

TABLE OF CONTENTS

Abstract	III
Acknowledgements	IV
Dedication	V
Table of Contents	VI
List of Figures.....	X
List of Tables.....	XV
List of Abbreviations.....	XVI
1. Introduction	1
1.1 Motivation and Problem Statement	1
1.2 Aim and Research Questions.....	3
1.3 Methodology	4
1.3.1 Testing Methods.....	4
1.3.2 Ex-Ante Evaluation and Expected Results	6
1.4 Structure of the Thesis	6
2. State-of-the-Art.....	8
2.1 Earth Pressure Balanced Tunnel Boring Machines	8
2.1.1 Functionality of EPB TBMs.....	8
2.1.2 Geotechnical Range of EPB Application	10
2.1.3 EPB Main Drive and Main Bearing.....	12
2.1.4 EPB operation, Main Drive Torque and Main Drive Speed	15
2.2 First Torque Estimation Approaches for Hard Rock TBMs.....	17
2.3 Empirical Torque Estimation Approach for EPB TBMs.....	18
2.4 Theoretical Torque Estimation Approaches for EPB TBMs	18
2.5 Challenges of Main Drive Torque Estimation.....	22
2.5.1 The problem with the empirical approach.....	22
2.5.2 The problem with theoretical approaches	23
2.5.3 Main Drive Utilization	28
2.6 Machine Learning for TBM performance prediction	29
3. Impact Factors and Reciprocal Effects	31
3.1 Design Related Impact Factors.....	31
3.1.1 Excavation Process	31
3.1.2 System Immanent Factors	34

3.2	Tribological Impact Factors	35
3.2.1	Friction	35
3.2.2	Solid Contact and Lubrication.....	36
3.2.3	Adhesion	39
3.2.4	Wear	41
3.2.5	Temperature	42
3.3	Geotechnical Impact Factors.....	43
3.4	Reciprocal Effects	45
3.4.1	Impact of Rheology.....	45
3.4.2	Impact of Operation Mode.....	46
3.4.3	Impact of Tilting Moment.....	46
4.	Machine Learning Approach	48
4.1	Software Tools for Statistical Analyses and Machine Learning	49
4.2	Workflow of Machine Learning Approach	50
4.3	Data Collection and Set-Up of Database.....	52
4.3.1	Reference Projects.....	52
4.3.2	Database	53
4.3.3	Types of Data and Variable Encoding	54
4.3.4	TBM Design Data	55
4.3.5	Geotechnical Data	55
4.3.6	TBM Operational Data.....	56
4.3.7	Virtual Sensors	59
4.4	Data Preparation and Feature Engineering.....	61
4.4.1	Descriptive Statistics.....	61
4.4.2	Data Cleaning and Noise Reduction	62
4.4.3	Missing Values	62
4.4.4	Outliers	63
4.4.5	Standardization and Normalization.....	63
4.4.6	Dimensionality Reduction.....	64
4.4.7	Modification of Frequency Distribution	64
4.5	Pattern Recognition and Clustering	65
4.5.1	Hierarchical Clustering.....	65
4.5.2	K-Means Clustering.....	65
4.5.3	Artificial Neural Networks	66

4.6	Feature Selection.....	66
4.6.1	Pearson’s and Spearman’s Coefficient of Correlation.....	67
4.6.2	RreliefF Algorithm.....	68
4.6.3	Neighbourhood Component Analysis – NCA.....	68
4.7	Training and Testing of Machine Learning Models.....	69
4.8	Selection of Predictive Machine Learning Algorithms	71
4.8.1	Regression Models.....	71
4.8.2	Support Vector Machines.....	72
4.8.3	Decision Trees.....	73
4.8.4	Tree Ensembles.....	73
4.8.5	Gaussian Process Regression.....	74
4.9	Model Evaluation	75
4.9.1	Evaluation Metric	75
4.9.2	Cost Function	76
4.9.3	Residual Analysis.....	77
4.9.4	Model Validation	78
4.9.5	Accuracy - Interpretability Trade-off.....	78
4.9.6	Bias - Variance Trade-off	78
4.9.7	Robustness - Tidiness Trade-off	79
4.10	Sensitivity Analysis	80
5.	Results and Machine Learning Process.....	82
5.1	Results of State-of the-Art Analyses.....	82
5.2	Results of Impact Factor and Reciprocal Effect Analyses.....	84
5.3	Results of Machine Learning Modelling.....	91
5.3.1	Results of Data Preparation and Feature Engineering	91
5.3.2	Results of Pattern Recognition and Clustering.....	110
5.3.3	Results of Feature Selection	115
5.3.4	Results of Sensitivity Analysis.....	119
5.3.5	Results of Residual Analysis.....	120
5.3.6	Results of Model Validation.....	125
5.4	Maximum Torque Evaluation	129
5.5	Predictive Model for Main Drive Torque Estimation	133
6.	Risks and Limitations.....	135

7. Conclusion and Outlook	136
References.....	139
Appendix A 1 – Project Overview Reference Project A.....	153
Appendix A 2 – Project Overview Reference Project B.....	154
Appendix A 3 – Project Overview Reference Project C.....	155
Appendix A 4 – Project Overview Reference Project D	156
Appendix A 5 – Project Overview Reference Project E	157
Appendix A 6 – Project Overview Reference Project F	158
Appendix A 7 – Project Overview Reference Project G	159
Appendix A 8 – Project Overview Reference Project H	160
Appendix A 9 – Project Overview Reference Project I.....	161
Appendix A 10 – Project Overview Reference Project J.....	162
Appendix A 11 – Project Overview Reference Project K.....	163
Appendix A 12 – Project Overview Reference Project L	164
Appendix B 1 – Results Data Preparation – Cleaned Data.....	165
Appendix B 2 – Results Data Preparation – Standardized Data.....	166
Appendix B 3 – Results Data Preparation – Outlier 2 Std. Dev. from Median.....	167
Appendix B 4 – Results Data Preparation – Outlier 3 Std. Dev. from Mean.....	168
Appendix B 5 – Results Data Preparation – 15-fold cross validation.....	169
Appendix B 6 – Results Data Preparation – Log Transformed Target Value.....	170
Appendix B 7 – Results Data Preparation – PCA on Standardized Data	171
Appendix C 1 –Performance Selected Features – Pearson’s Coefficient.....	172
Appendix C 2 –Performance Selected Features – Spearman’s Coefficient	173
Appendix C 3 –Performance Selected Features – RreliefF, k=10.....	174
Appendix C 4 –Performance Selected Features - NCA.....	175
Appendix C 5 –Performance Selected Features – Manual Selection	176
Curriculum Vitae.....	CLXXVII