

Contents

1	Introduction	1
1.1	Digitization, Digitalization and Digital Transformation	3
1.2	Problem Statement and Vision	4
1.3	Thesis outline	6
2	Simulation in Construction Management	9
2.1	The Simulation	9
2.2	Types of Simulation Methods and Models	12
2.2.1	Network Scheduling Techniques	12
2.2.2	Petri Nets	17
2.2.3	Monte-Carlo Simulation	19
2.2.4	Agent Based Simulation	19
2.2.5	Continuous Simulation	20
2.2.6	Discrete Event Simulation	22
2.2.7	Surrogate Models	24
2.3	General Purpose Simulation Frameworks in the Construction Industry	29
2.3.1	CYCLONE – A Popular GPS Framework	30
2.3.2	GPS Frameworks Inspired by CYCLONE	33
2.4	Special Purpose Simulation Frameworks in Tunneling and Injection Grouting	37
2.4.1	SPS for Utility Tunneling	38
2.4.2	Decision Aids for Tunneling (DAT)	39
2.4.3	Interaction Modeling in Mechanized Tunneling (SFB 837)	41
2.4.4	Other Simulation Based Tools and Techniques	42
2.5	Research Gaps	43
3	Motivation and Objectives	45
4	Methodological Framework	47
4.1	Statistics	47
4.1.1	Probability Density Function	47
4.1.2	Cumulative Distribution Function	48
4.1.3	Statistical Measures	49
4.2	Monte-Carlo Method	51
4.2.1	Law of Large Numbers	52
4.2.2	Central Limit Theoreme	52
4.2.3	Mone-Carlo Simulation	54
4.3	Markov Chains	54
4.3.1	Properties	55

4.3.2	Calculating with Markov Chains	56
4.3.3	Markov-Chain Monte-Carlo Simulation	57
4.4	Graph Theory	57
4.4.1	Types of Graphs and their Sub-Structures	58
4.4.2	Transitive Hull	60
4.4.3	Searching in Graphs	61
4.5	Numerical Optimization	63
4.5.1	Evolutionary Algorithms	64
4.5.2	Single-Objective Genetic Algorithms	64
4.5.3	Multi-Objective Genetic Algorithm	68
4.5.4	Mixed-Integer Genetic Algorithm	70
4.6	Deep Learning	70
4.6.1	Structure of Artificial Neural Networks	71
4.6.2	Training Artificial Neural Networks	73
5	Digitalization of Construction Site	77
5.1	Description of Construction Site “Tunnel Feuerbach”	78
5.1.1	Local Geology and Anhydrite Swelling	79
5.1.2	Anhydrite Concept	81
5.1.3	Process of radial injection grouting (measure no. 3)	83
5.1.4	Digitization of Injection Process	87
5.2	Selection of Input Data	89
5.3	Data Cleaning	91
5.3.1	Merging of Split Processes	91
5.3.2	Time Gaps	92
5.3.3	Very Short Processes	93
5.3.4	Adding and Correcting Location Tags	93
5.3.5	Identification and Labeling of Maintenance Processes	94
5.3.6	Identification and Labeling of IDLE Processes	94
5.4	Transformation of Data	95
5.4.1	The Data Structure: <code>strucData</code>	95
5.4.2	The Data Structure: <code>strucBores</code>	96
5.5	Data Mining	97
5.5.1	Axes and Tunnel Tube Identifiers	97
5.5.2	Number of Instances and Total Durations of Processes	98
5.5.3	Muda Analysis	99
5.5.4	Distribution of Processes over a 24h Workday	101
5.5.5	Process Duration	103
5.5.6	Machine Location in Tunnel	106
5.5.7	Number of Injections and Process Duration per Day	107
5.5.8	Number of Injections and Grout Volume per Borehole	108
5.5.9	Grout Volume vs. Injection Time	117
5.6	Grout Volume Forecast	121
5.6.1	Forecast with Cross-Correlation Analysis	121
5.6.2	Forecast with Stochastic Model	124

5.6.3	Forecast with Artificial Neural Networks	130
5.6.4	Discussion of Results of the Presented Grout Volume Forecast Methods	140
6	Project Duration Forecast	141
6.1	Time-Discrete Single Server Model (SSPS)	141
6.1.1	Model	141
6.1.2	Sampling and Forecast	148
6.1.3	Dealing with Insufficient Samples	149
6.1.4	Discussion of Results	150
6.2	Time-Discrete Multi-Server Model for AC Units (MSPS)	150
6.2.1	Model	151
6.2.2	Integration of Monte-Carlo Method	153
6.2.3	Wording for Sample Size and Forecast Duration	153
6.2.4	GBPlan Implementation	153
6.3	Discussion of Results	153
6.3.1	Convergence of Monte-Carlo Simulation	154
6.3.2	Total Project Time Forecast	156
6.3.3	Partial Project Time Forecast	159
6.3.4	Summary of Results	164
7	Pareto Optimization Under Consideration of Collaboration of Injection Units	165
7.1	Time-Discrete Model for AC & PU Units (MSPS2)	166
7.1.1	General Structure	167
7.1.2	Scenarios	167
7.1.3	AC-PU Interaction	168
7.1.4	Cost Function	171
7.1.5	Source Code Optimization	171
7.1.6	Genetic Multi Objective Optimization	172
7.1.7	GBPlan Implementation	176
7.2	Project Cost Model	176
7.2.1	Size of Machine Park	177
7.2.2	Number of Workers	178
7.2.3	Wage Costs	181
7.2.4	Machine Costs	182
7.2.5	Material and Energy Costs	184
7.2.6	Support Material	185
7.2.7	Delay Costs	186
7.2.8	Costs of Opportunity	186
7.2.9	GBPlan Implementation	187
7.3	Discussion of Results	187
7.3.1	Optimization of the Number of Injection Units	188
7.3.2	Optimization of Injection Unit Deployment Date	191

8	Pareto Optimization of Project Time and Cost in Confined Working Environment	199
8.1	Time- and Location Discrete Model (MSPS3)	199
8.1.1	General Design Pattern: The Model-View-Controller	200
8.1.2	Model of Project	203
8.1.3	Model of Tunnel	203
8.1.4	Model of Machine	207
8.1.5	Model of Time	208
8.1.6	Model of KPIs	208
8.2	Algorithms for the Time- and Location Discrete Model	210
8.2.1	Basic Program Sequence	210
8.2.2	Path Search and Traffic Rules	212
8.2.3	Obstruction and Shifting	213
8.2.4	Calculation of Project Cost	215
8.3	Discussion of Results	215
8.3.1	Simulation Scenario	215
8.3.2	Computation Time	216
8.3.3	Structure of Result Diagrams and Tables	217
8.3.4	Project Duration-Cost Analysis	218
8.3.5	Project Duration-Shunt Duration Analysis	221
8.3.6	Project Cost-Shunt Duration Analysis	225
8.3.7	Summary	228
9	Summary and Outlook	229
9.1	Summary	229
9.2	Outlook	234
	Bibliography	237
	Appendix A Notation	273
	Appendix B List of Abbreviations	277
	Appendix C Tables and Figures	281
C.1	Status Diagrams of Construction Site	281
C.1.1	Position of Injection Units in Time-Location Diagram	281
C.1.2	Duration of Different Process Types per Day	283
C.2	Result Tables of Artificial Neural Network Grout Volume Forecast	287
C.3	MSPS1 Result Histograms of Monte-Carlo Simulation	290
C.4	MSPS1 Result Diagrams of Total Project Time Forecast	297
C.4.1	Total Project Time Forecast for Tube 251H, GEA1	297
C.4.2	Total Project Time Forecast for Tube 251H, GEA2	300
C.4.3	Total Project Time Forecast for Tube 251H, GEA3	303
C.4.4	Total Project Time Forecast for Tube 251H, GEA1-3	306
C.4.5	Total Project Time Forecast for Tube 258H, GEA2	309
C.4.6	Total Project Time Forecast for Tube 258H, GEA3	312

C.4.7	Total Project Time Forecast for Tube 258H, GEA1-3	315
C.5	MSPS1 Result Diagrams of Partial Project Time Forecast	318
C.5.1	Partial Time Forecast, Sample Size $s = 500$, Tube 258H, GEA1-3 .	318
C.5.2	Partial Time Forecast, Sample Size $s = 1000$, Tube 258H, GEA1-3 .	321
C.5.3	Partial Time Forecast, Sample Size $s = 1500$, Tube 258H, GEA1-3 .	324
C.5.4	Partial Time Forecast, Sample Size $s = 3000$, Tube 258H, GEA1-3 .	327
C.5.5	Partial Time Forecast, Sample Size $s = 4000$, 258H, GEA1-3	330
C.6	MSPS3 Result Tables	333
C.7	Parameter Settings of MATLAB Optimization Algorithm	336
C.8	Hardware and Software Specifications	336
Appendix D Company Presentations		339
D.1	Renesco GmbH	339
D.2	eguana GmbH	340
Appendix E Pre-Publications		341