

# TABLE OF CONTENTS

<b>CHAPTER 1 – INTRODUCTION</b>	<b>29</b>
1.1    The Pest Control Case Study . . . . .	32
1.2    The HLB Case Study . . . . .	34
1.3    Thesis Organization . . . . .	37
<b>CHAPTER 2 – THEORETICAL FOUNDATIONS</b>	<b>41</b>
2.1    Spatial Data Warehouse Design . . . . .	41
2.1.1    Conceptual Modeling . . . . .	41
2.1.1.1    Entity-Relationship Model and Unified Modeling Language .	42
2.1.1.2    Multidimensional Modeling . . . . .	43
2.1.1.3    Spatial Data . . . . .	44
2.1.1.4    Multidimensional and Spatial Data Cubes . . . . .	45
2.1.2    Logical Design . . . . .	46
2.1.2.1    Relational Databases . . . . .	47
2.1.2.2    Spatial Extensions of Database Management Systems . . . .	48
2.1.2.3    Relational Representation of Spatial Data Warehouses . . . .	49
2.1.3    Physical Design . . . . .	52
2.1.3.1    Bitmap Index and Bitmap Join Index . . . . .	52
2.1.3.2    Spatial Indices . . . . .	54
2.2    Uncertain Data Management . . . . .	59

2.2.1	Probabilistic Data . . . . .	60
2.2.1.1	Probabilistic Data Warehouses . . . . .	61
2.2.1.2	Probabilistic Spatial Data . . . . .	61
2.2.2	Fuzzy Data . . . . .	63
2.2.2.1	Fuzzy Data Warehouses . . . . .	63
2.3	Spatial Vagueness . . . . .	65
2.3.1	Exact Models for Spatial Vagueness . . . . .	67
2.3.1.1	Vague Spatial Data Types . . . . .	68
2.3.1.2	Vague Spatial Geometric Set Operators . . . . .	70
2.3.1.3	Vague Topological Relationships . . . . .	71
2.3.2	Fuzzy Models for Spatial Vagueness . . . . .	72
2.3.2.1	Fuzzy Spatial Data Types . . . . .	72
2.3.2.2	Fuzzy Spatial Operators . . . . .	76
2.3.2.3	Fuzzy Spatial Topological Relationships . . . . .	77
2.3.3	Implementations for Fuzzy Models . . . . .	78
2.3.3.1	Spatial Plateau Objects . . . . .	79
2.3.3.2	Lines with Gradual Transitions . . . . .	80
2.3.3.3	Bitmaps . . . . .	80
2.3.3.4	Triangulated Irregular Networks . . . . .	81
2.3.3.5	Fuzzy Minimum Bounding Rectangles . . . . .	81
2.3.4	Summary . . . . .	82
<b>CHAPTER 3 – RELATED WORK</b>		<b>85</b>
3.1	Conceptual Modeling and Logical Design of Spatial Data Warehouses . . . . .	85
3.1.1	The MultiDim Conceptual Model . . . . .	86
3.1.2	UML Profiles . . . . .	88
3.1.3	The Spatial Data Warehouse Metamodel . . . . .	90

3.1.4	Discussion . . . . .	91
3.2	Spatial Vagueness in Spatial Data Warehouses . . . . .	92
3.2.1	The Fuzzy Spatial Data Warehouse . . . . .	92
3.2.2	Conceptual Frameworks for Risk Assessment . . . . .	94
3.2.3	The RADSOLAP Method . . . . .	96
3.2.4	Discussion . . . . .	98
3.3	Indices for Spatial Data Warehouses . . . . .	99
3.3.1	aR-tree . . . . .	99
3.3.2	SB-index . . . . .	101
3.3.3	Discussion . . . . .	103
3.4	Indices for Vague Regions . . . . .	104
3.4.1	Vague R-tree . . . . .	104
3.4.2	FMBR R-tree . . . . .	105
3.4.3	Discussion . . . . .	107
3.5	Summary . . . . .	107

## **CHAPTER 4 – CONCEPTUAL DESIGN OF VAGUE SPATIAL DATA WAREHOUSES 111**

4.1	Conceptual Modeling of Vague Spatial Data Warehouses . . . . .	112
4.2	Attributes . . . . .	115
4.3	Hierarchies . . . . .	120
4.3.1	Hierarchy Operator . . . . .	120
4.3.2	Properties of Hierarchies . . . . .	123
4.3.3	Categories of Hierarchies . . . . .	126
4.4	Multidimensional Cube with Vague Spatial Data . . . . .	127
4.4.1	Dimensions . . . . .	127
4.4.2	Measures . . . . .	128
4.4.3	Cube . . . . .	128

4.4.4	Vague Spatial Fact . . . . .	130
4.4.5	Lattice of Cuboids . . . . .	132
4.5	Vague Spatial Predicates . . . . .	134
4.5.1	Spatial Range Queries . . . . .	135
4.5.2	The Vague Spatial Range Query . . . . .	138
4.6	Vague Spatial Aggregation Functions . . . . .	140
4.6.1	Vague Spatial Union . . . . .	140
4.6.2	Vague Spatial Intersection . . . . .	141
4.6.3	Vague Spatial Difference . . . . .	142
4.7	Vague Spatial Online Analytical Processing . . . . .	144
4.8	Reusing Existing Models and Implementations . . . . .	146
4.8.1	Arbitrary Geometries . . . . .	146
4.8.2	Bitmaps . . . . .	147
4.8.3	Triangulations . . . . .	147
4.8.4	Lines with Gradual Transitions . . . . .	150
4.9	The Vague Spatial MultiDim Conceptual Model . . . . .	151
4.9.1	Fundamentals . . . . .	152
4.9.1.1	Data Types . . . . .	152
4.9.1.2	Certitude and Dubiety . . . . .	154
4.9.1.3	Vague Topological Constraints . . . . .	154
4.9.2	Attributes, Levels and Members . . . . .	155
4.9.3	Dimensions and Hierarchies . . . . .	157
4.9.4	Fact and Measures . . . . .	160
4.10	Summary . . . . .	164

## **CHAPTER 5 – LOGICAL DESIGN OF VAGUE SPATIAL DATA WAREHOUSES 167**

5.1	Relational Representation of Vague Spatial Data Warehouses . . . . .	168
-----	--	-----

5.2	Implementations for the Vague Spatial Attribute . . . . .	170
5.2.1	Separate Tables for Certitude and Dubiety . . . . .	171
5.2.2	A Single Table for Certitude and Dubiety . . . . .	174
5.2.3	User Defined Types . . . . .	177
5.2.4	A Pair of Arrays . . . . .	179
5.2.5	One Multiple Geometry And One Array of Membership Values . . . . .	181
5.2.6	Monovalued Certitude and Monovalued Dubiety . . . . .	184
5.2.7	2D Geometry With Measure or 3D Geometry . . . . .	184
5.2.8	Discussion . . . . .	186
5.3	Vague Spatial Attribute . . . . .	187
5.4	Vague Spatial Level and Vague Spatial Member . . . . .	191
5.5	Hierarchies . . . . .	194
5.6	Fact and Vague Spatial Measure . . . . .	195
5.7	Vague Spatial Fact . . . . .	197
5.7.1	Relational Representation . . . . .	198
5.7.2	Numeric Measures and Crisp Spatial Measures . . . . .	199
5.7.3	Vague Spatial Measures . . . . .	201
5.7.4	Loading a Vague Spatial Fact Table . . . . .	205
5.7.5	Discussion . . . . .	206
5.8	Vague Topological Constraints . . . . .	208
5.8.1	Pairwise Evaluation of Sets of Topological Relationships . . . . .	208
5.8.2	Hierarchy . . . . .	211
5.8.3	Spatial Fact . . . . .	214
5.8.4	Intra Level and Intra Fact . . . . .	217
5.9	Vague Spatial Online Analytical Processing . . . . .	219
5.9.1	Accessors . . . . .	219

5.9.2	Vague Spatial Predicates . . . . .	222
5.9.3	Vague Spatial Aggregation Functions . . . . .	228
5.9.4	Slice-and-Dice, Roll-Up, and Drill-Down . . . . .	229
5.10	Summary . . . . .	231

## **CHAPTER 6 – PHYSICAL DESIGN OF VAGUE SPATIAL DATA WAREHOUSES 235**

6.1	Indexing Vague Spatial Data Warehouses . . . . .	235
6.2	Evaluation of a DBMS and of Indices for Spatial Data Warehouses . . . . .	237
6.2.1	Containment Range Queries against Vague Point Sets . . . . .	237
6.2.1.1	Workbench and Platforms . . . . .	238
6.2.1.2	Workload . . . . .	240
6.2.1.3	Results . . . . .	240
6.2.2	Intersection Range Queries against Vague Regions . . . . .	241
6.2.2.1	Workbench and Platforms . . . . .	242
6.2.2.2	Workload . . . . .	243
6.2.2.3	Results . . . . .	245
6.2.3	Vague Spatial Range Queries against Vague Regions . . . . .	246
6.2.3.1	Workbench and Platforms . . . . .	247
6.2.3.2	Workload . . . . .	247
6.2.3.3	Extending the SB-index . . . . .	249
6.2.3.4	Results . . . . .	249
6.2.4	Discussion . . . . .	250
6.3	The Vague Spatial Bitmap Index . . . . .	251
6.3.1	Maximum Area Inscribed Polygon . . . . .	252
6.3.2	Data Structure . . . . .	252
6.3.3	Building Operation . . . . .	253
6.3.4	Processing Queries containing Spatial Range Queries . . . . .	256

6.3.4.1	Filtering with a Conservative Approximation . . . . .	258
6.3.4.2	Filtering with a Conservative Approximation and a Progressive Approximation . . . . .	259
6.3.4.3	Particularities of Querying the Dubiety . . . . .	261
6.3.4.4	Calling the Procedures . . . . .	262
6.3.5	Processing Queries Containing a Vague Spatial Range Query . . . . .	264
6.3.5.1	Filtering with a Conservative Approximation . . . . .	266
6.3.5.2	Filtering with a Conservative Approximation and a Progressive Approximation . . . . .	268
6.3.5.3	Calling the Procedures . . . . .	270
6.4	Evaluation of the VSB-index . . . . .	271
6.4.1	Experimental Setup . . . . .	272
6.4.1.1	Workbench and Platforms . . . . .	272
6.4.1.2	Workload . . . . .	275
6.4.2	Intersection Range Queries over the Real Vague SDW . . . . .	276
6.4.2.1	IRQobject and IRQdubiety . . . . .	277
6.4.2.2	IRQcertitude . . . . .	278
6.4.3	Intersection Range Queries over the Synthetic Vague SDW . . . . .	280
6.4.3.1	IRQobject and IRQdubiety . . . . .	280
6.4.3.2	IRQcertitude . . . . .	282
6.4.4	Containment Range Queries over the Synthetic Vague SDW . . . . .	282
6.4.4.1	CRQobject and CRQdubiety . . . . .	283
6.4.4.2	CRQcertitude . . . . .	285
6.4.5	Vague Spatial Range Queries over the Synthetic Vague SDW . . . . .	285
6.4.5.1	Test Configurations . . . . .	286
6.4.5.2	Results . . . . .	287
6.4.6	Building Costs and Storage Requirements . . . . .	288

6.5 Summary . . . . .	290
<b>CHAPTER 7 – CONCLUSION AND FUTURE WORK</b>	<b>295</b>
<b>REFERENCES</b>	<b>301</b>
<b>GLOSSARY</b>	<b>317</b>
<b>APPENDIX A – USER-DEFINED FUNCTIONS</b>	<b>319</b>
<b>APPENDIX B – PROCEDURES OF THE VSB-INDEX</b>	<b>323</b>