## CONTENTS

List of Abb	List of Abbreviations		
1. Introdu	ction	1	
1.1 Init	ial Situation	1	
1.2 Pro	blem Identification	3	
1.3 Obj	ectives	6	
1.4 The	matic Classification of the Dissertation	7	
1.5 Exp	perience and Background of the Author	8	
1.6 Stru	acture of the Dissertation	9	
2. Researc	h Methodology and Approach	13	
2.1 Res	earch Methodology	13	
2.2 Res	earch Approaches	14	
2.3 Des	ign Research Methodology	14	
2.4 Me	thodology and Approach Designed for this Dissertation	15	
3. Termin	ology	19	
3.1 Cog	gnitive Functions	19	
3.1.1	Definitions of Function in the Engineering Design Literature	20	
3.1.2	Conclusions from the Function Definitions in Literature	22	
3.1.3	Definition of Cognitive Function	24	
3.2 Co	gnitive Products	26	
3.2.1	Definition of Product	26	
3.2.2	Definition of Cognitive Product	27	
4. Backgr	ound	29	
4.1 Dev	velopment of Cognitive Products	29	
4.1.1	Paradigms and Viewpoints of Cognition	30	
4.1.2	Development Approaches of Cognitive Products	31	
4.1.3	Cognitive Functions in Engineering Design	32	



	4.1.4	Procedural Models for the Development of Cognitive Products	34
	4.1.5	Cognitive Architectures	39
	4.1.6	Models and Methods for the Development of Cognitive Products	43
	4.2 1	ndividuals of the Cognitive Product Class	49
	4.2.1	Mechatronic Systems	49
	4.2.2	Adaptable Products	50
	4.2.3	Smart Products	52
	4.2.4	Cyber-Physical Systems	53
	4.2.5	Internet of Things and Services	53
	4.2.6	Self-Optimizing Systems	54
	4.2.7	Cognitive Technical Systems	55
	4.3	Functional Modeling and Formal Function Representation	56
	4.3.	Functional Modeling in Engineering Design	56
	4.3.2	Functional Modeling in Different Domains	57
	4.3.	Formal Representation in Functional Modeling	58
	4.4	Research Clarification	58
	4.4.	Research Gaps	59
	4.4.	2 Research Questions	61
	4.4.	B Research Goals	64
5.	Ana	ysis of Cognitive Product Development Approaches	67
	5.1	New Cognitive Product Development in Student Classes	68
	5.2	Testing the Applicability of the Reconciled Functional Basis to Model a Mechatronic Product	88
	5.3	Analysis of Development Approaches for Cognitive Products in Academic Research Projects	92
	5.4	Analysis of Cognitive Functions in Literature	111
	5.5	Analysis of Flows among Cognitive Functions in Literature	116
	5. <b>6</b>	Discussing and Relating the Previous Findings	120
	5.7	Conclusion	121
6.	Sup	porting the Development of Cognitive Products	125
	6.1	Support Outline	126

	6.1	.1	Scope of the Support	127
6.1.2 Rec		.2	Requirements to Improve the Existing Situation	12 <b>8</b>
	6.2	Crea	ating a Taxonomy of Cognitive Functions	130
	6.3	For	nal Functional Modeling of Cognitive Products	134
6.4 Procedural Model for the I		Pro	cedural Model for the Development of Cognitive Products	13 <b>8</b>
	6.5	Met	hod to Systematically Integrate Cognitive Functions into Product Concepts	141
	6.6	Cor	clusion	159
7.	Ini	tial H	Evaluation of the Developed Support	161
	7.1	Goa	ls of the Evaluation	162
	7.2	Eva	luation Approach	162
	7.3	Pilo	t Studies of the Initial Functional Modeling Approaches	164
	7.3	8.1	Retrospective Functional Modeling of a Coffee Robot Waiter	164
	7.3	3.2	Integration of Cognitive Functions into a Washing Machine	169
	7.3	3.3	Discussion	176
	7.4	App to S	olication of the Development Models and Methods upport Cognitive Product Development in two Case Studies in Industry	176
	7.4	l.1	Case Study 1: Smart Tools	177
	7.4	1.2	Case Study 2: Cognitive Capital Good for the Automation Industry	1 <b>96</b>
	7.4	1.3	Discussion	202
	7.5	Exp	pert Evaluation of the Developed Support	203
	7.6	Cor	nclusions from the Initial Support Evaluation	206
7.6.1		5.1	Verification	207
7.6.2		5.2	Validation	210
	7.6	5.3	Conclusion	212
8	. Re	flecti	ion	215
	<b>8</b> .1	Res	earch Contributions	215
	8.2	Lin	nitations	220
	8.3	Imp	olications for Industry	222
	8.4	Imp	plications for Research	223
9	. Su	mma	ary and Outlook	225
	9.1	Sur	nmary	225

9.2	Outlook	228
10. References		231
11. Ap	249	
11.1	Specific Questionnaire to Evaluate the PBL-Class	250
11.2	Questionnaire to Analyze the Development Approaches for Cognitive Products in Academic Research Projects	252
11.3	Results of the Diary Method used in Case Study 1	261
11.4	Questionnaire to Evaluate the Developed Support	263
11.5	Evaluation of the Questionnaire for Case Study 1	265
11.6	Evaluation of the Questionnaire for Case Study 2	267
11.7	Evaluation of the Questionnaire of the Expert Evaluation	269
12. Lis	st of Dissertations	273