

Contents

Foreword <i>by Manuel Silva</i>	V
Preface	IX
Contents	XIII
Notation	IXX
1 Bases of Petri Nets	1
1.1 BASIC CONCEPTS	1
1.1.1 Places, Transitions, and Arcs	1
1.1.2 Marking	2
1.1.3 Firing of a Transition	3
1.1.4 Autonomous and Non-Autonomous Petri Nets	4
1.1.5 The Essential Characteristics	5
1.2 SPECIAL PETRI NETS	5
1.2.1 Particular Structures	6
1.2.1.1 <i>State Graph</i>	7
1.2.1.2 <i>Event Graph</i>	7
1.2.1.3 <i>Conflict Free Petri Net</i>	8
1.2.1.4 <i>Free Choice Petri Net</i>	8
1.2.1.5 <i>Simple Petri Net</i>	8
1.2.1.6 <i>Pure Petri Net</i>	9
1.2.2 Abbreviations and Extensions	9
1.2.2.1 <i>Generalized Petri Nets</i>	9
1.2.2.2 <i>Finite Capacity Petri Nets</i>	11
1.2.2.3 <i>Colored Petri Nets</i>	12
1.2.2.4 <i>Extended Petri Nets</i>	13
1.2.2.5 <i>Priority Petri Nets</i>	15
1.2.2.6 <i>Non-Autonomous Petri Nets</i>	16
1.2.2.7 <i>Continuous and Hybrid Petri Nets</i>	17
1.2.2.8 <i>Conclusion</i>	17
1.3 MODELING OF SOME CONCEPTS	17
NOTES and REFERENCES	20
2 Properties of Petri Nets	21
2.1 PRESENTATION OF THE MAIN PROPERTIES	21
2.1.1 Notations and Definitions	21

2.1.2	Bounded Petri Net, Safe Petri Net	24
2.1.3	Liveness and Deadlock	25
2.1.4	Conflicts	30
2.1.4.1	<i>Effective Conflict</i>	30
2.1.4.2	<i>Concurrency and Multiple Firing</i>	30
2.1.4.3	<i>Persistence</i>	32
2.1.4.4	<i>Enabling Degree and General Conflict</i>	32
2.1.5	Invariants	34
2.1.5.1	<i>Conservative Component</i>	34
2.1.5.2	<i>Repetitive Component</i>	35
2.2	SEEKING THE PROPERTIES OF PETRI NETS	37
2.2.1	Graph of Markings and Coverability Root Tree	38
2.2.1.1	<i>Graph of Markings</i>	38
2.2.1.2	<i>Coverability Root Tree</i>	39
2.2.2	Linear Algebra	42
2.2.2.1	<i>Notations and Definitions</i>	42
2.2.2.2	<i>Fundamental Equation</i>	44
2.2.2.3	<i>Conservative Components & Marking Invariants</i>	46
2.2.2.4	<i>Repetitive Components & Firing Invariants</i>	49
2.2.2.5	<i>Seeking P-invariants and T-invariants</i>	50
2.2.3	Reduction Methods Preserving Some Properties	52
2.2.4	Other Results	53
2.2.4.1	<i>Strongly Connected Event Graphs</i>	53
2.2.4.2	<i>Siphons and Traps</i>	54
2.2.4.3	<i>Liveness Related to Other Properties</i>	56
2.2.5	Concluding Remarks	57
2.2.5.1	<i>Structuring</i>	57
2.2.5.2	<i>Analysis Software</i>	59
	NOTES and REFERENCES	59
3	Non-Autonomous Petri Nets	61
3.1	INTRODUCTION	61
3.2	SYNCHRONIZED PETRI NETS	63
3.2.1	Principle	64
3.2.1.1	<i>Basic Behaviors and Concepts</i>	64
3.2.1.2	<i>Illustrative Examples</i>	67
3.2.1.3	<i>Simultaneous Events</i>	69
3.2.2	Iterated Firing On Occurrence of an External Event	70
3.2.2.1	<i>Elementary Firing Sequence</i>	70
3.2.2.2	<i>Iterated Firing</i>	73
3.2.2.3	<i>Coverability root tree of the stable reachable markings</i>	75
3.2.3	Properties of the Synchronized PNs	79
3.2.3.1	<i>Promptness or Stability</i>	79
3.2.3.2	<i>Boundedness, Safeness, Liveness, Deadlock-Freeness</i>	82
3.2.3.3	<i>Environment</i>	86
3.3	INTERPRETED PETRI NETS	88
3.3.1	Definition of a Control Interpreted Petri Net	89

3.3.2	Interpretation Algorithm of a Control Interpreted PN	93
3.3.3	Interpreted PN Without Outputs: Generalization of the Concept of Synchronized PN	96
3.4	TIMED PETRI NETS	98
3.4.1	General Information	98
3.4.2	Constant Timing	101
3.4.2.1	<i>P-Timed Petri Nets</i>	101
3.4.2.2	<i>T-Timed Petri Nets</i>	103
3.4.2.3	<i>Stationary Behavior</i>	107
3.4.3	Stochastic Petri Nets	109
3.4.3.1	<i>Basic Model</i>	109
3.4.3.2	<i>Generalized Stochastic Petri Net</i>	112
3.4.3.3	<i>Analysis and Simulation of Stochastic PNs</i>	113
	NOTES and REFERENCES	114
4	Autonomous Continuous and Hybrid Petri Nets	117
4.1	MOTIVATION	117
4.2	AUTONOMOUS CONTINUOUS PETRI NETS	119
4.2.1	From Discrete Petri Net To Continuous Petri Net	119
4.2.2	Definition	121
4.2.3	Reachability and Conflicts	123
4.2.3.1	<i>Reachability Graph</i>	124
4.2.3.2	<i>Firing Sequence and Reachability Space</i>	126
4.2.3.3	<i>Conflicts</i>	128
4.2.4	Comments about units	129
4.3	AUTONOMOUS HYBRID PETRI NETS	130
4.3.1	Intuitive presentation	131
4.3.2	Definition	134
4.3.3	Reachability and conflicts	137
4.3.3.1	<i>Reachability Graph</i>	137
4.3.3.2	<i>Firing Sequence and Reachability Space</i>	141
4.3.3.3	<i>Conflicts</i>	142
4.4	PROPERTIES OF AUTONOMOUS CONTINUOUS AND HYBRID PETRI NETS	143
4.4.1	Definitions and Properties Similar for Discrete and Continuous Petri Nets	143
4.4.1.1	<i>Definitions</i>	143
4.4.1.2	<i>Properties</i>	144
4.4.2	Reachability and Limit Reachability for a Continuous PNs	145
4.4.3	ϵ -Liveness for a Continuous Petri Net	148
4.4.4	Lim-Liveness for a Continuous Petri Net	149
4.4.5	Properties for a Hybrid Petri Net	151
4.4.5.1	<i>Similar Definitions and Properties</i>	151
4.4.5.2	<i>Reachability and Liveness</i>	151
4.4.5.3	<i>Incidence Matrix</i>	152

4.5	EXTENDED HYBRID PETRI NETS	153
4.5.1	Threshold Test	153
4.5.2	Zero Test and Arc Weight 0^+	154
4.5.3	Marking 0^+	156
4.5.4	Definition	157
	NOTES and REFERENCES	158
5	Timed Continuous Petri Nets	159
5.1	DEFINITION OF THE MODEL	159
5.1.1	Limit Case of a Discrete Timed Petri Net	160
5.1.2	Analysis of Some Basic Behaviors	161
5.1.2.1	<i>Sequences of Transitions, Same Maximal Speeds</i>	162
5.1.2.2	<i>Sequences of Transitions, Different Maximal Speeds</i>	166
5.1.2.3	<i>Synchronization</i>	169
5.1.2.4	<i>Timed Continuous Petri Net With a Circuit</i>	170
5.1.2.5	<i>Infinite Maximal Speed</i>	172
5.1.3	Definitions	174
5.1.3.1	<i>Definition and Notation</i>	174
5.1.3.2	<i>Enabling</i>	175
5.1.3.3	<i>Balance</i>	177
5.1.3.4	<i>Evolution Graph</i>	179
5.2	CONFLICTS	180
5.2.1	Existence of an Actual Conflict	180
5.2.2	Conflict Resolution	182
5.3	SPEED CALCULATION ALGORITHMS	184
5.3.1	There is No Structural Conflict	185
5.3.2	Resolution By Priorities	187
5.3.2.1	<i>Expected Results And Problems To Be Solved</i>	187
5.3.2.2	<i>Setting Up the Set of Surely Firable Transitions</i>	191
5.3.2.3	<i>Algorithm And Application</i>	195
5.3.3	Resolution By Sharings And Priorities	200
5.3.3.1	<i>Single Sharing Between Two Transitions</i>	200
5.3.3.2	<i>One or Several Sharings Among Transitions</i>	203
5.3.3.3	<i>Algorithm</i>	208
5.3.4	Complete Algorithm For All IB-states	213
5.4	PROPERTIES	216
5.4.1	Illustratory Examples	216
5.4.1.1	<i>A Simple Production System</i>	216
5.4.1.2	<i>About Marking 0^+</i>	218
5.4.2	General Properties	220
5.4.3	Modeling Power	223
5.5	MAXIMAL SPEEDS FUNCTIONS OF TIME	225
	NOTES and REFERENCES	227

6 Timed Hybrid Petri Nets	231
6.1 DEFINITION OF THE MODEL	231
6.1.1 Flow Rate and Maximal Firing Speed	232
6.1.2 Illustrative Example	235
6.1.3 Events To Be Considered	237
6.1.4 Conflict Resolutions	238
6.1.5 Formal Definitions	241
6.1.5.1 <i>Definition and Notations</i>	241
6.1.5.2 <i>Enabling in Timed Hybrid Petri Nets</i>	243
6.1.5.3 <i>Evolution Graph</i>	246
6.2 ALGORITHM	248
6.2.1 Resolution for a Case 4 Conflict	249
6.2.1.1 <i>Resolution by Priority</i>	249
6.2.1.2 <i>Resolution by Sharing</i>	251
6.2.1.3 <i>Algorithmic Resolution</i>	253
6.2.2 Consequences of Various Events	254
6.2.3 Timed Hybrid PNs Automatically Treated in Algorithm 6.1	256
6.2.3.1 <i>Hybrid PN Restricted to a Continuous PN</i>	256
6.2.3.2 <i>Consistency of Resolution Rules</i>	258
6.2.4 Algorithm for Building the Evolution Graph	262
6.2.5 Resolution of a Case Not Treated by Algorithm 6.1	268
6.3 VARIANTS OF THE MODEL	269
6.3.1 Synchronized D-Transitions	270
6.3.2 Stochastic Timings for D-Transitions	273
6.3.3 Hybrid Petri Nets with Time Transitions	274
6.3.4 C-Transitions with Flow Rates Functions of Time	275
6.3.5 Colored Hybrid Petri Net	277
6.4 EXTENDED TIMED HYBRID PETRI NETS	278
6.4.1 Modeling of Zero Buffers	279
6.4.2 Arc Weight 0* for Testing if a C-Place is Empty	282
6.4.3 Pure Delay of a Continuous Flow	285
6.4.3.1 <i>Simple Conveyor</i>	285
6.4.3.2 <i>Various Behaviors of a Conveyor</i>	288
6.4.3.3 <i>Fluid Example</i>	291
6.4.4 Conclusion on Timed Extended Hybrid Petri Nets	292
NOTES and REFERENCES	293
7 Hybrid Petri Nets with Speeds Depending on the C-Marking	295
7.1 APPROXIMATION OF TIMED DISCRETE SYSTEMS BY VHPNs	295
7.1.1 Weakness of Basic Timed Hybrid PNs for Small Numbers	296
7.1.2 Simple Cases of Variable Speed Hybrid PN	297
7.1.3 General Case of VHPN	301
7.1.3.1 <i>Conflicts</i>	301
7.1.3.2 <i>Definition of the Model</i>	303
7.1.3.3 <i>Properties</i>	308

7.1.4 Application Examples	310
7.1.4.1 Example 1	310
7.1.4.2 Example 2	312
7.2 ASYMPTOTIC HYBRID PETRI NETS (AHPNs)	316
7.2.1 A C-Transition Has a Single Input C-Place	316
7.2.1.1 Constant Feeding Speed of Input C-Place	316
7.2.1.2 Change of Feeding Speed of the Input C-Place	319
7.2.2 Several Input C-Places	321
7.2.3 Generalization	323
7.2.4 Differences Between VHPN and AHPN Behaviors	326
7.3 OTHER MODELS	330
7.3.1 Liquid Flow	330
7.3.2 Differential Hybrid Petri Nets	331
7.3.3 Transfer Line with Operation-Dependent Failures	335
NOTES and REFERENCES	336
Postface	339
Appendices	345
A Regular Expressions and Languages	345
B Conflict Resolution	347
C Elements of Graph Theory	351
D Algebra of Events	353
E About Grafcet	357
F Modeling Power of Synchronized Petri Nets	363
G Timed PNs Are Special Cases of Synchronized Petri Nets	365
H Time Petri Nets	371
I Linearity of the Fundamental Equation for Continuous Petri Nets	375
J Notation 0^* and Non-Standard Analysis	379
K Sharing Between Two Transitions	381
L Graph of Relations Among Conflicts	387
M Piecewise Constant Maximal Speeds	391
N From Hybrid Petri Nets to Hybrid Automata	399
O P&T-Timed Petri Nets and Modeling Power	405
Exercises	411
Solutions to Exercises	453
References	525
Index	541