performed	• optional
• performed first	• performed only after QLRA
• risk-level	• project/programme level
• based on a person's perception or judgment (**subjective**)	• based on verified and specific data (**objective**)
• no calculations, relatively straight forward	• complex calculations
• no special software/tools needed	• special software/tools required
• quick	• time consuming
• explorative	• conclusive
• important for **early identification of new risks** and tracking effectiveness of mitigation measures	• important for **strategic decisions** and stakeholders (performed sporadically/when necessary)
• hard to estimate contingency	• output: reliable estimate of contingency (cost /time)
• potential impact of risks assessed individually (risk by risk)	• estimates combined effect of all risks

Table 8: Differences between Qualitative and Quantitative Risk Analysis

Quantitative risk analysis is analysis of the highest priority risks (strategic risks of the programme). It always considers strategic risks but may in some cases consider operational level risks (requiring more complex models). Through quantitative risk analysis, an assessment of the probability of achieving specific project objectives (total cost/end date) is possible. It also provides a basis for strategic decision making when there is uncertainty and enables creation of realistic and achievable cost, schedule, or scope targets.

3.5. Quantitative Risk Analysis Applied in V1 NPP Decommissioning

Monte Carlo simulation was applied in V1 NPP Decommissioning Project for two basic types of analysis – analysis of V1 NPP Decommissioning Project schedule and analysis of the V1 NPP Decommissioning Project cost (see Figure 4).

In the area of decommissioning cost determination, the Monte Carlo simulation was applied to obtain a robust and reliable estimate of the V1 NPP Decommissioning contingency in 2014, 2017 and 2021 (Detailed Decommissioning Plan 2014, 2017 and 2021). The cost simulation model, (including input data and assumptions, etc.) was created several times. This document summarizes the development and differences between the respective cost models are summarized.

The second area in which the Monte Carlo simulation is applied in V1 NPP decommissioning is scheduling (see Figure 4). The first application of Monte Carlo simulation on decommissioning schedule was carried out in 2021, based on the request of the stakeholders to quantify the impact of the strategic time related risks on the decommissioning schedule. Subsequently, this model was updated at the beginning of 2022.

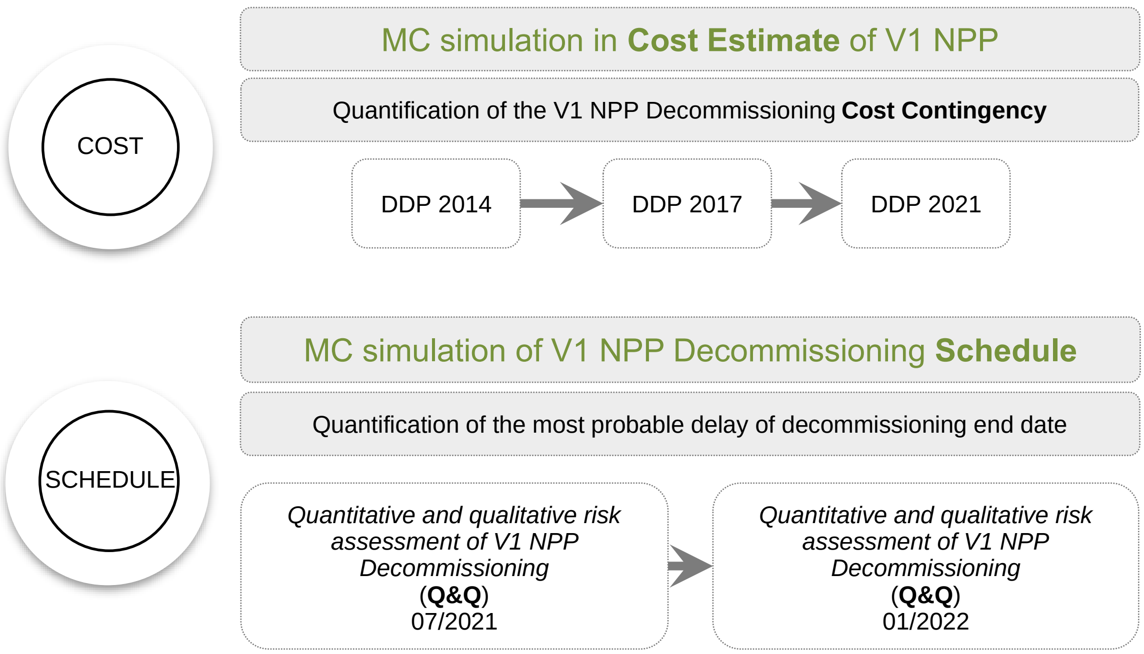


Figure 4: Development of two applications of MC Simulation in V1 NPP Decommissioning

4. MONTE CARLO SIMULATIONS

4.1. Technical Basis

Monte Carlo (MC) Simulation is a mathematical technique used to estimate the possible outcomes of an uncertain event (element of chance is basis of this simulation). Before running the MC simulation, the model is to be defined. In general, there are two types of models:

- **deterministic model** – allows to calculate the future event exactly, without considering the randomness. For deterministic modelling, all data needs to be available to predict (determine) the outcome with certainty.
- **stochastic model** - has the capacity to include the uncertainties in the input data. Stochastic models possess some inherent randomness - the same set of parameter values and initial conditions will lead to an ensemble of different outputs.

Monte Carlo Simulation represents stochastic modelling. It predicts a set of outcomes based on an estimated range of values – the input data, which are uncertain, and are defined by probabilistic distribution (as e.g., uniform, or normal distribution). The results are recalculated over and over (the number of recalculations is referred to as number of iterations), and every recalculation (iteration) is using a different set of random numbers within the defined probabilistic distribution of uncertain variables of the model. The output of Monte Carlo simulation provides the information on possible results using a probabilistic distribution. This means (in the case of decommissioning costs), that the cost is not estimated as one value, but by a probabilistic distribution of values. The likelihood of occurrence of maximum of this distribution is 100%.

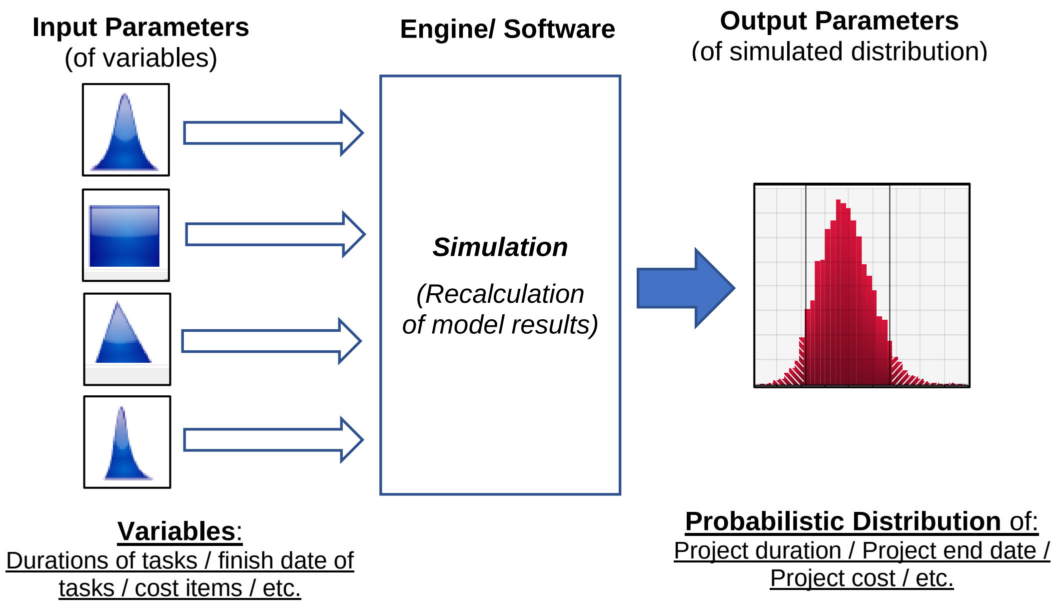


Figure 5: MC Simulation Scheme (generated by JAVYS Company).

> Monte Carlo Simulation represents stochastic modelling. In a deterministic model, the result is the same every time the model is run. In a stochastic model, the results will differ from simulation to simulation (of the same model), because there's an element of randomness.

Regardless of what software/tool you use, Monte Carlo simulation involves three basic steps:

1. Setting up the model and identifying the variables.
2. Estimation of probability distributions of the variables. This is based on the historical data and/or the experts' subjective judgment.
3. Running of the simulation. Number of the iterations is decided – how many results are gathered to make up a representative sample of possible combinations of results.

4.2. Tools / Software

There are several software allowing the MC simulation. E.g.: Crystal Ball (from Oracle), Primavera (from Oracle), @RISK (from Palisade), Analytica (from Lumina Decision Systems), etc.

The basic information that must be known prior to selecting a software package includes the type of model that is to be simulated. In case of V1 NPP Decommissioning the software was used to simulate both cost and schedule. In case of schedule modelling, a decision has to be made whether a simpler model is to be simulated (in which both **uncertainty and risk** are simulated within the probabilistic distribution of decommissioning activity - variable) or whether a more detailed model is to be simulated (in which the **uncertainty** is simulated within the probabilistic distribution of decommissioning activity – variable, and the **risk occurrence** and subsequent delay are simulated separately).

The software used for the simulation of cost and schedule was @RISK software, a MS Excel add-in (version 7.6.1 supports MS Project).

⚠	Version 7.6.1 of software @RISK supports MS Project – allows the modelling of decommissioning schedule. Newer versions as to 2022 do not support MS Project.

4.3. Areas of Application in Decommissioning

The V1 NPP Decommissioning Project applied the MC simulation in two areas:

1. <u>Quantification of V1 NPP Decommissioning cost contingency (in 2014, 2017 and 2021).</u>

Benefits of application of Monte Carlo simulation in decommissioning cost:

- Decommissioning cost contingency is estimated in compliance with internationally recommended and approved technique.
- MC provides a statistically robust method for aggregating the cost uncertainty into overall decommissioning project level cost estimate.
- MC provides overall decommissioning project cost estimate represented by a range of possible costs with associated confidence intervals.
- The model is dynamic - cost model can be updated when new information becomes available.
- Result of application of MC is cost estimate, which is considered an objective by the stakeholders, and supports the decision making on the strategic level of management.

2. Simulation of V1 NPP Decommissioning end date (2021, 2022).

Benefits of application of Monte Carlo simulation in decommissioning scheduling:

- Objectively quantifying the probability of achieving the decommissioning end date in compliance with schedule.
- Quantification of the most probable delay of the decommissioning project.
- Examination/confirmation of the most significant drivers of the possible delay of decommissioning completion (*Tornado figure*, one of the outputs of MC simulation, provides information on the decommissioning activities with the highest impact on the variability of the completion date).

Other examples of application of Monte Carlo simulation in decommissioning include for example:

- **calculations of induced radioactivity in the concrete containment vessel** of a high temperature gas cooled reactor-pebble bed module **to predict the decommissioning problems** (*Li, Wenqian, Li, Hong, et. al.., 2013).*
- Monte Carlo simulations together with practical experimental measurements can be applied in **calibrating a decommissioning clearance box monitor** (*Bochud, François, at. al., 2009).*
- In the research of irradiated Graphite Processing Approaches, the Monte Carlo and general radiochemistry integrated approach has been developed *to study materials activation and support radiological characterization campaign* (*Mossini, Eros, et. al., 2018)*
- **MC based virtual reality platform allows real-time visualization of the dose rate** due to one or more radiation sources (*Takeshi Takata, et. al., 2020).*

5. USE CASE 1 (SCHEDULE ASSESSMENT) – QUANTITATIVE RISK ASSESSMENT OF THE V1 NPP DECOMMISSIONING SCHEDULE

5.1. Methodology

Decommissioning project time schedule is subject to future occurring events, risks, including situations and conditions that may vary over time, whose occurrence is uncertain during the development phases of the project itself. Such future occurring events translate into variations of the estimated total project duration and the decommissioning completion time.

To estimate the probability of the achievement of the base estimate of V1 NPP decommissioning and to obtain the probability distribution of the V1 NPP decommissioning schedule the probabilistic scenario simulation approach was applied in 2021 and 2022 (also referred to "Quantitative risk assessment for the time related risks using Monte Carlo simulation Method").

Important key words are:

- **Decommissioning Schedule Base Estimate** – the base estimate is an estimated time schedule of decommissioning project, in which there is no time contingency for the impact of uncertainty and risks occurrence.
- **Contingency** – in this case is a provision of additional time to be considered in the project schedule base estimate to account for specific events that are expected to be known with a detail at later stage. Time contingency considers activities whose exact value in terms of time is not presently known in detail (or no sufficient information about it is presently available) and to which uncertainty or risk is attributed. It is a reserve for covering the impact of time related risks, whose occurrence can result in time schedule variations.

Based on the results of MC simulation of schedule:

1. The probability of achieving project completion in scheduled time is determined,
2. The value of contingency (in this case additional duration) is determined

Point 2 is dependent on stakeholders' risk propensity. E.g., if the stakeholders are "risk averse" and have a low-risk propensity, the value of the contingency would be higher, meaning that the contingency will cover the additional time necessary to achieve e.g., 70, 80, 95% probability. If the stakeholders have high risk propensity and are "risk seeking", the contingency would be lower.

- **Monte Carlo simulation** - the Monte Carlo (MC) simulation is a class of computational algorithms that relies on repeated simulation to compute or iterate project cost or project duration including uncertainty and risks. Input values are selected randomly from assigned probability distributions of input variables, to calculate a statistical distribution for total project cost or total project duration.
- **Iterations** - the number of iterations informs on how many times the durations of respective activities of V1 NPP decommissioning were randomly determined within the simulation (in both simulations of V1 NPP decommissioning schedule 10,000 iterations were applied).
- **Data distribution –** is the type of probabilistic distribution of the input data (activity duration) applied in the simulation.

- **Parameters of distribution –** every probabilistic distribution is defined by parameters. E.g., a Three-point distribution is defined by: minimum (low) and maximum (high) and most likely.

Via application of Monte Carlo simulation on the V1 NPP Decommissioning schedule, the answers to following question were obtained:

- *Is the project finish date realistic?*
- *What is the probability of completing the project on the target date?*
- *What is the most probable delay?*
- *Is there sufficient time contingency in the schedule?*
- *What are the key decommissioning activities significantly influencing the end date?*

The starting point of creating the decommissioning schedule simulation model is the **decommissioning schedule** itself. The more detailed the decommissioning activities within the schedule (both the detailed schedule and lower-level schedule) are the more detailed the model and the results will be. However, creation of the very detailed schedule (complex schedule) is significantly time consuming and creates more room for mistakes in interlinkages and dependencies between activates within the schedule.

> The level of detail of the decommissioning schedule to be simulated using Monte Carlo simulation is equally important as the correctly captured dependencies/interlinkages of activities within the schedule!

The second important input data is the **risk register of the time related risks**. As the impact on the decommissioning deadline is the main reason for the simulation of schedule, this risk register must include all the strategic time related decommissioning risks. Or in other words, all risks that have potential impact on the decommissioning deadline. When selecting the time related risk to be modelled, assumptions/decisions must be made on the risks to be included in the simulation:

- **Only strategic time related risk will be modelled**. This simplification is applied correctly if all strategic risks are identified. This means that the strategic time related risks include not only risks which will directly impact the critical path of decommissioning activities, but that experts also identified strategic risks which do not impact the critical path directly (may impact sub-critical path).
- **Strategic and (part/all) operational time related risks will be modelled**. Operational level time related risk is the risk with potential impact on the completion of a partial activity of decommissioning (decommissioning sub-project in the case of V1 NPP), but the activity for which this risk impacts is not on the critical path, nor on the sub-critical path of decommissioning. The delay of this activity, even if the risk occurred in full force, would not impact (alone) the overall completion of decommissioning.

> Strategic time related risks are always to be included in the modelling of decommissioning deadline. Including the operational level time related risks is optional.

In the case of V1 NPP, in the models simulated in 2021 and early 2022, only the strategic time related risks were modelled. This decision was made based on the facts that a high-level schedule (less detailed schedule) was modelled. Furthermore, the added value of considering operational level risks is only realised after completing the model (there may or not be added value; model results dictate this). If operational risks were to be modelled, a higher level of schedule desegregation (detailed schedule) would have been necessary to include in the model.

Operators may decide to model detailed schedule and include operational level risks since such detailed modelling may discover, for example, partial activity for which several operational time related risks may cumulate. In combination with delay (occurrence of risks) in predecessor activity, this partial activity may get on the critical path/sub-critical path of decommissioning. Currently, a more detailed model based on a detailed schedule of V1 NPP Decommissioning, which includes selected operational level risk, is under development by PMU Consultant and JAVYS.

> ⚠ If the operational level time related risks are planned to be included in the simulation of decommissioning schedule, this schedule is to be as detailed as possible.

After the decision on the level of complexity of the decommissioning schedule and the decision whether the operational level risks will be included in the simulation, the type of model is applied based on the next decision. Before the decision on the **type of schedule model**, the difference between uncertainty and risk is to be properly comprehended, as well as a check on the level of complexity of the current base schedule. A summary is provided below on the steps to be taken:

Figure 6: Decision Process of Selection of Schedule Model

> ⚠ Always differ between **uncertainty and risk**. These are not synonyms!

According to Lechler, Edington, & Gao, 2012, "classic project management does not clearly differentiate between risks and uncertainty". The concepts are explained in detail below and are supplemented by Figure 7:

- ***Risk*** is measurable and predictable as it is assessed by *probability of occurrence and impact in case of occurrence* (this impact can be negative in case of risk, but also positive in case of opportunity). The occurrence of a risk would create a significant impact on schedule by affecting one or few of decommissioning activities. Risk is often referred to as the ´´known-unknown´´
- ***Uncertainty*** is not measurable and not predictable; it is the lack of certainty about an event. Uncertainty is not the impact of one specific situation, but several insignificant deviations. Each of these several deviations have limited impact on the decommissioning activities themselves, but when combined, they may disrupt the overall decommissioning project baseline. Uncertainties are referred to as the ´´unknown-unknown´´.,

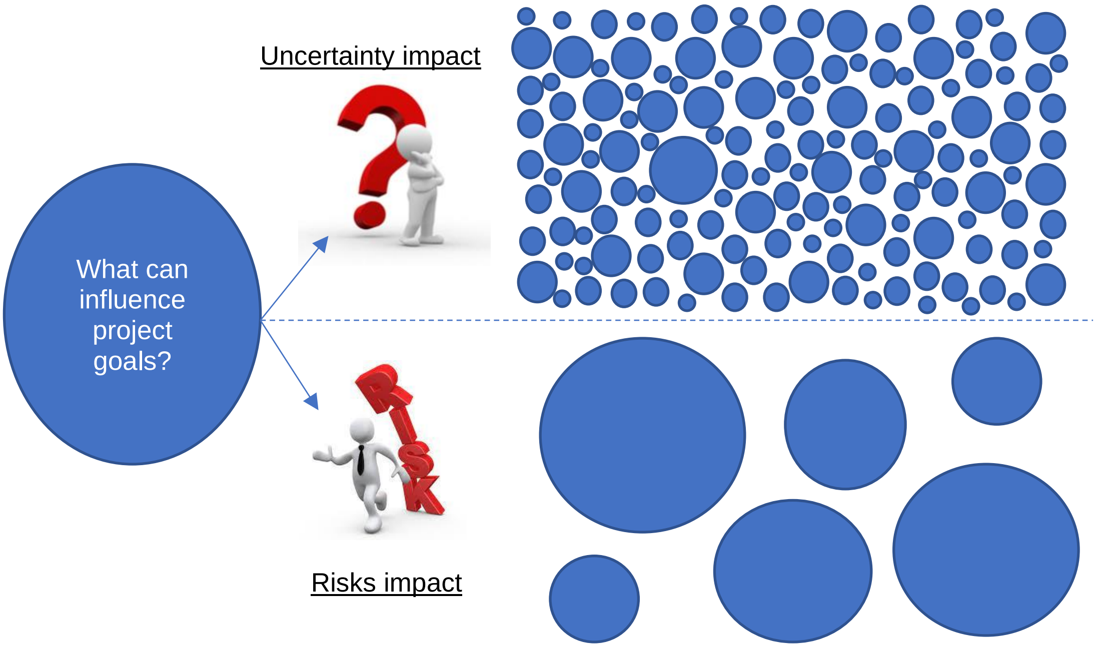


Figure 7: Impact of Uncertainty and Risks on Decommissioning.

> Once the difference between the risk and uncertainty is clear the decision is to be made whether these two would be modelled together or separately within the simulation.

The Monte Carlo simulation considers both uncertainty and risk providing more realistic estimates of outcome and basis for contingency determination. There are two basic possibilities on how to model risks and uncertainties with the decommissioning schedule. The 1st approach is the simplified simulation in which the risks and uncertainty are considered together for every decommissioning activity. In this simplified model the expert panel (group responsible for estimating site-specific input data) estimates both the risks and uncertainty, which may impact specific decommissioning activity within the probabilistic distribution of this activity. In the 2nd approach the impact of uncertainty and risk is modelled separately within the simulation. Uncertainty is modelled within the probabilistic distribution of the activity duration and occurrence of risk with its impact is modelled standalone (see Figure 8 below).

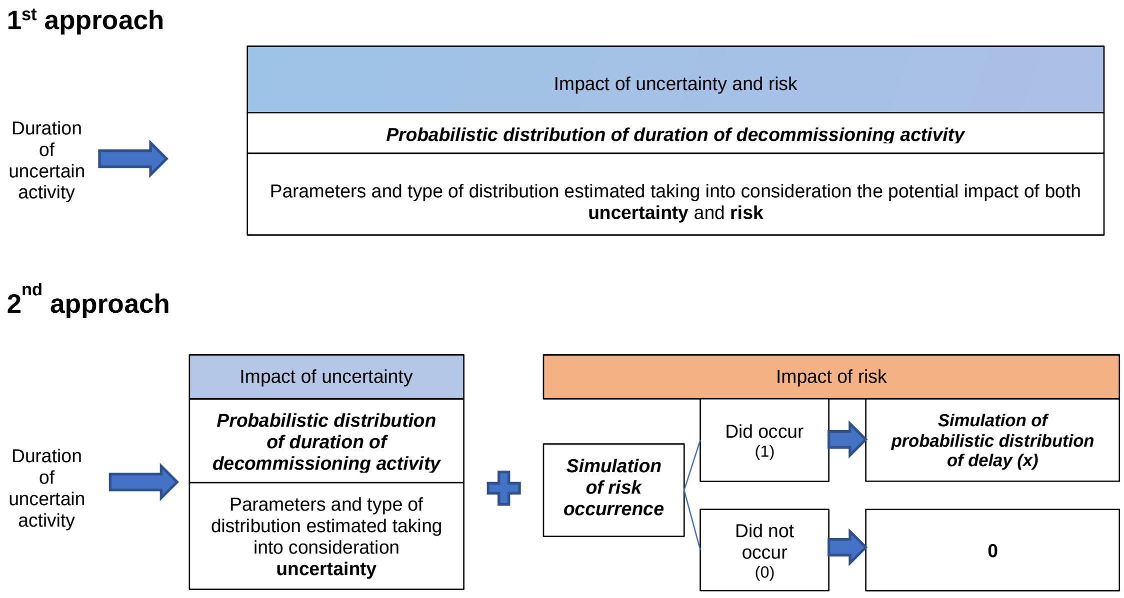


Figure 8: Two Approaches to Simulation of Decommissioning Schedule

Note, that in the 2nd approach (Figure 9), the risk is not modelled in the frame of the probabilistic distribution of the decommissioning activity duration, but its occurrence is simulated as a discrete variable (integer value, which may be 1 in case of occurrence and 0 in case of non-occurrence). *E.g., we may be dealing with specific decommissioning activity whose whole duration is 100 days according to the schedule. In the 2nd approach the experts may estimate the uncertainty by defining the activity duration as triangular distribution with the most likely value at 100 days, minimum at 95 days, and maximum at 105 days. They also define that the specific risk related to this activity has the likelihood of occurrence 60% (and 40% of non-occurrence). If the risk occurs the most probable delay may be defined as e.g., 50 days (as most likely delay), 40 days as minimum delay, and 70 days as maximum delay.*

> When selecting the probabilistic distribution of the duration of decommissioning activity (or probabilistic distribution of delay if risks are modelled separately) the first decision is whether the probabilistic distribution to be applied is continuous or discrete. Afterwards the decision on specific type of probabilistic distribution is done. **Discrete** delivers results in integer values (whole days), while **continuous** delivers results in hours and minutes.

In the case of V1 NPP, in both models simulated in 2021 and early 2022, the 1st simplified approach was applied. In the following subchapters the process of setting up the simplified model and results will be described in more detail in following order:

- Assumptions of the model (incl. software, decommissioning schedule).
- Input data – selection of variables (uncertain decommissioning schedule activities).
- Input data – selection of the probability distribution of variables.
- Input data – determination of parameters of probabilistic distribution of variables.
- Simulation – definition of output cell and running of simulation.
- Interpretation of results.

5.2. Assumptions

A model is a simplified version of reality. Regardless of the model sophistication, all models are approximations of reality, but allow predictions on future development. Usually, simple models are preferred over complex ones. Overly complex models are time and cost demanding for development, as they may be hard to understand for personnel/stakeholders not involved in the process of their development. To develop a simplified version of reality it is unavoidable to make **simplifying assumptions**. Assumptions are basically experts' beliefs based on previous experience and information available to them when creating the model.

> **Always include all assumptions when you distribute the results of analysis.**
>
> Assumptions are an inseparable part of any model results presentation → if the assumptions are not provided with the results, then the informative capability is lost.

Assumptions related to MC modelling of decommissioning schedule shall include at least the following information:

- **Assumption 1** – related to **decommissioning schedule** to be modelled. The decommissioning schedule itself is a simplified version of reality. Therefore, every schedule developed has its own assumptions. As the schedule is further used for the development of the model including the uncertainty and risk, all the original assumptions made while developing the schedule apply to the MC simulation. Original assumptions of the schedule may be related to e.g.: working allowed/not allowed during weekends, double shifts included, or the original schedule considers only one shift (and the double shifts represent a form for mitigation measures), assumptions on the dependencies between activities, etc.

- **Assumption 2** – shall clearly inform whether the original schedule includes the contingency or not. If yes (contingency included), it shall be noted whether this contingency was properly analysed in the MC simulation.

  In both simulations of V1 NPP schedule, the simulated models do not include the contingency (it was omitted from the model).

- **Assumption 3 –** shall inform whether strategic or strategic and operational level risks are being modelled.

  In case on V1 NPP decommissioning in both models only strategic risks were modelled.

- **Assumption 4 –** shall inform whether the risks and uncertainty were modelled together or whether they were modelled separately.

  In case on V1 NPP decommissioning, in both models (2021, 2022) the risks and uncertainty were modelled together in frame of the probabilistic distribution of the variables (durations of specific decommissioning activities.

- **Assumption 5 –** is related to risk register. As the analysis was carried out twice, the strategic risk register was updated as necessary.

  *In the second simulation (01/2022), **ceased time related risks on strategic level were not considered** in the Monte Carlo modelling. For simulation in 01/2022, all time related risks are incorporated into the modelling as re-assessed as to 01/2022 (meaning that initial values are not considered, but the actual estimation is considered for those active risk where the re-assessment led to change (right side of the Risk Register is not empty). Those risks, which are active (non-*

ceased) and the re-assessment did not change the risk impact and probability of occurrence, are incorporated into the modelling with original values.

- **Assumption 6 –** addresses the ***on-going decommissioning activities*** and how they were treated. As it is clear that completed activities carry no risk or uncertainty, and planned activities carry risk and uncertainty in full force.

  For activities as part of the V1 NPP decommissioning, the uncertainty and risks were estimated only for that part of the duration of the on-going activity which was still to be completed.

- **Assumption 7 –** addresses the selection of the probabilistic distribution of the input data (variables of the model).

  Type of probabilistic distribution of the variable (input data) is selected either from discrete (variable with countable integer values as outcomes) or continuous (variable with any fractional value as outcome) types of probabilistic distributions.

5.3. Input Data

As part of any analysis or model:

1. Simplifying assumption are to be provided,
2. All input data are to be stated.

This is done, so that any other party, based on the same input data and same assumptions, can verify the analysis. The input data in the MC simulation of the decommissioning schedule are:

- *decommissioning schedule (in our case V1 NPP decommissioning schedule MS Project),*
- *strategic time related risks risk register,*
- *MC simulation software (in our case @RISK software - version 7.6.1 supports MS Project),*
- *and the type of distribution and its parameters estimated by group of site experts.*

5.3.1. Identification of Variables – Decommissioning Schedule Activities

The basis of the set of input data is the **decommissioning schedule**, which shall include all decommissioning activities and their interlinkages. The level of detail of the decommissioning schedule is to be decided (highly complex, as simple as possible, etc.). This schedule is to be analysed by a group of site experts, who will determine **activities which are uncertain, and which are impacted in the case of occurrence of risks** (**variables of the model**).

> Include the personnel responsible for the development of the decommissioning schedule in the group of experts responsible for later steps (identification of variables, estimation of the probabilistic distribution of variables) of the MC simulation.

Decommissioning schedule may also include activities that are certain or represent a milestone, these are the **constants of the model**. Example of an activity, which is a constant is e. g. already completed activity, activity which is certain, or time contingency (if the decommissioning schedule includes contingency). One of the uses of MC simulation is to properly determine the decommissioning schedule contingency, or to analyse whether the exiting contingency is sufficient (not to assign contingency to a contingency).

Constants are never omitted from the model of schedule and represent an important part of the model.

The whole decommissioning schedule is always simulated. The software simulates the end date (in our case) or total duration, and both are a result of interlinkages and duration of all decommissioning activities. Simplified schedules are acceptable to use, but schedules with omitted activities should not be used. As by creating a simplified schedule with omitted activities (constants), the interlinkages would be broken, and the duration of activities which represent constants would not be taken into consideration – the results of simulation would be understated and biased.

Only exception – of a constant which may be omitted from the model - is the **time contingency** if it is already included in the schedule as a separate final activity.

The level of detail of the decommissioning schedule influences the MC simulation output. If the aim of the simulation is mainly to obtain the most probable delay, or to quantify the decommissioning contingency, then a simpler schedule is appropriate. However, if the aim is to identify the very detailed activities, which may affect the deadline, the schedule should be as complex as possible. Advantages of very detailed decommissioning schedule in simulation may prevail to the complexity of development of such schedule.

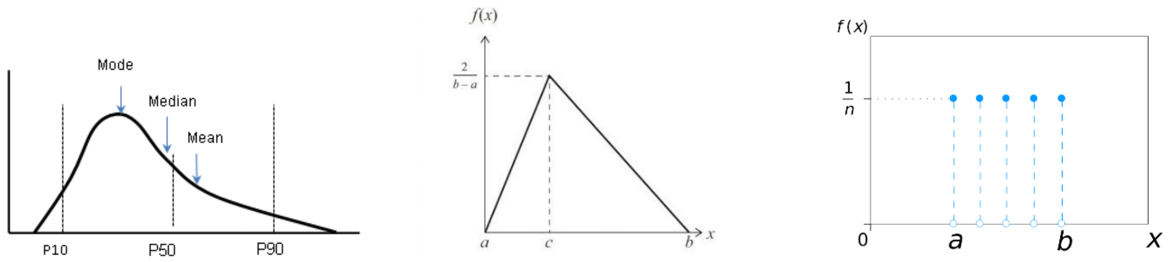
Consider the results expected to be obtained from the MC simulation before deciding how detailed the decommissioning schedule used in the simulation will be.

5.3.2. Selection of the Probability Distribution of Variables

Once the group of site experts have determined which activities of the schedule are uncertain and how the occurrence of risk may impact these activities, they need to decide on the type of probabilistic distribution of these activities. The V1 NPP applied in 2021 and 2022 a simplified approach (1st approach, see Section 5.1) in which both uncertainty and risk are modelled within the probabilistic distribution on the activity duration.

Some of the applicable distributions are depicted in Figure 10 below.

The uncertain activities of the schedule (variables of the model) are then assessed by the group of experts together with the risks register. Then, for every activity for which the risks have potential impact on the activity, the activities are linked. One risk may have potential impact on one decommissioning activity or on several decommissioning activities. If the risk impacts more than one activity, then its total maximum potential impact (the delay it may cause to the entire decommissioning program) has to be distributed among the affected activities.



Parameters of Log- Normal distribution:

- **mean**
  (activity duration)
- **standard deviation**
  (variability in % x activity duration)

Parameters of Triangular distribution:

- **Minimum**
  (Low value, lower limit location parameter, a)
- **Maximum**
  (High value, upper limit location parameter, b)
- **Most likely value**
  (Mode, shape parameter, defines peak of ∆, c)

Parameters of Uniform distribution:

- **Minimum (a)**
- **Maximum (b)**

Figure 11: Examples of Types Probabilistic Distributions with Their Parameters.

Then based on the estimate on the potential impact of both uncertainty and risks, the type of the distribution and the parameters of the distribution are set up by the expert panel. All of the uncertain activities within the schedule may have the same type of probabilistic distribution, or the experts may decide that several types of distribution will be applied in the schedule (based on the available expectations of the experts).

If the experts decide to apply **discrete** probabilistic distribution of variables – the values (duration of activity modelled within simulation) will be estimated as integer (whole days), and if the experts decide to apply **continuous** distribution – the values (duration of activity modelled within simulation) will be estimated as days and fractions of days. If we assess the three types of the probabilistic distributions in Figure 13, the following may be concluded:

- **Log-normal distribution** has the peak (mode - most likely value) and the median (50% percentile) lower than mean (weighted average). The mode, median and mean are the characteristics of log normal distribution. The parameters (which define it) are the mean and standard deviation. The mean is the originally estimated duration of the decommissioning activity, this means that within the simulation more than 50% of samples (iterated values) will be lower than mean.

> *One of the assumptions of the V1 NPP decommissioning schedule is that the project is in the final stage, where the schedule has been optimised, and nearly all opportunities within the schedule were used. The schedule is tight, activity durations are estimated without contingency; close to the minimum required time in which it is possible to complete the activity. Therefore, application of log-normal distribution, which will place most of the simulated values to be lower than the originally estimated duration of the specific decommissioning activity is not correct for V1 NPP decommissioning schedule.*

- **Triangular distribution** (see Figure 9) has three parameters: Minimum also referred to as low value (lower limit location parameter – a), maximum also referred to as high value (upper limit location parameter – b) and most likely value also referred to as mode (c), which is a shape parameter (defines peak of triangle). Triangular distribution is easy to use, as the experts are usually able to tell the maximum delay and soonest completion of activity they expect.

In both simulations of V1 NPP decommissioning schedule the triangular distribution was used for the variables.

- **Uniform distribution** is the distribution with equally likely outcomes. In a discrete uniform distribution, outcomes are discrete and have the same probability. It is considered trivial, and it is convenient to use it e.g., if the experts have no specific expectations on the future events (are not able to estimate whether the delay is more probable than sooner completion of activity). In uniform distribution the values around the mean do not occur more frequently.

One of the assumptions of V1 NPP decommissioning schedule is that the durations of activities were estimated correctly, it is expected that the values will be more frequent near the original value and that the delay is more probable than sooner completion (if the sooner completion is allowed). Therefore, uniform distribution was not applied.

The selected probability distribution shall comply with the expectations and assumption of the experts on the estimates of the future events.

Several types of probabilistic distribution may be used within the same simulation for different decommissioning activities.

5.3.3. Determination of Distribution Parameters of Input Data

As in the previous step, a triangular probability distribution of variables was selected by experts. Now in this step, the values of the parameters of the triangular distribution of variables are to be estimated. Triangular distribution has three parameters – the *most likely value*, which is the decommissioning activity duration, and two more parameters to be estimated by the expert panel (*minimum and maximum*).

The number of parameters which have to be inserted into the model depends on the type of probabilistic distribution of the input data.

The parameters applied in the simulation of the V1 NPP decommissioning schedule in January 2022 are stated in Table 9. This table includes information on the risks which were considered together with the uncertainty when estimating the parameters. These parameters (low duration and high duration) were the input to the MC simulation. The information on the duration of the activity was already included in the input data – the schedule in MS project.

Task name	Low duration	Most Likely duration	High duration	
Temporary storage of material from V1 NPP decommissioning - phase 1 (C8-B.02)				
Commencement day				
Inception documentation elaboration and approval	43	43	48	
Commencement of the Contractor´s mobilization to start the works and subsequent preparation of premises for reconstruction of CB 811	10	10	12	
Demolition works	33	33	37	

Implementation of individual construction project works	183	183	220	
Installation of technology at individual CB 811, CB 811/1, CB 811/2	205	205	247	
Relevant state administration authorities documentation elaboration and approval in line with the Act No. 541/2004 Coll., and with the Act No. 87/2018 Coll.	32	32	36	
Issuance of the license for the operation of storage facilities by the relevant state administration bodies - phase 1	45	45	79	
Project D4.2				
Commencement day				
Complete Annular Water Tank (AWT) dismantling, fragmentation, and material management (Unit 2)				constant
Complete Reactor Pressure Vessel (RPV) dismantling, fragmentation, and material management (Unit 1)				constant
Complete Reactor Internal Structures (RIS) dismantling, fragmentation, and material management (1xPTU, 1x CB, 1xBSB corresponding to one unit – Phase 2)	86	86	104	Risk 1,7,8
Complete Reactor Pressure Vessel (RPV) dismantling, fragmentation, and material management (Unit 2)	33	33	50	Risk 1,7,8
Drainage of pools of wet cutting workplaces	32	32	36	Risk 1,
Processing of liquid RAW from pools	39	39	43	Risk 1,19
Complete dismantling and fragmentation of the Active water treatment system (Unit 2) and material management	106	106	117	Risk 1,
Complete SGs dismantling, fragmentation and material management (6 pcs corresponding to one unit – Phase 2)	209	209	251	Risk 1,6
Complete removal and material management activities of the activated and contaminated part of the concrete of the Reactor Shaft Unit 1 and 2	520	577	635	Risk 1,7,8,9
Dismantling of installed workplaces and facilities for fragmentation, packaging, and transport of components	299	314	330	Risk 1,
Complete dismantling of liners of containment (Unit 1 and 2) and material management	259	259	285	Risk 1,
Completion of Final Clean-up, conditioning of all affected areas and demobilization of all Contractor's equipment and materials and their transport from the site, and their decontamination if necessary	228	228	240	Risk 1,
Project D4.4C				
Commencement day				
Documentation approval: Detailed design; Affected licencing documentation according to Section 2.4.1.3; Work Procedures	88	92	106	Risk 1,
Approval of licencing and design documentation by relevant state administration authorities	53	53	80	Risk 1,
Removal and fixation of sludge from the tanks	183	183	220	Risk 1,6,7,8
Documentation approval: Cost Benefit Analysis Report on decontamination methods	55	55	58	Risk 1,
Preparatory activities for Phase 1 of dismantling: Completion of preparatory works and tag-out, mobilization, inspections, cleaning, implementation of radiation protection measures, establishment of workplaces, establishment of general auxiliary...				constant
Dismantling of certified dosimetry systems, system for deactivation in SK 201, removal of dangerous materials from the Controlled area, dismantling of tanks in CB 801:V1: SK013/3, SK013/4, SK013/5	22	22	34	Risk 1,6,7,8
Preparatory activities for Phase 2 of dismantling: Completion of preparatory works and tag-out, mobilization, inspections, cleaning, implementation of radiation protection measures, establishment of workplaces, establishment of general auxiliary...	253	253	304	Risk 1,6,7,8
Removal and fixation of sludge from tanks after the evaporator shut down	358	358	502	Risk 1,20
Decontamination of metallic contaminated materials (CMM) from D4.4C at C7-A3 facilities	148	173	174	Risk 1,4,5,26

Decontamination of the tanks, drainage, sludge removal, decontamination, dismantling and fragmentation, transport, tag-out activities of all equipment within scope of works in the Auxiliary Building (Including evaporator dismantling)	645	645	710	Risk 1,6,7,8,20
Completion of drainage, sludge removal, in-situ decontamination, dismantling and fragmentation, sorting and transport, tag-out activities of all equipment and material within scope of works in the Reactor Building (Including C7-A3 facilities dismantling)	644	644	741	Risk 1,6,7,8,20,25
Completion of drainage, sludge removal, in-situ decontamination, dismantling and fragmentation, sorting and transport of all equipment and material within scope of works in other buildings and areas	644	644	677	Risk 1,
Completion of final clean-up, conditioning of all affected areas and demobilization. Approval of As-built documentation	126	126	139	Risk 7
Project D4.7				
1st stage of the tendering process (Prequalification)	21	21	64	Risk 1,10,24
2nd stage of the tendering process (Technical and financial evaluation)	142	166	258	Risk 1,10
Technical and licensing documentation and approval process	364	364	419	Risk 3,16
Modifications in buildings CB 800, CB 801, CB 490	474	474	546	Risk 17
Cross-sectional modifications throughout the site	979	979	1077	Risk 17
Dismantling of free equipment and iron structures in CB 800, CB 801, CB 490, CB 803	316	332	382	Risk 7,8,14
Dismantling of equipment and iron structures after the completion of the D4.4C project in CB 800, CB 801, CB 490, CB 803	93	97	127	Risk 13,14
Decontamination of concrete surfaces CB 800, CB 801	512	512	615	Risk 7,9,18,22
Cross-sectional demolition in the whole area	846	939	1033	Risk 2,6,15
Demolition work of buildings CB 800, CB 801, CB 490, CB 803	380	380	495	Risk 2,6,12,15,18
Backfilling of pits after buildings CB 800, CB 801, CB 490, CB 803, and final radiation monitoring	129	129	155	Risk 2,
Licensing process	150	150	211	Risk 16,21

Table 10: Parameters of Variables of Simplified V1 NPP Decommissioning Schedule Model

5.4. Running of Monte Carlo Simulation

Once all input data are available (schedule, variables of schedule and type of their probabilistic distribution and its parameters) the MC simulation may be carried out. In this section we will demonstrate the simulation in the software @RISK software version 7.6.1 supports MS Project.

Note that MC simulation on other software does not vary significantly from the software applied in this analysis.

The software is executed by clicking on icon on the desktop after its installation. If the MS Excel is not opened at the time of the initialization of software @RISK, the MS Excel will open simultaneously with @RISK (as it is an add-in to MS Excel).

It is convenient not to have any unnecessary MS Excel files opened when working with @RISK.

After the software is initialized the pop-up widow will be shown in MS Excel, providing example models and resources. At the same time a new tab is added to MS Excel, the “@RISK” tab.

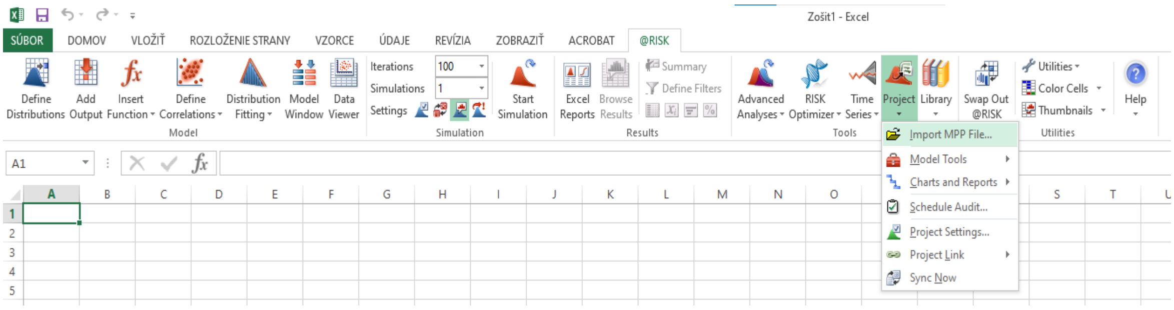


Figure 12: @RISK (Version 7.6.1) tab in MS Excel

The first part of the input data to be transferred to MS Excel is the **decommissioning schedule**. The schedule will be imported to MS Excel (see Figure 10). In the tab @RISK in MS excel we go to “Project” icon and select “Import MPP File…”. When the relevant MPP file is selected and confirmed the data will be automatically transferred to MS Excel and at the same time the relevant schedule file will be opened at the MS Project.

> ⚠ Do not close the MS Project file with the schedule, which was automatically opened with the import of the schedule data from it. The MPP file becomes an integral part of the model, and when the simulation is running the modelled values from the probabilistic distribution are being sent to MS Project and the schedule is being updated several times with the determination of the end date.

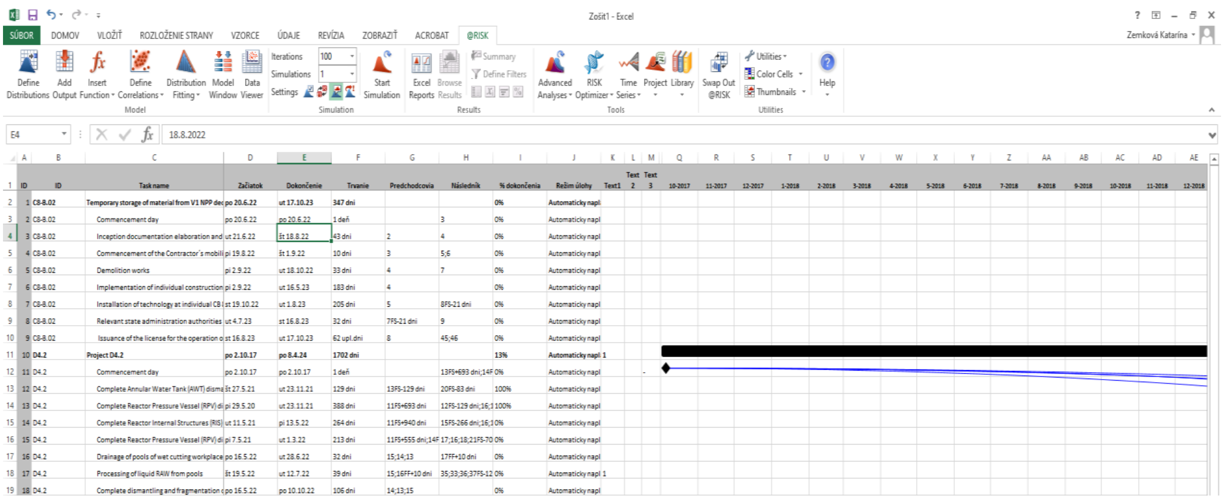


Figure 13: Decommissioning Schedule Imported to MS Excel

After importing file with the simplified Decommissioning schedule of V1 NPP as to January 2022, the MS Project is being opened and the data are downloaded to MS excel (see Figure 11). The next step is the definition of the variables. The lines/rows, which represent uncertain variables, need to be defined as probabilistic distribution in line with the data in Figure 11.

In line with Figure 11, the first variable to be defined is the activity of “Inception documentation elaboration and approval” in frame of project C8-B.02. The variable to be defined is the duration of this activity, therefore we click on the cell F4, which is the estimated duration of this activity (43 days).

> ⚠ The variables are the duration of activities; therefore, the variables will be always defined in column duration ("trvanie") – column F of Figure 15.

Once we are standing on cell F4, we go to tab @RISK and select "Define Distributions" (see Figure 12).

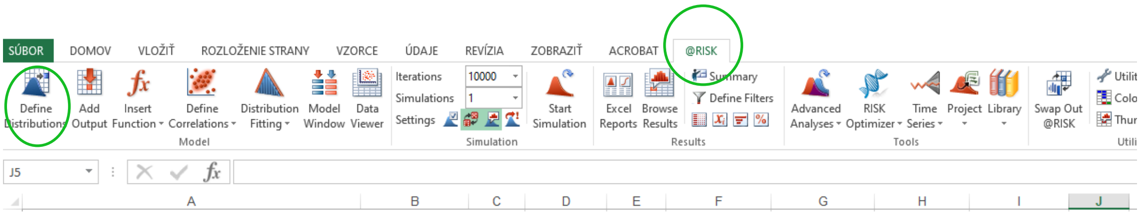


Figure 14: "Define Distribution" of Variables

From the various distribution we select the Triangular (under continuous) and confirm it by clicking on "Select Distribution".

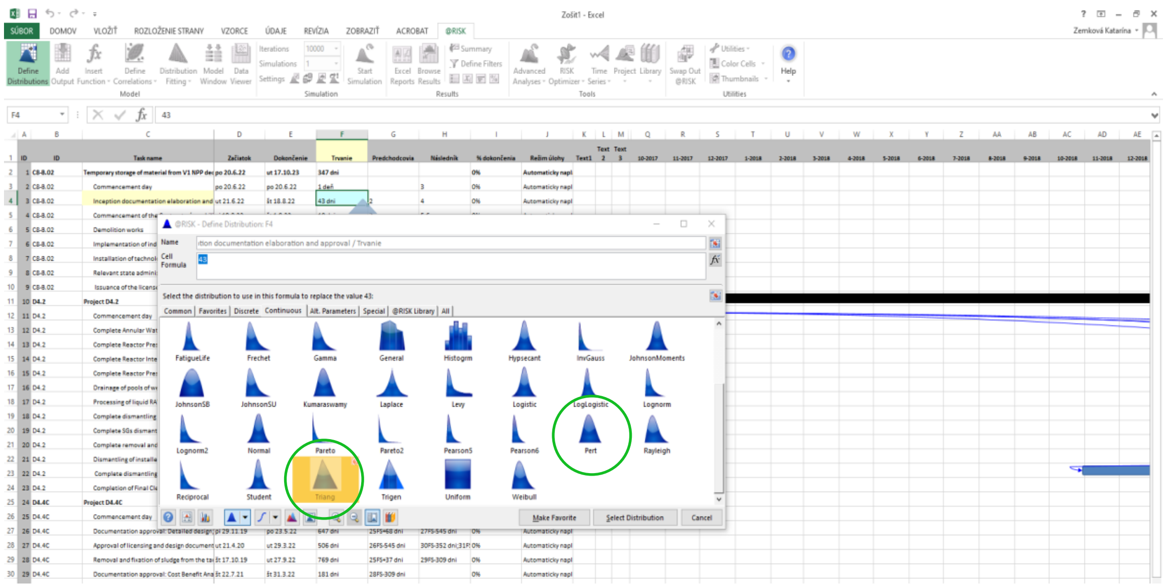


Figure 15: Select Distribution

Afterward the parameters of triangular distribution are to be filled in. They can be typed in manually (Figure 14 – see "a"). Or they can be cell referenced (see Figure 14 - "b").

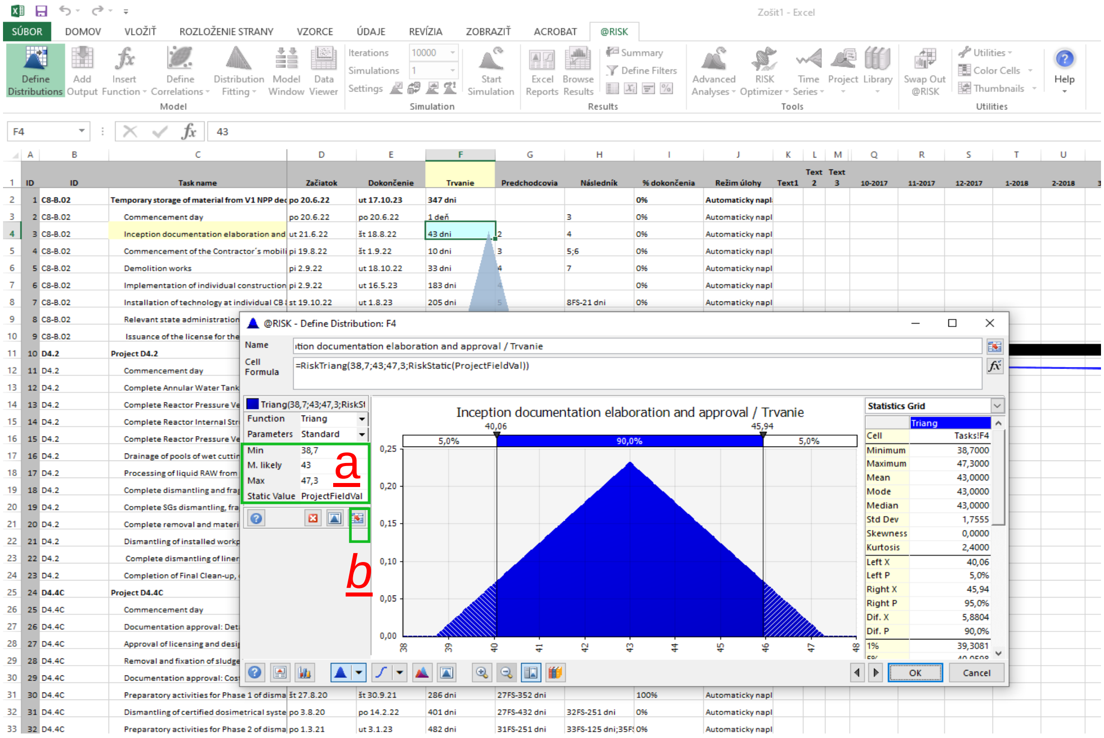


Figure 16: Filling in Parameters of Probabilistic Distribution of Variable

The cell referencing is an advantage, as when we keep the parameters separately stated in MS excel cells, we may more easily change them (by simple rewriting of the cell content), and we may also copy and paste the formula in the variable cell to other variables.

If we decide to fill in the parameters by cell referencing (by clicking on "b" in Figure 14), we firstly need to create a separate table of parameters for every variable in the model. We may simply insert to the xls file the Table 7. After clicking on "b" in Figure 14, which is the icon of "Assign Excel references as Arguments", the following window will pop-up:

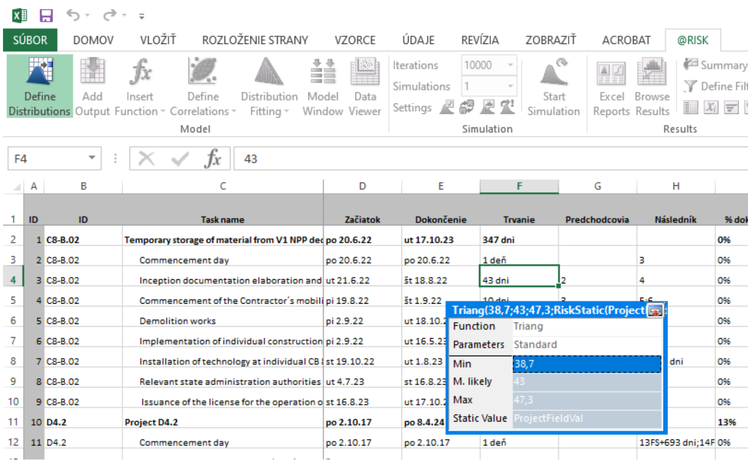


Figure 17: Cell Referencing

We need to make the reference to the minimum “min” and maximum “max”, and the most likely value which is the original duration of the decommissioning activity. After the cell referencing, in the probabilistic distribution depiction, the cell references will be shown as opposed to numeric values (see Figure 16).

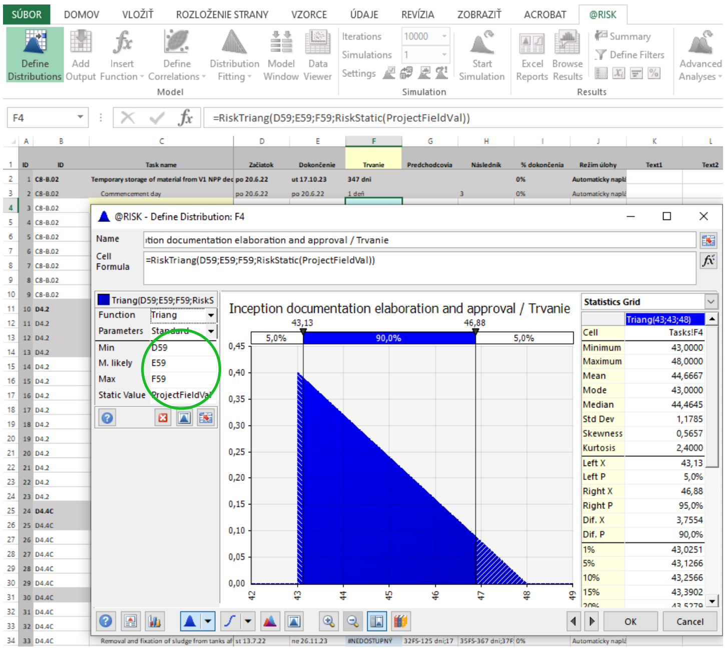
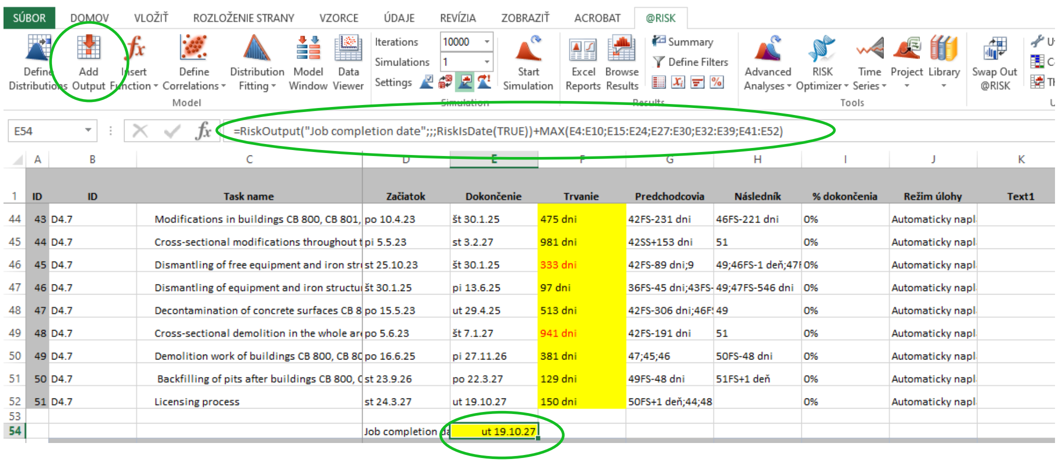


Figure 18: Defined Probabilistic Distribution of Input Variable (by Cell Referencing)

After all the variables are defined as a probabilistic distribution of values, the last step (before carrying out the simulation) is to define the output cell. The output in the decommissioning schedule model is the day of the completion of the decommissioning. Therefore, the output cell will be defined as the *maximum of the finish dates of all activities* (which will always be the same as the completion of the very last activity within the decommissioning schedule; hence there are two ways how to define the output cell):

- Definition of the output cell as the completion of the last activity within the schedule. We will click on the cell corresponding to the “Finish date” of the last activity of the schedule. The go to tab @RISK and select “Add output”.
- Definition of the output cell as the maximum of completion dates of all decommissioning activities. In the blank cell we will define the function “max” out of the whole column of the finish dates. Then when standing on this cell go to tab @RISK and select “Add output”. See Figure 19.



ID	ID	Task name	Začiatok	Dokončenie	Trvanie	Predchodcovia	Následník	% dokončenia	Režim úlohy	Text1
43	D4.7	Modifications in buildings CB 800, CB 801,	po 10.4.23	št 30.1.25	475 dni	42FS-231 dni	46FS-221 dni	0%	Automaticky napl	
44	D4.7	Cross-sectional modifications throughout t	pi 5.5.23	st 3.2.27	981 dni	42SS+153 dni	51	0%	Automaticky napl	
45	D4.7	Dismantling of free equipment and iron str	st 25.10.23	št 30.1.25	333 dni	42FS-89 dni;9	49;46FS-1 deň;47	0%	Automaticky napl	
46	D4.7	Dismantling of equipment and iron structu	št 30.1.25	pi 13.6.25	97 dni	36FS-45 dni;43FS-	49;47FS-546 dni	0%	Automaticky napl	
47	D4.7	Decontamination of concrete surfaces CB 8	po 15.5.23	ut 29.4.25	513 dni	42FS-306 dni;46F	49	0%	Automaticky napl	
48	D4.7	Cross-sectional demolition in the whole ar	po 5.6.23	št 7.1.27	941 dni	42FS-191 dni	51	0%	Automaticky napl	
49	D4.7	Demolition work of buildings CB 800, CB 80	po 16.6.25	pi 27.11.26	381 dni	47;45;46	50FS-48 dni	0%	Automaticky napl	
50	D4.7	Backfilling of pits after buildings CB 800, C	st 23.9.26	po 22.3.27	129 dni	49FS-48 dni	51FS+1 deň	0%	Automaticky napl	
51	D4.7	Licensing process	st 24.3.27	ut 19.10.27	150 dni	50FS+1 deň;44;48		0%	Automaticky napl	
			Job completion da	ut 19.10.27						

Figure 20: Definition of the Output Cell

After the variables and output cell are defined, the MC simulation may be carried out. The last decision before carrying out the simulation is to decide on the number of iterations (i.e.: how many times the end date of the decommissioning will be computed within the simulation).

The simulation duration depends on the number of variables (lines = activities simulated) and mainly on the number of iterations within one simulation. Simulation with 10,000 iterations can take about two or more hours. The processes which take the most time in the MC analysis include:

- *The work of experts who consider, line by line, whether the activity is a variable or constant,*
- *Identifying (by experts) which risks relate to each activity,*
- *What is their (the risk´s) maximum separate (or combined impact) on this specific activity (depending on whether the model combined the risks impact with uncertainty, or whether risk occurrence is simulated one by one),*
- *Determining whether all strategic risks were considered,*
- *Determining whether the risk(s) were considered for every activity that they may impact, and whether opportunities are also modelled.*

The V1 NPP decommissioning end date was iterated 10,000 times.

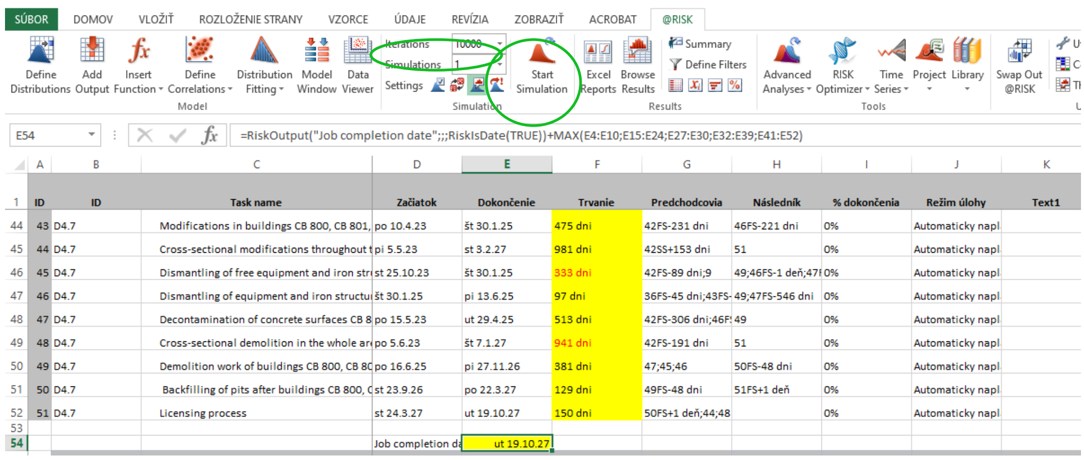


Figure 21: Running the MC Simulation

There must be a compromise in terms of the number of iterations you run for a calculation. A low number of iterations will limit the convergence and reliability of the calculation and too many iterations (e.g., 1,000,000) may penalize the optimization of resources (computational time) dedicated to the calculation.

> In our experience, running 10,000 iterations is a good balance in terms of computational time vs reliability of outcomes.

5.5. Interpretation of Results

Before drawing specific conclusions from the simulation, an examination of the graph of the simulation results is useful first. The red area of the Figure 19 is the **histogram**, it represents the distribution of the numerical data. The entire range of values (simulated completion of the decommissioning program) obtained in the simulation is divided into intervals. The number of the values which are depicted in the histogram is 10,000, as the simulation was carried out with 10,000 iterations. For every interval it is counted how many values fall into it (how many iterated end-dates of the decommissioning program from the 10,000 iterations fall into each interval). The higher the red bar is, the more values fall into the interval. On **vertical axis** is the frequency (count of each bin), and on **horizontal axis** is the list of bins/categories.

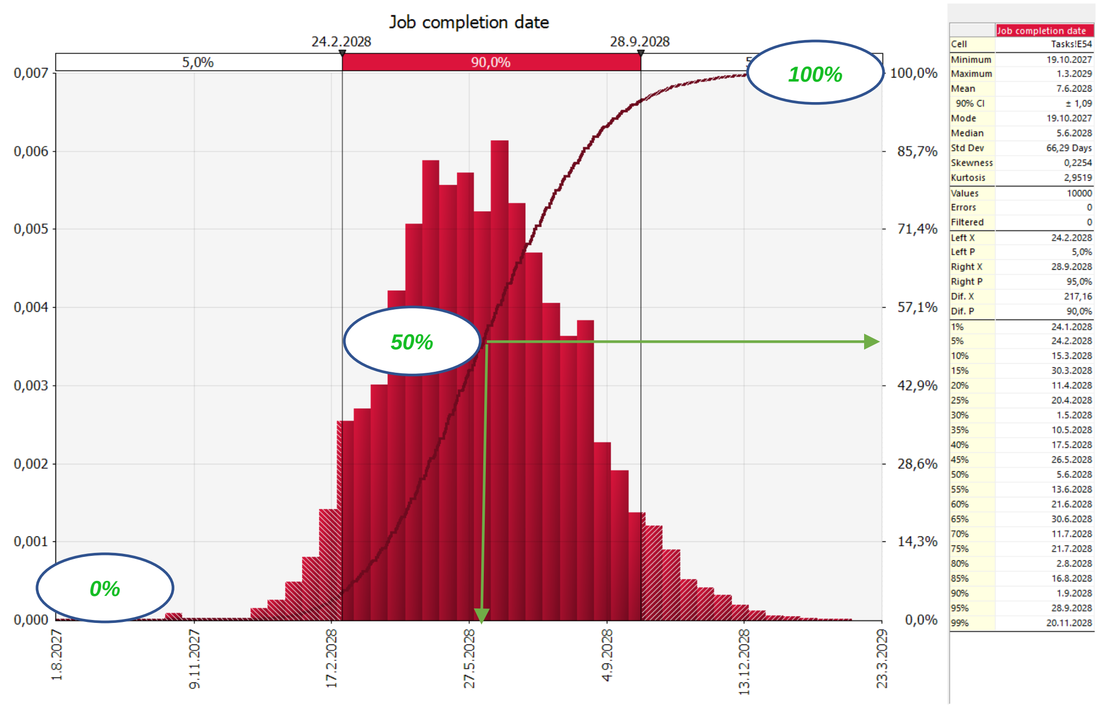


Figure 22: Histogram of V1 NPP Decommissioning Base Estimate Time Schedule – Model 1b

> By cursor the distribution of the three sections dividing the 100% interval can be moved by dragging the two triangles at the bar.

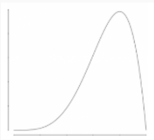
5.5.1. Descriptive Statistics

Skewness (see descriptive statistics in Figure 23) is 0.23. The interpretation of skewness is as follows:

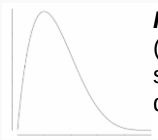
- If less than −1 or greater than +1 then the distribution is **highly skewed.**
- If between −1 and −½ or between +½ and +1, then the distribution is **moderately skewed.**
- If between −½ and +½, the distribution can be called **approximately symmetric.**

Our distribution is approximately symmetric.

Skewness may be examined also graphically:



Left skew
(-) negatively skewed distribution

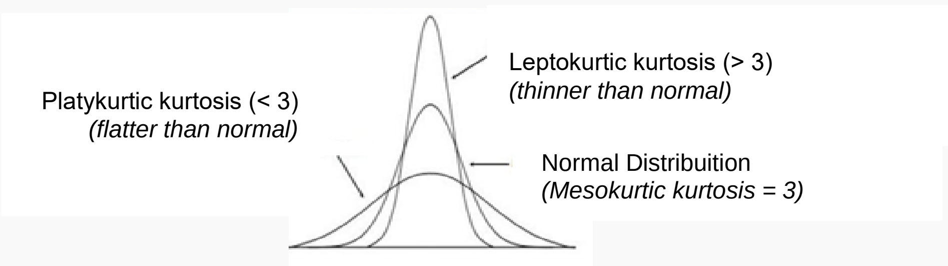


Right skew
(+) positively skewed distribution

No skew
Skewness = 0

Kurtosis (see description statistics in Figure 23) is 2.95 (close to 3). Probabilistic distribution of decommissioning completion is nearly normal.

Kurtosis may be examined also graphically:



We may add the **cumulative distribution function** into histogram (see Figure 19). It is **S-shaped curve**. It starts with 0% probability, at half – meaning 50% or median, it changes the shape and increases to100%.

Classical interpretation of results is e.g.: There is a 5% probability that the decommissioning will be completed by 24.2.2028. There is a 50% probability the decommissioning will be completed by 6.6.2028.

Other descriptive statistics are the minimum, the maximum and the mean. The **minimum**, or the soonest simulated end-date of decommissioning is 19/10/2027. The **maximum**, or the latest (highest) simulated end-date of decommissioning is 1/3/2029. **Mean**, is the sum of all the iterated end dates of decommissioning within the simulation of the model divided by the total number of iterations (10,000). Mean of our simulation is 7.6.2028 (see Figure 19).

It is advantageous to examine the result by using the *Tornado plot*.

The *Tornado plot* shows (Figure 20) the activities with the highest impact on decommissioning completion. The baseline = 7.6.2028 is the mean of iterated values (iterated end-dates). The activity at the top of Tornado shows the schedule activity with the highest potential impact on the decommissioning deadline/fulfilling the objective. However, at the same time, sooner completion of this activity may significantly shorten the duration decommissioning. The activities identified by Tornado plot, are the activities to which the resources for mitigation measures shall be allocated, and close attention is to be paid to them.

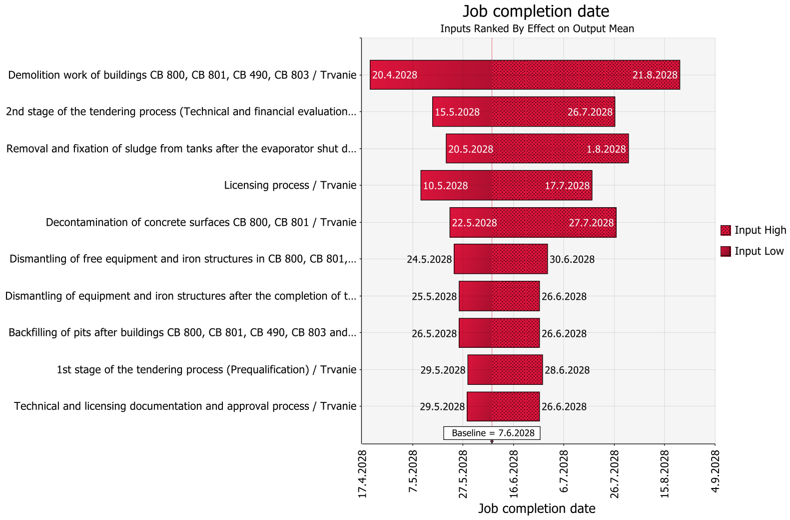


Figure 23: Tornado Plot of V1 NPP Decommissioning Schedule – Change in Output Mean

Figure 21 represents the tornado plot showing **Contribution to Variance**, the length of the bar shown for each input distribution is the amount of change in the output attributable to each input. Contribution to Variance is displayed as magnitude and direction. All bars are displayed to the right, so Contribution to Variance in % can be easily compared between bars.

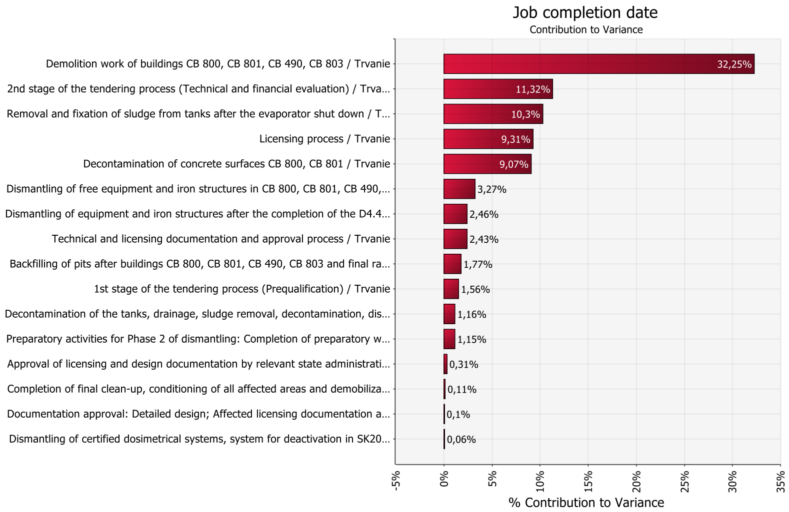


Figure 24: Tornado Plot of V1 NPP Decommissioning Schedule – % Contribution to Variance

5.6. What Went Well

The application of Monte Carlo method in the simulation of the V1 NPP decommissioning deadline:

- Confirmed that if no strategic risk occurs, the decommissioning deadline will be met.
- Gave the estimate of the most probable delay.
- Showed added value of Quantitative Risk Assessment on top of Qualitative assessment, so that stakeholders have a picture of the probability of completion in accordance with the schedule.

In the experience of JAVYS, the following practices are useful in the application of Monte Carlo simulations to the analysis of decommissioning deadlines:

- Manage operational risks from which, several may be escalated to strategic level) directly with the project manager and project team. Project managers can be supported by Risks Specialist (in the case of JAVYS this person was also responsible for V1 NPP Decommissioning scheduling) and Risks Analyst (with statistical background). Risks Specialist and Risks Analyst shall cooperate on a daily basis.

- Proper attention must be paid to the elaboration of a **strategic risk register of the time related risks**. This risk register must include all the strategic time related decommissioning risks. In other words, all risks that have potential impact on the decommissioning deadline. If any of these risks is omitted the results would be biased.

- Involvement of stakeholders in the revision and commenting of strategic time related risks register has significant added value (as the stakeholders may add independent insight to strategic expectations).

- Decommissioning schedule modelling benefits from a discussion activity by activity between the Project Managers (responsible for specific activities) and Risks Specialist, Risks Analyst and members of expert panel responsible for estimation of input data, when collecting the input data.

- Non-omission of constants (certain activities with no uncertainty and no risks) from the model of schedule is essential since they represent an important part of the model. The software used by JAVYS simulates the end date or total duration, and both are a result of interlinkages and duration of all decommissioning activities. Schedules with omitted activities should not be used as the interlinkages would be broken (the results of simulation would be understated and biased).

- If the decommissioning project is already in the implementation phase (not planning phase), specific attention needs to be paid to ***on-going decommissioning activities.*** In case of V1 NPP, the uncertainty and risks were estimated only for that part of the duration of the on-going activity which was still to be completed.

- Determination of the probabilistic distribution of input data – of respective decommissioning activities is based on the decision of the Risks Analyst (having statistical background) based on the information from an expert panel (expectations of experts on the future development of the activity: do experts assume that the activity may be also completed sooner than planned duration?, what is magnitude of the expected delay?, do the experts assume that completion with specific magnitude of delay is more likely or are they not capable of identifying the most likely delay and all values within the delay range have the same probability of occurrence?, etc.).

- A preliminary graphical examination of the rusts must be conducted before the interpretation of results and conclusions on the simulation result. The aim of this preliminary graphical examination is to detect significant outlier impacting the overall result. During the simulation it may also occur that the outcome is stuck and returning the same result. In this case it would need to be run again, or the result can significantly differ from expectations (which may be caused by mistakes in input data – interlinkages of activates or numerical mistakes).

- When drawing conclusions, the histogram informing on the probability distribution of respective simulated decommissioning competition dates shall be supplemented by ***Tornado plot***. The *Tornado plot* identifies the activities with the highest impact on decommissioning completion. The activity at the top of Tornado represents the schedule activity with the highest potential impact on the decommissioning deadline/fulfilling the objective. However, at the same time, sooner completion of this activity may significantly shorten the duration decommissioning. The activities identified by Tornado plot, are the activities to which the resources for mitigation measures shall be allocated, and close attention is to be paid to them.

These conclusions may be used by other decommissioning operators in Europe as good practices in the application of Monte Carlo simulation to the analysis of decommissioning planning.

5.7. Even Better If

During the application of the Monte Carlo simulation of the V1 NPP decommissioning deadline, some areas for future improvement were identified. These areas may help other organizations learn and prepare for similar challenges in Monte Carlo simulation applications.

- The application on more desegregated decommissioning schedule is viewed as highly advantageous.
- It is advantageous to carry out such an analysis from the early stages of the decommissioning and update it regularly – to have an estimate of the most probable delay and its development.
- There is a possibility to simulate the risks and uncertainty separately in future models.
- There is also the possibility to include the operational level risks on more desegregated decommissioning schedule. They are not foreseen to impact the outcome, however, may indicate decommissioning activates on which significant number of risks cumulate and are close to critical path.
- It is also possible to incorporate both strategic and operational risks within the decommissioning schedule. There may be value added in doing so; particularly interlinkages between the detailed schedule are modelled correctly.
- There are two basic possibilities on how to model risks and uncertainties with the decommissioning schedule. The 1st approach is the simplified simulation in which the risks and uncertainty are considered together for every decommissioning activity. In this simplified model the expert panel (group responsible for estimating site-specific input data) estimates both the risks and uncertainty, which may impact specific decommissioning activity within the probabilistic distribution of this activity. In the 2nd approach the impact of uncertainty and risk is modelled separately within the simulation. Uncertainty is modelled within the probabilistic

distribution of the activity duration and occurrence of risk with its impact is modelled standalone

In the case of V1 NPP decommissioning, in both models (2021, 2022) the risks and uncertainty were modelled together in frame of the probabilistic distribution of the variables (durations of specific decommissioning activities**. It might be useful to examine the differences between the MC outputs if the 2nd approach (separate modelling of uncertainty and risk) was used.**

6. USE CASE 2 (COST ESTIMATE) – QUANTIFICATION OF BOHUNICE V1 NPP DECOMISSIONING COST ISDC CONTINGENCY

6.1. Methodology

Before quantifying the decommissioning cost contingency, the Base Cost of decommissioning is to be determined in compliance with international recommendations and structure, which will allow international comparison and consistency. The V1 NPP decommissioning cost is estimated in compliance with **Internationals Structure for Decommissioning Costing** (ISDC) at ISDC level III.

> Development of base cost of decommissioning in compliance of "OECD (2012), *International Structure for Decommissioning Costing (ISDC) of Nuclear Installations*, Series: Radioactive Waste Management, OECD Publishing, Paris", will ensure that all potential cost items will be considered when developing the cost estimate.

MC simulation have been internationally applied to quantify the decommissioning cost contingency for decades. The V1 NPP decommissioning cost contingency was estimated by MC simulation in 2014, 2017 and 2021, when the Detailed Decommissioning Plan was updated. Quantification of contingency in 2017 and 2021, was fully in compliance with OECD-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities" methodology.

> Report of *OEDC-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", 2017, Report No. 7344*, is the latest and recommended literature for developing decommissioning project baseline cost estimate. It is advantageous to familiarize with it before continuing reading this document.

In compliance with OEDC-NEA Report No. 7344, the elements of the cost estimate are depicted below in Figure 22.

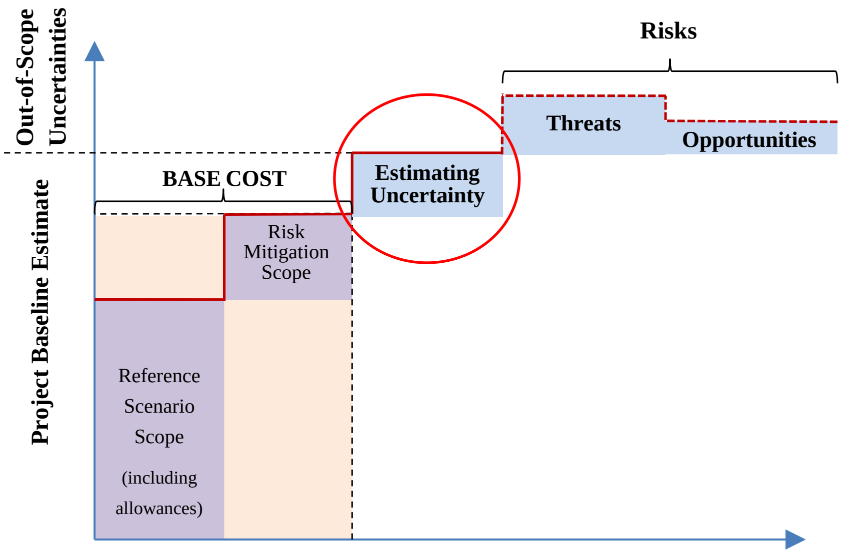


Figure 25: Elements of a Cost Estimate

It is important that according to the OEDC-NEA methodology, the **Base Cost** of decommissioning project already includes **Allowances** and **Risk mitigation scope** (for those risks that are in the scope off the decommissioning project).

Base Cost is defined as (OECD-NEA, 2017):

- estimated cost of the base scope of the project as defined by the assumptions, exclusions, constraints, boundary conditions, data sources and methodology of cost estimation. Base Cost does not include any provision for Estimating Uncertainty or out-of-scope uncertainties.

Allowances are defined as (OECD-NEA, 2017):

- provisions for known activities included in the Base Cost, but whose exact values are not presently known.

Estimating Uncertainty is defined as (OECD-NEA, 2017):

- Provision for uncertainties that are associated with the defined project scope (in-scope). Estimating uncertainty is part of Project baseline Estimate. It is also referred to as ISDC contingency and it is assumed to be fully spent during the execution of the project.

Estimating Uncertainty (ISDC contingency) is assumed to be fully spent during the execution of the project according to OECD-NEA, 2017 (this will impact the results of the quantification of ISDC contingency via Monte Carlo simulation).

Project Baseline Estimate is defined as (OECD-NEA, 2017):

- estimated cost of base scope of the project as defined by the assumptions, exclusions, constraints, boundary conditions, data sources and methodology of cost estimation, including provisions for the Estimating uncertainty. It excludes provision for any risk considered beyond the defined project scope but includes any added risk-mitigation scope.

Project Baseline including allowances, risk mitigation scope for in-scope of the project risk and Estimating Uncertainty represents acceptable decommissioning cost estimate

Risks, which are beyond the Project Baseline estimate (see Figure 22), are the risk outside the defined project scope. These may be funded or unfunded. This additional funding is made according to the risk propensity (how the organization/company/state/stakeholders are prepared or willing to fund the project in order to complete the project objectives).

Quantification of the additional funding for out-of-scope risks (risks above project baseline estimate) is optional.

As the V1 NPP is in the final stages of the decommissioning, it may seem reasonable to analyse not only the Estimating Uncertainty, but also the cost of funding of main external risks via MC simulation. However, binding resources for costs that may not occur should be avoided. Furthermore, funding for out-of-scope risks may also be determined considering their occurrence/foreseen occurrence based on the estimation of the cost to implement specific mitigation measures. This goes beyond MC simulation but would allow cost comparison between possible mitigation measures.

In the following subchapters, the process (step by step) of estimation of the Project Baseline Cost Estimate of the V1 NPP will be described. In general, the process of the development of model for simulation of decommissioning cost may be divided into following steps:

1. summarizing the model **assumptions**
2. **input data** definition - (within this step - for input data which are variables of the model, the probabilistic distribution is to be defined together with the estimation/determination of this probabilistic distribution)
3. inserting/setting up the model into selected software and **running Monte Carlo Simulation**
4. Interpretation of results and summarizing the conclusion and recommendations

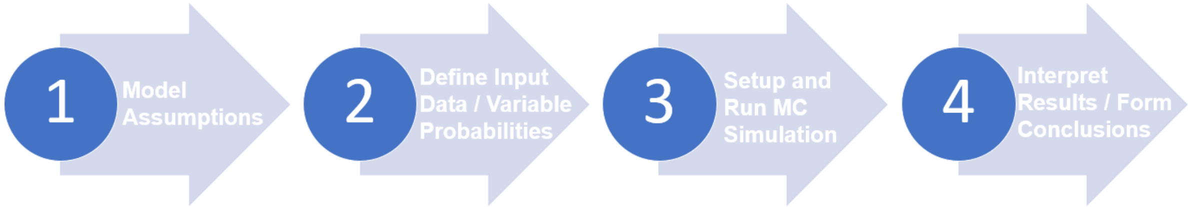


Figure 26: Decommissioning Cost Modelling Process

Differences (development) of the cost models of V1 NPP decommissioning in 2014, 2017 and 2021 will be also summarized.

This chapter will include real data and information on the V1 NPP cost estimation, but the software simulation section (subchapter 6.4) will be demonstrated through use of a highly simplified hypothetical example.

6.2. Assumptions

A model is a simplified version of reality no matter how sophisticated the model is, all models are approximations of reality, but allow predictions on future development. Usually, simple models are preferred over complex ones. Overly complex models are time intensive and cost demanding for development and may be hard to understand for personnel/stakeholders not involved in the process of their development. To develop a model of reality it is unavoidable to make **simplifying assumptions**. Assumptions are basically experts' beliefs based on previous experience and information available to them when creating the model.

Always include all assumptions in your analysis results distribution.

Assumptions are inseparable part of any model results presentation, if the assumptions are not provided with the results, then the informative capability of the analysis is zero.

Assumptions related to MC modelling of V1 NPP decommissioning in 2021 included:

- **Assumption 1** – related to **decommissioning cost base estimate** to be modelled. The decommissioning cost quantification is a simplified version of reality. Therefore, every cost estimate (without contingency) developed has its own assumptions. Original assumptions related to development of V1 NPP decommissioning cost estimate included, for example the, following:

- *Compliance with the ISDC structure,*
- *Compliance with the decommissioning project schedule,*
- *For completed projects, the cost is presented in euros at a time they were spent. For future projects the cost is presented in Euros of the year when the estimation is carried out*
- *Impact of inflation was considered in accordance with the methodological recommendation of the National Bank of Slovakia (NBS), etc.*

- **Assumption 2** - ISDC contingency is quantified in compliance with the OECD-NEA methodology (report of OEDC-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", 2017, Report No. 7344). Applying the Monte Carlo method.
- **Assumption 3** - in compliance with assumption 2, the allowances and the cost of the mitigation of in-scope risks is included in base estimate of the V1 NN decommissioning cost.
- **Assumption 4** – addresses the identification of variables and how the ***on-going decommissioning activities*** were addressed in the model. *In the V1 NPP model no unforeseen costs are considered for already completed projects. Contingencies for projects under implementation are determined based on the Monte Carlo methodology and are applied only from the second half of the year 2021 until the end of decommissioning in 2027. For all the projects under implementation before the first half of the year 2021, contingencies are not applied.*
- **Assumption 7** – addresses the selection of the probabilistic distribution of the input data (variables of the model – decommissioning cost items). The log-normal distribution was applied.

6.3. Input Data

As part of any analysis or model:

1. Simplifying assumptions need to be provided,
2. All input data need to be stated.

This is done, so that any other party, based on the same input data and same assumptions, can verify the analysis. The input data in the MC simulation of the decommissioning costs are:

- decommissioning base cost estimate in ISDC structure
- MC simulation software (in our case @RISK software - version 7.6.1 was used in this document)
- and the type of probabilistic distribution and its parameters estimated by group of site experts.

6.3.1. Selection of ISDC Level III Cost Items

After the base cost of V1 NPP decommissioning is updated (not including the ISDC contingency), a group of experts is asked to identify the variables of decommissioning project cost model.

> ⚠ Variable – specific decommissioning activity at ISDC level III may be in progress during the preparation of decommissioning cost estimate.
>
> The contingency is to be quantified only for the part of the total cost of the item, which was not spent (not completed). See assumption no. 4.

Not every ISDC level III cost item is a variable. Variables are only the ISDC level III cost items to which contingency is to be added. Example of constants of V1 NPP cost estimate model, 2021:

- *already completed activities (whose cost was already accrued),*
- *part of total cost of ISDC level III activity, which was already spent (some activities may be in progress during the preparation of the cost estimate),*
- *other ISDC level III cost items determined by the experts to be constants. E.g. The model did not include any ISDC III sub-level activities falling under the main level of ISDC I no. 1, 2, 3, 9, and 10. These activities have either been completed (e.g. 01 - Pre-decommissioning actions, 02 – Facility shutdown activities), or the activities were not relevant to the objectives and defined form of achieving the objectives of V1 NPP Decommissioning Project (03 - Additional activities for safe enclosure or entombment; 09 - Research and development) or were excluded with regard to the assumptions of a quantification model of estimating uncertainty (10). From the main level of ISDC I no. 11 (Miscellaneous expenditures) only one item on ISDC level III. – 11.0100 related to the project D0.01 was included in the base cost.*

> Constants can be omitted from the decommissioning cost model.

In cost models **constants may stay in the simulation of the model** (the modelled total baseline cost estimate will also include their contribution to the total baseline cost). But **they can also be omitted**. The modelled total baseline cost estimate, in this case, will not include contribution of cost items which are constant, but these can be simply added to the total value. This is advantageous e.g., when time to deliver the results is limited and constant costs can be quantified and added to the MC simulation results later (case of V1 NPP cost estimation in 2021).

6.3.2. Quantification of the Value of Cost Items

As in the case of V1 NPP cost estimate the constants were omitted from the simulation, the list of input data included ISDC level III items which were planned for the future or ongoing. Their value was quantified from half of 2021 till 2027. This value of every item represents the mean of probability distribution of variables.

6.3.3. Selection of Distribution of Input Data

Once the group of site experts determined the value and timing of the cost items (and identified constants - cost items and part of cost items representing already completed works and part of works falling under ongoing decommissioning activities), the probabilistic distribution on the cost items may be selected.

The selected probability distribution shall comply with the expectations and assumption of the experts on the estimates of the future events.

Let's consider again the three probabilistic distributions in Figure 9 (Log-normal, Triangular and Uniform). In this case the Log-normal distribution was selected as the experience gained from the V1 NPP decommissioning project shows that, as a general rule, the final awarded price is usually lower than the initially estimated price. This fact is properly considered with the use of the Log Normal distribution.

Final awarded price may be lower than initially estimated price, based on the experience gained by JAVYS during the decommissioning project of Bohunice V1 NPP.

The Log-normal distribution is widely used in cost estimates [1], and it was applied in all three Monte Carlo simulations of V1 NPP decommissioning cost in frame of DDP 2014, DDP 2017 and DDP 2021.

If expert panel have different expectations on different cost items, several types of probabilistic distributions may be applied in the model.

When selecting the distribution, it is convenient to consider all the types of distribution which are defined in selected software

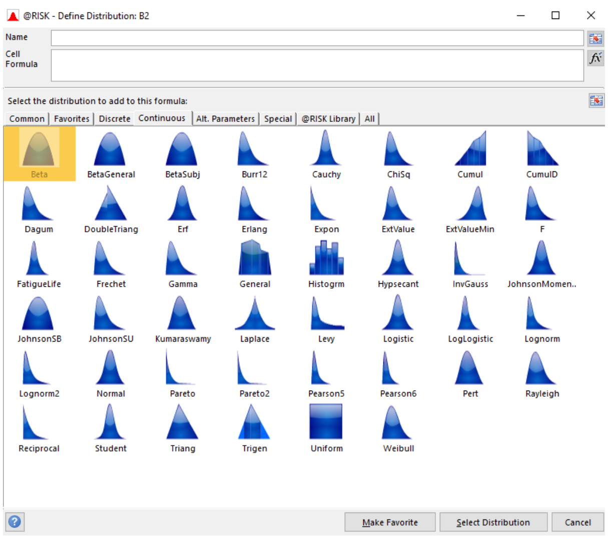


Figure 27: Types of Continuous Distributions in the frame of @RISK Software.

When selecting the distribution, it is convenient to consider all the types of distribution which are defined in selected software. If we consider the continuous distributions in the software @RISK, the selection is shown in Figure 24.

[1] Used amongst construction, finance, and oil and gas sectors to name a few applications.

6.3.4. Determination of Distribution Parameters of Input Data

As the Log-normal distribution was selected, two parameters will be applied for its definition: (see Figure 9):

- **Mean of the probability distribution.** Mean for respective decommissioning activities at the ISDC III level was determined to be the budgeted cost for given activity (without contingency for unforeseen events, including allowances) for the period of 07/2021 – 12/2027 (i.e., costs in previous periods were considered to be constants, which are certain, and no uncertainty is assigned to them).
- The model did not include any ISDC III sub-level activities falling under the main level of ISDC I no. 1, 2, 3, 9, and 10. These activities have either been completed (e.g. 01 - Pre-decommissioning actions, 02 – Facility shutdown activities), or the activities were not relevant to the objectives and defined form of achieving the objectives of V1 NPP Decommissioning Project (03 - Additional activities for safe enclosure or entombment; 09 - Research and development) or were excluded with regard to the assumptions of a quantification model of estimating uncertainty (10). From the main level of ISDC I no. 11 (Miscellaneous expenditures) only one item on ISDC level III. – 11.0100 related to the project D0.01 was included in the base cost.
- The items with a zero-value achieved in the period 07/2021 – 12/2027 were excluded from the activities at the ISDC level III, as well as operating costs of JAVYS, as, i.e., costs related to management and support activities, site infrastructure and operation.
- **Standard deviation.** The uncertainty within a project scope was determined as a variability of the expected cost of an activity in percentage for individual activities of V1 NPP Decommissioning Project at the ISDC III level. This was established based on international recommendations and expert assessment of JAVYS, as. **Standard deviation (Std)** is for each activity at the level of ISDC III determined as follows:

$$Std_i = \textit{(\% uncertainty of an ISDC III}_i\textit{ activity)} \quad \times \quad \textit{(budgeted cost of an ISDC III}_i\textit{ activity)}$$

Where: i – is a sub-project of V1 NPP decommissioning

In simpler terms, the **mean** is the budgeted cost for given ISDC level III cost item (from the base cost estimate), and the **standard deviation** is quantified as the variability in % multiplied by the budgeted cost of the item.

> It is convenient to familiarize with the international recommendations on variability before estimating the site-specific input data.

Note that there are international recommendations on variability, as the Log-normal distribution is widely used in cost estimates. Table 8 compares the international recommendations for variability in cost estimates in decommissioning. These recommendation on variability are to be considered, however the maturity, progress, and site-specific information, e.g., on operation are also to be considered. In general, we consider these recommendations as best practices for not yet commenced projects in the cost estimating phase.

The left side of Table 8 summarizes the recommendations from the already mentioned OECD-NEA report from 2017, and the right side summarizes the recommendation from the study from year 1986. The non-highlighted values are exactly the same. E.g., the study from 2017 recommended 50% variability for decontamination activities, the study from 1986, recommended the same variability. This confirms that the application of Monte Carlo simulation in decommissioning is not new and was applied for decades. These International recommendations on the scope of variability or uncertainty of cost of respective decommissioning activities have the indicative character. This means that every decommissioning project should set up a group of experts to assess the decommissioning cost items and to estimate the site and project specific character and expectations on the cost, and to estimate specific uncertainties.

Source: OEDC-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", 2017, Report No. 7344			***Source: AIF/NESP-036 Guidelines for Producing Commercial Nuclear Power Plant Decommissioning Cost Estimates, 1986***	
Category in the cost estimate	**Estimating uncertainty provision (%)**		**Category**	**Contingency (%)**
Decontamination	50		Decontamination	50
Contaminated Component Removal	25		Contaminated Component Removal	25
Contaminated Component packaging	10		Low specific activity (LSA)Packaging	10
N.A.	*N.A.*		LSA shipping	15
N.A.	*N.A.*		LSA Burial	25
Reactor Segmentation	75		Reactor Wessel and internals removal	75
Reactor Waste Packaging	25		Reactor packaging	25
N.A.	*N.A.*		Reactor shipping	25
N.A.	*N.A.*		Reactor Burial	50
N.A.	*N.A.*		Steam generator, Pressurizer, Pressurized Reactor Cool. Pumps & piping Removals / Boiling water reactor Circulation system pumps and piping removals	25
Non-Radioactive Component Removal	15		Clean Component and Concrete Removals, Clean Waste Disposal	15
Heavy Equipment and Tooling	15		*N.A.*	*N.A.*
Supplies	25		Supplies and Consumables	25
Engineering	15		Engineering, Project management, Demolition management	15
Energy	15		*N.A.*	*N.A.*
Characterization and Termination Surveys	30		*N.A.*	*N.A.*
Taxes and Fees	10		*N.A.*	*N.A.*
Insurance	10		*N.A.*	*N.A.*
Staffing	15		Utility and decommissioning operations contractor **staff** costs	15
Waste Processing (metal melt)	15		*N.A.*	*N.A.*

Table 11: International Recommendations on Uncertainty in Decommissioning Cost Estimates.

The quantification of contingency of V1 NPP decommissioning cost was carried out in frame of DDP 2014, DDP 2017 and DDP 2021. Therefore, the model evolved. In all three models, the input variables, or cost items to which contingency was to be added had Log-normal distribution. However, the uncertainty in percentages in respective models was reassessed.

In **DDP 2014 (1st MC model of V1 NPP Decommissioning cost)**, the simulation was carried out by previous PMU Consultant. Model for quantification from 2014 determined percentages of uncertainty for ISDC I level activities (and applied to all sub-items on level III) and distinguished whether budgeted costs are planned within 3 years or above 3 years from the time of the model elaboration (see Table 9). The time dependence of the uncertainty percentages implied that the model would be changing along the project. That meant that the re-evaluation of the cost assessment would result in lower and lower uncertainties until the project completion date in which the uncertainty will finally be zero. **However, this model was highly simplified as it defined the uncertainty on ISDC level I, then applied in on level III and it neglected the difference between respective ISDC level III items.**

Main activities		**Uncertainty < 3 years**	**Uncertainty > 3 years**
1	Pre-decommissioning actions	10%	10%
2	Facility shutdown activities	22%	50%
4	Dismantling activities within controlled area	22%	50%
5	Waste processing, storage, and disposal	14%	22%
6	Site infrastructure and operation	12%	15%
7	Conventional dismantling, demolition, and site restoration	12%	15%
8	Project management, engineering, and support	12%	15%
10	Fuel and nuclear material	15%	25%
11	Miscellaneous expenditures	12%	15%

Table 12: Uncertainty Estimates in 1st MC Model of V1 NPP Decommissioning Cost (2014).

In **DDP 2017** and **DDP 2021**, the model was set up and simulated solely by JAVYS. In these models every ISDC cost item at level III was assessed separately by a group of JAVYS´ on-site experts.

Table 10 captures the development of estimating on uncertainty in V1 NPP cost models for estimating uncertainty simulated in 2017 and 2021 (in the case of cost items related to implementation of D4.2 project as an example). Experts considered every ISDC level III activity separately and estimated the variability at highly complex level - ISDC level III activity. These models are therefore more detailed, compared to model from 2014. Table 10 shows that in 2021 the uncertainty related to main activities of the D4.2 project decreased, this is since D4.2 project was already under implementation, with significant progress.

Project	ISDC III Code	ISDC III level activity	DDP 2017	DDP 2021
			Variability (in-scope uncertainty)	Variability (in-scope uncertainty)
D4.2	04.0103	Procurement of special tools for dismantling the reactor systems	30%	10%
D4.2	04.0105	Procurement of special tools for dismantling other components or structures	30%	10%
D4.2	04.0201	Reconfiguration of existing services, facilities, and site to support dismantling	30%	10%
D4.2	04.0203	On-going radiological characterisation during dismantling	20%	10%
D4.2	04.0302	Removal of sludge and products from remaining systems	30%	30%
D4.2	04.0501	Dismantling of reactor internals	50%	20%
D4.2	04.0502	Dismantling of reactor vessel and core components	50%	20%
D4.2	04.0503	Dismantling of other primary loop components	20%	5%
D4.2	04.0506	Dismantling of external thermal/biological shields	25%	10%
D4.2	04.0601	Dismantling of auxiliary systems	25%	25%
D4.2	04.0602	Dismantling of remaining components	25%	25%
D4.2	04.0701	Removal of embedded elements in buildings (mogilnik)	25%	25%
D4.2	04.0702	Removal of contaminated structures (kolpak)	15%	5%
D4.2	05.0101	Establishing the waste management system	20%	5%
D4.2	05.0103	Procurement of additional equipment for management historical/legacy waste	N.A.	25%
D4.2	05.0105	Demobilisation/decommissioning of waste management system	20%	20%
D4.2	05.0302	Retrieval and processing	25%	25%
D4.2	05.0307	Containers	25%	25%
D4.2	05.0802	Retrieval and processing	25%	25%
D4.2	05.0807	Containers	25%	25%
D4.2	05.0902	Retrieval and processing	N.A.	25%
D4.2	05.0907	Containers	30%	5%
D4.2	05.1002	Treatment and packaging	N.A.	10%
D4.2	05.1201	Treatment and packaging	10%	10%
D4.2	05.1203	Transport of hazardous waste	10%	10%
D4.2	05.1204	Disposal of hazardous waste at dedicated waste dumps	10%	10%
D4.2	05.1205	Transport of conventional waste	10%	10%
D4.2	05.1206	Disposal of conventional waste at conventional waste dumps	10%	10%
D4.2	08.0701	Core management group	5%	5%
D4.2	08.0801	Engineering support	5%	5%

Table 13: Uncertainty Estimates in 2nd (2017) and 3rd (2021) Cost Model of V1 NPP.

6.4. Monte Carlo Simulation

In this part the simulation of decommissioning cost will be presented for a highly simplified hypothetical example in software @RISK. After initialization of the software there is a new tab in MS Excel – the @RISK tab.

	A	B
1	**EXAMPLE COST MODEL (FICTIONAL DATA - highly aggregated on ISDC level I)**	
2		
3–4	Category in the cost estimate	Cost (in €)
5	04 - Dismantling activities within the controlled area	50 000 000,00 €
6	05 - Waste processing, storage and disposal	80 000 000,00 €
7	06- Site infrastructure and operation	10 000 000,00 €
8	07 - Conventional dismantling, demolition and site restoration	100 000 000,00 €
9	08 - Project management, engineering and support	30 000 000,00 €
10	11 - Miscellaneous expenditures /e.g. insurance/	20 000 000,00 €
11	**TOTAL COST (without ISDC contingency)**	**290 000 000,00 €**

Table 14: Simplified Hypothetical Example Decommissioning Cost Model.

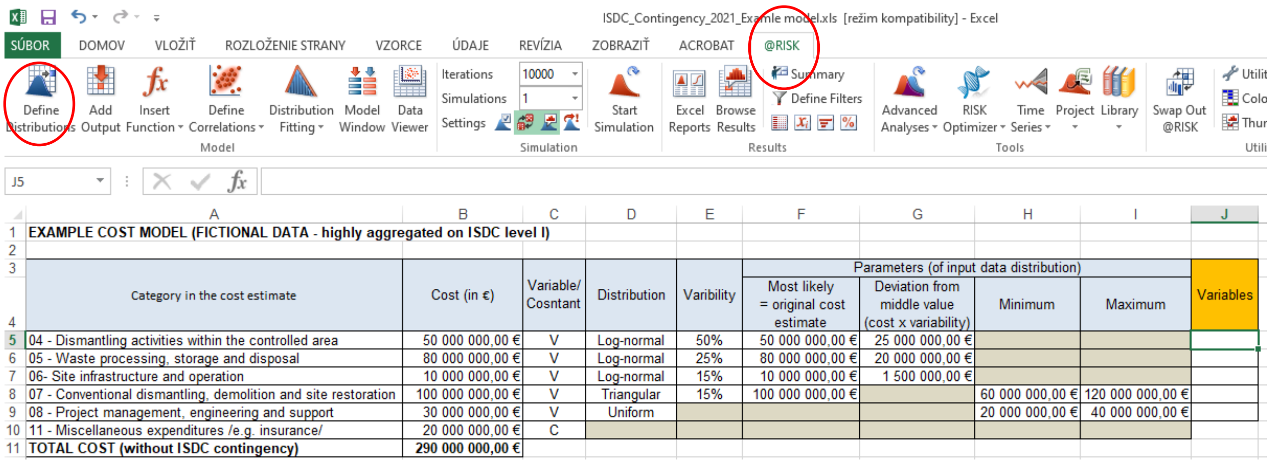
After the base cost is determined the group of experts firstly assess the cost items one by one and determine which of the cost items are variable. For example, in our hypothetical example the last item 11 – Miscellaneous expenditures will not require contingency, and therefore will represent a constant of the model (see Table 11).

In the next step, the type of the probabilistic distribution of the variables of the model is to be determined. The experts have different expectations for the cost items and have a little knowledge on the development of cost of project management. They determine the distributions as stated in Table 12.

	A	B	C	D
1	**EXAMPLE COST MODEL (FICTIONAL DATA - highly aggregated on ISDC level I)**			
2				
3–4	Category in the cost estimate	Cost (in €)	Variable/ Cosntant	Distribution
5	04 - Dismantling activities within the controlled area	50 000 000,00 €	V	Log-normal
6	05 - Waste processing, storage and disposal	80 000 000,00 €	V	Log-normal
7	06- Site infrastructure and operation	10 000 000,00 €	V	Log-normal
8	07 - Conventional dismantling, demolition and site restoration	100 000 000,00 €	V	Triangular
9	08 - Project management, engineering and support	30 000 000,00 €	V	Uniform
10	11 - Miscellaneous expenditures /e.g. insurance/	20 000 000,00 €	C	
11	**TOTAL COST (without ISDC contingency)**	**290 000 000,00 €**		

Table 15: Determining Variables and Their Distribution - Hypothetical Cost Model.

As different types of probabilistic distributions are applied within the simulation, the parameters will also differ in accordance with the type of the distribution. The parameters of the selected distribution in our hypothetical example are stated in Figure 25.



	A	B	C	D	E	F	G	H	I	J
1	EXAMPLE COST MODEL (FICTIONAL DATA - highly aggregated on ISDC level I)									
2										
3						Parameters (of input data distribution)				
4	Category in the cost estimate	Cost (in €)	Variable/ Constant	Distribution	Varibility	Most likely = original cost estimate	Deviation from middle value (cost x variability)	Minimum	Maximum	Variables
5	04 - Dismantling activities within the controlled area	50 000 000,00 €	V	Log-normal	50%	50 000 000,00 €	25 000 000,00 €			
6	05 - Waste processing, storage and disposal	80 000 000,00 €	V	Log-normal	25%	80 000 000,00 €	20 000 000,00 €			
7	06- Site infrastructure and operation	10 000 000,00 €	V	Log-normal	15%	10 000 000,00 €	1 500 000,00 €			
8	07 - Conventional dismantling, demolition and site restoration	100 000 000,00 €	V	Triangular	15%	100 000 000,00 €		60 000 000,00 €	120 000 000,00 €	
9	08 - Project management, engineering and support	30 000 000,00 €	V	Uniform				20 000 000,00 €	40 000 000,00 €	
10	11 - Miscellaneous expenditures /e.g. insurance/	20 000 000,00 €	C							
11	TOTAL COST (without ISDC contingency)	290 000 000,00 €								

Figure 28: Parameters of Different Types Probabilistic Distributions –Hypothetical Cost Model.

After all the parameters are estimated, the variables cell set up as a probabilistic distribution may be defined. A new column for variables is created. We start defining the model by setting up the formula of the first variable by positioning the cursor in the cell of the first variable - J5. Then go to @RISK tab and click on the “Define Distribution” (see Figure 25).

As the first hypothetical variable has the log-normal distribution, in the pop-up window we will select the ´´Lognorm´´ distribution (under ´´continuous tab´´) and confirm the selection by clicking on “Select distribution” (see Figure 26).

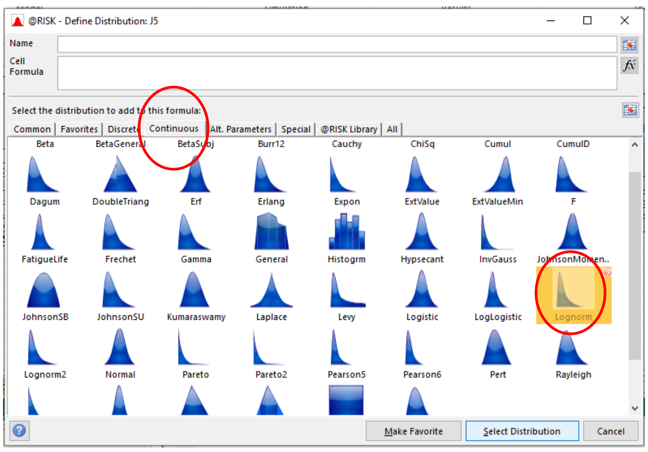


Figure 29: Pop-up window – Define Distribution.

After the selection of distribution in the following pop-up window the parameters will be defined. We will not fill them in manually but will make cell references by clicking on the icon – assign excel reference as arguments (see Figure 27).

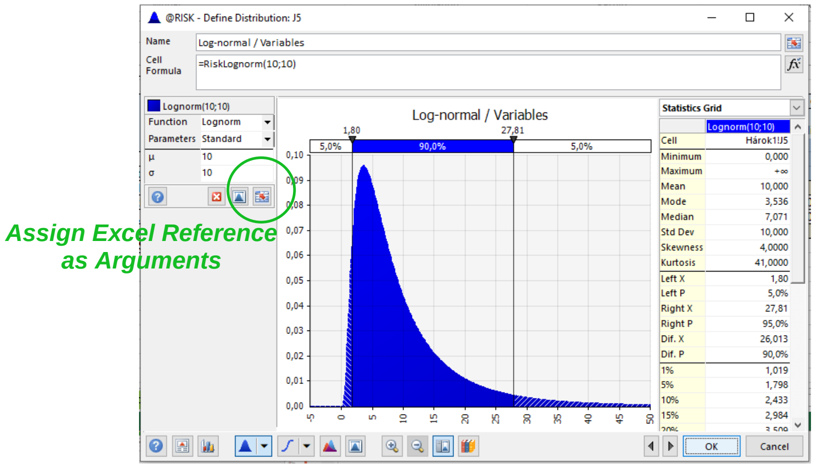


Figure 30: Pop-up Window – Definition of Parameters of Probabilistic Distribution.

After clicking on the icon *Assign Excel Reference Arguments*, we will get the small pop-up window (see Figure 28). In this window we will firstly click in the cell defining the mean (µ - mu) and then click in cell F5. And then click in the pop-un window in cell defining the standard deviation (σ - sigma) and then click in cell G5. The data will be uploaded by clicking on the right top corner icon of the pop-up window (see Figure 28).

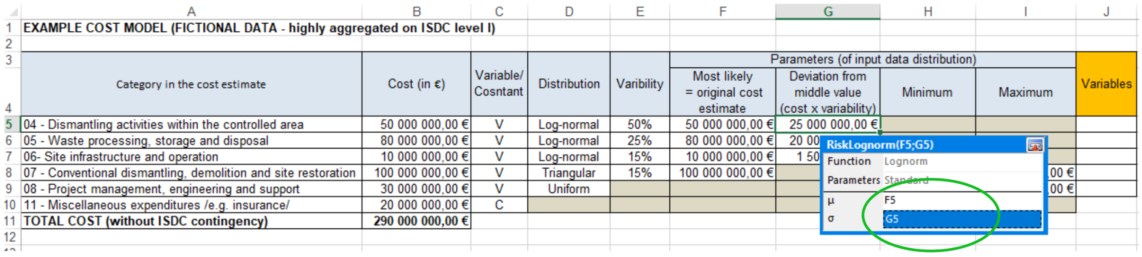


Figure 31: Pop-up Window – Definition of Parameters of Probabilistic Distribution.

Afterwards, we get the defined probabilistic distribution of the first variable. In the section of parameters, we see the cell references and the shape of distribution now depicts the referenced parameters (see Figure 29). By clicking the “OK” the first variable is defined.

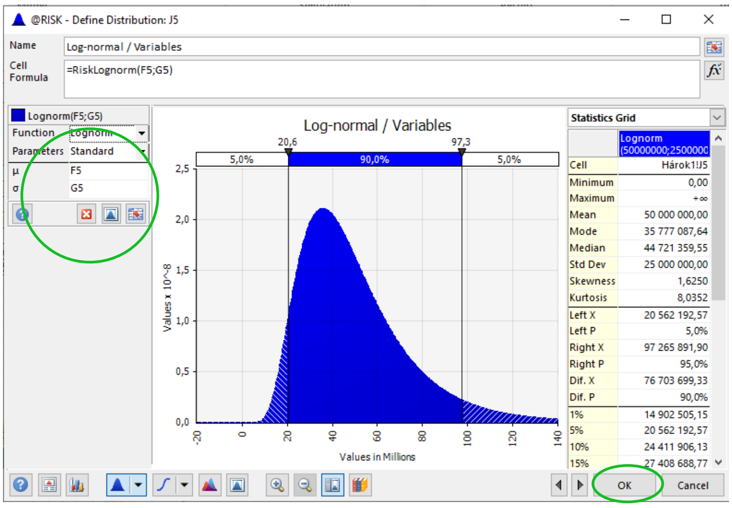


Figure 32: Pop-up window – Defined Parameters of Probabilistic Distribution.

In the same manner we will define the rest of the variables of the hypothetical model. Only the definition of the output cell is to be defined before the simulation. Output cell is the cell in which the total decommissioning cost are being recalculated within the simulation. As we are quantifying the total cost of decommissioning. Our cost is a sum of respective cost items. Therefore, output cell will be a sum of variable cost items and constant cost items (see Figure 30). Firstly, we will create a simple sum of cost items. Then we will stand on summing cell and select "Add output" on @RISK tab and confirm that this is the output cell by clicking on "OK". Now our model is defined, and we may run the simulation.

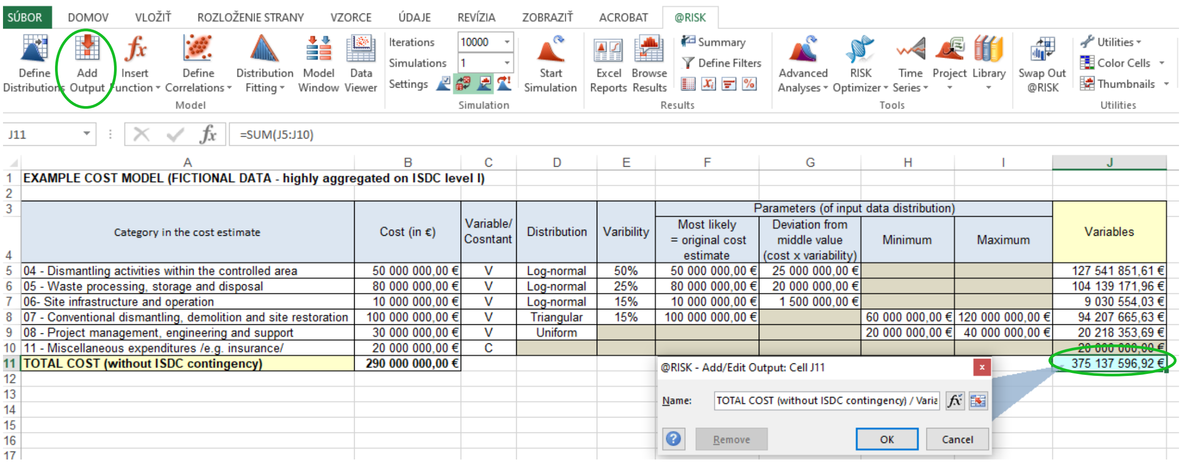


Figure 33: Definition of Output Cell

Firstly, we will decide on how many times the result is to be computed within the simulation by adjusting the number of Iteration under "Simulation" within @RISK tab. Then by clicking on the "Start simulation" under "Simulation" within @RISK tab, the simulation is initialized.

There must be a compromise in terms of the number of iterations you run for a calculation. Not enough iterations will limit the convergence and reliability of the calculation and too many (e.g.,1,000,000) may penalize the optimization of resources (computational time) dedicated to the calculation.

In JAVYS experience, running 10000 iterations is a good balance in terms of computational time vs reliability of outcomes.

After the simulation is completed in all the variable cells, the output cell will show the simulated result for one iteration. These values have no real interpretable value, as it represents just one of the e.g., 10,000 iterations. The graphical outputs are to be interpreted.

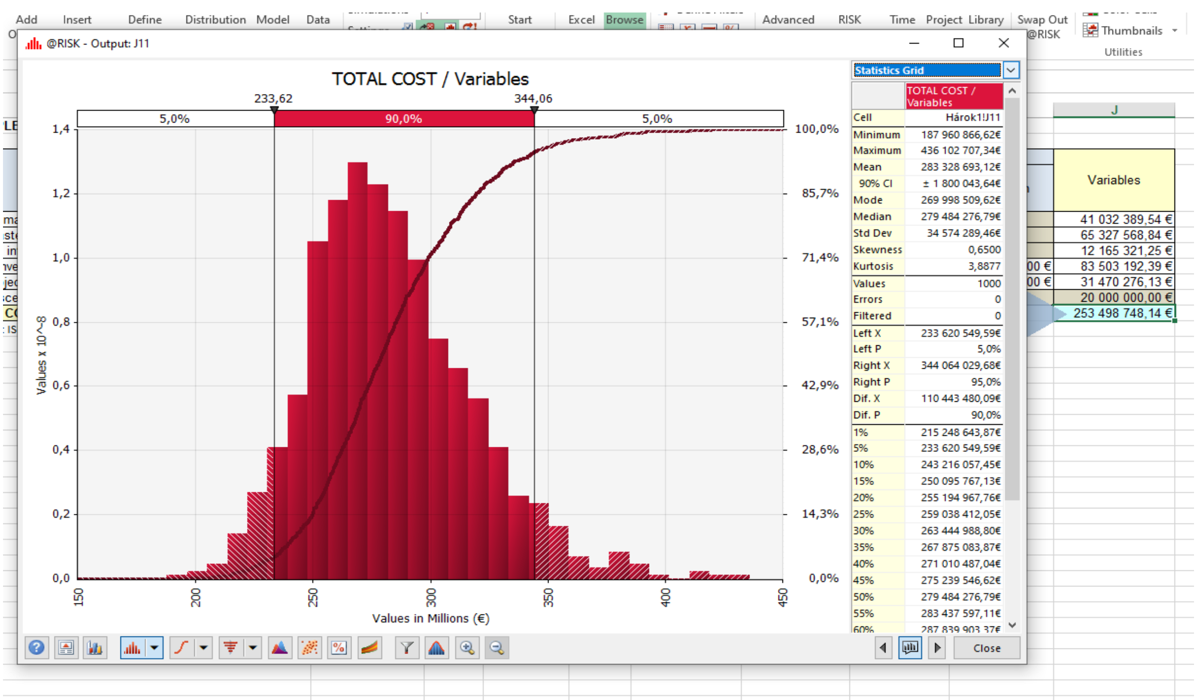


Figure 34: Simulation Output of the V1 NPP Cost Model in 2021.

6.5. Interpretation of Results

The results of the simplified hypothetical example will NOT be interpreted. The results of the actual V1 NPP decommissioning cost model from 2021 WILL be interpreted. This model included 180 variables, for which the uncertainty was estimated by JAVYS´ on site-experts.

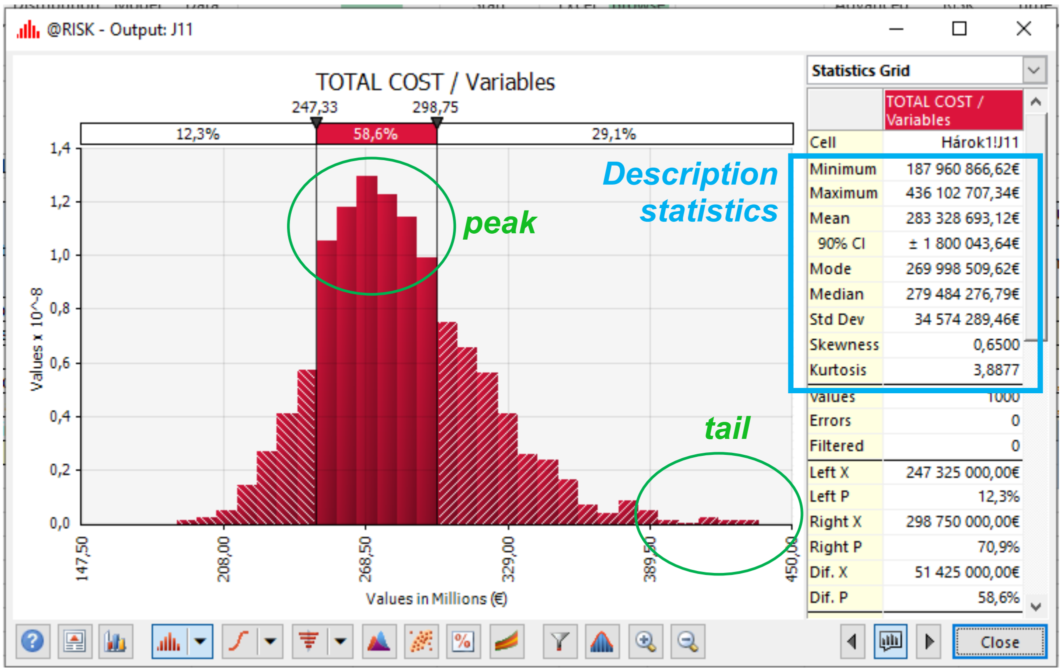


Figure 35: Histogram (Output of the Simulation of the V1 NPP Model in 2021).

Before drawing specific conclusions from the simulation, a graphical examination of the results is completed first. The red area of the Figure 32 is the **histogram**, it represents the distribution of the numerical data. The entire range of values (simulated total cost) obtained in the simulation is divided into intervals. The number of the values which are depicted in the histogram is 10,000, as the simulation was carried out with 10,000 iterations. For every interval it is counted how many values fall into it. The higher the red bar is, the more values fall into the interval. On **vertical axis** is the frequency (count of each bin), and on **horizontal axis** is the list of bins/categories. The interval of a bin in our case is approximately 10 million €. Approximately 60% of the simulated values of the total project baseline cost estimate fall into intervals between €247 Million to €298 Million (peak of the probabilistic distribution of the output).

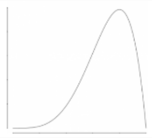
👍	Using the cursor, the three sections of the distribution that divide the 100% interval can be moved by dragging the two triangles at the bar.

Skewness (see description statistics in Figure 40) is 0.65. The interpretation of skewness is as follows:

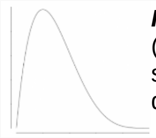
- If less than −1 or greater than +1 then the distribution is **highly skewed.**
- If between −1 and −½ or between +½ and +1, then the distribution is **moderately skewed.**
- If between −½ and +½, the distribution can be called **approximately symmetric.**

Our distribution is moderately skewed compared to the normal distribution. Also, the side to which the distribution is skewed is examined. Our skewness is higher than 0 (normal distribution), therefore it is positively skewed.

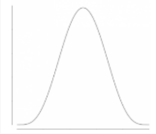
Skewness may be examined also graphically:



Left skew
(-) negatively skewed distribution



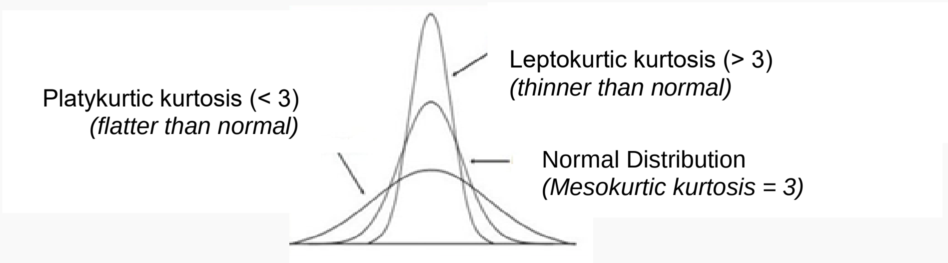
Right skew
(+) positively skewed distribution



No skew
Skewness = 0

Kurtosis (see description statistics in Figure 32) is 3.8877. Compared to the normal distribution, probabilistic distribution of decommissioning cost is leptokurtic (thinner than normal.

Kurtosis may be examined also graphically:



We may add the **cumulative distribution function** into histogram (see Figure 33). It is a **S-shaped curve**. It starts with 0% probability, at half – meaning 50% or median, it changes the shape and increases till 100%.

Classical interpretation of results is e.g.: With 50% probability the decommissioning cost will not be higher than 279 million €. With 90 % probability the decommissioning cost will not be higher than 329 million €.

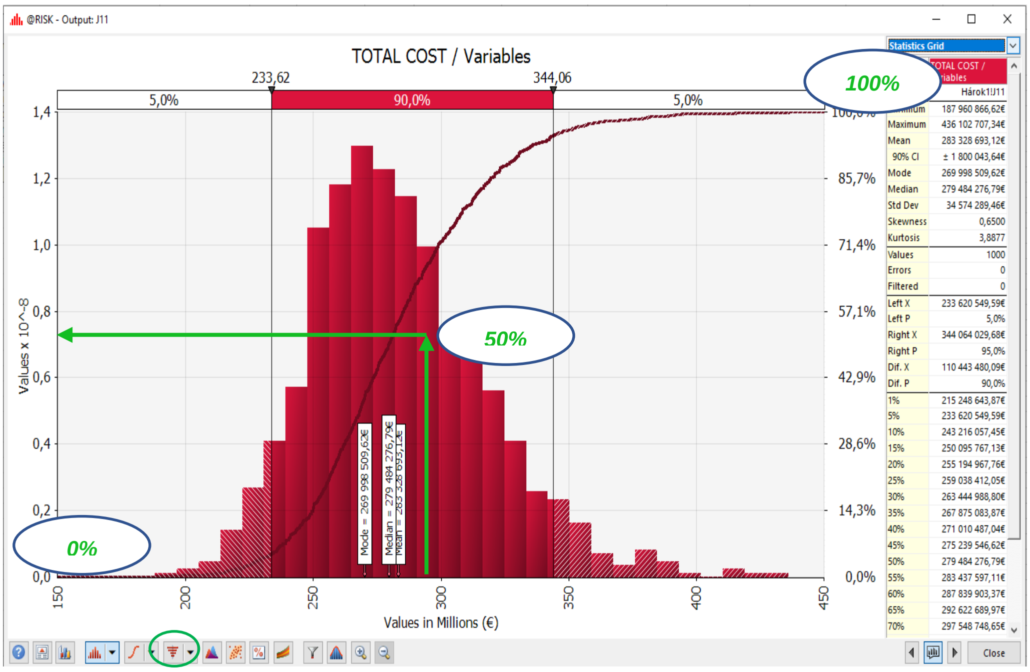


Figure 36: S-curve (Output of the Simulation of the V1 NPP Cost Model in 2021).

In classic models the decision maker decides their own risk propensity e.g., risk averse and ensures funding to e.g., 95%, or risk seeking and ensures funding to e.g., 55% of probability.

> ⚠ Interpretation of results needs to comply with applied methodology and assumptions of the model.

As the latest study on decommissioning cost (applied to this model), **it is assumed that whole ISDC contingency will be spent.**

OEDC-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", 2017, Report No. 7344: Estimating uncertainty (ISDC contingency) – "The 100% confidence level is used because of the assumption that all of this money will be fully spent during the project execution, in line with the ISDC"

It basically means that the decommissioning funding has to be at least 436 million € (the value of maximum or at 100%) to cover estimating uncertainty. Later, the estimator(s) are to further decide whether to add additional funding to cover out-of-scope uncertainties and risks.

> ⚠ This approach - the 100% coverage of funds, in JAVYS´ opinion may drastically bias the efficiency or correct estimation, as sometimes there may be a significant outlier at the tail of the probabilistic distribution of the output.

In compliance with the applied methodology the interpretation of the results is as follows:

After performing the Monte Carlo simulation based on cost estimate of individual V1 NPP decommissioning activities at the ISDC III level and their probability distribution functions, the probability distribution of the total V1 NPP decommissioning costs and the **Project Baseline Estimate** for the period 07/2021 - 12/2027 was determined. Budgeted costs of the sub-projects of V1 NPP decommissioning Project, including the sub-projects for RAW management in the period 07/2021-12/2027 represent the amount of 328,612 million € (this base cost does not include: all items representing operating costs, ISDC level III - 11.0104 - Specific external services and payments, representing the cost of EBRD and SIEA, and items related to projects D4.4B, A1.10 and C8-B.01).

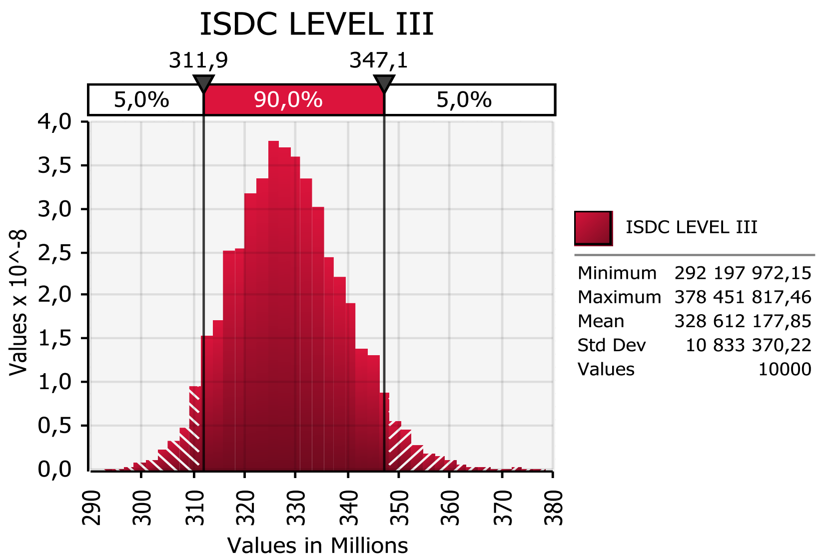


Figure 37: Distribution Probability for Estimating Uncertainty of V1 NPP.

In accordance with the ISDC assumptions and OECD-NEA report, assuming that the entire ISDC contingency will be 100% used, the results of the Monte Carlo analysis indicate that the Base Cost should be increased by approximately 15.17% (i.e., 49,84 Million €) so that a 100% confidence interval is covered. The likelihood that such a result is reached is 1/n, where n is the number of simulations (i.e., the scenario of 378,451 million € will be reached with a probability of 1/10,000).

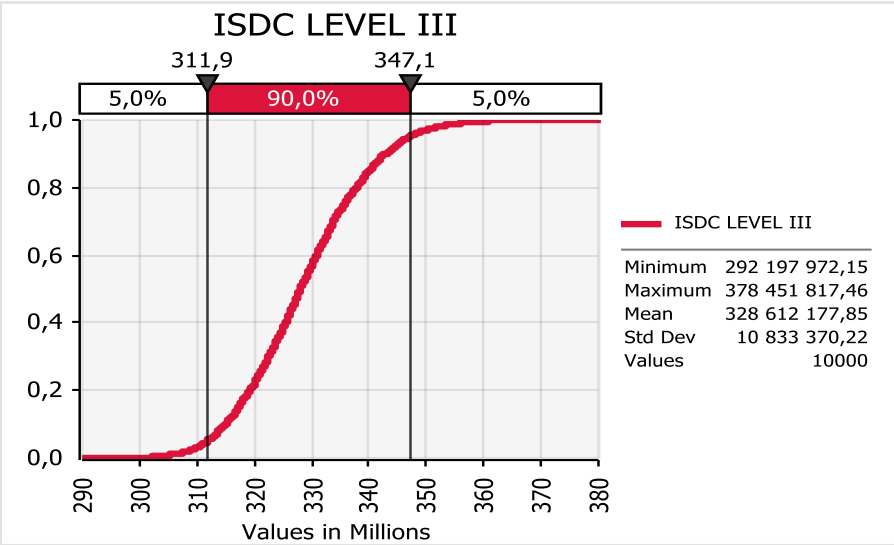


Figure 38: Cumulative Probability for Estimating Uncertainty of V1 NPP.

Distribution of the overall quantified estimating uncertainty of V1 NPP Decommissioning Project into individual items of ISDC III

The contribution of the estimating uncertainty of V1 NPP Decommissioning Project in the period 07/2021 - 12/2027 represents 49,839,694 €. If the probability simulation method was not applied to the calculation, but the uncertainty was quantified only as a variability for individual items at the ISDC III level in an upward trending direction, the contingency to cover the uncertainties within the scope of V1 NPP Decommissioning Project would represent 37,931,346 €.

The ISDC contingency (estimating uncertainty) was determined globally for the whole decommissioning project and subsequently, this amount was split between the individual decommissioning activities at the ISDC III level as follows:

Estimating uncertainty ISDC III$_{ij}$ =

$$\frac{\text{Budgeted costs ISDC III}_{ij} \text{ X Variability ISDC III}_{ij}}{\Sigma \text{ (Budgeted costs ISDC III}_{ij} \text{ X Variability ISDC III}_{ij})} \quad \text{X} \quad \text{Estimating uncertainty of V1 NPP}$$

Where: i - indicates ith activity at the ISDC III level; ***j*** *- indicates the jth sub-project of the V1 NPP decommissioning;* ***Estimating uncertainty of V1 NPP*** *- represents a contribution to the Base Cost to cover in-scope uncertainty quantified by the Monte Carlo simulation method.*

Summary of the results of in-scope uncertainty quantification

The outputs of quantification of V1 NPP Decommissioning Project contingency for the period 07/2021 - 12/2027 are summarized in Figure 36. The Base Cost (budgeted costs for the period 07/2021 - 12/2027) is 328,612 million € and it includes Allowances (contributions for predicted variability of input parameters) and risk mitigation range but excludes items to which no contingency has been applied (operating costs of JAVYS, as, i.e., costs related to management and support activities, site infrastructure and operation).

The ISDC contingency (estimating uncertainty) within the defined project scope for the period 07/2021 - 12/2027 is in the amount of 49,84 million €. This estimating uncertainty covers the costs associated with such factors as variability of input data (radiological parameters, parameters of objects, etc.), variability associated with the selected estimation methodology, variability related to design maturity, availability of qualified workforce, price variability after contract award, but excludes inflation and price escalation that are considered as an uncertainty beyond the project scope.

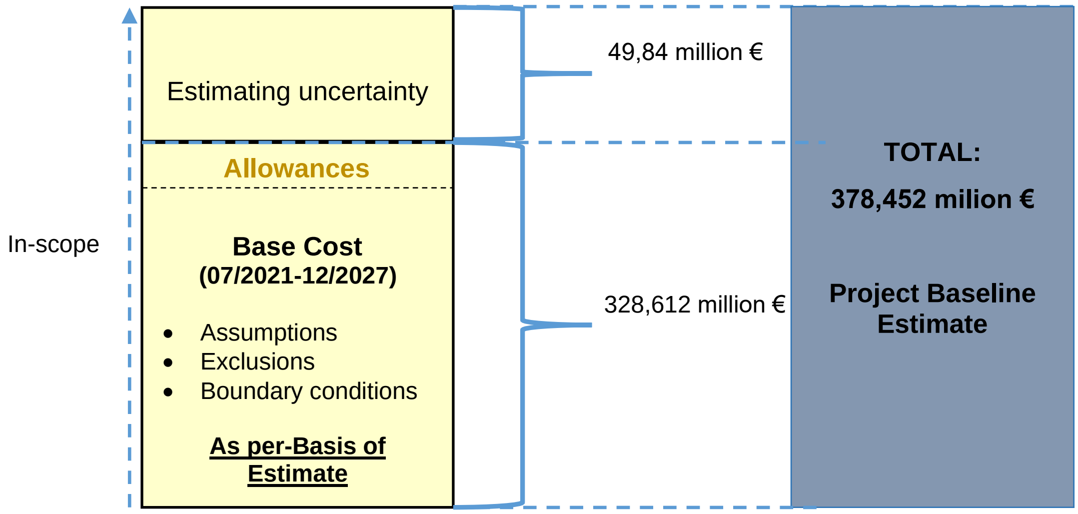


Figure 39: Results of Contingency Quantification of V1 NPP Decommissioning.

Considering the calculated contingency (resulting from the application of the Monte Carlo method) and estimated Base Cost, the V1 NPP Decommissioning Project Baseline cost estimate for the period 07/2021 – 12/2027 was determined in the amount of 378,452 million €.

6.6. What Went Well

The compliance with the international methodology of cost estimates in decommissioning is significant. It is necessary that the decommissioning cost contingency is estimated using proper modelling methods, as the stakeholders require such estimates to obtain as reliable results as possible.

The output of MC simulation on decommissioning cost is dependent on the:

- reliability of the base cost estimate (to which the contingency is to be added)
- complexity of the cost items
- and correctness of the estimates of uncertainty of cost items by site experts.

Monte Carlo simulation was applied in V1 NPP to estimate the decommissioning cost contingency from 2014, and the model underwent significant improvement mainly in the level of detail. There are years of experience in the estimating of the base cost, where complexity of cost items reaches ISDC level III (highest possible).

From the simulations carried out so far by JAVYS, the following practices were identified as beneficial for other organizations conducting similar works:

- Report of *OEDC-NEA - "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", 2017, Report No. 7344*, is sufficient source of methodology for developing decommissioning project baseline cost estimate.
- Proper attention needs to be paid to the composition of the team responsible for cost model development and input data. The team should include: personnel responsible for cost estimation and estimation of cost items, personnel involved in planning of future decommissioning activities, representatives of decommissioning projects (project managers), statisticians (to be involved in model construction and to advise of the selection of probabilistic distributions for the input data, which rely on the expectations of the rest of the team in regard to future development of respective decommissioning activities).
- The statistician is necessary, not only to support the model development, but also to be involved in the interpretation of results. The statistician involved in the V1 NPP decommissioning is an internal employee, with 10 years familiarization on the V1 NPP decommissioning project (which is considered as a good practice by JAVYS).
- JAVYS recommends familiarizing with the international recommendations on the value of variability of decommissioning cost before estimating the site-specific input data. However, every site is to estimate their own site-specific input data based on the phase of their project, their progress, and other site-specific information (e.g., operations and challenges should also be considered).
- JAVYS considers the Project Baseline including allowances, risk mitigation scope for in-scope of the project risk and Estimating Uncertainty as an acceptable decommissioning cost estimate.
- Risks, which are beyond the Project Baseline estimate, are the risks outside the defined project scope and may be funded or unfunded. Estimation of the cost of funding of main external risks via MC simulation is to be considered further. The resources for costs imposed by external risks (which may not occur), are bound. Funding for out-of-scope risks may be also determined in case of their occurrence/foreseen occurrence, based on the estimation of the cost of implementation of specific mitigation measures (which is more detailed than MC and enables a comparison of cost of several mitigation options).
- Maturity of the project is to be considered when developing the model and estimating the input data. The fact that there may be on-going decommissioning activities needs to be addressed in the model.
- At least 10,000 iterations (recalculation of result) are to be included to obtain the output probabilistic distribution. It is a good balance in terms of computational time vs reliability of outcomes.

6.7. Even Better If

- There is a possibility to estimate also the cost of funding of main external risks via MC simulation. However, the estimate of V1 NPP Decommissioning cost still does not include the provision for risks out of the project scope, as it was not considered to be necessary for V1 NPP Decommissioning (these costs may / may not occur).
- There is also be a possibility to further quantify the cost of out-of-scope risks mitigation, vi comparison of cost potential risk mitigation measures variants. This approach, is considered by JAVYS more accurate than the quantification of the out-out scope risks funding via MC simulation.
- Sharing the knowledge on the development of reliable decommissioning cost estimates and the information of the uncertainty assigned to various cost item, is currently of high importance. Mainly detailed information on the recommended uncertainty levels for specific cost estimate items at a complex level (e.g., ISDC III level) can be an advantage.

7. CONCLUSIONS / FINAL REMARKS

In this document, the V1 NPP site-specific modifications of international recommendations in the area of Qualitative Risk management in decommissioning are provided for end users. It is important to highlight that international methodology and guidelines for qualitative risk management are solely recommendations. Every decommissioning site has to assess these recommendations and adjust them based on the specific resources, challenges, and activities faced within their own decommissioning project. International recommendations are also compared to methodologies applied in the V1 NPP Decommissioning project, to give the reader an idea in which part the V1 NPP methodology is adjusted and why. This may help other decommissioning projects in early project stages.

The second part of this document is dedicated to the qualitative risk analysis. Monte Carlo simulation of both the decommissioning schedule and decommissioning costs are performed with sample schedules / costs.

The recommendations for application of MC simulation of the decommissioning schedule require further attention from supra-national organizations. That is, if there would be international recommendations on the level of uncertainty of specific decommissioning activities, it would be clear to all stakeholders that the decommissioning schedule is not deterministic.

The experience acquired in V1 NPP decommissioning is that both earlier and delayed partial decommissioning sub-projects may be viewed by the stakeholder as “bad project management” or “improper planning”. If the decommissioning schedule is viewed from the start as uncertain and subjected to risks occurrence, the completion with specific % of delay compared to the total decommissioning duration could be also viewed as successful completion. Any decommissioning project has several objectives, and the completion in compliance with a deterministic deadline is less important than safety or minimizing the burden on future generations by producing as little radioactive waste as possible.

The MC simulation of the V1 NPP decommissioning deadline presented in this report was carried out at a highly simplified level with respect to activities, with the emphasis on properly including all strategic time related risks that had potential to impact the decommissioning deadline. However, in schedule modelling, there is significant room for improvement: using more complex and specific activities as schedule inputs, inclusion of operational level risks, changing the methodology so that both uncertainty and risks can be modelled separately. These improvements are currently being examined by the JAVYS and PMU Consultant.

International methodology for the application of Monte Carlo simulation in decommissioning cost estimates has been developed in detail in the Report of *OEDC-NEA - “Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities”*. However, operators may further benefit from more detailed information on the recommended uncertainty levels for specific cost estimate items at a complex level (e.g., ISDC III level). This has been identified as an advantage (since international recommendations for uncertainty are available only at a simplified level).

The examples, insights and recommendations in this report can be considered by other operators in Europe when using the international methodology for the application of Monte Carlo simulation in decommissioning cost estimates and stochastic simulation of decommissioning schedule. This has been developed in detail in this document.