

---

# Contents

---

|   |    |
|---|----|
| <b>Introduction</b> . . . . .                               | xi |
| <b>Part 1. Short Review of Petri Net Modeling</b> . . . . . | 1  |
| <b>Introduction to Part 1</b> . . . . .                     | 3  |
| <b>Chapter 1. Autonomous Petri Nets</b> . . . . .           | 5  |
| 1.1. Unmarked Petri nets . . . . .                          | 5  |
| 1.1.1. Definitions . . . . .                                | 5  |
| 1.1.2. Drawing . . . . .                                    | 6  |
| 1.1.3. Other definitions . . . . .                          | 7  |
| 1.2. Marking of a PN . . . . .                              | 7  |
| 1.2.1. Order relation on markings . . . . .                 | 8  |
| 1.2.2. Enabled transition . . . . .                         | 9  |
| 1.3. Dynamics of autonomous PNs . . . . .                   | 9  |
| 1.3.1. Firing of a transition . . . . .                     | 9  |
| 1.3.2. Transition matrix . . . . .                          | 11 |
| 1.3.3. Firing sequence . . . . .                            | 11 |
| 1.3.4. Reachable marking . . . . .                          | 12 |
| 1.3.5. Fundamental equation . . . . .                       | 12 |
| 1.3.6. Properties of PN . . . . .                           | 14 |
| 1.3.7. Other properties . . . . .                           | 14 |
| 1.3.8. Invariants in a PN . . . . .                         | 15 |
| 1.3.9. Reachability graph . . . . .                         | 16 |

|  |    |
|--|----|
| <b>Chapter 2. Petri Nets and Event Languages</b> . . . . .                     | 19 |
| 2.1. Labeled PNs . . . . .   | 19 |
| 2.1.1. Formal definition . . . . .   | 19 |
| 2.1.2. Generated and marked languages . . . . .                                | 20 |
| 2.2. Example . . . . .   | 21 |
| <b>Chapter 3. Comparison Petri Nets –<br/>Finite State Automaton</b> . . . . . | 25 |
| 3.1. Language expression . . . . .   | 26 |
| 3.2. Building of the models . . . . .  | 27 |
| 3.2.1. Synchronization of submodels . . . . .                                  | 28 |
| 3.2.2. Resource sharing . . . . .  | 29 |
| 3.2.3. Construction by refinement . . . . .                                    | 30 |
| 3.3. Compactness of the model . . . . .  | 32 |
| <b>Chapter 4. Some Extensions of Petri Nets</b> . . . . .                      | 35 |
| 4.1. PN with inhibitor arcs . . . . .  | 35 |
| 4.2. Timed PN . . . . .  | 36 |
| 4.2.1. P-timed Petri nets . . . . .  | 37 |
| 4.2.2. T-timed Petri nets . . . . .  | 37 |
| 4.3. Synchronized PN . . . . .   | 38 |
| 4.4. Timed synchronized PN . . . . .   | 40 |
| 4.5. Interpreted PN . . . . .  | 41 |
| 4.6. Colored PN . . . . .  | 42 |
| 4.6.1. Introduction example . . . . .  | 42 |
| 4.6.2. Formal definition . . . . .   | 45 |
| 4.6.3. A dedicated software CPN Tools . . . . .                                | 46 |
| <b>Conclusion to Part 1</b> . . . . .  | 51 |
| <b>Part 2. A Formal Approach to Risk Assessment</b> . . . . .                  | 53 |
| <b>Introduction to Part 2</b> . . . . .  | 51 |
| <b>Chapter 5. Ontology-based Accidental Process</b> . . . . .                  | 61 |
| 5.1. Preliminary definitions . . . . .   | 61 |
| 5.2. Elementary entities: HSE and VTE . . . . .                                | 63 |

---

|  |           |
|--|-----------|
| 5.2.1. Hazard supplier entity (HSE) . . . . .                                | 63        |
| 5.2.2. Vulnerable target entity (VTE) . . . . .                              | 63        |
| 5.3. Elementary situations and elementary events . . . . .                   | 64        |
| 5.3.1. State versus situation . . . . .                                      | 64        |
| 5.3.2. Initial situation (IS) . . . . .                                      | 64        |
| 5.3.3. Initiating event (IEv) . . . . .                                      | 64        |
| 5.3.4. Hazard situation (HS) . . . . .                                       | 65        |
| 5.3.5. Exposure event (EEv) . . . . .  | 65        |
| 5.3.6. Exposure situation (ES) . . . . .                                     | 65        |
| 5.3.7. Accident situation . . . . .  | 65        |
| 5.3.8. Hazardous (feared) event (HEv) . . . . .                              | 65        |
| 5.4. Conclusion . . . . .  | 66        |
| <b>Chapter 6. Petri Net Modeling of the<br/>Accidental Process</b> . . . . . | <b>67</b> |
| 6.1. Elementary process . . . . .  | 68        |
| 6.2. Sequence of elementary processes . . . . .                              | 71        |
| 6.3. Modeling the action of a safety barrier . . . . .                       | 71        |
| 6.4. Modeling of a cumulative process . . . . .                              | 73        |
| 6.5. PN as a support for risk assessment . . . . .                           | 75        |
| 6.5.1. Modeling of the damage . . . . .                                      | 75        |
| 6.5.2. Modeling of the event frequencies . . . . .                           | 75        |
| 6.5.3. CPN Tools implementation . . . . .                                    | 77        |
| 6.5.4. Evaluation rule of the risk . . . . .                                 | 83        |
| 6.6. Conclusion . . . . .  | 86        |
| <b>Chapter 7. Illustrative Example</b> . . . . .                             | <b>87</b> |
| 7.1. Functional description . . . . .  | 87        |
| 7.2. Building of an accidental process . . . . .                             | 88        |
| 7.2.1. First elementary process . . . . .                                    | 88        |
| 7.2.2. Second elementary process . . . . .                                   | 91        |
| 7.2.3. Parallel process . . . . .  | 92        |
| 7.2.4. The whole model . . . . .   | 92        |
| 7.3. Conclusion . . . . .  | 94        |

|  |     |
|--|-----|
| <b>Chapter 8. Design and Safety Assessment Cycle</b> . . . .                     | 95  |
| 8.1. Five essential steps . . . . .  | 95  |
| 8.2. Ontological interest . . . . .  | 98  |
| <b>Conclusion to Part 2</b> . . . . .  | 101 |
| <b>Part 3. Stochastic Petri Nets</b> . . . . .                                   | 103 |
| <b>Introduction to Part 3</b> . . . . .  | 105 |
| <b>Chapter 9. Basic Concept</b> . . . . .  | 107 |
| 9.1. Introductory example . . . . .  | 107 |
| 9.2. Formal definition . . . . .   | 108 |
| <b>Chapter 10. Semantics, Properties and Evolution Rules of an SPN</b> . . . . . | 111 |
| 10.1. Conservatism properties . . . . .  | 112 |
| 10.1.1. Conservatism of the mean marking in steady state                         | 112 |
| 10.1.2. Conservatism of the flow in steady state . . . . .                       | 113 |
| 10.2. Mean sojourn time in a place of a SPN . . . . .                            | 113 |
| 10.3. Equivalent Markov process . . . . .  | 114 |
| 10.4. Example of SPN for systems dependability modeling and assessment . . . . . | 116 |
| <b>Chapter 11. Simplification of Complex Models</b> . . . . .                    | 121 |
| 11.1. Introduction . . . . .   | 121 |
| 11.2. System modeling . . . . .  | 122 |
| 11.3. Presentation of the quantitative analysis method . . . . .                 | 124 |
| 11.3.1. Steps to obtain an aggregated Markov graph . . . . .                     | 124 |
| 11.3.2. Toward a direct establishment of a reduced Markov graph . . . . .        | 137 |
| 11.4. Example . . . . .  | 137 |
| 11.4.1. Failure modeling . . . . .   | 138 |
| 11.4.2. Study of the different functional and hardware solutions . . . . .       | 139 |
| 11.4.3. Evaluation of the weighting coefficients from the Petri nets . . . . .   | 144 |
| 11.4.4. Conclusion . . . . .   | 147 |

|   |         |
|---|---------|
| <b>Chapter 12. Extensions of SPN</b> . . . . .  | 149     |
| 12.1. Introduction . . . . .  | 149     |
| 12.2. Relationship between stochastic Petri nets and<br>stochastic processes . . . . .                              | 150     |
| 12.3. The transition firing policy . . . . .  | 151     |
| 12.4. Associated stochastic processes . . . . .   | 151     |
| 12.4.1. Temporal memory based on resampling . . . . .   | 152     |
| 12.4.2. Temporal memory based on age memory or on<br>enabling memory . . . . .                                      | 153     |
| 12.4.3. Stochastic process underlying a stochastic PN . . . . .   | 154     |
| 12.4.4. Embedded Markov chain of the stochastic process . . . . .   | 157     |
| 12.4.5. Application to a case study . . . . .   | 159     |
| 12.5. Synchronization problem in generalized stochastic<br>Petri nets . . . . .                                     | 162     |
| 12.5.1. GSPN with internal synchronization . . . . .  | 162     |
| 12.5.2. SPN with predicates and assertions . . . . .  | 164     |
| 12.6. Conclusion . . . . .  | 168     |
| <br><b>Part 4. Applications of Stochastic Petri Nets to<br/>Assessment Problems in Industrial Systems</b> . . . . . | <br>169 |
| <br><b>Introduction to Part 4</b> . . . . .   | <br>171 |
| <br><b>Chapter 13. Application in Dynamic Reliability</b> . . . . .   | <br>175 |
| 13.1. Presentation of the system and hypothesis . . . . .   | 175     |
| 13.2. System modeling with Petri net . . . . .  | 177     |
| 13.3. Methodology application . . . . .   | 179     |
| 13.4. Construction of an aggregated Markov graph . . . . .  | 180     |
| 13.5. Conclusion . . . . .  | 185     |
| <br><b>Chapter 14. Classical Dependability Assessment</b> . . . . .   | <br>187 |
| 14.1. Availability study of a nuclear power plant subsystem . . . . .   | 187     |
| 14.1.1. CPN modeling . . . . .  | 188     |
| 14.1.2. Reliability and dependability assessment . . . . .  | 192     |
| 14.1.3. Conclusion . . . . .  | 196     |
| 14.2. Common causes failures in nuclear plants (safety<br>oriented) . . . . .                                       | 197     |

|  |     |
|--|-----|
| 14.2.1. The Atwood model . . . . .                       | 197 |
| 14.2.2. Case study . . . . .                             | 199 |
| 14.2.3. Probabilistic dependability assessment . . . . . | 208 |
| 14.2.4. Conclusion . . . . .                             | 212 |

**Chapter 15. Impact of Failures on System**

|  |     |
|--|-----|
| <b>Performances</b> . . . . .                                      | 213 |
| 15.1. Reliability evaluation of networked control system . . . . . | 213 |
| 15.1.1. Statement of the problem . . . . .                         | 213 |
| 15.1.2. Reliability criteria of an NCS . . . . .                   | 215 |
| 15.1.3. Elements of modeling . . . . .                             | 216 |
| 15.1.4. Simulation and results . . . . .                           | 225 |
| 15.1.5. Evaluation of reliability . . . . .                        | 230 |
| 15.1.6. Conclusion . . . . .                                       | 230 |
| 15.2. Railway signaling . . . . .                                  | 231 |
| 15.2.1. Introduction . . . . .                                     | 231 |
| 15.2.2. Interest . . . . .   | 233 |
| 15.2.3. Signaling system specifications . . . . .                  | 234 |
| 15.2.4. Elements to be modeled . . . . .                           | 235 |
| 15.2.5. Architecture of the model . . . . .                        | 236 |
| 15.2.6. Example of an elementary model . . . . .                   | 237 |
| 15.2.7. Incident generation . . . . .                              | 239 |
| 15.2.8. Results . . . . .  | 239 |
| 15.2.9. Conclusion . . . . .                                       | 242 |
| <b>Conclusion</b> . . . . .  | 245 |
| <b>Appendix</b> . . . . .  | 247 |
| <b>Bibliography</b> . . . . .                                      | 251 |
| <b>Index</b> . . . . .   | 261 |