**Appendix A:** Synthetic review of the methods in the literature

Table A.1 Synthetic review of the methods in the literature

|  |  |  |  |
| --- | --- | --- | --- |
| **Method** | **Use and objective** | **Characteristics and criteria**  | **Methods** |
| Predictive Capability Maturity Model(Oberkampf, Pilch and Trucano, 2007) | Assesses the level of maturity of computational modeling and simulation methods. | Semi-quantitative assessment of maturity with respect to six criteria: (i) representation and geometric fidelity; (ii) physics and material model fidelity; (iii) code verification; (iv) solution verification; (v) model validation; (vi) uncertainty quantification and sensitivity analysis. | Experts’ knowledge. |
| Prediction capability of a prognostic method(Di Maio *et al.*, 2015), (Zeng *et al.*, 2016) | Assesses the prediction quality of prognostic tools. | An indicator of prognostic performance assessed qualitatively and quantitatively given: a. The RUL model predication quality, which is assessed “*quantitatively”* based on: (i) Timeliness weighted error bias; (ii) sample mean error; (iii) mean absolute percentage error; (iv) mean square error; (v) sample median error; (vi) performance; (vii) weighted prediction spread; (viii) sample standard deviation; (ix) root mean square error; (x) prediction spread.b. The trustworthiness of method, which includes: (i) reliability; (ii) resources requirement; (iii) mathematical modeling adequacy; (iv) validity. | Experts’ knowledge; weighted average of criteria within AHP. |
| Modeling and Simulation (M&S) credibility model (NASA, 2013) | Assesses the credibility of M&S tools. | Credibility assessed semi-quantitatively based on: (i) M&S development, including verification and validation; (ii) M&S operations, including input pedigree (a record of traceability from the input data source), results uncertainty and results robustness; (iii) supporting evidence, including the use history, M&S management and people qualifications. | Scoring protocols and experts’ knowledge. |
| Knowledge assessment(Flage and Aven, 2009) | Expresses the knowledge on which risk assessment is based.  | SoK qualitatively assessed as minor, moderate or significant, based on: (i) phenomenological understanding of the problem; (ii) availability of reliable data; (iii) reasonability of assumptions made; (iv) agreement (consensus) among experts (i.e., low value-ladenness). | Evaluation protocols and experts’ knowledge. |
| Assumption deviation risk(Aven, 2013b), (Berner and Flage, 2016) | Assesses the possibility and criticality of risk deviations. | Semi-quantitative rough evaluation of the uncertainty associated to an assumption and the sensitivity of the model output to such assumption. | Experts’ knowledge and local, one-at-a-time sensitivity analysis.  |
| Evaluation of model uncertainty, credibility and applicability(Droguett and Mosleh, 2008 and 2014) | Assesses model uncertainty. | Comparison of model predictions and real data, within a Bayesian framework. | Bayesian methodology where information about models are available in the form of homogeneous and nonhomogeneous performance data (pairs of experimental observations and model predictions). |

**Appendix B: Method used to translate the hierarchical tree attributes into a semi-quantitative scale**

The following table presents the guidelines adopted in this paper to translate the attributes of the hierarchical tree into a semi-quantitative scale. Such guidelines are defined based on discussions and suggestions provided by EDF analysts, with relevant experience in the problem ad case study at hand.

Table B.1 A semi-quantitative scale for the hierarchical tree attributes

|  |  |
| --- | --- |
| **Parameter** | **Translation “real number → scale 1/9”** |
| Number of approximations $(Ap=T\_{12})$ | Low number of approximation and low believed effect of their aggregate on the outputs: 9Few approximations with low effect of their aggregate: 7Moderate number of approximations with acceptable effect of their effect on the outputs: 5High number of approximations with high effect of their aggregate on the outputs: 3High number of approximations with sever effect of their aggregate on the outputs: 1The even number are left for the intermediate cases |
| Number of equations and correlations ($Q=T\_{111})$ | 1-2 equations : 13 equations : 24 equations or 1 (Boolean logic equation) : 3..>9 equations : 9 |
| Number of state rates and model parameters ($Mp=T\_{112}$) | 0-2: 13-5: 2..>32: 9 |
| Number of dependency relations considered ($Dr=T\_{113}$) | 0 dependency relations considered : 11%-12.5% of the failures rates are considered dependent on the failure of other components: 213.5%-25%: 326%-37.5%: 4..>88.5% All components failures are dependent on other components failures : 9  |
| Number of assumptions ($As=T\_{212}$) | Directly related to the actual number of assumptions used. |
| Impact (Sensitivity analysis and indications)($I=T\_{211}$) | The impact is related to the assumptions. The difference between the values of failure rate with and without the assumption should be estimated. A score between 1-9 is given for each assumption, and the final score is then averaged over all assumptions.1. No repairs: assuming no component repairs, at time 500, we obtain a probability of failure which is 500 times higher as compared to the case when the repair is considered (Figs 9-12 (Lin, 2016))
2. One directional dependency: assuming only one-direction dependency of the valve degradation from the degradation and vibration of the pump, decreases the valve reliability of about 3 times (Figs 9-21(Lin, 2016))
3. Human error: In case of human error (omission in closing the manual valve), we obtain a probability of failure of RHR which is 1.096 times higher. Nevertheless, the human error probability is very small.
4. No random shocks: assuming no random shocks results in a relative difference in the failure rate of the components. in particular, there is a reduction of (-2.99%-19823.08%) with respect to the case with the random shocks (Table II (Lin, 2016))
 |
| Consistency of data ($C=T\_{221}$) | The expert should give a score between 1-9 evaluating of the consistency of data, taking into account the source of data, its compatibility and relevance to the components that need to be analyzed.As in the case study the data is collected from the same type of reactors 900 Mwe, it is highly consistent: the consistency is given a score of 8.However, we cannot guarantee a perfect consistency, as the information about a specific component might be collected from other components that are similar but slightly different: e.g., the failure rate of RHR pumps is calculated taking into account failures of all pumps in the reactor. |
| Amount of data (Number/amount of sources)($Ad=T\_{222}$) | The following classification is adopted according to the suggestions of EDF experts:> 25 reactor years of experience : 125-50: 251-100: 3101-175: 4176-275: 5276-400: 6401-550: 7551-725: 8Over 725: 9 |

**Appendix C: Trustworthiness attributes evaluation for Fault Tree (FT) M1**

Table C.1 Trustworthiness attributes evaluation for Fault Tree (FT)

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Direct score** | **Relative score** | **Note** |
| $$Ap=T\_{12}$$ | 7 | 6 | 7 minimal cut sets |
| $$Q=T\_{111}$$ | 1 | 3 | 1 equation (Boolean logic): failure probability based on “rare event” approximation |
| $$Mp=T\_{112}$$ | 8 | 3 | 8 failure rates for 8 basic events |
| $$Dr=T\_{113}$$ | 0 | 1 | No dependency relations considered |
| $$As=T\_{212}$$ | 4 | 5 | No repairsNo dependency relations between components and failure mechanismsHuman errorNo random shocks |
| $$I=T\_{211}$$ | 3 | 3441Avg: 3 | Based on the sensitivity analysis performed by (Lin, 2016) and the analysis performed using Risk Spectrum Software by EDF1. No repairs: assuming no component repairs, at time 500, we obtain a probability of failure which is 500 times higher as compared to the case when the repair is considered (Figs 9-12 (Lin, 2016))
2. No directional relation considered
3. Human error: In case of human error (omission in closing the manual valve) we obtain a probability of failure of RHR which is 1.096 times higher. Nevertheless, the human error probability is very small.
4. No random shocks: assuming no random shocks results in a relative difference in the failure rate of the components. in particular, there is a reduction of (-2.99%-19823.08%) with respect to the case with the random shocks (Table II (Lin, 2016))
 |
| $$C=T\_{221}$$ | 8 | 8 | The data are collected from application of SAFO (OMF-reliability-centered-maintenance-feedback computer assisted collection on 7 CP1-CP2 sites and report on data.As this data is collected from the same type of reactors 900 MWe it is highly consistent. On the other hand, we cannot guarantee a “perfect” consistency, as the information about a specific component might be collected from other, similar but possibly different, components: e.g., the failure rate of RHR motor operated valves is calculated taking into account failures of all motor operated valves in the reactor. |
| $$Ad=T\_{222} $$ | 275 | 5 | EDF internal reports on data collected between 1980 and 1992, or 275 years reactor for each component. |

**Appendix D: Trustworthiness attributes evaluation for Multi-State Physics-based Model (MSMP) M2**

Table D.1 Trustworthiness attributes evaluation for Multi-State Physics-based Model (MSMP)

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Direct score** | **Relative score** | **Note** |
| $$Ap=T\_{12}$$ | 7 | 7 | No relevant approximation |
| $$Q=T\_{111}$$ | 9 | 8 | 4 multi-state models3 physical equations for valve and diaphragm behavior2 threshold equations for $D\_{v}$ and $D\_{D}$ (denote respectively: the number of cycles of solicitation of the valve over time and the thickness loss of the pipe over time) |
| $$Mp=T\_{112}$$ | 18 | 7 | -5 transitions rates in the multi-state model- 11 parameters for physical equations for the valve and diaphragm - 2 parameters for the modeling of number of cycles and thickness loss(18 parameters in total) |
| $$Dr=T\_{113}$$ | 1 | 4 | 1 dependency relation considered between the valve and the pump |
| $$As=T\_{212}$$ | 3 | 6 | No repairs 1 directional dependency: the dependency of the valve degradation on the pump degradation and vibrationNo random shocks |
| $$I=T\_{211}$$ | 3.3333 | 361Avg: 10/3 | Based on the sensitivity analysis performed by (Lin, 2016):1. No repairs: assuming no component repairs, at time 500, we obtain a probability of failure which is 500 times higher as compared to the case when the repair is considered (figs 9-12 (Lin, 2016))
2. One directional dependency: assuming only one direction dependency of the valve degradation on the degradation and vibration of the pump decreases the valve reliability of about 3 times (Figs 9-21 (Lin, 2016))
3. No random shocks: assuming no random shocks results in a relative difference in the failure rate of the components. in particular, there is a reduction of (-2.99%-19823.08%) with respect to the case with the random shocks (Table II (Lin, 2016))
 |
| $$C=T\_{221}$$ | 5 | 5 | The data are collected from internal technical reports:-Pump 621.95 years reactor (PWR 900 MWe, PWR 1300 MWe, PWR N4)PWR 900: 2PWR 1300, N4: 2-Breaker 420 Years reactor (PWR1300 MWe, CPY)CPY: 18PWR 1300:19-Contactor 528.21 years reactor (1300 MWe, CPY, PWR N4)CPY: 26PWR 1300: 48PWR N4-1400: 29- Motor 626.42 years reactor (900 MWe, 1300 MWe, Palier PWR N4)CPY: 43PWR 1300: 36PWR N4-1400: 34Even though the data collected in EDF internal reports comes from different sources with different types of reactors, it is still consistent as the different components are very similar. |
| $$Ad=T\_{222}$$ | 549.15 | 8 | -Pump : 621.95 years reactor-Breaker: 420 Years reactor -Contactor : 528.21 years reactor - Motor : 626.42 years reactor  |