# A Distributed Dynamic Simulation Mechanism for Buildings Automation and Control Systems

Proefschrift

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# Table of Contents

**SUMMARY** ........ **XXI**

**SAMENVATTING** ........ **XXIII**

**RESUME** ........ **XXV**

**PART I: BACKGROUND AND PROBLEM ANALYSIS** ........ **1**

**1. GENERAL INTRODUCTION** ........ **2**

1.1. A COMPREHENSIVE FRAMEWORK FOR AUTOMATED BUILDINGS ........ 3
1.2. HISTORICAL PERSPECTIVE ........ 6
1.3. TOOLS FOR ANALYSING BUILDING ENVIRONMENTAL CONTROL SYSTEMS ........ 8
1.4. RESEARCH OBJECTIVES AND METHODOLOGY ........ 9
1.5. THESIS OUTLINE ........ 10

**2. PROBLEM STATEMENT AND RESEARCH CONTEXT** ........ **12**

2.1. INTRODUCTION ........ 12
2.2. THE CHALLENGE OF BUILDING PERFORMANCE SIMULATION ........ 12
2.3. THE CHALLENGE OF ADVANCED CONTROL SYSTEMS IN BUILDINGS ........ 13
  *2.4.1. Formal Analysis of Existing Control Technologies in Buildings* ........ *14*
  *2.4.2. Modelling and Implementation Issues in Advanced Control Systems* ........ *17*
2.4. THE CHALLENGE OF RUN-TIME COUPLING DIFFERENT SIMULATION TOOLS ........ 18
2.5. THE CHALLENGE OF DISTRIBUTED CONTROL SYSTEMS IN BUILDINGS ........ 20
2.6. THE CHALLENGE OF BUILDING AUTOMATION AND CONTROL SYSTEMS ........ 21
    Data Communication in Automated Buildings ........ 22
    Real-Time Electricity Markets in Automated Buildings ........ 23
2.7. RESEARCH METHODOLOGY ........ 23
  *2.4.1. Systems Engineering and Its Applications* ........ *24*
  *2.4.2. Systems Engineering Process* ........ *26*
  *2.4.3. Context and Application* ........ *27*
  *2.4.4. The V lifecycle Model* ........ *28*
    Feasibility Studies ........ 29
    Concept of Operations Phase ........ 29
    System Requirements Phase ........ 30
    System Design Phase ........ 32
    Development and Implementation Phase ........ 34
    Testing and Integration Phase ........ 36
    System Verification and Validation ........ 38
    System operation and deployment ........ 42
  *2.4.5. Mapping the SE Process into the SDLC Diagram* ........ *44*
  *2.4.6. Trade-Off Analyses* ........ *45*
2.8. SUMMARY ........ 47

**3. STATE OF THE ART** ........ **48**

3.1. INTRODUCTION ........ 48
3.2. COUPLING AND DISTRIBUTED SYSTEMS ........ 49
  *3.4.1. Static and Dynamic Coupling* ........ *50*
  *3.4.2. Producer-Consumer Coupling* ........ *51*
  *3.4.3. Client-Server Coupling* ........ *51*
3.3. LITERATURE REVIEW ON SHARED DEVELOPMENT ........ 52
  *3.4.1. Data Model Integration* ........ *52*

*3.4.2. Data Model Interoperation* 52
Data Model Sharing 53
Data Model Exchange 53
*3.4.3. Process Based Model Interoperability* 53
*3.4.4. Process Oriented Cooperative Models* 56
3.4. CANDIDATE SE STANDARDS FOR DISTRIBUTED SYSTEMS SIMULATION 56
*3.4.1. Distributed Interactive Simulation* 57
*3.4.2. Synthetic Environment Data Representation and Interchange Specification* 58
*3.4.3. Aggregate Level Simulation Protocol* 58
*3.4.4. High-Level Architecture* 59
*3.4.5. AP-233: an International SE Standard for Data Exchange* 60
*3.4.6. EIA -632: Processes for Engineering a System* 60
3.5. OTHER POSSIBILITIES FOR SIMULATION IN DISTRIBUTED ENVIRONMENTS 61
*3.4.1. Parallel Discrete Event Simulation* 61
*3.4.2. Parallel Virtual Machine* 62
*3.4.3. Message Passing Interface* 62
3.6. BUILDING AUTOMATION AND CONTROL SYSTEMS: A REVIEW 62
*3.4.1. Advanced control systems* 63
*3.4.2. Distributed Control Systems* 65
*3.4.3. Building Control HVAC&R Equipment and Lighting Components* 66
*3.4.4. Multi-Agent Systems for Automated Buildings* 68
*3.4.5. Advanced Control and Systems Engineering* 69
3.7. SYSTEMS ENGINEERING IN THE BUILDING DOMAIN: A BRIEF REVIEW 70
3.8. CONCLUSION 71

**PART II: DESIGN APPROACHES AND APPLICATION CHARACTERIZATION 73**

**4. PROPOSED APPROACHES 74**

4.1. INTRODUCTION 74
4.2. GENERAL APPROACH 74
*4.4.1. ANSI/EIA-632 Application Guidelines* 77
4.3. APPLICATION CHARACTERIZATION 77
*4.4.1. Networked Control Systems in Automated Buildings* 78
*4.4.2. Integration of Control Systems in Building Performance Simulation* 80
*4.4.3. Distributed Control and Building Performance Simulation* 81
*4.4.4. Communication Systems for Automated Buildings* 83
*4.4.5. A Practical Approach to Representing BACS Technology in Simulation* 83
4.4. STRATEGY FOR INTEGRATING ADVANCED CONTROL SYSTEMS IN BUILDINGS 86
*4.4.1. Application of Hybrid Systems to Automated Buildings* 87
*4.4.2. Modelling and Analysis of Control Systems Using Hybrid Statecharts* 89
*4.4.3. Concepts for Analyzing and Designing MASs for Automated buildings* 91
*4.4.4. Concept of Designing HICAs for ABs* 92
*4.4.5. Formal Methodology for Verification and Validation of Hybrid Statecharts* 94
4.5. CONCLUSION 95

**5. RATIONAL DESIGN CRITERIA FOR RUN-TIME COUPLING 96**

5.1. INTRODUCTION 96
5.2. DETERMINATION OF REQUIREMENTS 96
*5.4.1. Concept of Operations* 96
*5.4.2. System Requirements* 98
5.3. DIFFERENT IPC MECHANISMS FOR RUN-TIME COUPLING 99
*5.4.1. Non-Distributed Communication Systems* 99
Use of Pipes 99
Use of Files 100
Use of Shared memory 100
System V 101
*5.4.2. Distributed System Technologies* 102

Sockets ..........102
Remote Procedure Call ..........104
Remote Method Invocation ..........104
Distributed Computing Environment ..........104
Distributed Component Object Model ..........105
.NET ..........105
Common Object Request Broker Architecture ..........105
5.4. RUN-TIME COUPLING AND CONTROL SYSTEM PERFORMANCE ANALYSIS ..........106
*5.4.1. Run-Time Coupling Quality of Service ..........106*
*5.4.2. Control System Quality of Performance ..........107*
*5.4.3. Communication Bandwidth versus Control Systems Performance ..........110*
*5.4.4. Choice of Time-Step in Simulation by Run-Time Coupling ..........110*
5.5. SELECTING AN IPC MECHANISM FOR RUN-TIME COUPLING ..........110
*5.4.1. Measuring Time ..........111*
*5.4.2. System Configuration ..........111*
*5.4.3. Performance Comparison ..........111*
Pipe Results ..........111
File Results ..........112
Shared Memory Results ..........113
Socket Results ..........114
CORBA Results ..........115
*5.4.4. Performance Analysis ..........116*
5.6. CLASSIFICATION OF DIFFERENT IPC MECHANISMS ..........116
5.7. CONCLUSION ..........117

**6. DEVELOPMENT AND IMPLEMENTATION ISSUES FOR RUN-TIME COUPLING ..118**

6.1. INTRODUCTION ..........118
6.2. SE IN THE DEVELOPMENT OF RUN-TIME COUPLING ..........118
6.3. DEVELOPMENT AND IMPLEMENTATION OF RUN-TIME COUPLING ..........121
*6.4.1. Network Sockets to ESP-r and Matlab/Simulink Bindings ..........122*
Interfacing Client Socket APIs to ESP-r ..........124
Interfacing Server Socket APIs to Matlab/Simulink ..........124
*6.4.2. System-Level Design of Run-Time Coupling ..........125*
Extension of Run-Time Coupling to Represent BACS Technology in Simulation ..........126
*6.4.3. Timing Characteristics of Run-Time Coupling ..........128*
6.4. TRANSLATING REQUIREMENTS SPECIFICATION TO IMPLEMENTATION ..........131
*6.4.1. Data Exchange and Representation in Normal Mode ..........131*
Data Exchange in Text Mode ..........131
Data Exchange in Binary Format ..........131
Experimental Studies on the Effects of Communication Time Delays on the Performance and Stability of Building Control Applications ..........133
*Experiments in a Homogeneous Environment* ..........134
*Experiments in Heterogeneous Environments* ..........136
Mathematical Formulation of Communication-based Control Systems ..........138
*6.4.2. Data Exchange and Representation in Real Mode ..........142*
Web-Services using XML and SOAP ..........143
Representation of Different Protocol Specifications ..........144
Implementation of Web-Services in Run-Time Coupling ..........145
Experimental Study of Data-Exchange Performance in XML Format ..........147
*6.4.3. Modes of Communication or Transmission in Run-Time Coupling ..........148*
Synchronous Mode ..........149
Asynchronous Mode ..........149
Partially Synchronous Mode ..........150
Experimental Results with a Building Control Application ..........151
*Standalone Simulation* ..........151
*Distributed Simulations* ..........152
*Performance Analysis* ..........155
*An Iterative Approach to Run-Time Coupling between ESP-r and Matlab/Simulink* ..........156
*Convergence in Asynchronous Mode* ..........157
*6.4.4. Types of Simulation by Run-Time Coupling ..........158*

Simulation of Continuous Control Systems 158
Simulation of Discrete Control Systems 159
Experimental Studies on Different Types of Simulation by Run-Time Coupling 159
Experiments with Distributed Simulations on Heterogeneous Environments 163
Experiments with Distributed Simulations on Grid Computing Environments 166
*6.4.5. Performance Enhancements 171*
Framework for Discrete Event Systems Specification/Run-Time Coupling Between ESP-r and Matlab/Simulink 171
System Entity Structure 172
*6.4.6. The Blackboard Model 173*
6.5. CONCLUSION 174

**7. VERIFICATION AND VALIDATION OF RUN-TIME COUPLING[*] 175**

7.1. INTRODUCTION 175
7.2. VERIFICATION AND VALIDATION 176
*7.4.1. Objectives and Goals 176*
*7.4.2. Dependability 177*
*7.4.3. Types of Errors in Distributed Control Systems 179*
*7.4.4. Rationale for a Generic V&V Methodology 180*
*7.4.5. Concept 182*
7.3. ROLE OF VERIFICATION AND VALIDATION IN SDLC 183
*7.4.1. Verification 183*
*7.4.2. Validation 184*
*7.4.3. Formal Methods 185*
7.4. MODELLING AND ANALYZING OF RUN-TIME COUPLING BETWEEN ESP-R AND MATLAB/SIMULINK USING PETRI NETS 186
*7.4.1. Brief Introduction to Petri Nets 187*
*7.4.2. Modelling with Ordinary Petri Nets 187*
*7.4.3. Modelling with Coloured Petri Nets 189*
*7.4.4. Dependability Modelling using Petri Nets 191*
Inversion of CPN Models 192
Application to Run-Time Coupling between ESP-r and Matlab/Simulink 193
Validating the Inversion of CPN Models 193
*7.4.5. Simulation Performance Results 193*
7.5. CONCLUSION 194

**PART III: INTEGRATION, APPLICATION AND SIMULATION OF ADVANCED CONTROL SYSTEMS IN BUILDINGS 196**

**8. INTEGRATION OF ADVANCED CONTROL SYSTEMS IN BUILDING PERFORMANCE APPLICATIONS 197**

8.1. INTRODUCTION 197
8.2. ANALYSIS AND SYNTHESIS OF NETWORK-BASED CONTROL SYSTEMS USING RUN-TIME COUPLING BETWEEN ESP-R AND MATLAB/SIMULINK 197
*8.4.1. Performance Comparison of Continuous, Discrete, and Network-Based Control Systems 197*
*8.4.2. Simulation Results 198*
*8.4.3. Discussion 200*
*8.4.4. Distributed Simulation between Matlab/Simulink and Multiple ESP-r(s) 200*
*8.4.5. Theoretical Analysis 201*
Time Delays Shorter Than One Sampling Period 202
Time Delay Longer Than One Sampling Period 202
8.3. DESIGN OF CONTROL SYSTEMS FOR BUILDING AND PLANT MODELS BY RUN-TIME COUPLING BETWEEN ESP-R AND MATLAB/SIMULINK 203
*8.4.1. Basic and Conventional Control Methods 203*
*8.4.2. Intelligent Control Methods 203*
*8.4.3. Modern Control Methods 203*

*8.4.4. Hybrid Control Systems ..... 204*
Continuous-Time and Discrete-Event Control Systems ..... 205
Hybrid Automaton ..... 206
Modelling Hybrid Statecharts ..... 207
Stability ..... 207
Verification ..... 208
Supervisory Control ..... 208
Intelligent Control ..... 208
Modern Control ..... 208
Application Example ..... 208
8.4. AUTOMATED BUILDINGS ..... 210
*8.4.1. Automation Tasks ..... 210*
*8.4.2. Application of Systems Engineering Practices in Design of Advanced Control Systems for Building Performance Applications ..... 210*
*8.4.3. Improvements in efficiency and productivity of buildings ..... 211*
8.5. MULTI-AGENT SYSTEMS ..... 211
*8.4.1. Overview ..... 211*
*8.4.2. Characteristics of Multi-Agent Systems ..... 211*
*8.4.3. Application of Multi-Agent Systems to Building Performance ..... 212*
8.6. MODELLING AND SIMULATION OF MULTI-AGENT SYSTEMS IN BUILDINGS ..... 212
*8.4.1. Reactive Agent ..... 214*
*8.4.2. Deliberative Agent ..... 215*
*8.4.3. Hybrid Intelligent Control Agent ..... 217*
*8.4.4. Discussion ..... 218*
8.7. APPROACH TO PEAK ELECTRICITY DEMAND MANAGEMENT ..... 218
8.8. DESIGN CONTROL STRATEGIES FOR BUILDING PERFORMANCE APPLICATIONS ..... 220
8.9. CONCLUSION ..... 221

**9. CASE STUDY: APPLICATION OF ADVANCED CONTROL SYSTEMS IN A REAL BUILDING ..... 222**

9.1. INTRODUCTION ..... 222
9.2. TEST-CELL FACILITY: CASE STUDY ..... 222
9.3. OBJECTIVE OF THE CASE STUDY ..... 225
9.4. SPECIFICATION COMPONENTS OF TEST-CELL ..... 225
*9.4.1. Double Skin Facade ..... 225*
Motorised windows ..... 225
Motorised Venetian Blinds ..... 226
Motorised Dampers ..... 226
*9.4.2. HVAC Equipment and Lighting Components ..... 226*
Airflow Supply ..... 226
Artificial Lighting ..... 226
Auxiliary Heating ..... 226
Auxiliary Cooling ..... 226
Humidifier ..... 226
*9.4.3. Functioning Mode of Test-cell Components ..... 226*
*9.4.4. Components of the Monitoring Room ..... 227*
Data Acquisition ..... 227
Computer ..... 227
9.5. APPLICATION OF ADVANCED CONTROL SYSTEMS ..... 227
*9.4.1. Analysis and Modelling ..... 227*
Test-cell Occupied ..... 228
*a) Thermal Comfort* ..... 228
Heating Mode ..... 228
Cooling Mode ..... 229
Humidification Mode ..... 230
Dehumidification Mode ..... 231
*b) Indoor Air Quality* ..... 232
Natural Ventilation ..... 244
Mechanical Ventilation ..... 247

Hybrid Ventilation ....................................................................................................250
*c) Visual Comfort*....................................................................................................251
Artificial Light Mode ....................................................................................................252
Natural Light Mode....................................................................................................252
*Principal reason of designing appropriate control systems for solar-shading devices*....................252
*Natural light*....................................................................................................253
*Sun's equations of motion* ....................................................................................................254
*Solar radiation on the facade*....................................................................................................256
*Visual Comfort*....................................................................................................257
*Work plane illuminance* ....................................................................................................260
*Active control strategy* ....................................................................................................260
*Thermal model for DSF with venetian blinds*....................................................................................................264
*Position of blinds* ....................................................................................................266
*Blade angle* ....................................................................................................267
*Daylight illuminance calculation*....................................................................................................270
Test-cell Unoccupied....................................................................................................275
*9.4.2. Design of Control Systems Based on a Hierarchical Concept*....................................275
*9.4.3. Synthesis of Automated Control Systems for Building Performance Applications*.......277
Matlab/Simulink and Stateflow....................................................................................................278
Design Method and Control for Large-Scale Building Performance Applications..................................279
Modelling and Synthesis ....................................................................................................280
9.6. EXPERIMENTAL RESULTS....................................................................................................284
*Winter period*....................................................................................................284
*Summer period*....................................................................................................287
*Discussions* ....................................................................................................289
9.7. CONCLUSION....................................................................................................290

**10. APPLICABILITY OF ADVANCED CONTROL SYSTEMS IN BUILDING PERFORMANCE SIMULATION ....................................................................................................292**

10.1. INTRODUCTION ....................................................................................................292
10.2. TEST-CELL CASE STUDY ....................................................................................................292
10.3. MODELLING APPROACH....................................................................................................293
*10.4.1. Modelling of the Test-cell and Its Double Skin Facade*...............................................294
*10.4.2. Modelling the Test-cell's Active Modes*....................................................................................................295
Modelling the Heating Mode....................................................................................................295
Modelling the Cooling Mode ....................................................................................................295
Modelling the Humidifying Mode....................................................................................................297
Modelling Artificial Light Mode....................................................................................................297
Modelling Mechanical Ventilation....................................................................................................297
*10.4.3. Modelling the Test-cell's Passive Modes* ....................................................................................................299
Modelling Natural Ventilation....................................................................................................299
Modelling Natural Light Mode....................................................................................................300
10.4. DESIGNING CONTROL SYSTEMS ON MATLAB/SIMULINK USING RUN-TIME COUPLING WITH ESP-R 301
10.5. ESP-R AND MATLAB USER INTERFACES FOR RUN-TIME COUPLING ...............................303
10.6. SIMULATION RESULTS ....................................................................................................305
*Winter period*....................................................................................................306
*Summer period*....................................................................................................308
*Discussion*....................................................................................................311
10.7. CONCLUSION....................................................................................................312

**11. GENERAL CONCLUSION ....................................................................................................313**

11.1. CONCLUSIONS ....................................................................................................313
11.2. RESEARCH RESULTS AND CONTRIBUTIONS ....................................................................................................316
11.3. RECOMMENDATIONS FOR FUTURE RESEARCH ....................................................................................................317

**APPENDIX A ....................................................................................................319**

SYSTEMS DEVELOPMENT LIFE CYCLE ....................................................................................................319
*Waterfall Model* ....................................................................................................*319*

*Spiral Model* .......... *319*
*Incremental Model* .......... *320*
*Agile/Extreme Model* .......... *320*

**APPENDIX B .......... 321**

ANSI / EIA-632 PROCESSES AND ACTIVITIES .......... 321

**APPENDIX C .......... 322**

DISTRIBUTED DYNAMIC SIMULATION MECHANISM .......... 322

**APPENDIX D .......... 326**

EXPERIMENTS WITH MULTIPLE INSTANCES OF ESPR IN PARALLEL AND DISTRIBUTED SIMULATIONS WITH MATLAB/SIMULINK .......... 326

**APPENDIX E .......... 338**

TEST-CELL SPECIFICATIONS .......... 338

**REFERENCES .......... 339**

# List of Figures and Tables

Figure 1.1. Energy consumption by end use in EU residential and tertiary buildings ............................3
Figure 1.2. A complete understanding of BACS functional aspects ........................................................5
Figure 1.3. CCS architecture (left) versus DCS architecture (right) .......................................................6
Table 1.1. Standards based AB protocols.................................................................................................7
Figure 1.4. Common framework of BACS architecture for third-generation ABs .................................9
Figure 2.1. Dynamic interactions among physical aspects and occupant comfort in a building............13
Table 2.1. Several important applications for existing control technologies used in building...............15
Figure 2.2. Control system using a simple heating coil (left) and its equivalent control diagram (right) .........................................................................................................................................16
Figure 2.3. PID control (left) and combined manual and PID control (right) ......................................18
Figure 2.4. A schematic view of shared task developments in integrated building simulation environments with external software packages and tools.............................................................19
Figure 2.5. Functional breakdown (or decomposition) of a complex control problem .........................20
Figure 2.6. General BACS architecture..................................................................................................21
Table 2.2. Most significant requirements for achieving BACS efficiency............................................22
Figure 2.7. From the V-diagram to the iterative, modular design .........................................................23
Figure 2.8. Evolution of the SE Standards .............................................................................................25
Figure 2.9. The ANSI/EIA-632 standard (processes for engineering a system) ...................................26
Figure 2.10. Enterprise-based lifecycle phases ......................................................................................27
Figure 2.11. Schematic diagram of the V lifecycle ................................................................................28
Figure 2.12. Process for establishing requirements discovery ..............................................................30
Figure 2.13. Relationships of requirements engineering........................................................................31
Figure 2.14. The generic framework: System concept (left) and building block (right)........................33
Figure 2.15. Functional decomposition of a system...............................................................................33
Figure 2.16. System-of-systems concept.................................................................................................34
Figure 2.17. SDLC (left) vs. interaction of systems and M&S concepts (right) ...................................35
Figure 2.18. Data flow testing................................................................................................................38
Figure 2.19. Technical evaluation processes..........................................................................................41
Figure 2.20. The simplest form of a requirements traceability matrix ..................................................41
Figure 2.21. A basic form of the HoQ structure.....................................................................................43
Figure 2.22. Trade-off analysis process, expanded from .......................................................................46
Figure 2.23. Example of a trade-off analysis table.................................................................................47
Figure 3.1. Schematic view of coupling with UML...............................................................................50
Figure 3.2. Integrated framework for managing knowledge across levels (or layers) of conceptual interoperability .......................................................................................................................54
Table 3.1. Overview of the LISI maturity model ...................................................................................55
Figure 3.3. A modern BACS architectural solution ...............................................................................63
Figure 3.4. The practical implementation of hierarchical layers in control systems .............................64
Figure 3.5. Different modes of a computer based control systems .......................................................65
Figure 3.6. Approach to managing the development of large-scale control systems .............................70
Figure 3.7. the view of a building as a system .....................................................................................71
Figure 4.1. A hierarchical approach to the systematic characterization of a distributed dynamic simulation mechanism for BACS....................................................................................................75
Figure 4.2. A 3D matrix integrating different knowledge skills in the design process ..........................76
Figure 4.3. A methodological approach to characterizing building control application.........................77
Figure 4.4. Typical structure of a networked (or distributed) building control system .........................78
Figure 4.5. Performance comparison of continuous, digital and networked control systems ................79
Figure 4.6. Closed loop building control application (or system) by run-time coupling between ESP-r and Matlab/Simulink..........................................................................................................80
Figure 4.7. Multiple closed-loop building zone, plant and flow control applications by run-time coupling between ESP-r and Matlab/Simulink ..............................................................................81

Figure 4.8. Conceptual architecture of distributed control and building performance simulation .........82
Figure 4.9.  Run-time coupling between ESP-r and Matlab/Simulink using web-services ....................83
Figure 4.10.  A practical approach to run-time coupling Matlab/Simulink with multiple ESP-r(s).......84
Figure 4.11.  A practical framework of representing BACS architecture in simulation ........................85
Figure 4.12. A general approach to run-time coupling different building simulation tools ...................85
Figure 4.13. A strategy for integrating classical and advanced control technologies in buildings.........86
Figure 4.14. A building control application expressed as a tree diagram..............................................87
Figure 4.15. Hierarchical design of control systems in building performance simulation .....................88
Figure 4.16. A simple example of a building heating process and its HCS modelled separately ..........89
Figure 4.17. Concept of an extended hybrid Statechart ..........................................................................90
Figure 4.18. An MAS in a building environment...................................................................................92
Figure 4.19. Concept of HICA for a building performance application.................................................93
Figure 4.20. Functional approach to V&V activities at multiple levels of abstraction ..........................94
Table 5.1. Different control possibilities in run-time coupling ...............................................................97
Figure 5.1. Exchange of data between CME and BPS within an OSI model .........................................98
Table 5.2. Number of all variables that ESP-r exchanges with Matlab/Simulink .................................98
Figure 5.2. Run-time coupling between Matlab/Simulink and multiple ESP-r(s) using pipes...............99
Figure 5.3. Run-time coupling between Matlab/Simulink and multiple ESP-r(s) using files ..............100
Figure 5.4. Run-time coupling between Matlab/Simulink and multiple ESP-r(s) using shared memory ...........................................................................................................................................101
Figure 5.5. Run-time coupling between Matlab/Simulink and multiple ESP-r(s) using sockets .........102
Figure 5.6. Run-time coupling between Matlab/Simulink and multiple ESP-r(s) using ORBs ...........106
Figure 5.7. Schematic view of run-time coupling of a building model and its control ........................108
Figure 5.8. Impact of time delay mean and variance on the performance of control systems..............109
Figure 5.9. Throughput results for pipe data rate .................................................................................112
Figure 5.10. Throughput results for file data rate..................................................................................112
Figure 5.11. Throughput results for shared memory data rate when the consumer copies data to its local addressing space before exploiting them.....................................................................................113
Figure 5.12. Throughput results for shared memory data rate when the consumer exploits data directly from the shared segment ...............................................................................................................114
Figure 5.13. Throughput results using stream and datagram sockets....................................................114
Figure 5.14. Throughput results using stream sockets when exchanging data in binary format ..........115
Figure 5.15. Throughput results using CORBA ...................................................................................115
Table 5.3. Trade-off analysis of different IPC mechanisms .................................................................117
Figure 6.1. Example of a generic framework for the architectural representation of an SoS concept .119
Figure 6.2. Distributed control modelling and building performance simulation ...............................121
Figure 6.3. Detailed conceptual design of run-time coupling between ESP-r and Matlab/Simulink ...122
Table 6.1.  Different permutations between Matlab, Simulink and C/C++ programs..........................125
Figure 6.4.  System-level design of run-time coupling between ESP-r and Matlab/Simulink .............126
Figure 6.5. Conceptual view of how matespexge toolbox is multi-threaded with multiple ESP-r(s): representation in a conventional way (left) and its equivalence in the V lifecycle model (right) 127
Figure 6.6. Simplified example of a design of self-updating control systems: representation in a conventional way (left) and its equivalence in the V lifecycle model (right)..............................128
Figure 6.7. A timing diagram for run-time coupling between Matlab/Simulink and ESP-r.................129
Figure 6.8. A timing diagram for run-time coupling between Matalb/Simulink and multiple ESP-r(s) ...........................................................................................................................................130
Figure 6.9. A simplified example of exchanging data structures between Matlab/Simulink  and ESP-r running on different machines using a binary format.....................................................................132
Figure 6.10. Experimental results regarding elapsed times of 660 instances of data exchange in distributed simulations between one or more ESP-r(s) and Matlab/Simulink in the same environment.................................................................................................................................134
Figure 6.11. Experimental results regarding elapsed times of 1100 instances of data exchange in distributed simulations between one or more ESP-r(s) and Matlab/Simulink in the same environment.................................................................................................................................135

Figure 6.12. Experimental results regarding elapsed times of 660 instances of data exchange in distributed simulations between one or more ESP-r(s) and Matlab/Simulink in different environments ........ 136
Figure 6.13 Experimental results regarding elapsed times of 1100 instances of data exchange in distributed simulations between one or more ESP-r(s) and Matlab/Simulink in different environments ........ 137
Figure 6.14. Timing diagram of time delay propagations ........ 139
Figure 6.15. A simple example of a feedback control system subjected to time delays ........ 140
Figure 6.16. Step responses of the system without delays (a), and with delays (b and c) ........ 140
Figure 6.17. A typical example of a sampled-data closed-loop control system ........ 141
Figure 6.18. Possible closed-loop system pole locations in the z-plane domain ........ 141
Figure 6.19. Example of BACnet object property (left) versus LonWork SNVT item (right) ........ 145
Figure 6.20. Implementation of web-services using XML and SOAP within run-time coupling between ESP-r and Matlab/Simulink ........ 146
Figure 6.21. XML document for a BACnet request (left) and a LonWorks request (right) ........ 146
Figure 6.22. XML document for a BACnet response (left) and a LonWorks response (right) ........ 147
Figure 6.23. Response times for data exchange in XML between ESP-r and Matlab/Simulink ........ 148
Figure 6.24. Run-time coupling between ESP-r and Matlab/Simulink in synchronous mode ........ 149
Figure 6.25. Run-time coupling between ESP-r and Matlab/Simulink in asynchronous mode ........ 149
Figure 6.26. Run-time coupling between ESP-r and Matlab/Simulink in partially synchronized mode: ........ 150
ESP-r asynchronized and Matlab/Simulink synchronized (left) versus ESP-r synchronized and Matlab/Simulink asynchronized (right) ........ 150
Figure 6.27. A simple building model with an internal on-off control implemented in ESP-r ........ 151
Figure 6.28. Simulation results obtained from a standalone simulation using only ESP-r ........ 152
Figure 6.29. A simple building model with an external on-off control implemented in Matlab ........ 152
Figure 6.30. Simulation results obtained by run-time coupling between ESP-r and Matlab/Simulink in synchronous mode ........ 153
Figure 6.31 Simulation results obtained by run-time coupling between ESP-r and Matlab/Simulink in asynchronous mode ........ 154
Figure 6.32. Simulation results obtained by run-time coupling between ESP-r and Matlab/Simulink in partially synchronous mode (ESP-r synchronized and Matlab/Simulink asynchronized ........ 154
Figure 6.33. Simulation results obtained by run-time coupling between ESP-r and Matlab/Simulink in partially synchronous mode (ESP-r asynchronized and Matlab/Simulink synchronized) ........ 155
Figure 6.34. Continuous-time control system (left) vs. discrete-time control system (right) ........ 159
Figure 6.35. Simulation results obtained with a continuous PI control system ........ 160
Figure 6.36. Simulation results obtained with a digital PI control system ........ 160
Figure 6.37. Simulation results obtained for a PI control system by run-time coupling between ESP-r and Matlab/Simulink in asynchronous mode ........ 160
Figure 6.38. Simulation results obtained for a PI control system by run-time coupling between ESP-rand Matlab/Simulink in partially synchronous mode (ESP-r synchronized and Matlab/Simulink asynchronized) ........ 161
Figure 6.39. Simulation results obtained for a PI control system by run-time coupling between ESP-rand Matlab/Simulink in partially synchronous mode (ESP-r asynchronized and Matlab/Simulink synchronized) ........ 161
Figure 6.40. A simple discrete-event control system (left) and an example of its sample path (right) 162
Figure 6.41. Simulation results obtained for a discrete-event control system using run-time coupling between ESP-r and Matab/Simulink in synchronous, asynchronous and partially synchronous modes ........ 162
Figure 6.42. Distributed simulations by run-time coupling between ESP-r and Matlab/Simulink running on a heterogeneous network of different machines ........ 163
Figure 6.43. Simulation results obtained for a PI control system by run-time coupling between ESP-r and Matlab/Simulink in synchronous mode ........ 163
Figure 6.44. Simulation results obtained for a PI control system by run-time coupling between ESP-r and Matlab/Simulink in asynchronous mode ........ 164

Figure 6.45. Simulation results obtained for a PI control system by run-time coupling between ESP-r and Matlab/Simulink in partially synchronous mode (ESP-r synchronized and Matlab/Simulink asynchronized) ....164
Figure 6.46. Simulation results obtained for a PI control system by run-time coupling between ESP-r and Matlab/Simulink in partially synchronous mode (ESP-r asynchronized and Matlab/Simulink synchronized) ....164
Figure 6.47. Simulation results obtained for a discrete-event control system by run-time coupling between ESP-r and Matab/Simulink in synchronous, asynchronous and partially synchronous modes for simulation time steps of 2 min and 1 min....165
Figure 6.48. Distributed simulations by run-time coupling between Matlab/Simulink and two ESP-r(s) running on grid computing environments. ....166
Figure 6.49. Simulation results obtained for a PI control system by run-time coupling between Matlab/Simulink and two ESP-r(s) in synchronous mode ....167
Figure 6.50. Simulation results obtained for a PI control system by run-time coupling between Matlab/Simulink and two ESP-r(s) in asynchronous mode....167
Figure 6.51. Simulation results obtained for a PI control system by run-time coupling between Matlab/Simulink and two ESP-r(s) in partially synchronous mode (ESP-r(s) synchronized and Matlab/Simulink asynchronized) ....168
Figure 6.52. Simulation results obtained for a PI control system by run-time coupling between Matlab/Simulink and two ESP-r(s) in partially synchronous mode (ESP-r(s) asynchronized and Matlab/Simulink synchronized) ....168
Figure 6.53. Simulation results obtained for a discrete-event control system by run-time coupling between Matab/Simulink and ESP-r 1 in synchronous, asynchronous and partially synchronous modes for simulation time steps of 2 min and 1 min....169
Figure 6.53. Simulation results obtained for a discrete-event control system by run-time coupling between Matab/Simulink and ESP-r 2 in synchronous, asynchronous and partially synchronous modes for simulation time steps of 2 min and 1 min....170
Figure 6.55. A comprehensive M&S framework with a layered view of DEVS and SES....173
Figure 7.1. Components of dependability ....177
Table 7.1. Trade-off analysis of V&V methods/standards and the application areas of V&V in dependable DCSs ....181
Figure 7.2. Verification activities of run-time coupling throughout the V-lifecycle model....184
Figure 7.3. Validation activities of run-time coupling throughout the V-lifecycle model ....185
Figure 7.4. Modelling of different properties of run-time coupling between ESP-r and Matlab/Simulink using uncoloured Petri nets ....188
Figure 7.5. A Petri nets model of run-time coupling between ESP-r and Matlab/Simulink ....189
Figure 7.6. CPN model of run-time coupling between ESP-r and Matlab/Simulink ....190
Figure 7.7. Sequence chart of data exchange between ESP-r and Matlab/Simulink....191
Figure 7.8. Response times of backward, forward and total network time delays ....194
Figure 8.1. Control system configurations: (a) continuous, (b, d1 and d2).networked, and (c) discrete ....198
Figure 8.3. Run-time coupling between Matlab/Simulink and two ESP-r(s)....200
Figure 8.5. Design of modern control systems for building performance applications using run-time coupling between Matlab/Simulink and ESP-r ....204
Figure 8.6. Design of HCS using run-time coupling between ESP-r and Matlab/Simulink....205
Figure 8.7. Hybrid automaton ....206
Figure 8.8. Schematic representation of an active low-pass filter in an electrical circuit (left) and its hybrid statechart equivalent (right) ....208
Figure 8.10. A well-established way of designing advanced control systems ....210
Figure 8.11. The basic architecture of an autonomous agent ....213
Figure 8.12. Classification of sequential decision-making problems....213
Figure 8.13. A typical representation of the reactive agent....214
Figure 8.14. Simulation results obtained by the reactive agent....215
Figure 8.15. A typical representation of the deliberative agent....216
Figure 8.16. Simulation results obtained by the deliberative agent....216
Figure 8.17. A typical representation of a HICA ....217

Figure 8.18. Simulation results obtained using the HICA ....218
Figure 8.19. A simplified overview of demand and price activity in the real-time electricity market for a 24-hour period ....219
Figure 8.20. Example of reading information of electricity pricing from the electronic market ....219
Figure 8.21. Display of the relationship of simulation data on the Mollier diagram ....220
Figure 9.1. Test-cell facility: outside view (left) and orientation (right). ....222
Figure 9.2. Test-cell facility: inside (left) and monitoring room (right) ....223
Figure 9.3. Total view of the test-cell and its monitoring room ....223
Figure 9.4. TestPoint interface. ....224
Figure 9.5. Window opening in the test-cell (right) and its equivalence in surface area (left) ....225
Table 9.1 Functioning mode of the passive and active components used in the test-cell ....227
Figure 9.6. Response of the indoor temperature to air supply conditions ....230
Figure 9.7. Gain factor ....230
Figure 9.8. A control strategy for regulating relative humidity and air temperature during winter and summer in the test-cell without using a dehumidifier ....231
Figure 9.9. Humidity control strategy using an adiabatic humidifier ....232
Table 9.2. Values for coefficients $a, m, n$, and $l$. ....234
Figure 9.10. Air openings in the DSF of the test-cell: side view (left) and front view (right) ....235
Table 9.3. Percentage, total area, and angle of the window openings ....235
Table 9.4. Effective area of the window openings for different positions of dampers and windows..236
Figure 9.11. Measurements of the effects on airflow due to solar radiation (left) and the wind speed (right) ....236
Table 9.5. Calculated amount of ventilation in terms of effective area of the window openings, solar radiation, and wind velocity, subsequent to Equation 9.21 ....237
Figure 9.12. Perpendicular wind ....239
Figure 9.13. Wind effects on the airflow through the opened windows: room air warmer than cavity air (left) and room air colder than cavity air (right) ....239
Figure 9.14. Buoyancy pressure across the window openings of the test-cell: room colder than cavity (right) and room warmer than cavity (left) ....240
Figure 9.15. Experimental results of the airflow rate in the presence of the wind speed: room colder than cavity (left) and room warmer than cavity (right) ....241
Figure 9.16. Experimental results of the airflow rate in the presence of solar radiation: room colder than cavity (left) and room warmer than cavity (right) ....242
Figure 9.17. Experimental results of the airflow rate in terms of temperature differences: room colder than cavity (left) and room warmer than cavity (right) ....243
Figure 9.18. Experimental results of the airflow rate in terms of temperature differences between the room and the cavity for three days under different weather conditions ....243
Figure 9.19. Supposed airflow pattern when using natural ventilation in the test-cell ....244
Figure 9.20. Model airflow pattern when using mechanical ventilation in the test-cell ....248
Figure 9.21. Monthly energy consumption for cooling and heating the test-cell with different blind positions ....253
Figure 9.22. Daylight in different seasons of the year ....254
Figure 9.23. The sun's position and declination toward the position of a building on earth ....254
Table 9.5. Typical scale of perception according to DGI ....257
Table 9.6. Position factor ....258
Figure 9.24. Geometry definition of the angles ....259
Figure 9.25. Representation of the radiating and receiving surfaces within the room ....260
Table 9.7. Classification of sky condition ....261
Table 9.8. Luminance of natural sources of light ....262
Figure 9.26. Proposed control strategy for artificial lighting and natural daylighting applications in a building – particularly the test-cell – using HCS ....262
Figure 9.27. Effects of venetian blinds on solar radiation ....264
Figure 9.28. Thermal static model for a DSF and a blind control ....265
Figure 9.29. Venetian blind occlusion steps (0 = fully opened, 1 =fully closed) ....266
Figure 9.30. Main components of the determination of the position of venetian blinds ....267
Figure 9.31. Reference for motorised rotation of blades ....268

Figure 9.32. Example of different positions of opening of the blades....268
Figure 9.33. Example of the sun's projection onto two adjacent blind slats: (a) when blades tilted upward, and (b) when blades tilted downward....269
Figure 9.34. Calculation of illuminance from a sky dome....270
Figure 9.35. A window and venetian blind combination: (a) total window blind surface, (b) the top part of the window covered by the blinds, and (c) the bottom part of the window not covered by the blinds....271
Figure 9.36. Configuration of a luminous flux from the sun and from sky patches....272
Figure 9.37. Hybrid statecharts model developed and implemented for control of both the position of the blinds and the angle of the blades in a venetian blind....274
Figure 9.38. An SoS approach to designing complex and large-scale building control systems....276
Figure 9.39. A Simulink model....280
Figure 9.40. Hybrid statechart....281
Figure 9.41. Statechart model....282
Figure 9.42. Occupied state....282
Figure 9.43. Calculation of the results of the sun positions and heights for 5 January....284
Figure 9.44. Experimental results obtained for control of the heating process....285
Figure 9.45. Experimental results obtained for control of the humidifying process....285
Figure 9.46. Experimental results obtained for control of the ventilation process.....286
Figure 9.47. Experimental results obtained for control of the lighting process....286
Figure 9.48. Calculation results of the sun's position and height for 3 July....287
Figure 9.49. Experimental results obtained for control of the cooling process....287
Figure 9.50. Experimental results obtained for control of the dehumidifying process....288
Figure 9.51. Experimental results obtained for control of the ventilation process....288
Figure 9.52. Experimental results obtained for control of the lighting process....289
Figure 10.1 Test-cell facility concept (left) and test-cell facility model (right).....292
Figure 10.2 Configuration and dimensions of the test-cell DSF....293
Figure 10.3. Model of the test-cell facility built on ESP-r....294
Figure 10.4. A schematic representation of the heating plant of the test-cell. Whereas the test-cell and its radiator are built in ESP-r, the control law is in Matlab/Simulink....295
Figure 10.5. A complete representation of the split air-conditioning system, including the common representation of a split air-conditioning unit (left) and a detailed schematic diagram of a split-system comprising an air-cooled condensing unit and an indoor evaporator coil (right)....296
Figure 10.6. A diagrammatic representation of the cooling mode. Whereas the test-cell and its cooler are built in ESP-r, the control law is in Matlab/Simulink....296
Figure 10.7. A schematic representation of the humidifying plant of the test-cell. Whereas the test-cell and its humidifier are built in ESP-r, the control law is in Matlab/Simulink....297
Figure 10.8. A diagrammatic representation of a fluid flow network for the mechanical ventilation mode of the test-cell with the position of the motorised dampers at the bottom of DSF set to open. Whereas the test-cell and its ventilation model are built in ESP-r, the control law is in Matlab/Simulink....298
Figure 10.9. A diagrammatic representation of a fluid flow network for the mechanical ventilation mode of the test-cell with the position of the motorised dampers at the bottom of the DSF set to closed. Whereas the test-cell and its ventilation model are built in ESP-r, the control law is in Matlab/Simulink.....298
Figure 10.10. A graphical representation of a fluid flow network for the test-cell's natural ventilation. Whereas the test-cell and its ventilation model are built in ESP-r, the control law is in Matlab/Simulink....299
Figure 10.11. A schematic representation of the natural light mode of the test-cell.....300
Whereas the test-cell and its daylight model are built in ESP-r, the control law is in Matlab/Simulink. ....300
Figure 10.12. A conceptual framework for the integration of advanced control systems in building performance simulation using run-time coupling between ESP-r and Matlab/Simulink....302
Figure 10.13. User interfaces for run-time coupling settings: ESP-r side (left) and Matlab side (right) ....303
Figure 10.14. The upgraded simulation controller menu in ESP-r....304

Figure 10.15. The upgraded menus of control laws for zone, plant system, and flow network in ESP-r ....304
Figure 10.16. The user interface for zone, plant and systems, and flow network control in Matlab/Simulink....305
Figure 10.17. Simulation results obtained for control of the heating mode ....306
Figure 10.18. Simulation results obtained for control of the humidifying process ....307
Figure 10.19. Simulation results obtained for control of the ventilation process....307
Figure 10.20. Simulation results of direct solar radiation and natural illuminance entering the room.308
Figure 10.21. Simulation results obtained for control of the cooling mode....308
Figure 10.22. Simulation results obtained for control of dehumidifying and humidifying processes..309
Figure 10.23. Simulation results obtained for control of the ventilation process....309
Figure 10.24. Simulation results of direct solar radiation and natural illuminance entering the room.310
Figure A.1. Waterfall SDLC model ....319
Figure A.2. Spiral SDLC model....319
Figure A.3. Incremental SDLC model ....320
Figure A.4. Agile (or Extreme) SDLC model....320
Table B.1. ANSI / EIA-632 Processes and Activities ....321
Figure C.1. (.m) file that reads and displays settings while run-time coupling ESP-r with Matlab/Simulink....322
Figure C.2. The .m file that exchanges data with ESP-r zones ....323
Figure C.3. The .m file that exchanges data with ESP-r plant and systems ....324
Figure C.4. The .m file that exchanges data with ESP-r flow networks....325
Figure D.1. Run-time coupling between 3 instances of ESP-rand Matlab/Simulink ....326
Figure D.2. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 3 ESP-r(s) in different communication modes for simulation time steps of 2 min. ....326
Figure D.3. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 3 ESP-r(s) in different communication modes for simulation time steps of 2 min. ....327
Figure D.4. Run-time coupling between 5 instances of ESP-rand Matlab/Simulink ....327
Figure D.5. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 5 ESP-r(s) in different communication modes for simulation time steps of 2 min. ....328
Figure D.6. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 5 ESP-r(s) in different communication modes for simulation time steps of 1 min. ....329
Figure D.7. Run-time coupling between 7 instances of ESP-rand Matlab/Simulink ....329
Figure D.8. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 7 ESP-r(s) in synchronous mode for simulation time steps of 2 and 1 min. ....330
Figure D.9. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 7 ESP-r(s) in asynchronous mode for simulation time steps of 2 and 1 min. ....330
Figure D.10. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink asynchronized and 7 ESP-r(s) synchronized for simulation time steps of 2 and 1 min. ....331
Figure D.11. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink synchronized and 7 ESP-r(s) asynchronized for simulation time steps of 2 and 1 min. ....332
Figure D.12. Run-time coupling between 9 instances of ESP-rand Matlab/Simulink ....332
Figure D.13. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 9 ESP-r(s) in synchronous mode for simulation time steps of 2 and 1 min. ....333
Figure D.14. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink and 9 ESP-r(s) in asynchronous mode for simulation time steps of 2 and 1 min. ....333
Figure D.15. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink asynchronized and 9 ESP-r(s) synchronized for simulation time steps of 2 and 1 min.. ....334

Figure D.16. Simulation results obtained for PI control system by run-time coupling between Matab/ Simulink synchronized and 9 ESP-r(s) asynchronized for simulation time steps of 2 and 1 min. ....................335
Figure D.17. Simulation results obtained for DES control system by run-time coupling between Matab/ Simulink and 9 ESP-r(s) in synchronous mode for simulation time steps of 2 and 1 min. ..........335
Figure D.18. Simulation results obtained for DES control system by run-time coupling between Matab/ Simulink and 9 ESP-r(s) in asynchronous mode for simulation time steps of 2 and 1 min. ........336
Figure D.19. Simulation results obtained for DES control system by run-time coupling between Matab/ Simulink asynchronized and 9 ESP-r(s) synchronized for simulation time steps of 2 and 1 min. ....................337
Figure D.20. Simulation results obtained for DES control system by run-time coupling between Matab/ Simulink synchronized and 9 ESP-r(s) asynchronized for simulation time steps of 2 and 1 min 337
Table E.1. TU Delft test-cell specifications ....................338

# List of Abbreviations

**A**
AB: automated building
A/D: analogue-to-digital
ACE: adaptive communication environment
ACK: acknowledgement
ADD: architectural design document
ADS: advanced distributed simulation
AEC: Architect Engineer Constriction
AHICA: advanced hybrid intelligent control agent
AHU: air-handling unit
AI: artificial intelligence
ALSP: aggregate level simulation protocol
ANSI/EIA: American National Standards Institute/Electronic Industries Association
AP: application protocol
API: application programming interface
ASCII: American standard code for information interchange
ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers

**B**
BA: building automation
BACS: building automation and control system
BEB: binary exponential backoff
BEMS: building energy management system
BES: building energy simulation
BIM: building information modelling
BMS: building management system
BOC: building operator console
BPS: building performance simulation
BSA: badge system agent
BSD: Berkeley Software Distribution

**C**
$C^4$ISR: command, control, communications, computers, intelligence, surveillance, and reconnaissance
CCS: centralized control system
CDR: common data representation
CEN: European Committee for Standardization
CFC: complex fenestration construction
CFD: computational fluid dynamics
CIE: Commission Internationale de l'Eclairage
CME: control modelling environment
$CO_2$: carbon dioxide
CPN: coloured Petri net
CPS: communicating sequential processes
CPU: central processing unit
CTL: computation tree logic

**D**
D/A: digital-to-analogue
DARBS: distributed algorithmic and rule-based blackboard system
DARPA: Defense Advanced Research Projects Agency
DCE: distributed computing environment
DCOM: distributed component object model
DCS: distributed control system
DDC: direct digital control
DDCM: direct digital control mode
DDE: Dynamic Data Exchange
DDG: degree of discomfort glare
DES: discrete-event system
DEVS: discrete event system specification
DFD: data flow diagram
DGI: daylight glare index
DGP: daylight glare probability
DIS: distributed interactive simulation
DLL: dynamic-link library
DMI: Desktop Management Interface
DMSO: Defense Modeling and Simulation Office
DoD: Department of Defense
DOE: Department of Energy
DSF: double skin facade
DXF: data exchange format

**E**
EERE: energy efficiency and renewable energy
EHSA: European Home Systems Association
EIA: Electronics Industry Association
EMS: energy management system
EPA: environmental parameter agent
EPBD: energy performance of building
ET: effective temperature
EU: European Union

**F**
FB: feedback
FF: feedforward
FIFO: first-in, first-out
FOM: federation object model
FSA: finite state automaton

FSM: finite state machine

**G**

GMT: Greenwich Mean Time
GPIB: General purpose interface bus

**H**

HCS: hybrid control system
HICA: hybrid intelligent control agent
HLA: High Level Architecture
HoQ: House of Quality
HTCPN: hierarchical timed coloured Petri net
HTTP: hypertext transfer protocol
HVAC&R: heating, ventilation, air-conditioning, and refrigeration
HVAC: heating, ventilating, and air-conditioning,

**I**

IAE: integral absolute error
IAI: International Alliance for Interoperability
IAQ: indoor air quality
IB: intelligent building
IBMS: intelligent building management system
ICCS: integrated communication and control system
IDL: interface definition language
IFC: industry foundation classes
IGES: initial graphics exchange specification
IIDEAS: integration of industrial data for exchange, access, and sharing
IIOP: inter-ORB protocol
INCOSE: International Council on Systems Engineering
IP: internet protocol
IPC: inter-process communication
IT: information technology
ITAE: integral time absolute error

**J**

JNI: Java native interface
JVM: Java virtual machine

**K**

KF: Kalman filter

**L**

LAN: local area network
LIS: language independent specification
LISI: levels of information systems interoperability
LON: LonWorks
LOTOS: language of temporal ordering specification
LP: logical processes
LQG: linear quadratic Gaussian
LQR: linear quadratic regulator
LSDCS: large-scale distributed control system
LTI: linear time-invariant

**M**

M&S: modelling and simulation
MAS: multi-agent system
MEX: Matlab executable
MIMO: multi-input and multi-output
MISO: multi-input and single-output
MPC: model predictive control
MPI: message passing interface
MQFD: maintenance quality function deployment
MTTF: mean time to failure
MTTR: mean time to repair

**N**

NAHB: National Association of Homes Builders
NASA: National Aeronautics and Space Administration
NCS: networked control system
NDR: network data representation
NEST: Novell Embedded Systems Technology
NFF: neutral file format
NIST: National Institute of Standards and Technology
NMF: neutral model format
NN: neural network
NPL: neutral pressure level
NPP: neutral pressure plane

**O**

OMG/CORBA: object management group/ common object request broker architecture
OMT: object model template
ORB: object request broker
ORPC: object remote procedure call
OS: operating system
OSF: Open Software Foundation
OSI: open systems interconnection

**P**

P2P: peer-to-peer
PCA: personal comfort agent
PDES: parallel discrete event simulation
PDU: protocol data units
PI: proportional integrator
PID: proportional integrator derivative
PLC: programmable logic controller
PMV: predicted mean vote
POSIX: portable operating system interface

PPD: percentage people dissatisfied
PPM: parts per million
PRJ: Building Project Manager
PVM: parallel virtual machine

**Q**
QFD: quality function deployment
QoP: quality of performance
QoS: quality of service

**R**
RA: room agent
RCS: real-time control system
RE: requirements engineering
RMI: remote method invocation
RPC: remote procedure call
RTI/HLA: run-time infrastructure/high level architecture
RTI: run-time infrastructure

**S**
SB: smart building
SCM: supervisory control mode
SDLC: system development lifecycle
SE: systems engineering
SEDRIS: synthetic environment data representation and interchange specification
SES: system entity structure
SISO: single-input and single-output
SLD: specification and description language
SNA: systems network architecture
SNVT: standard network variable type
SOAP: simple object access protocol
SOM: simulation object model
SoS: system-of-systems
SPN: stochastic Petri net
SRD: system requirements document
STEP: standard for the exchange of product model data
STF: SEDRIS transmittal format
SWN: stochastic well-formed net

**T**
TCP/IP: transmission control protocol/internet protocol
TCP: transmission control protocol
TMC: transparent multilayer construction
TPMs: technical performance measures
TPM: total productive maintenance
TQM: total quality management

**U**
UDP: user datagram protocol
UDS: Unix domain socket
UML: unified modelling language
URD: user requirements document

**V**
V&V: verification and validation
VDM: Statemate-Vienna design method
VV&A: verification, validation, and accreditation

**W**
WLAN: wireless local area network
WSDL: web services description language
WS-I: Web-Services Interoperability Organization

**X**
XDR: external data representation
XMI: XML metadata interchange
XML: extensible markup language
XSD: XML schema definition

**Z**
ZOH: zero-order hold

# Summary

> ***"Well done is better than well said."***
> –Benjamin Franklin

More than ever, the integration of innovative control systems in building environments is a key strategic means in providing building occupants with consistent thermal, visual, and indoor air quality comfort at the lowest energy use possible. Automated buildings (ABs) must respond to the requirements comprising demands of occupants and concerns of climatic environment changes. However, most of these requirements often change over time due particularly to changes occurring within buildings and/or to growing interest in both reducing energy consumption and improving occupants' comfort and well-being. To face up to such challenges and adapt ABs to the level desired by building occupants in particular, systematic and structured approaches based on systems engineering (SE) best practice were developed in this thesis to facilitate the application of advanced control methods such as intelligent hybrid control systems (HCSs) and multi-agent systems (MASs) to building environments.

ABs are a class of buildings that are automatically supervised and controlled by or from a central computer-based monitoring and control systems such as distributed control system (DCS) architecture or, more specifically, building automation and control system (BACS) architecture. Through the use of recent advances in computers, information technology, and communication protocols, modern BACS architecture has become an effective technology used in simultaneously supervising, monitoring, and controlling a range of building performance applications – including heating, ventilation, air-conditioning, lighting, air-handling units, as well as other tasks such as access control, energy management, and fault detection and diagnoses – of the building or a group of buildings over a standardized protocol such as BACnet and LonWorks. In order for BACS technology to adapt ABs to changing requirements by control systems design, experiments or similar analyses must be conducted to improve the automation and operational integrity of building HVAC&R equipment and lighting components. However, experiments are time-consuming and cost-prohibitive because they require at least 24 hours to obtain results and because implementing BACS architecture in a real building remains expensive. For these reasons, the objective of this thesis was first to develop and implement a distributed dynamic simulation mechanism with the capability of representing BACS technology in simulation by distributing two or more different software tools over a network. This was achieved by:

1. determining the feasibility of the study and identifying and describing systems engineering (SE) processes and tools and reflecting upon their contribution to the development and implementation of a distributed dynamic mechanism as well as to the integration of advanced control systems in building environments;
2. developing a SE framework for distributed control and building performance simulations to capture the design requirements effectively;
3. conducting the trade-off analysis based on the evaluation and performance comparison to select and choose the most appropriate solution among several alternatives for the development and implementation of run-time coupling between Matlab/Simulink and one or more ESP-r(s) over a network;
4. implementing run-time coupling between Matlab/Simulink and ESP-r with several options for including ASCII and binary data exchange formats as well as synchronous, asynchronous, and partially asynchronous communication modes;
5. extending run-time coupling between ESP-r and Matlab/Simulink to use multiple instances of ESP-r in a distributed and parallel simulations with Matlab/Simulink over a network in order to equivalently represent BACS architecture in simulation;

6. performing verification and validation (V&V) throughout the V lifecycle model of a distributed simulation mechanism to determine the degree of reliability to provide users with a sufficient degree of confidence in the simulation results obtained when using run-time coupling between Matlab/Simulink and ESP-r; and
7. demonstrating the applicability of advanced control systems in building performance simulation by run-time coupling between Matlab/Simulink and ESP-r .

Further, it was necessary to conduct experiments on the application of advanced control strategies to the real building, the test-cell case study. This was achieved by

1. preparing and setting up the test-cell and its equipment for experiments;
2. analyzing and experimenting with different control strategies for the regulation of complex processes such as the control of airflow rate through the test-cell;
3. developing a complete mathematical model for test-cell processes and devices including heating, cooling, humidifying, dehumidifying, mechanical ventilation, natural ventilation, artificial light and daylighting as well as for its ventilated double-skin-façade (DSF) ;
4. designing an automated control system based on a hierarchical concept for all test-cell processes and devices with the purposes of minimizing energy consumption and taking full advantage of natural resources including wind and sun;
5. conducting a series of experiments on the application of an automated control system to the test-cell case study.

With regard to the overall goal of this research – which is the automated control of building HVAC&R equipment and lighting components that embrace many complex disciplines, not only in the system of equipment or components themselves but also in the range of operating conditions, occupants' comfort, and energy efficiency – a methodology based on SE practice was developed. This methodology served to provide a structured and systematic framework for defining, describing, and evolving both the enabling product and the process needed to build the final product, and applied throughout the system lifecycle model (such as the V model) to all the activities (or phases) associated with development, implementation, verification, and application. In this research study, the enabling product refers to a distributed dynamic simulation mechanism, the process to the integration of advanced control systems in building environments, and the final product to an AB.

The main results of this research are indicated and quantified such that:

- using a distributed dynamic simulation mechanism allows modelling and simulation of complex multivariable building control and performance applications and facilitates the integration of advanced control systems in building performance simulation;
- developing a distributed dynamic simulation mechanism with the ability to distribute (i.e., by run-time coupling) two or more different software tools over a network in order to similarly represent BACS architecture in a simulation, as well as to model and simulate distributed control applications in buildings such as MASs in ABs; and
- applying automated control systems to building HVAC&R equipment and lighting components improves the comfort of building occupants, increases energy efficiency in buildings, and contributes to reduction of greenhouse gas emissions by taking full advantage of natural resources.

The main contribution of this research study is its demonstration that computer simulations can be used to provide practical solutions for enabling the integration of advanced control systems in building environments, and improving distributed control applications in buildings such as MASs in ABs.

Finally, the thesis is structured in three main parts, in which each part consists of three or four chapters that focus on their specificity developed in this study. To fully understand this thesis might require that the reader possess in-depth knowledge in a domain such as systems engineering, control engineering, building physics, communication networks, and computer network programming. For this reason, most sections in the thesis use detailed descriptions to give more in-depth insights into the subject under consideration.

# Samenvatting

## Een gedistribueerd dynamisch simulatiemechanisme voor gebouwautomatiserings- en regelsystemen.

> ***"Liever goed gedaan dan goed gezegd."***
> –Benjamin Franklin

Meer dan ooit is de integratie van innovatieve regelsystemen in de gebouwde omgeving de sleutel tot het bieden van een gegarandeerd comfort aan bewoners en gebruikers van gebouwen tegen een laag energiegebruik, zowel van thermisch comfort, verlichtingscomfort als een optimale binnenluchtkwaliteit. Geautomatiseerde gebouwen (AB's) moeten reageren op de eisen die de bewoners en gebruikers stellen en op veranderende klimatologische omstandigheden. Veel van die eisen veranderen in de tijd door veranderingen aan die gebouwen en toenemende aandacht voor het besparen van energie en het gelijktijdig verbeteren van het comfort en het beperken van gezondheidsrisico's voor bewoners en gebruikers. Dit proefschrift beschrijft een systematische en gestructureerde aanpak om bovengenoemde uitdagingen aan te gaan, gebaseerd op systems engineering (SE). Het betreft de toepassing van geavanceerde regelstrategieën als intelligente hybride regelsystemen (HCS's) en multi-agent systemen (MAS's) in de gebouwde omgeving.

AB's zijn een klasse gebouwen die worden gestuurd en geregeld door een centraal computergestuurd beheersysteem, waarvan de architectuur is gebaseerd op bijvoorbeeld een gedistribueerd regelsysteem (DCS) of, specifieker, een gebouwbeheer- en regelsysteem (BACS). Door het gebruik van recente ontwikkelingen in computer- en informatietechnologie blijkt de BACS-architectuur een effectieve technologie om een uiteenlopende reeks systemen die de gebouwprestatie beïnvloeden aan te sturen, gebruikmakend van gestandaardiseerde communicatieprotocollen als BACnet en LonWorks. Denk hierbij aan systemen voor verwarming, ventilatie, koeling, verlichting, luchtbehandeling, toegangscontrole, energiebeheer en foutdetectie en -diagnose. Om BACS-technologie voor AB's aan te passen aan de veranderende eisen die regelsysteemontwerp stelt zijn experimenten en analyses noodzakelijk die de automatisering en operationele integriteit verbeteren van klimaat- en verlichtingsinstallaties. Experimenten in een echt gebouw zijn echter tijdsintensief omdat ze steeds minimaal 24 uur in beslag nemen om voldoende meetresultaten te verkrijgen en kostbaar vanwege de implementatie van een BACS-architectuur. Daarom is een belangrijk doel van dit proefschrift om een gedistribueerd dynamisch simulatiemechanisme te ontwikkelen en te implementeren met de mogelijkheid BACS-technologie in een gebouw te simuleren in twee of meer softwareomgevingen die communiceren over een netwerk. Dit werd bereikt door:

1. Het uitvoeren van een haalbaarheidsstudie, het identificeren en beschrijven van de benodigde processen en gereedschappen qua SE voor de ontwikkeling en implementatie van een gedistribueerd dynamisch mechanisme en voor de integratie van geavanceerde regelsystemen in de gebouwde omgeving.
2. Het ontwikkelen van een SE-framework voor gedistribueerde regelingen en gebouwsimulaties voor het effectief vastleggen van de ontwerpuitgangspunten.
3. Het uitvoeren van een analyse voor het evalueren, vergelijken en kiezen van de beste mogelijkheid voor de ontwikkeling en implementatie van een methode voor run-time koppeling tussen één of meer instanties van Matlab/Simulink en ESP-r over een netwerk.
4. Het implementeren van de run-time koppeling tussen Matlab/Simulink en ESP-r met verschillende mogelijkheden voor data-uitwisselingsformaten (ASCII en binair) en communicatiemanieren (synchroon, asynchroon en gedeeltelijk asynchroon).
5. Het uitbreiden van de run-time koppeling tussen Matlab/Simulink en ESP-r met de mogelijkheid meer instanties van ESP-r te kunnen gebruiken in gedistribueerde en parallelle simulaties met Matlab/Simulink over een netwerk, met als doel een BACS-architectuur in simulatie te kunnen weergeven.

6. Het uitvoeren van verificatie en validatie (V&V) tijdens het V-lifecycle model van een gedistribueerd simulatiemechanisme om de betrouwbaarheid ervan te bepalen, met als doel gebruikers vertrouwen te geven in de simulatieresultaten van de run-time koppeling tussen Matlab/Simulink en ESP-r.
7. Het demonstreren van de toepasbaarheid van geavanceerde regelsystemen in gebouwsimulatie d.m.v. run-time koppeling tussen Matlab/Simulink en ESP-r.

Verder was het noodzakelijk om experimenten uit te voeren m.b.t. de toepassing van geavanceerde regelstrategieën op een echt gebouw middels een test-cell case study. Dit werd bereikt door:

1. Het voorbereiden en opzetten van de test-cell en de apparatuur voor de experimenten.
2. Het uitvoeren en analyseren van experimenten met verschillende strategieën voor het reguleren van complexe processen als de regeling van de luchtstroming door de test-cell.
3. Het ontwikkelen van een wiskundig model voor de processen en apparaten in de test-cell, waaronder verwarming, koeling, bevochtiging, ontvochtiging, mechanische ventilatie, natuurlijke ventilatie, kunstmatige verlichting en natuurlijke verlichting en de geventileerde dubbele huidgevel (DSF).
4. Het ontwerpen van een geautomatiseerd regelsysteem gebaseerd op een hiërarchisch concept voor de processen en apparaten in de test-cell met als doel het energiegebruik te minimaliseren door gebruik te maken van zoveel mogelijk natuurlijke bronnen als wind en zon.
5. Het uitvoeren van een serie experimenten m.b.t. de toepassing van geavanceerde regelingen op de test-cell case study.

Een methodologie gebaseerd op de SE-praktijk werd ontwikkeld ter ondersteuning van het doel van dit onderzoek, te weten de geautomatiseerde regeling van de klimaat- en verlichtingsinstallatie en componenten van een gebouw, die vele complexe disciplines omvat, niet alleen op het gebied van apparatuur en componenten maar ook op het gebied van operationele condities, het comfort van gebruikers en bewoners en energie-efficiëntie. Deze methodologie biedt een gestructureerd en systematisch raamwerk voor de definitie, beschrijving en ontwikkeling van het ondersteunende product en het proces om het eindproduct te kunnen ontwikkelen, en toegepast op gedurende de levensduur van het systeem (bijvoorbeeld volgens het V-model) op alle activiteiten (of fasen) van ontwikkeling, implementatie, verificatie en toepassing. Het ondersteunende product in deze studie is het mechanisme voor gedistribueerde dynamische simulatie; het proces is de integratie van geavanceerde regelsystemen in de gebouwde omgeving, en het eindproduct is een AB.

De belangrijkste resultaten van dit onderzoek zijn:

- Het gebruik van een mechanisme voor gedistribueerde dynamische simulatie ondersteunt het modelleren en simuleren van complexe multivariabele gebouwregelingen en maakt de integratie van geavanceerde regelsystemen in gebouwsimulatie mogelijk.
- Een mechanisme voor gedistribueerde dynamische simulatie werd gebouwd met de mogelijkheid om via run-time koppeling twee of meer verschillende softwareapplicaties te laten samenwerken waarbij zowel de BACS-architectuur als de gedistribueerde regelsystemen in gebouwen (zoals MAS's in AB's) konden worden gesimuleerd.
- Het toepassen van geautomatiseerde regelsystemen voor klimaat- en verlichtingsinstallaties verbetert het comfort van bewoners en gebruikers, verhoogt de energie-efficiëntie in gebouwen en draagt bij aan de reductie van de uitstoot van broeikasgassen door volledig gebruik te maken van natuurlijke bronnen.

De belangrijkste bijdrage van dit onderzoek is dat het aantoont dat computersimulaties kunnen worden gebruikt voor praktische oplossingen die de integratie van geavanceerde regelsystemen in de gebouwde omgeving mogelijk maken, en die gedistribueerde regelsystemen in gebouwen (zoals MAS's in AB's) verbeteren.

Tenslotte: het proefschrift is opgesplitst in drie delen, en ieder deel is weer opgedeeld in drie of vier hoofdstukken die elk een specifiek onderwerp van deze studie behandelen. Om het proefschrift volledig te kunnen begrijpen dient de lezer over gedetailleerde kennis te beschikken van gebieden als system engineering, regeltechniek, bouwfysica, communicatienetwerken en programmeren van computernetwerken. Daarom bevatten de meeste delen van dit proefschrift gedetailleerde beschrijvingen om meer inzicht te geven in deze onderwerpen.

# Résumé

## Un mécanisme de simulation dynamique distribuée pour les systèmes de contrôle et d’automatisation des bâtiments.

> “*Bien fait est mieux que bien dit.*”
> –Benjamin Franklin

Plus que jamais, l'intégration de systèmes de contrôle innovants dans les environnements des bâtiments est un moyen stratégique clé pour améliorer le confort des occupants pour garantir un confort thermique et visuel et une qualité de l'air intérieur avec une consommation d'énergie la plus faible possible. Les bâtiments automatisés (AB) doivent répondre à la fois aux exigences de confort des occupants et aux préoccupations environnementales liées au changement climatique. La plupart de ces exigences évoluent souvent au fil du temps. Pour faire face à ces défis et adapter les AB au niveau souhaité par les occupants des bâtiments , les approches systématiques et structurées basées sur les bonnes pratiques en ingénierie de systèmes (IS) ont été développées dans cette thèse pour faciliter l'application de stratégies de contrôle avancées telles que les systèmes hybrides de contrôle intelligent (HCSs) et les systèmes multi-agents (MASs) à des environnements de bâtiments.

Les bâtiments automatisés sont une classe de bâtiments qui sont automatiquement surveillées et contrôlées par ou à partir d'un système informatisé central de supervision et de contrôle à distance tel que le système de contrôle distribué (DCS) ou tel que, plus spécifiquement, le système de contrôle et d’automatisation des bâtiments (BACS). A travers l’utilisations des avancées récentes en informatique et en technologies de l'information ainsi que des protocoles de communication, l’architecture BACS est devenue une technologie efficace à utilisée pour, simultanément superviser, surveiller, contrôler ou réguler toute une variété d’applications de gestion énergétique et de performance – liée au chauffage, à la ventilation et à l’air conditionné (CVAC), à l'éclairage, aux unités de traitement d'air, ainsi qu’à d'autres tâches telles que le contrôle d'accès, la gestion d’énergie, la détection des défauts et le diagnostic – de bâtiment ou de groupes de bâtiments grâce aux protocoles standardisés BACnet ou LonWorks. Pour que la technologie BACS puisse adapter, grâce à la conception de systèmes de contrôle innovants, les bâtiments automatisés aux exigences qui évoluent, des expériences ou des analyses poussées doivent être menées pour améliorer l'automatisation et l’intégrité des systèmes de CVAC et d’éclairage des bâtiments. Cependant, les expériences sont longues et coûteuses car il faut un minimum de 24 heures afin d'obtenir des résultats de mesure suffisants et la mise en œuvre de l’architecture BACS dans un bâtiment réel reste chère et peu accessible. Pour ces raisons, le premier objectif de cette thèse a été de développer et de mettre en œuvre une simulation dynamique distribuée de la technologie BACS par une combinaison distribuée de deux ou plusieurs environnements logiciels qui communiquent sur un réseau. Ceci a été possible grâce à:

1. la réalisation d'une étude de faisabilité afin d’identifier et de décrire les processus et les outils nécessaires en termes d'IS pour le développement et la mise en œuvre d'un mécanisme de simulation dynamique distribuée pour l'intégration des systèmes de contrôle avancés dans les environnements de bâtiment;
2. l’élaboration d'un cadre IS pour les simulations distribuées de contrôle et des applications de performance des bâtiments pour capturer efficacement les exigences de conception;
3. la conduite de l'analyse de compromis basée sur l'évaluation et la comparaison de performance pour sélectionner et choisir la solution la plus appropriée parmi plusieurs alternatives pour le développement et la réalisation d’un couplage d'exécution entre Matlab/Simulink et un ou plusieurs ESP-r sur un réseau ;
4. la mise en œuvre du couplage d'exécution entre Matlab/Simulink et ESP- r avec plusieurs options y compris les formats d'échange de données (ASCII et binaire) ainsi que les modes de communication (synchrone, asynchrone, et partiellement synchrone);

5. l’élargissement du couplage d'exécution entre Matlab/Simulink et ESP- r pour avoir la possibilité d’utiliser plusieurs instances de ESP-r dans des simulations distribuées et parallèles avec Matlab/Simulink sur un réseau afin de représenter de manière équivalente l'architecture BACS dans la simulation ;
6. la mise au point d’un procédé de vérification et de validation (V & V), à travers le modèle, du cycle de vie en V du mécanisme de simulation distribuée pour déterminer le degré de fiabilité à fournir aux utilisateurs avec un degré de confiance suffisant dans les résultats de simulation obtenus avec le couplage d'exécution entre Matlab/Simulink et ESP- r ;
7. la démonstration de l'applicabilité des systèmes de contrôle avancés dans la simulation de performance de bâtiments par le couplage d'exécution entre Matlab/Simulink et ESP- r.

Ensuite, le deuxième objectif, nécessaire, était de mener des expériences sur des stratégies de contrôle avancées dans un bâtiment modèle réel. L'étude de cas a été effectuée sur une cellule d’essai ou de test (en laboratoire) en respectant les étapes suivantes:

1. préparation et mise en place de la cellule de test (ou d'essai) et du matériel pour les expériences ;
2. mise en œuvre et analyse des expériences de différentes stratégies de contrôle pour la régulation des processus complexes tels que le contrôle du débit d'air à travers la cellule de test;
3. élaboration d'un modèle mathématique complet des processus et des dispositifs de la cellule de test – y compris le chauffage, la climatisation, humidification, déshumidification, ventilation mécanique, ventilation naturelle, l'éclairage artificiel et l'éclairage naturel, ainsi que sa 'façade double peau ventilée (DSF) ;
4. conception d'un système de contrôle automatisé basé sur un concept hiérarchique de tous les processus et dispositifs de la cellule de test avec le but de minimiser la consommation d'énergie et profiter autant que possible des ressources naturelles telles que le vent et le soleil;
5. réalisation d'une série d'expériences sur l'application d'un système de contrôle (ou de commande) automatisée (et avancée) sur l'étude de cas de la cellule de test.

En ce qui concerne l’objectif global de ce travail de recherche – « conception d’une commande automatisée des systèmes CVAC&R et des d'éclairage des bâtiments » qui mobilise de nombreuses disciplines complexes, non seulement en termes de systèmes, mais également en termes de conditions d'exploitation, du confort des occupants, et de l'efficacité énergétique – une méthodologie basée sur la pratique IS a été développée et conçue. Cette méthodologie a permis de fournir un cadre structuré et systématique pour définir, décrire, et évaluer tant le produit amélioré (*enabling product*) que le processus nécessaire, pour ensemble construire le produit fini. Elle permet aussi d’appliquer le modèle complet du cycle de vie du système (tel que le modèle en V) à toutes les activités (ou étapes) associées au développement, à la mise en œuvre, à la vérification et à l’application. Dans cette étude, le produit amélioré se réfère au mécanisme de simulation dynamique distribuée, le processus à l’intégration des systèmes de contrôle avancés dans les environnements de bâtiments, et le produit fini à un AB.

Ce travail de recherche a permit:

- l’utilisation d’un mécanisme de simulation dynamique distribuée qui permet la modélisation et la simulation des applications multi-variables (ou à plusieurs variables) de contrôle de la performance des bâtiments, et qui facilite l'intégration des systèmes de commande avancés dans la simulation de la performance de bâtiments;
- l’élaboration d'un mécanisme de simulation dynamique distribuée avec la possibilité de distribuer (par un couplage d'exécution) de deux ou plusieurs environnements logiciel différents qui communiquent sur un réseau afin de représenter l'architecture BACS en simulation, ainsi que modéliser et simuler des applications de contrôle distribué dans les bâtiments tels que les applications de MASs dans les ABs;
- l'application de la commande automatisée aux systèmes CVAC&R et à l’éclairage de bâtiments. Cette commande permet d’améliorer le confort des occupants, d’augmenter l'efficacité énergétique dans les bâtiments, et de contribuer à la réduction des émissions de gaz à effet de serre en exploitant de manière sûre les ressources naturelle.

L'apport principal de cette étude est la démonstration que les simulations informatiques peuvent être utilisées pour apporter des solutions concrètes qui permettent l'intégration des systèmes de contrôle avancés dans les environnements de bâtiments, et l'amélioration des applications de contrôle (ou de commande) distribué dans les bâtiments tels que les applications de MASs dans les ABs.