

This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (<https://dspace.lboro.ac.uk/>) under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

**MINIMISING ENERGY USE AND
MOULD GROWTH RISK IN TROPICAL
HOSPITALS**

Abdul Murad Zainal Abidin
Department of Civil and Building Engineering
Loughborough University

A Doctoral Thesis submitted in partial fulfilment of the requirements for
the award of Doctor of Philosophy of Loughborough University

November 2012

ABSTRACT

Critical areas in a hospital, such as Intensive Care Units (ICUs) and isolation rooms, are designed to strict health standards. More often than not, these areas operate continuously to maintain designed indoor conditions in order to ensure the safety of patients, making them energy-intensive areas. Several attempts have been made to design them to be more energy-efficient. However, cases have emerged in hot and humid countries like Malaysia where combination of poor design, operation and maintenance practices, exacerbated by the humid outdoor conditions especially during night-time, have led to occurrences of mould growth in these critical areas. A question arise whether energy-efficient design of a critical area can be achieved without incurring a risk of mould growth due to factors like moisture transfer, or continuous part-load operation of HVAC systems. The objective of research in this thesis is to investigate the trade-off between optimizing the building and HVAC systems and minimizing the risk of mould growth in hospital buildings located in hot and humid climates.

The problem formulation is a single zone isolation room with dimensions based from a real-life isolation room of a district hospital in Malaysia. The design variables, namely HVAC systems and the details of building constructions were selected as input files for energy performance evaluation using EnergyPlus. The output from the simulation will be compared with the selected existing mould growth model during post-processing to determine the optimum solution. Simulation and the generation of solutions will be repeated until the most optimum solution is achieved.

A binary-encoded Genetic Algorithm (GA) was used as an approach to the minimisation of hospital building energy use. The GA is proven to be effective in performing multi-objective optimisation, since the objective functions for this research are more than one; namely, the minimum annual energy use in the isolation room and the critical indoor surface conditions, such as temperature and

relative humidity, below which there would be no mould growth. The research has shown that the normal practice of isolation room design for Malaysian hospitals does not work in minimising energy use and minimising the risk of mould growth and a new design guideline for isolation rooms in Malaysia is recommended.

The principal originality of the research will be the application of optimisation methods to investigate the relationship, or trade-off between energy use and the risk of mould growth, particularly for hospital buildings in a hot and humid climate. In this respect, the new knowledge will be on the optimisation procedure and required modelling/analysis components. This combinatorial approach would serve as decision making tool for building and HVAC systems designers in designing more energy-efficient overall environment systems in hospitals, with particular attention to critical areas that are operating continuously.

ACKNOWLEDGEMENT

I would like to thank my supervisors Professor Jonathan A. Wright and Dr Monjur Mourshed of the Civil and Building Engineering Department, Loughborough University, for their patience and guidance, and continued hard work during the work leading to this thesis. My deepest gratitude to my wife, Munirah, and my sons Sirhan, Suhail as well as my daughter Sorfina for their unending love and encouragement throughout my period of study. My father Zainal Abidin and mother Maimun, my sister Zamirah for her constant reminder. My gratitude also goes to my sponsor, the Public Service Department (on behalf of the Malaysian Government), and my employee, the Public Works Department Malaysia, for their support.

TABLE OF CONTENT

ABSTRACT	i
ACKNOWLEDGEMENT	iii
List of Figures	iv
List of Tables	viii
Chapter 1 Introduction	1
1.1 Mould Growth, Energy Use and Building Operation	3
1.2 Research Aims and Objectives	6
Chapter 2 Literature Review	9
2.1 Mould Growth	11
2.1.1 <i>Experimental Results</i>	11
2.1.2 <i>Mould Growth Prediction Models</i>	13
2.1.3 <i>Comparison of Approaches</i>	24
2.1.4 <i>Uncertainty in Mould Growth Analysis</i>	29
2.1.5 <i>Other Development in Mould Growth Research</i>	31
2.1.6 <i>Summary</i>	33
2.2 Building Optimisation	34
2.2.1 <i>Building Construction Optimisation</i>	34
2.2.2 <i>HVAC System Optimisation</i>	36
2.2.3 <i>HVAC Control System Optimisation</i>	38
2.2.4 <i>Summary</i>	41

2.3	Malaysian Hospital Design and Performance	42
2.3.1	<i>Design Standards</i>	42
2.3.2	<i>Available Studies</i>	43
2.3.3	<i>Measured Performance</i>	47
2.3.4	<i>Summary</i>	48
2.4	Chapter Summary	48
Chapter 3	Building Performance Simulation (BPS) and Optimisation Method	50
3.1	Selection of Building Performance Simulation (BPS)	52
3.1.1	<i>Overview of Existing BPS</i>	52
3.1.2	<i>Requirements and Selection of BPS Program</i>	54
3.1.3	<i>Overview of EnergyPlus</i>	56
3.1.4	<i>Heat Balance Equation in EnergyPlus</i>	56
3.1.5	<i>Heat and Moisture Transfer (HAMT) Model</i>	60
3.1.6	<i>Recent Researches and Discussion</i>	63
3.1.7	<i>Summary</i>	64
3.2	Selection of the Optimisation Method	65
3.2.1	<i>Multi-Objective Optimisation</i>	65
3.2.2	<i>Genetic Algorithm (GA) Search Method</i>	71
3.2.3	<i>Binary-coded and Gray coding GA</i>	75
3.2.4	<i>Binary Tournament Selection Operator</i>	76
3.2.5	<i>Uniform Crossover Operator</i>	77
3.2.6	<i>Mutation Operator</i>	79

3.2.7	<i>Parallel GA (PGA)</i>	80
3.2.8	<i>GA in Building Optimisation</i>	81
3.2.9	<i>Multi-Objective Optimisation Using NSGA-II</i>	84
3.2.10	<i>Summary</i>	90
3.3	Interlink of EnergyPlus with NSGA-II and Mould Risk Model	91
3.4	Chapter Summary	94
Chapter 4	Mould Risk Model	95
4.1	Mould Growth Model by Sedlbauer (2001)	97
4.2	Extended Mould Growth Model	100
4.2.1	<i>Modification of Mould Risk Model</i>	100
4.2.2	<i>Implementation of the Mould Risk Model</i>	107
4.2.3	<i>Summary</i>	109
4.3	Interface with Building Performance Simulation (BPS)	109
4.4	Chapter Summary	110
Chapter 5	A Benchmark Hospital Isolation Zone	111
5.1	Isolation Room Model	113
5.1.1	<i>Background Study</i>	113
5.1.2	<i>Operating Characteristics</i>	115
5.1.3	<i>Isolation Room Description</i>	116
5.1.4	<i>Summary</i>	119
5.2	Building Performance Simulation of Isolation Model	119
5.2.1	<i>Annual Simulation</i>	120

5.2.2	<i>Comparison between Annual and Monthly Simulation</i>	122
5.2.3	<i>Summary</i>	127
5.3	Zone Performance for Benchmark Design	128
5.3.1	<i>Single-walled Isolation Room</i>	128
5.3.2	<i>Results of Indoor Conditions</i>	130
5.3.3	<i>Results of Surface Temperature and RH</i>	131
5.3.4	<i>Double-walled Isolation Room</i>	135
5.3.5	<i>Results of Indoor Conditions</i>	136
5.3.6	<i>Results of Surface Temperature and RH</i>	137
5.3.7	<i>Effect of re-setting zone set-point</i>	141
5.3.8	<i>Discussion</i>	148
5.3.9	<i>Summary</i>	153
5.4	Alternative Design and Operation Case	153
5.4.1	<i>Proposed Alternative Design and Operation</i>	153
5.4.2	<i>Comparison with normal practice</i>	157
5.4.3	<i>Summary</i>	162
5.5	Scope of Optimisation Problem	163
5.5.1	<i>Building Construction</i>	163
5.5.2	<i>Room Temperature Set-Points</i>	168
5.5.3	<i>Room Temperature Night Set-back</i>	169
5.5.4	<i>Room RH Set-Points</i>	169
5.5.5	<i>Ventilation Rate</i>	172

5.5.6	<i>Constraints</i>	173
5.6	Chapter Summary	174
Chapter 6	Results and Analysis	176
6.1	Computation Process	178
6.2	Solution Characteristics	178
6.2.1	<i>Trade-off Analysis</i>	178
6.2.2	<i>Problem Variable Analysis</i>	183
6.2.3	<i>Analysis of Building Performance</i>	186
6.3	Detailed Optimisation Results	188
6.3.1	<i>Optimised Solutions</i>	188
6.3.2	<i>Temperature Set-Point Optimisation Results</i>	191
6.3.3	<i>RH Set-Point Optimisation Results</i>	195
6.3.4	<i>Air Flow Rate Optimisation Results</i>	197
6.3.5	<i>Wall Construction Optimisation Results</i>	201
6.3.6	<i>Window Size Optimisation Results</i>	203
6.3.7	<i>Roof Type Optimisation Results</i>	206
6.3.8	<i>Mould Risk Results</i>	207
6.3.9	<i>Energy Use Results</i>	210
6.3.10	<i>Discussion</i>	212
6.3.11	<i>Summary</i>	215
6.4	Selection Criteria	217
6.4.1	<i>Decision Making</i>	217
6.4.2	<i>Suitability for Thermal Comfort</i>	218

6.4.3	<i>Controllability of Temperature and RH</i>	219
6.4.4	<i>System / Building Capital Costs</i>	219
6.4.5	<i>Comparisons against Normal Practice</i>	220
6.4.6	<i>Proximity of Solutions to the Mould Risk</i>	220
6.5	Chapter Summary	221
Chapter 7	Conclusions and Recommendations	222
7.1	Chapters Summary	224
7.2	Conclusions of Research	228
7.2.1	<i>Trade-Off between HVAC Energy Use and Mould Growth Risk</i>	228
7.2.2	<i>Heat Recovery Mechanism for Moisture Control and Energy Reduction</i>	230
7.2.3	<i>Review of Isolation Room Design in Malaysian Climate</i>	231
7.2.4	<i>Elements of Uncertainty in Isolation Room</i>	231
7.3	Contributions of Research	232
7.4	Limitations and Recommendation for Further Research	233
7.4.1	<i>Mould Growth Model</i>	233
7.4.2	<i>HVAC Design and Control Strategy</i>	234
7.4.3	<i>Interaction with Other Areas</i>	235
7.4.4	<i>Building Construction</i>	235
7.4.5	<i>Thermal Comfort and Contamination Removal Effectiveness</i>	235

REFERENCE

BIBLIOGRAPHY

List of Figures

2.1	Structure of Chapter 2	10
2.2	Predicted surface conditions in winter conditions and limit curves for different mould species (Clarke <i>et al</i> , 1999)	16
2.3	Generalised isopleth systems with LIM for health risk class A (Top), and class B/C (Bottom) (Sedlbauer, 2001)	19
2.4	Generalised isopleth systems and LIM for substrate group I (Top) and substrate group II (Bottom) (Sedlbauer, 2001)	20
2.5	Comparison of growth limit curves of different models (Ojanen <i>et al</i> , 2007)	27
3.1	Structure of Chapter 3	51
3.2	Goals of multi-objective optimisation (Deb, 2004)	66
3.3	Decision variable search space and objective function search space for multi-objective optimisation (Deb, 2004)	69
3.4	Objective space for two minimum objective functions (Deb, 2004)	70
3.5	GA Operations	73
3.6	Illustrated Principle Workings of Tournament Selection (after Yang and Soh, 1997)	76
3.7	Impact of selection and Crossover Operators on Population (after Deb, 2004)	78
3.8	Uniform cross-over	79
3.9	Master-slave parallel GA (Cantú-Paz, 1997)	81
3.10	NSGA-II procedure (Deb <i>et al</i> , 2002)	85
3.11	Rank (a) and cuboid (b) concepts used by NSGA -II (Salazar <i>et al</i> , 2006)	86

3.12	Ideal set of non-dominated convergence (Deb, 2004)	87
3.13	Multicriteria optimisation between investment and energy consumption (Chantrelle <i>et al</i> , 2011)	89
3.14	Interlink of NSGA-II, EnergyPlus simulation and mould risk model	92
4.1	Structure of Chapter 4	96
4.2	Generalised Isopleth system for spore germination, valid for all fungi species or hazardous class A (top) and B/C (below), with “d” denotes days (after Sedlbauer, 2001)	98
4.3	Mould Risk Germination Time	103
4.4	Generalised Germination Isopleth System (the dashed lines below limit isoline indicate varying measures of no risk)	105
4.5	Mould Risk for Surface Conditions Held Constant for 30 Days	108
5.1	Structure of Chapter 5	112
5.2	Schematic view of Isolation Room and Ward	117
5.3	Annual outdoor dry bulb temperature for Kuala Lumpur	121
5.4	Annual outdoor relative humidity for Kuala Lumpur	121
5.5	March hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions	122
5.6	June hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions.	123
5.7	September hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions	124
5.8	December hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions	125
5.9	Annual surface temperature for single-walled Isolation Room	126
5.10	Annual surface relative humidity for single-walled Isolation Room	127

5.11	A single wall construction for benchmark design.	129
5.12	Indoor conditions for Benchmark design	130
5.13	HVAC energy use for Single-Walled Isolation Room with conventional HVAC system	131
5.14	Wall surface temperatures for Benchmark design	132
5.15	Wall surface relative humidity for Benchmark design	133
5.16	A double wall construction for benchmark design	135
5.17	Room Conditions for Double-Walled Isolation Room	136
5.18	HVAC energy use for Double-Walled Isolation Room with conventional HVAC system	137
5.19	Wall surface temperatures for Double-Walled Isolation Room	138
5.20	Wall surface relative humidity for double-walled Isolation Room	139
5.21	Indoor conditions for Single-Walled Isolation Room at 19°C set-point	142
5.22	Surface temperature profiles for Single-Walled Isolation Room at 19°C set-point	143
5.23	Surface relative humidity profiles for Single-Walled Isolation Room at 19°C set-point	143
5.24	Indoor conditions of Double-Walled Isolation Room at 19°C set-point	144
5.25	HVAC energy consumption for Double-Walled Isolation Room at 19°C set-point	145
5.26	Surface Temperature for Double-Walled Isolation Room at 19°C Set-Point	145
5.27	Surface Relative Humidity for Double-Walled Isolation Room at 19°C Set-Point	146
5.28	Indoor Conditions for Alternative design	155
5.29	Surface temperature for alternative design	156
5.30	Surface relative humidity for alternative design	157

5.31	Room temperature profiles three versions of Isolation Room	158
5.32	Room relative humidity profiles for three versions of Isolation Room	158
5.33	HVAC total cooling energy profiles for the alternative design and the normal practice	159
6.1	Structure of Chapter 6	177
6.2	Trade-off between Energy Use and Risk of Mould Growth (with the boxed values being grouped on the Zone Relative Humidity Set-point)	181
6.3	Mould Risk and Surface Relative Humidity (with the boxed values being grouped on the Zone Relative Humidity Setpoint)	182
6.4	Trade-off for Different Zone Temperature Set-point Upper Bounds	184
6.5	Trade-Off between Energy Use and Mould Risk	188
6.6	Optimised Solutions after 125 Generations	189
6.7	Comparison in cooling energy between 24°C/50% RH and 28°C/50% RH set-points	192
6.8	Total Energy Use between 24°C/50% RH and 28°C/50% RH set-points	193
6.9	Bias RH Set-Point Error	196
6.10	Relationship between Supply Air Flow Rate and Fan Energy	199
6.11	Relationship between Total Energy Use and the Supply Air Flow Rate	200
6.12	Relationship between Mould Risk and Supply Air Flow Rate	200
6.13	Relationship between Total Energy Use and the Glazed Area	205
6.14	Relationship between Mould Risk and Glazed Area	205
6.15	Pareto optimal solutions based on room set-points	213

List of Tables

2.1	Comparison between existing mould growth models	25
2.2	Comparison of indoor design conditions	43
5.1	Probability of risk of mould growth on all surfaces for Benchmark Design	133
5.2	Probability of risk of mould growth on all surfaces for Double-walled Isolation Room	140
5.3	Comparisons of mould growth risk probability on internal surfaces for Single-Walled and Double-Walled Isolation Room at 19°C set-point	146
5.4	Comparison of mould growth risk probability for alternative case and normal practice	160
5.5	Impact of putting vapour barrier on the probability of mould growth for double-walled and alternative case	162
5.6	Construction details for wall assembly	165
5.7	Construction details for roof, floor and window	166
5.8	Window dimensions and corresponding index number for alternative design	167
5.9	Summary of optimised building construction variables	167
5.10	Indoor design condition used as the basis for optimisation of temperature set-points	168
5.11	Constraints for alternative design	174
5.12	Summary of optimised HVAC control strategy variables	174
6.1	Energy Use, Risk of Mould Growth and Problem Variables	180
6.2	Energy Use, Risk of Mould Growth and Building Performance Metrics	187

6.3	Corresponding objective functions and set-points for the optimised solutions and the benchmark design	191
6.4	Daytime Bias Set-Point Error	194
6.5	Air flow rate and energy use for optimised solutions and the benchmark design	198
6.6	Data for 70% RH set-points	201
6.7	Wall Construction Optimisation Results	202
6.8	Window Size Optimisation Results	204
6.9	Roof Construction Optimisation Results	207
6.10	Mould risk components of the optimised solutions	208
6.11	Energy Components of the Optimised Solutions	211
6.12	Differences in total energy and mould risk for neighbouring solutions	214
6.13	Optimised and Base Case Designs	218

Chapter 1

Introduction

In Malaysia, a ten-storey, 704-bed Pandan Hospital in the southern part of the Malay Peninsula worth 500 million Malaysian Ringgit (MYR) (approximately £74 million) was ordered closed by the Ministry of Health in September 25, 2004 when mould species *Aspergillus fumigatus* and *Penicillium spp* were discovered on the walls of an operating theatre and on medical equipment. The closure received wide media coverage and became a subject of scrutiny by the Malaysian Anti-Corruption Agency in order to determine any irregularity during its construction. Remediation works included applying anti-microbial treatment on the affected areas. The hospital was re-opened on February 16, 2006.

No sooner than the first case resolved than another mould-related damage in healthcare buildings occurred involving a MYR404 million (approximately £63 million) Ampang Hospital, which is close to the capital of Kuala Lumpur. It started operation in early 2006 and is meant as a referral centre for haematology to reduce the patient load on Kuala Lumpur Hospital. However, mould growth was detected on the ceilings of the paediatric clinic after one year in operation. A rather simplistic explanation offered by the Minister of Health was the clinic is located below the intensive care unit (ICU), where the units air-conditioning system for the ICU was set to operate at a temperature range of 18°C to 20°C and turned on 24 hours a day. Conversely, the paediatric clinic has its air conditioning turned on only eight hours a day.

The ICU was designed to be operating continuously with the indoor conditions (temperature and relative humidity) monitored closely. Conversely, the paediatric clinic was not as critical as the ICU or isolation rooms and was designed to be operating intermittently. Having a paediatric ward below the ICU required that proper insulation materials (such as polyurethane foam) and methods be installed to prevent heat and moisture transfer between the

two zones. One consequence of not putting proper insulation was that the surface temperature of the floor slab became lower than the dew-point of air space above the ceiling due to the heat transfer between the two zones, and led to condensation of water vapour on the slab. Over time, the condensed water vapour was absorbed by the ceiling tiles until they were damp and became suitable media for germination of ubiquitous mould spores.

Another explanation given was regarding the air-conditioning system for the ICU, operating at the room temperature range of 18°C to 20°C. A point that is not directly apparent is the uncertain element of user behaviour and its impact on the energy use, as well as the potential of mould growth. It was observed that the temperature range was much lower than that recommended by health facilities design standards, and there was a possibility of user intervention. The implication was the air-conditioning operated at higher energy consumption and possibly condensation occurred on surfaces over time.

Patient critical areas like the isolation rooms and the ICU are designed to be operated continuously with the indoor conditions (temperature and relative humidity) monitored closely. Thus, the heating, ventilating, and air conditioning (HVAC) systems serving these areas are designed to be operated continuously in order to maintain the conditions. The implication is that these areas tend to have high HVAC system energy consumption, resulting in high carbon emissions from continuous electricity consumption.

There are many issues that are faced by the building designers, building operators, and the end users in ensuring the critical patient areas operate according to its design function, and at the same time trying to reduce energy consumption which may bring about problems such as mould growth.

1.1 Mould Growth, Energy Use, and Building Operation

Mould growth is undesirable in buildings because it causes damage to surface finishes, unsightly stains and, more seriously, imposes health hazards to occupants. This is more problematic for critical buildings like hospitals, where the patients may have weak immune systems and may be exposed to infection, either by direct contact with mould itself, or by inhalation of mould spores. The potential for mould growth is even higher when the hospitals are located in tropical countries like Malaysia, which have hot and humid climates. Cases have emerged where combination of poor design, operation and maintenance practices, exacerbated by the humid outdoor conditions especially during night-time, have led to occurrences of mould growth in these critical areas.

Currently, the design criteria for isolation rooms and its HVAC systems in Malaysia are based on the standards and guidelines published in the western countries, like the United States of America and the United Kingdom, the climates of which are varied. In contrast, the Malaysian climate is hot and humid throughout the year, where the diurnal temperature variation is very low and the ambient relative humidity consistently high with a minimum average dry bulb temperature of 27°C and minimum average relative humidity (RH) of 79%. However, during night-time, the ambient RH of the hot and humid climate is close to 100%. In fact, the building and the system are designed based on guidelines not tailored to local climate. This has huge impact on overall energy use since very high energy use is needed to cool and dehumidify highly humid outdoor air to comply with the design requirement for 24 hours.

The difference in climate also results in different response of building occupants to the built environment. In the hot and humid climate like Malaysia, hospital building users respond better to higher temperature range than that in the western countries (Yau and Chew, 2009).

Apart from the HVAC system design, the considerable difference in climates between Malaysia and the western countries has a big influence on the choice of construction materials for a building and how they are installed. For example, timber-based construction is not practiced in Malaysia as much as in the UK since materials such as the oriental–strand board (OSB) has higher affinity to moisture absorbance compared to brick, and this can lead to mould growth and decay after long exposure to highly humid environment. Position of vapour barrier in the wall is also influenced by the climate difference. In Malaysia, it is critical for the vapour barrier to be placed in the outermost layer of an external wall as first defence against moisture ingress. By contrast, the climate in the UK necessitates that the vapour barrier is installed at the innermost layer of a building wall assembly.

The way that the building is operated can also increase energy use. Building operators need to understand the building envelope, such as the hygrothermal performance of the double brick wall with insulation, and the building services like the HVAC systems. They also need to have a practical and cost-effective maintenance plan.

The design of a HVAC system is subject to uncertainties, such as the amount of moisture generation inside the building from occupants or processes. This attribute is linked to occupancy which is difficult to quantify during design. It forces designers to apply a factor of safety, which can be arbitrary. Incorrect factors of safety may result in the system being incorrectly sized.

Another uncertainty to consider is user behavior that affects the overall performance of the HVAC system. Building occupants respond to the indoor conditions accordingly to achieve appropriate levels of thermal comfort. One response is to lower the room temperature to be below the recommended setting, as was seen in the Ampang Hospital example. The cooling coil then ends up cooling and dehumidifying outside its operating range, thus increases the energy consumption

and decreases its efficiency. Another response is to open windows to let fresh air coming into the occupied area. Infiltration of outside air that is not accounted for in design brings unwanted moisture into the room. The HVAC system would then not be able to control the room relative humidity (RH). The excess moisture is absorbed by the room surface, a consequence of which there is a probability of mould growth on that surface.

HVAC system energy use might be reduced through optimised system operation. However, this may increase the risk of mould growth. For instance, reducing cooling operation may reduce energy use, but could also reduce the dehumidifying effect on the incoming ventilation air, with the result that humidity, and the risk of mould growth, in the occupied space is increased.

In order to maintain indoor conditions as required by the health design guidelines, a number of areas in hospitals require the continuous operation of the HVAC systems, such as surgery rooms and intensive therapy units. Continuous operation of the HVAC systems incurs high energy use. If the hospital is located in a hot and humid climate, the energy use is much higher than encountered in the temperate climate, in which increased level of dehumidification is required before the conditioned air is supplied into these specialised areas.

There is a need, therefore, to minimise the high energy use of the HVAC systems that serve the critical areas in tropical hospitals, and at the same time minimize the risk of mould growing in these areas (which if it occurs may be detrimental to the health of occupants, especially the patients). This can be achieved through the use of model-based optimisation which can be used to find design solutions and system operating strategies that minimise energy use or the risk of mould growth. Model-based optimisation can also be used to investigate the trade-off between conflicting design goals, such as the trade-off between energy use and the risk of mould growth.

Currently, there is no study which establishes the relationship, or trade-off, between minimisation of energy consumption, by way of optimizing the HVAC systems and the building fabric, and the minimisation of the risk of mould growth in hospitals. This is particularly the case for specialised units such as isolation rooms, where the HVAC systems are operated continuously and located in tropical climates. Thus, the aim of this research is to investigate the trade-off between building (HVAC system) energy use and the risk of mould growth in hospital buildings located in hot and humid climates. This research also aims to highlight the uncertainties that arise from existing mould growth prediction model.

1.2 Research Aims and Objectives

The aim of this research is to investigate the minimisation of both the energy use and the risk of mould growth in hospital buildings located in a tropical climate such as Malaysia, while identifying the relationship between these two criteria. To achieve this requires a development of an approach based on the use of simulation and numerical optimisation.

The research objectives that meet this aim are:

- To conduct a literature review on mould growth, building optimisation, and design and performance of hospitals in Malaysia (**Chapter 2**);
- To identify a building performance simulation tool that is able to simulate the building HVAC system energy use and the environmental conditions necessary for predicting the risk of mould growth (**Chapter 3**);

- To investigate and select a suitable optimisation method that can be used to minimise building energy use and the risk of mould growth, and to identify the trade-off between the two goals (**Chapter 3**);
- To select a suitable mould growth model and further develop the model for predicting the risk of mould growth (**Chapter 4**);
- To develop an example optimisation problem for a benchmark isolation room located in a hot and humid tropical climate, such as Malaysia and to evaluate the performance of the isolation room design practice using the simulation (**Chapter 5**);
- To investigate the optimum construction and operation of the benchmark isolation room and the trade-off between energy use and the risk of mould growth (**Chapter 6**);
- To draw conclusions about which design solutions and operating strategies minimise energy use and the risk of mould growth, and to draw conclusions as to the extent to which a trade-off exists between energy use and mould growth, and propose recommendations for further research (**Chapter 7**).

The originality of the research is in the application of optimisation methods to investigate the relationship, or trade-off between energy use and the risk of mould growth, particularly for hospital buildings located in a hot and humid climate. In this respect, the new knowledge is focused on the required modeling/analysis components together with the trade-off between energy use and mould growth. The approach serves as decision making tool for the design of energy-efficient buildings in hot-humid climates, particularly specialized units requiring continuous operation.

The next chapter (**Chapter 2**) reviews existing literature survey in the areas of mould growth research and mould growth models. An overview of the building, HVAC system and HVAC control system optimization is also presented. The normal practices of Malaysian hospital design and the measured performance against those practices are discussed.

Chapter 2

Literature Review

Chapter 1 gave an introduction to the mould growth issues in Malaysian hospitals, and the difficulties encountered by building designers, operators and users in achieving indoor environment quality and thermal comfort. The structure of this chapter is shown in **Figure 2.1**, where it starts with discussion of the factors leading to mould growth in buildings and the extent to which there is a "risk" of mould growth in buildings, and procedures for predicting the risk, have been studied in existing literature. It also gives an overview of existing modeling approaches available in predicting mould growth. The development of building optimisation, specifically building construction, HVAC system, and HVAC system operation is also covered. Finally, current design practice for hospital design in Malaysia and the comparison with measured performance in available literature are discussed.

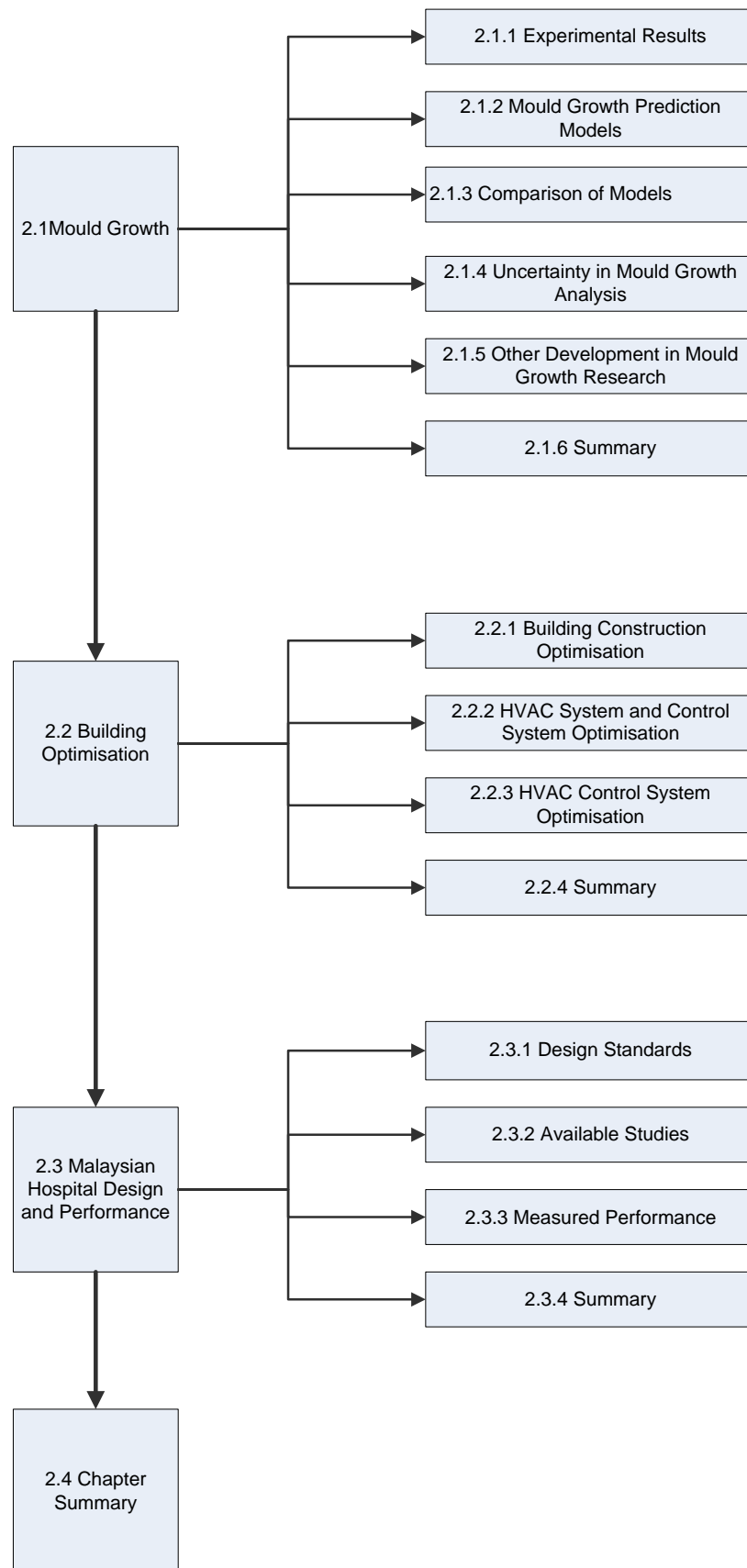


Figure 2.1: Structure of Chapter 2

2.1 Mould Growth

Moulds are not desirable in buildings for three primary reasons: they cause decay of materials, including structural members; they cause objectionable staining (Adan, 1994); and they can have negative health impacts. They also produce mycotoxins and volatile organic compounds (VOCs) (Straube, 1999; Wilkins *et al*, 2000), which causes substantial construction, health and business risks (Flanagan and Jewell, 2003).

Fungal growth in buildings requires nutrients from furniture or building materials such as fibre-glass insulation (Ezeonu *et al*, 1994), of which an extensive literature review regarding mould growth on this particular material is done by Van Loo *et al* (2004); a temperature in the range of 22 to 35°C; the presence of moisture in the materials, with the risk increases considerably when the surface relative humidity (RH) goes beyond 80% (Pasanen *et al*, 1992); the type of substance in terms of organic fraction in a material (D'Orazio *et al*, 2009); and an exposure time which varies from days to months. Mould growth also stems from internal surface condensation of a building (Becker, 1984).

This section discusses the range of experimental results pertaining to mould growth and the various mould growth prediction models that are used in predicting the growth risk in building.

2.1.1 Experimental Results

Research has been conducted to establish the moisture requirements for mould growth, beginning with a comprehensive study by Block (1953). It was found that the water-absorbing properties of the substrate play an important role in determining the limiting humidity of the atmosphere at which mildew will occur. The fungus is incapable of obtaining moisture for growth directly from the atmosphere but derives it from the substrate which obtains the moisture from the atmosphere. The substrate moisture is also affected by airflow and temperature as well as relative humidity (Horner, 2006),

and also the capillary absorption of water in the building materials like gypsum and wood board (Pasanen *et al*, 2000). Different moisture regimes can also affect the response to fungal growth on insulation materials (Klamer *et al*, 2004).

The influence of moisture in terms of its requirements for mould growth in buildings was discussed in detail by Grant *et al* (1989), with particular regard to a parameter known as water activity (A_w) in building materials. Water activity is defined as the ratio of vapour pressure of water above a sample to that of pure water under the same conditions (temperature and humidity) and is expressed as a fraction, $A_w = RH/100$, where RH refers to the relative humidity of the substrate. It is used to represent the water that is not bound with the molecules in a sample. This unbound water can support the mould growth in which the spores can obtain it from the atmosphere using osmotic process through its semi-permeable membrane.

Mould growth on susceptible surfaces of building materials can be avoided if the water activity (A_w) is maintained at below 0.80. This is achieved through combinations of room air temperature and relative humidity according to the thermal properties of the building walls (Grant *et al*, 1989). By keeping building materials, such as ceiling tiles dry, the mould growth could also be avoided (Chang *et al*, 1995). However, in the context of the hot and humid climate, cooling and drying the ventilation is needed to avoid the surface water activity going above 0.8 (Hens, 1999).

Research on conditions leading to mould growth and the methods of predicting and tackling the problem in temperate countries is extensive. However, very little research of similar nature has been conducted for buildings in hot and humid climates. One such study was reported by Lim *et al* (1989), where tests were conducted on the National University of

Singapore faculty buildings to isolate and identify the mould species that are resistant to fungicides. A small number of mould species that were isolated in this study, such as *Aspergillus versicolor*, were also found in buildings in the cold and dry climates, thus proving that certain species are not localised. However, the scope of study precludes the effects that moisture content and surface temperature would have on the propagation of mould. Furthermore, this study advocates the use of fungicide, a rather curative measure than a preventive or predictive measure.

2.1.2 Mould Growth Prediction Models

The existence of mould inside buildings poses health hazards for its occupants. There are methods to ameliorate the mould damaged surfaces in buildings by applying disinfectant or fungicide. However, this corrective action is taken when the damage caused by mould growth is already widespread. The application of chemical detergents also has its disadvantages in that it poses a hazard to the occupants and incurs higher buildings maintenance costs. It is therefore more practical to take into account the risk/probability of mould growth during early stages of building design. This has led to the development of a number of established mould growth prediction models.

Adan (1994), introduced Time-of-Wetness (TOW) as a measure of water availability for mould growth under transient conditions. The TOW was defined as the ratio of cyclic *wet* period, that is the period when the relative humidity (RH) near a surface is greater than ($RH \geq 80\%$), and cyclic period. Since this approach is developed from laboratory experiment, the cyclic period refers to the period of between 6 and 12 weeks during which gypsum-based materials were inoculated with fungus. The materials then were exposed at various RH settings. Mould growth remains weak as long as TOW stays below 0.5, which represents 50 percent of duration. If the value is above that

figure, the growth rate increases rapidly to reach the steady state value for $TOW=1$.

The limitations of this approach were that it was based on the experimental results using a single fungal species and the substrates used were limited to gypsum-based materials. Another limitation was that the cyclic period depended on the time determined in the experiments. Finally, temperature was not considered a key parameter to fungal growth in this approach.

Clarke *et al* (1999) formulated the critical mould growth limits into a mould prediction computer program. The growth model uses data taken from an extensive literature review. Mould samples were also collected from houses in Edinburgh, UK, and were germinated in the laboratory. The mould species were identified and assigned into categories. The critical limits for the growth of the mould species were mathematically described in terms of growth limit curves, or isopleths, that define the minimum combination of temperature and relative humidity for which growth will occur. Each curve was generated from a series of data points on a Temperature (T)–Relative Humidity (RH) plot and was mathematically fitted by using a third-order polynomial equation in the form of $a_0 + a_1T + a_2T^2 + a_3T^3 = RH$. The prediction model uses temperature and partial vapour pressure as transport potentials for moisture in a 1-Dimensional, coupled heat and moisture transport model. The prediction model has been incorporated into the ESP-r transient building simulation program (Clarke, 1985).

The differences in results of mould growth between categories of mould species can also be taken as a measure of uncertainty, particularly the conditions between the limit curves. The limit curves describe the limiting surface conditions, based on surface temperature and surface relative humidity data

points, for which different categories of mould will germinate. Questions are also raised on the conditions that are not accounted for directly by the limit curves but may lead to mould growth. To illustrate this point, **Figure 2.2** shows the distribution of data points superimposed on the generic mould growth limit curves, taken from extended simulation of a test house in representative winter conditions over one week, with surface temperature range of 0 to 5°C and the surface relative humidity range of between 75% and 100%. The mould species were represented by categories based on level of affinity towards surface relative humidity. The lowest growth limit curve belongs to a mould species category A which is highly xerophilic, or that which favours 'dry' surface, B for xerophilic category, C for moderately xerophilic, D for moderately hydrophilic, E for hydrophilic, and category F represents the mould species which is highly hydrophilic, or that which favours very damp surface condition. This led to the conclusion that mould growth spanned across all the growth categories.

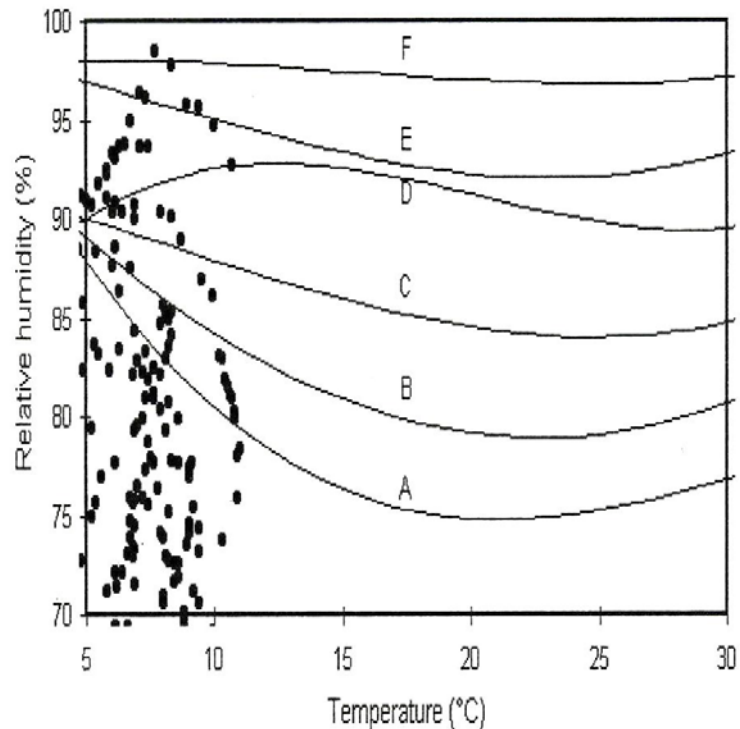


Figure 2.2: Predicted surface conditions in winter conditions and limit curves for different mould species (Clarke *et al*, 1999)

The limitation of this mould growth model is that the curves are based on data obtained from conditions that are controlled in laboratories, and where the principal determinants were maintained at fixed values. The model is therefore unable to indicate the dynamic effects of temperature and/or humidity on mould growth and as such is a steady-state model.

There is also a question as to whether the mould will cease to grow at conditions immediately below the limit curves, or if the growth will slowly recede when the conditions go further from the curve.

The mould growth model by Hukka and Viitanen (1999) uses a visual scale as a method of quantification. Mould growth on wooden materials is predicted using a mathematical model developed from laboratory test of mould growth. The model

depends on the critical relative humidity (RH_{crit}) required for the initiation of mould growth, which is a function of temperature. Based on the temperature range of 5.0-40.0°C, the critical relative humidity can be expressed as a boundary curve of a polynomial function shown as equation (1):

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0 & \text{when } T \leq 20 \\ 80\% & \text{when } T \geq 20 \end{cases} \quad (1)$$

The critical relative humidity when surface temperature is above 20°C coincides with the guidelines stated in the International Energy Agency Annex 14 Guideline on Condensation and Energy (IEA, 1990). It was observed that growth mould fungi and time period needed for the initiation of mould growth are mainly regulated by water activity, temperature, exposure time and surface quality of the substrate.

Presently, the model gives special attention to growth on wood and wooden material surfaces, even though the authors recognize the future possibility of applying the model on materials other than pure wood.

Oreszczyn et al (1999), developed the Condensation Targeter II (CD2), moisture production calculation procedure, which has been extensively used to predict the mould growth in the United Kingdom dwellings. The procedure incorporated a monthly calculation to investigate when the critical conditions for mould growth occur, in which it determined conditions on the dwelling surfaces, including cold bridges. It also allowed seasonal variations in the ventilation rate to be examined. The model incorporated thermal modelling and moisture modelling. The thermal model is used to predict the internal temperature, which is determined by the heat loss of the building, the type of heating system, control and other sources of internal heat gain. The thermal models used are Building Research Establishment Domestic Energy Model, or BREDEM-12 (Anderson *et al*,

2001), that calculates a seasonal average internal temperature and uses modified heating season degree days to characterize the external climate, and BREDEM-8 (Anderson *et al*, 2001), which predicts mean monthly energy consumption and temperatures from mean external temperature and solar radiation.

The moisture model is used to predict the internal vapour pressure which, when combined with the temperature, can be used along with psychrometric data to predict both monthly airspace and surface relative humidity. The risk of mould growth relates to the critical surface relative humidity.

The model makes several assumptions. Firstly, the critical surface relative humidity in a building, above which mould growth would occur are; 80% RH for wall surfaces, ceilings and floors and 100% surface relative humidity at the glazing; Secondly, moisture transfer only occurs through bulk air movement between inside and outside the building, thus ignoring diffusion through the fabric and hygroscopic adsorption/desorption. Finally, it only models average conditions and not the peak conditions.

Sedlbauer (2001 and 2002) developed a procedure that consists of two prediction models that are based on each other, namely the isopleths termed Lowest Isopleths for Mould (LIM) and a transient biohygrothermal model. The LIM model differentiates the mould species according to the health risk they impose on building occupants, termed as hazard classes. The hazard class A is defined as fungus or its metabolic products that are highly pathogenic and should not be allowed to occur; class B for the fungus as a pathogen that may cause allergic reactions if exposed for over a long period; and class C is for the fungus that is not dangerous to health, but may cause

economic damage if formed. The generalized LIMs for both the hazard classes were shown in **Figure 2.3**.

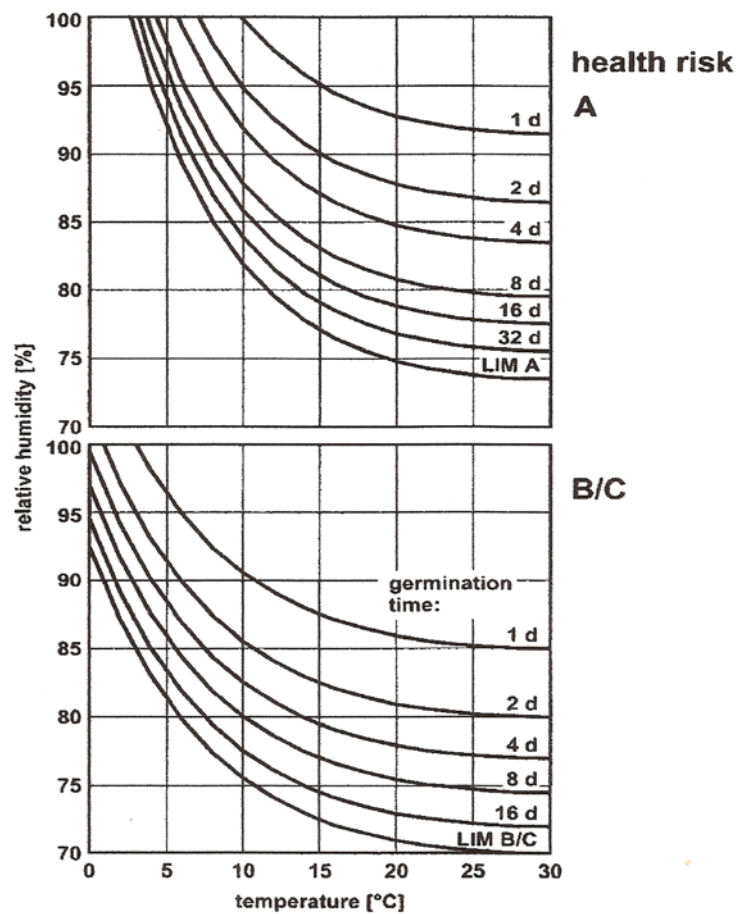


Figure 2.3: Generalised isopleth systems with LIM for health risk class A (Top), and class B/C (Bottom) (Sedlbauer, 2001)

LIMs are based on measured biological data under laboratory conditions and represent the growth prerequisites for all fungi in each hazard class. LIMs therefore are the resulting lowest boundary lines for possible fungus activity. They also describe spore germination time and growth rates of mould according to the substrate groups, as shown in **Figure 2.4**.

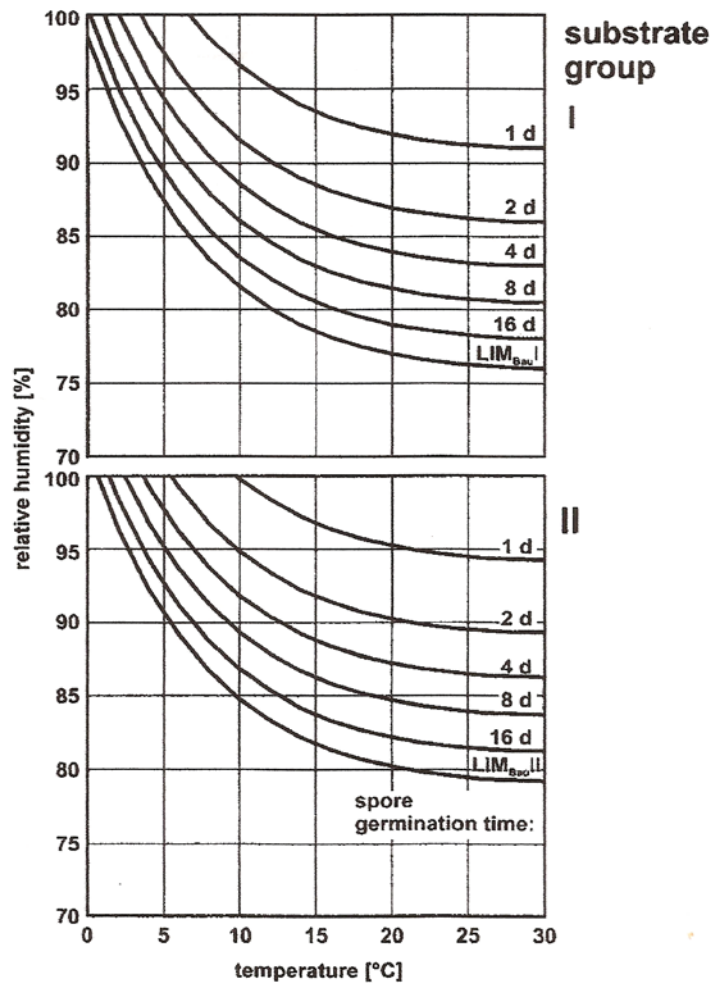


Figure 2.4: Generalised isopleth systems and LIM for substrate group I (Top) and substrate group II (Bottom) (Sedlbauer, 2001).

Actual building materials are categorized into substrate groups; for example, Group I is classified as biologically very usable substrates (e.g. wallpapers, plasterboard), and Group II is classified as substrate with porous structures (plaster, mineral building materials). The Lowest Isopleths for Mould (LIM) I and II correspond to these groups. Stating that the temperature, humidity and substrate conditions are the boundary conditions for fungi growth, he asserts that they must be present simultaneously and not treated as steady-state conditions.

The LIM approach is further developed into is known as the biohygrothermal model, the basics of which can be referred from studies by Sedlbauer (2001) and Sedlbauer *et al* (2003). This model is based on the fundamental idea that fungal spores have a certain osmotic potential across the spore walls due to differences in the concentration of salts, sugars and additional substances. It takes into account the changing surface temperature and relative humidity and predicts the moisture balance independence of realistic unsteady boundary conditions as found in buildings, and in so doing permits the prediction of mould growth probabilities. The moisture balance (mostly the conditions of spores) is predicted as effected by realistic unsteady boundary conditions as found in buildings, in order to permit predictions of growth probabilities.

The biohygrothermal model is incorporated into a simulation program *WUFI-Bio*, Sedlbauer (2001, 2003), that predicts the mould growth under transient conditions. The determination of critical moisture content is achieved through the calculation of resulting water content in a modeled mould spore when exposed to transient conditions and comparison to the critical water content, above which the spore will germinate and mould will start to grow. The assumption for this method is the water absorption of spores is calculated with the diffusion approach; and the critical moisture content is determined by the means of isopleths.

The limitation of the model is the influence factors such pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered, which may affect the determined germination time of mould spores. The material parameters are not directly measured but were inferred from other experiments with spore-forming bacteria, specific biological experiments must be conducted to support the model. The activity inside the spores also cannot be modeled

and described mathematically. Therefore, the substrates are not considered directly at the biohygrothermal calculations. The moisture storage function used for mould fungal spores was measured for bacteria and slightly modified, due to the absence of existing measured values for mould spores.

Moon and Augenbroe (2004) predicted mould growth based on the availability of detailed information of the physical state of the materials in the building over time. The focus was to develop performance indicators that express the mould growth risk in existing building as a result of uncertainties in building parameters. Isopleths for mould spores were used to establish a standard mould generation graph. This was compared with embedded mould protection method incorporated into the ESP-r simulation program (Clarke *et al*, 1999) and the conservative mould prevention criterion of 80% relative humidity threshold set by IEA Annex 14(1990).

Consideration of uncertainties was based on the premise of the deterministic use of the current simulation models being inadequate for assessing all possible types of mould risks in real-life buildings. Therefore, a mix of existing simulation tools was used as a method to address the uncertainties. The EnergyPlus (Crawley *et al*, 2001) simulation was combined with air infiltration model COMIS to deliver zone conditions, namely room temperature and relative humidity, which in turn were used as the interior boundary conditions for the hygrothermal envelope model WUFI (Kunzel, 1994) to determine the surface conditions. The hygrothermal results from both simulations were then combined with thermal bridges results from the KOBRA simulation tool (PHYSIBEL, 2002) to determine the local environmental conditions.

In addition to the standard major factors influencing the mould growth, four other major “non-standard” mould cause categories were identified, namely spore source, substrate condition, HVAC maintenance and operation, and local building details. Each cause category consists of parameters, or attributes to potential mould growth not captured in building simulations but are present in real-life buildings. For example, the parameters in the HVAC maintenance and operation category are the risk of outside air infiltration due to pressurisation, air tightness of facades, HVAC shutdown operation, and so on.

Using a database of mould growth occurrences and field data of existing buildings, the parameters were factorised using methods such as factorial analysis or Latin Hypercube Sampling in order to evaluate their dominance, and their values were computed into empirical factors that represent the cause categories. A hypothetical performance indicator for mould growth, PI , was then formed, and expressed in equation (2) as

$$PI = PI^* + F_a + F_b + F_c + F_d \quad (2)$$

Where,

PI^* = Outcome of idealised standard simulation obtained from the mixed simulation method

F_a = Cause factor representing spore source category

F_b = Cause factor representing substrate condition category

F_c = Cause factor representing substrate condition category
HVAC maintenance and operation category

F_d = Cause factor representing building details category

The limitations of this model are that it can only be used for mould remediation case on existing building and not for new buildings. The mixed simulation method adopted results in increased accuracy for idealised simulation part of the performance indicator but it suggests an increase in computing cost. Obtaining as much information as possible from database of mould growth occurrences and field data to evaluate the “non-standard” mould cause categories also suggests an increase in complexity of the mould growth risk analysis. Methods for quantifying the cause factors still need to be developed for the performance indicator to be meaningful.

2.1.3 Comparison of Approaches

The different approaches taken by each model previously explained and their limitations are shown in **Table 2.1**.

Table 2.1: Comparison between existing mould growth models

Model	Author	Method	Limitations
Time of Wetness (TOW)	Adan (1994)	Indication of limit value for the relative humidity in hours/day	Influence of temperature is not considered
ESP-r	Clarke & Rowan (1999)	Superimposition of the calculated surface conditions on the mould growth limitation curves Limit curves based on categories of species derived from controlled experiments and previous published researches	No statements concerning time Uncertainty of growth between limit curves for given surface conditions Dependence on the substrate is not considered
LATENITE	Hukka & Viitanen (1999)	Using critical surface relative humidity based on mould index (mathematical in nature) Derived from laboratory experiments for visual inspection	Applicable only to pure pine and spruce sapwood (substrate specific isopleths) Uncertainty with regards to other materials
Biohygrothermal	Krus & Sedlbauer (2001)	Lowest Isopleth for Mould (LIM) based on categories of substrates Calculation of moisture content in mould spores Spores as a biological wall simulated in WUFI-Bio	Hard to acquire the required moisture properties for a spore More complex computation
Probabilistic Mould Risk Indicator	Moon & Augenbroe (2005)	Mixed simulation approach using existing software combined with uncertainty analysis Using normal distribution to determine order of uncertain parameters	Fungal spore transportation and local air flow around trouble spots were not considered Approach too complex with increased computing time

From **Table 2.1**, it can be seen that there is a mixture of different approaches; one was based on a specific threshold value of one key parameter (surface relative humidity) after a specific period of surface exposure. Another adopts a similar path while introducing an index of mould growth based on visual observation. Another method assesses the risk as the functions of surface temperature and relative humidity and relates them with the temperature ranges at which different mould species will grow. The time factor was also considered where two aspects were looked at; one is the time for spore germination, and the time during which a surface was exposed to damp condition. Finally, the latest approach was to incorporate uncertainty analysis to assess the dynamics of a number of building parameters not captured in simulation but do attribute to mould growth.

The comparison of different models in **Table 2.1** was shown again in the form of growth limit curves as shown in **Figure 2.5**.

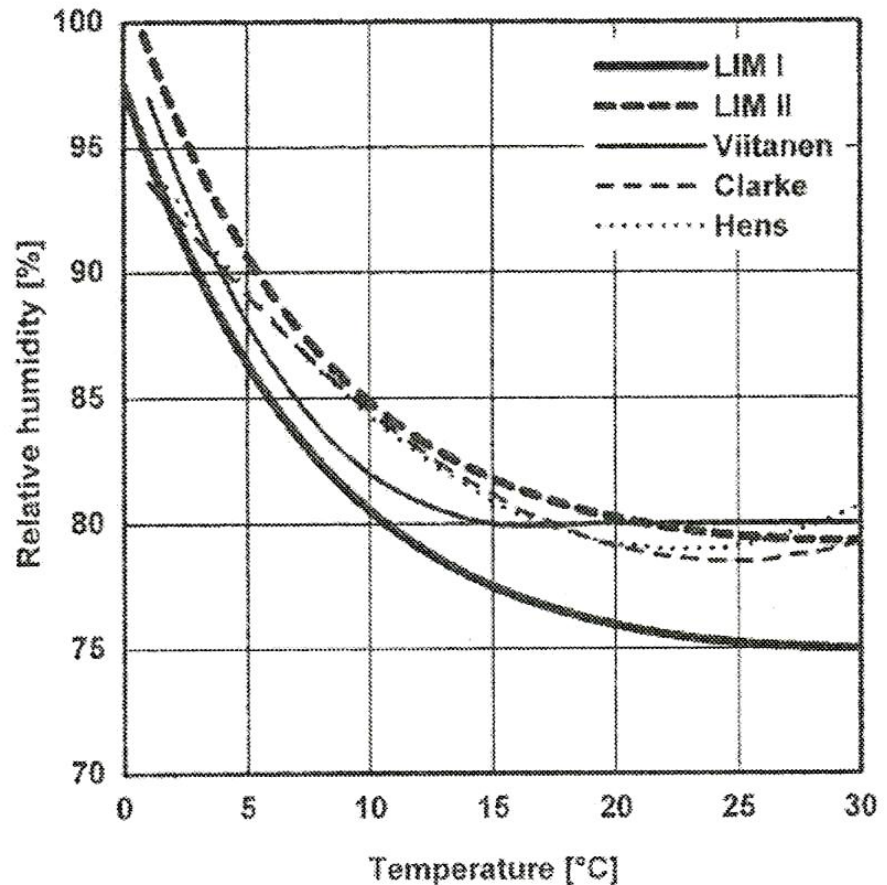


Figure 2.5: Comparison of growth limit curves of different models (Ojanen *et al*, 2007).

The comparisons in **Figure 2.5** show a good agreement among the models with regards to the critical condition above which mould will grow (25°C and relative humidity of between 75 to 80 percent at the surface), apart from the Lowest Isopleth for Mould (LIM) curve I by Sedlbauer (2001). There is little discrepancy between the models with regards to the surface conditions at the range of temperature between 0 to 5°C and the relative humidity of between 90 to 100 percent. However, there is divergence between the limit curves as the surface temperature increases and the surface relative humidity decreases.

It is worthy of note that although some curves seem to overlap, indicating typical response to the changing conditions, there are noted differences between the methods. The first difference is in the growth media. Clarke *et al* (1999) used agar substrates as medium for mould species extracted from actual house and also used inoculated wallpaper and germinated the mould inside climate chamber for comparison of results. The result by Hens (1999) is based on experiment using wheat extract agar. Hukka and Viitanen (1999) used laboratory sample of pine and sprucewood. Sedlbauer (2001) categorised actual building material into substrate groups where Group I is classified as biologically very usable substrates (e.g. wallpapers, plasterboard), and Group II is classified as substrate with porous structures (plaster, mineral building materials). The Lowest Isopleths for Mould (LIM) I and II correspond to these Groups.

The second difference is the method of derivation. The limit curves by Clarke *et al* (1999) are derived from curve-fitting the data points obtained from previously published researches and from their own experiments. The same applies to the curve by Hens (1999) even though the parabolic equation for critical surface humidity is a second order function. Curves by Hukka and Viitanen (1999) are derived from multiple regression and laboratory samples with priorities on wood.

Another difference is what the curves represent. Curves by Clarke *et al* (1999) and Hens (1999) are represented by the same species. The curve by Hukka and Viitanen (1999) relates to the species that grow on wood which has different surface condition requirements. Lowest Isopleths for Mould (LIM) by Sedlbauer (2001) implied that the curves represent the lowest possible fungus activity, below which there will be no mould growth. The emphasis is on particular species that exist in a building and harmful to occupants.

A more recent comparative study of all the available mould growth prediction models was by Vereecken and Roels (2012). The study recognised the deterministic approach of the models but noted that the different assumptions in the prediction methods of each model lead to contradictory results of the probability of mould growth. A suggestion was made to develop prediction models that include a spread in germination time and growth rate.

At present, there is no available literature on mould growth model that indicated whether the period of exposure of a wall surface to indoor condition is either successive or accumulative; accumulative being there is an amount of time during which drying of surface occurs. Sedlbauer (2001), for example, indicated that exposure time on each of the isopleth is the time required to support mould growth. A new model by Krus and Sedlbauer (2007) suggested that the risk of mould growth can be integrated with time. However, it is not mentioned in both studies whether the exposure time is successive and the length of time between the wet-periods of the exposed surfaces is also not known. For the purpose of the research, the model by Krus and Sedlbauer (2007) is useful since the drying periods in tropical climate are likely to be short.

2.1.4 Uncertainty in Mould Growth Analysis

It is important to highlight the probable uncertainties that may be present in the existing mould growth prediction models and their contribution to the results obtained in this research.

- a) There are uncertainties in the actual/transient surface conditions due to the modelling simplifications, and the extent to which the existing mould growth models adequately account for the influential “boundary conditions” for mould growth, such as moisture sources and infiltration.

- b) The response of different species of mould to conditions brought about by parameters such as temperature, humidity, substrate (whether wood or gypsum), and material properties, all of which may vary. To illustrate, the critical surface humidity levels above which mould will grow also vary with different surfaces; for wood, gypsum and fibreboard, the critical surface humidity is between 80% and 95%, whereas for wallpaper, it is between 75% and 95% (Viitanen and Salonvaara, 2001).

- c) Indoor conditions have a significant impact on mould growth potential. These include the building operation which involves user behaviour that is very difficult to quantify, the ventilation rates, the thermostat set point values, and the schedule of operation.

- d) The type of HVAC system and their mode of operation influence the speed at which indoor conditions are achieved and maintained, and therefore the risk that conditions suitable for mould growth will occur.

- e) Building configuration involves building orientation and insulation layer thickness, either by design or construction. Insulation thickness vary according to where it is applied, whether in the floor, cavity wall or roof, this in turn influences the uniformity of surface conditions.

- f) The climate conditions and micro-climate influences, the internal humidity and potential for mould growth.

2.1.5 Other Development in Mould Growth Research

In addition to the mould growth models mentioned above, recent research by Johansson *et al* (2009) took into account existing mould growth models, namely the 80% RH threshold value set by the IEA Annex 14 (1990), and the lowest isopleths for mould (LIM) method proposed by Sedlbauer (2001), and converted them into indices to predict mould growth on rendered building facades. They concluded that the orientation and thermal inertia, have major influences on the surface humidity levels of the facades. In addition to the mentioned parameters, wind-driven rain also has a significant impact on the hygrothermal properties of a building envelope, particularly the moisture content in walls which may lead to potential mould growth at the edges. (Abuku *et al*, 2009). Having stagnant air at internal wall corners may also contribute to mould growth due to increased relative humidity within the region as a result of low convective effect (dos Santos *et al*, 2009).

A study by Woloszyn *et al* (2009) used a combination of relative humidity-sensitive ventilation with building materials that possess moisture-buffering capacity as one of the solutions to reduce energy demand and reduce variations in indoor relative humidity. However, there is no conclusion on the influence of continuously introducing external air with very high moisture content at very high air change into a building on the energy consumption and indoor RH variation. The scope of research was limited to the residential building in the cold and dry climate.

A novel approach of assessing the risk of mould growth on building materials using spatial and frequency domain analysis was also developed (Aibinu *et al*, 2009). The method uses digital image processing, digital signal processing and shape analysis of the image of mould infestation visible on the surface of a building material. It is only applicable at a stage when

growth is evident or symptomatic and when remedial action is required.

There are a few building standards and guidelines available that give specific requirements on minimising mould growth on building surfaces. However, they are limited in the context of indoor air conditions. The British Standard BS 5250 (2002) assumes that the surface relative humidity for the external wall of a room could support mould growth if the room relative humidity stays at 70 % for a long period of time, the length of which is not specified. For winter condition, the standards assumed that the wall surface relative humidity will be 10% higher than that in the room. No indication is given as to the exposure time required, either successively or accumulatively, to sustain the conditions. There is also no suggestion on what the specific conditions should be at, or what the room relative humidity should be during summer.

The Department of Public Works Malaysia has launched its own Guidelines on the Prevention of Mould Growth in Buildings (2009). Similar to the BS 5250, it only gives simplified condition criteria for indoor air. The temperature range for possible mould growth is between 5° and 50°C, while the room relative humidity is consistently above 70%.

An ASHRAE Standard 160: Criteria for Moisture-Control Design Analysis in Buildings was launched in 2009. The standard was created with the intention to provide performance-based procedure for moisture design analysis for all types of buildings (TenWolde, 2008). At the time of writing, ASHRAE has amended the requirement to minimise the potential of mould growth on surfaces of building envelope, where the 30-day running average surface RH shall be less than 80% (RH<80%) when the 30-day running average surface temperature is between 5°C and 40°C (ASHRAE, 2011). This requirement is

considered to be sufficient to predict mould growth and makes the standard easier to use. However, comparing the ASHRAE standard with the LIM by Sedlbauer (2001) indicated that mould growth is still likely to occur at surface RH below 80% where it takes less than 30 days for spores to germinate. The conditions set by the ASHRAE standard also favour the highly xerophilic and xerophilic mould species categories based on the model by Clarke et al (1999).

2.1.6 Summary

The literature survey on existing mould growth models was conducted, with the different approaches to mould growth prediction, their benefits and limitations explained in detail. Adan (1994) adopted a specific threshold value of only one key parameter (surface relative humidity) after a specific period of surface exposure. Hukka and Viitanen (1999) adopted a similar path while introducing an index of mould growth based on visual observation on building materials made of pine and spruce but not other building materials. Clarke *et al* (1999) assessed the mould risk as the functions of surface temperature and relative humidity as well as mould categories but excluding the time factor. The time factor was also considered from two aspects; one is the time for spore germination, and another during which a surface was exposed to damp condition. Finally, Moon and Augenbroe (2004) incorporated complex causal effect approach to assess the dynamics of a number of building parameters not captured in simulation but do contribute to mould growth.

The mould growth model must be able to incorporate temperature, surface RH and time taken for mould species to grow, since the three parameters interlink with each other. The temperature and RH range must be relevant to the appropriate climate, which in the case of this study, is hot and humid. The mould risk model should also not be limited to a few mould

species. In view of the requirements, an approach using Lowest Isoleths for Mould (LIM) developed by Sedlbauer (2001) was selected for this research since it incorporates surface temperature, surface RH, and the spore germination time. In addition to those parameters, the condition of substrates, or media on which mould grows, is also treated as another critical factor. The range for surface temperature and RH for this model is suitable for the hot and humid climate. The generalized LIM takes into consideration the hazard classes of the mould species available and the conditions of the surfaces on which they would grow.

2.2 Building Optimisation

This section reviews literature on the optimisation of building construction, HVAC systems, and the HVAC systems operation to arrive at optimal solutions relative to design goals.

2.2.1 Building Construction Optimisation

Earlier efforts were made in optimising energy usage to reduce costs, either by embedding energy analyses into the optimisation structure (Jurovics, 1978), or applying an optimisation model to office building design in different climatic regions (Al-Homoud, 1997). In other studies, the focus was to achieve necessary condition in terms of temperature and relative humidity without reliance on active energy, by taking into account major climatic design elements such as the percentage of fenestration, building orientation, outdoor wind velocity and daylight factors (Ajibola, 1993).

A few studies include optimisation of the thermal behaviour of tropical buildings (Romero *et al*, 2001), the building optimisation in the Mediterranean climate (Znouda *et al*, 2007) and building energy performance for buildings in the hot and dry climate of the Middle East (Radhi, 2008).

Building optimisation can be applied during early stages of design using an abstract building shell form during early design stage to reduce the construction cost and seasonal demand for heat energy (Adamski, 2007). This approach, however, is not limited to the context of space like floor shape (Wang *et al*, 2006); it is also possible to extend optimisation to other aspects of a building like building envelope features (Tuhus-Dubrow and Krarti, 2010), the fenestration such as the number of windows, window aspect ratio on a façade, glazing types and areas (Suga *et al*, 2009; Wright and Mourshed, 2009; Caldas and Norford, 2003; Holst, 2003), as well as maximising both thermal insulation and thermal inertia of multilayered walls (Shi, 2011; Sambou *et al*, 2009). Applying multi-objective optimisation increases building energy efficiency, by identifying a number of optimal design solution (Diakaki *et al*, 2008).

Recent researches into the context of building construction optimisation include a study by Fialho *et al* (2011) where a framework for architects was provided that defines the architectural and structural design of a building. In a way, this is in the same vein as the study by Adamski (2007). The objective functions that form the basis of the framework were the minimisation of both energy consumption and the construction costs of a building. A single building was selected with variables being optimised were the orientation angle of the building and wall insulation details. The insulation materials with corresponding thermal resistance (measured in $\text{m}^2\text{K/W}$) and cost per square metre (measured in $\text{€}/\text{m}^2$) were categorised according to different thicknesses.

The algorithm selected was Hype, which is a hyper-volume-based multi-objective evolutionary algorithm used to evaluate the fitness of the non-dominated solutions. The solutions generated by Hype were then simulated in the building

performance simulation program EnergyPlus (2002) to evaluate the energy consumption.

A similar approach was taken by Shi (2011) where simulation was coupled with genetic algorithm to optimise the insulation usage and space conditioning load; an approach that is similar to that taken by Tuhus-Dubrow and Krarti (2010), albeit at a more detailed stage in building design. Shi (2011) supports the view that traditional manual trial-and-error approach in building design is time-consuming, and optimisation can improve design efficiency and assist building designers in finding optimal design solutions.

The researches mentioned above did not cover specific areas such as the isolation room. There is a limited body of knowledge regarding the optimisation of hospital buildings, even though there attempts, such as optimisation of an architectural layout a hospital room by Mendez *et al* (2008) using ventilation pattern to find a feasible layout that has the most efficient ventilation. Therefore, the specific area regarding the optimisation of construction details for isolation rooms in tropical hospitals with the aim of minimising energy consumption and minimising the risk of mould growth on building surfaces is still not fully explored, this being the focus of this research.

Building construction optimisation in recent research covers a number of building parameters, namely the building shape, the window-to-wall ratio, and wall insulation.

2.2.2 HVAC System Optimisation

In addition to optimising the building construction, be it the shape or construction materials, there are also a large number of researches that touches on the optimisation of HVAC topology. From the context of HVAC system design for healthcare facilities in tropical countries, Yau (2006 and 2008)

investigated the use of heat pipe heat exchanger (HPHE) system in operating rooms in Malaysian hospitals as a new approach to reducing energy use while at the same time complying with the strict indoor conditions for an operating room.

The inclusion of heat recovery in a HVAC system, particularly desiccant-based recovery mechanism in hot and humid climate, was reviewed in the study by Sekhar (2007). That it leads to a considerable reduction in energy use in removing moisture from the system in the form of latent load was shown by Kosar (2006), where the desiccant dehumidifier was used in the DX system to shift the sensible load to latent load, thereby reducing the sensible heat ratio (SHR) from 0.75, as rated by the American Refrigeration Institute (ARI), to 0.5. There is energy required to regenerate the desiccant but it was outweighed by significant energy saving potential due to elimination of overcooling and re-heating processes, as suggested by Daou *et al* (2006). The application of heat recovery in Malaysian hospitals in the form of desiccant wheel is found mainly in the operating rooms but not in isolation room, where overcooling and re-heating of the outside air was the norm.

Another area for improvement in this aspect was the cooling coil performance through effective number of rows of cooling coils (Sekhar and Tan, 2009). The dehumidifying performance of the cooling coil was optimised by reducing effective surface area of cooling coil, which in effect reducing the sensible heat ratio. The outcome is the improvement of dehumidifying performance as well as the reduction in energy consumption, since overcooling is avoided.

Thermal comfort of building occupants tends to be compromised by minimising energy usage. Identifying the trade-off between the energy cost and zone thermal discomfort

by optimising the elements of the building design problems was attempted (Wright *et al*, 2002). Recent works of similar aspect include that by Huh and Brandemuehl (2008), in which they attempted to develop optimal operational strategies for a direct expansion (DX) HVAC system with respect to both energy consumption and thermal comfort for hot and humid climate. The optimal strategies were achieved by applying numerical optimisation techniques, where the interactions between the cooling load and the indoor condition were estimated using an extension of the modified bin method. The study by Huh and Brandemuehl (2008) however was limited to the DX type HVAC system and the chilled water system was excluded. Since the DX type is the system of choice for this research, a more detailed explanation is given in **Chapter 5**.

From the context of optimised chilled water system, the study by Lu *et al* (2005) with a single objective of minimising the power consumption of the in-building section of the centralised HVAC system, namely chiller, chilled water pump and the blower fan. The optimum performance was achieved by operating the in-building HVAC components at the optimal set points calculated in real time with the changing cooling load.

2.2.3 HVAC Control System Optimisation

HVAC system operation can be optimized via the supervisory control strategy and the set-points with the objective of minimising energy use, regardless of the system type. A study by Ren and Wright (1997) used a predictive controller as a control strategy for fabric thermal storage systems.

It is also possible to determine the combinations of design parameters by considering objectives and constraint, the combination of parameters being optimised using one-objective problem used by Djuric *et al* (2007) by coupling EnergyPlus

(2002) with a generic optimisation program GenOpt (Wetter, 2001)

The optimisation of HVAC control systems to minimise energy consumption using an evolutionary algorithm has been a subject of a number of studies, with particular attention to the use of a genetic algorithm (GA) as a search method, as attempted by Wright *et al* (2002).

Optimisation of HVAC system operation is not limited to using genetic algorithm as a search method; a coupled simulation-evolutionary programming approach suggested by Fong *et al* (2008) also provides a holistic energy management approach and has a potential to replace traditional parametric studies for HVAC optimisation problems based on trial-and-error, or estimation, approach, using optimisation of existing supervisory control strategy of mechanical ventilation and air conditioning set-points in subway stations as examples.

Recent researches also showed that optimising HVAC control system as a strategy to reduce energy consumption is also valid for existing HVAC system without compromising indoor air quality, as was shown by Kusiak *et al* (2011). The study used the objective functions of energy consumption and the indoor air quality constraint. Objective functions were the total energy consumption of an existing HVAC system, including the fan, pump, and the re-heat power, while the room temperature and humidity objective functions were treated as constraints to satisfy the indoor air quality for the air handling unit system. In other words, the objective functions were the energy consumption and the IAQ constraints. The optimised control set-points for the system were the supply air temperature and the supply air static pressure. The treatment of the objective function and the constraints determined the choice of search algorithm. The search algorithm used was strength pareto

evolutionary algorithm coupled with local search (SPEA-LS). Basically, the SPEA finds the pareto optimal solutions after a number of generations and the local search finds the most optimum solution among the converged pareto solutions.

Gacto *et al* (2010) uses Fuzzy Logic Controller combined with a variant of SPEA2 (Zitzler *et al*, 2001) search algorithm to specifically reduce energy consumption and reduce the complexity of the fuzzy logic rules to improve the HVAC system performance. One novel method in optimising the HVAC system was to control the CO₂ concentration to reduce HVAC system energy use (Congradac and Kulic, 2009). The single objective function was the reduction of energy costs of chiller where the chiller kWh was optimised based on the allowable range of CO₂ concentration in return air; the outside air CO₂ concentration is calculated at 300 parts per million (ppm). Optimisation using genetic algorithm from MATLAB while the chilled water system was simulated using EnergyPlus. The study showed that the lower the CO₂ concentration in return air towards that of the outside air, more outside air must be taken in, which resulted in an increase in the chiller kWh to cool the water.

Optimisation using evolutionary algorithm such NSGA-II (Deb *et al*, 2002) and SPEA2 produce more robust and diverse results that are more efficient compared to traditional trial-and-error approach. They are valid for new as well as existing building and HVAC system designs.

Most of the optimisation problems have two objective functions, mainly minimisation of total energy consumption and maximising thermal comfort of occupants, even though there is one study where the objective function in question is treated as a constraint. Almost all of the studies were conducted involving

occupants in offices and residential areas and rarely, if at all, involved the occupants in hospitals, much less for buildings and HVAC system for critical hospital areas with continuous operation of its HVAC system such as an isolation room. For different climates the design solutions proposed by the algorithm differed considerably. The same building layout needs to have different design components according to the climate it is located in order to optimise its environmental performance.

2.2.4 Summary

A survey was completed on the methods of building optimisation. Recent research opted for a combined approach of using simulation with an evolutionary algorithm such as a genetic algorithm or evolutionary programming to arrive at a number of optimal solutions. Optimisation of HVAC system components and system control strategy has the minimisation of total energy use as the objective function. From the review, the optimised variables for new as well as existing installations, mainly involve system set-points. Finding a single optimum solution with a single-objective are rare in real-life building optimisation problems. From the literature survey, most problems have more than one design goal, usually concerning minimising energy cost and maximising thermal comfort. The aim of this research is to find a trade-off between energy use and risk of mould growth, this not having been researched to date. The nature of the problem is multi-objective since there are two design goals that need to be considered. Since the design goals need to be minimised, there is bound to be conflict between the two, and hence a trade-off. Using a coupled simulation with genetic algorithm (GA) is the most suitable method since the GA is capable of handling a large number of population of candidate solutions from a single simulation, these solutions then forming the trade-off between the energy

use and the risk of mould growth. The building construction, HVAC system and its control strategy are parameters to be optimised.

2.3 Malaysian Hospital Design and Performance

This section reviews literature on the design standards and available literature on healthcare facilities, with particular attention to design of isolation rooms. It then tries to relate the survey with the design of isolation rooms in Malaysia hospitals and how their actual performances compare against the existing design standards.

2.3.1 Design Standards

A number of design guidelines and standards are available for critical patient care areas such as the ASHRAE Standard 170 (2008) for Ventilation of Health Care Facilities, the Guidelines for Healthcare Facilities (2006) by the American Institute of Architects (AIA), the Health Technical Memorandum 2015 on the Ventilation of Healthcare Buildings, and for isolation rooms by the Center for Disease Control and Prevention, or CDC (2005). However, design requirements for the ventilation of isolation rooms vary among these publications. There was also insufficient evidence or empirical data to support the minimum ventilation requirement for the isolation room (Li *et al*, 2007).

Currently, there is no general design guideline for Malaysian hospitals, an issue made clear by Yau *et al* (2011). As a result, designers use the guidelines which are tailored to the temperate climate. The closest thing to the most relevant Malaysian building design manual is the Malaysian Standard MS 1525:2007 Code of Practice for all non-residential buildings, except there is no provision for healthcare buildings in this standard. The comparison between conditions set by the guidelines and standards can be seen in **Table 2.2**.

Table 2.2: Comparison of indoor design conditions

Standards/ Code of Practice	Indoor design temperature (°C)	Indoor design relative humidity (%)
Malaysian Standards MS 1525:2007	23 - 26	55 - 70
ASHRAE Std 170-2008	21 - 24	Max 60
AIA Guide (2006)	22-24	-

2.3.2 Available Studies

The research on isolation rooms were mainly focused on improving ventilation efficiency in order to provide thermal comfort and to prevent cross-infection across the room, such as modelling inter-zone air-flow between the isolation room and the adjacent spaces (Yik and Powell, 2003), and the degree of which the patients were being protected from contaminants using room differential pressures (Phillips *et al*, 2004).

Maintaining indoor air quality (IAQ) in an isolation room involves very high ventilation rate to ensure the level of air contamination is as low as possible (as shown by Tung *et al* (2009), the air change rate can be as high as 24h^{-1}). Providing natural ventilation by opening all windows in an isolation room is also a means of infection control, by having large amount of fresh air into the room for dilution (Qian *et al*, 2010; Lomas and Ji, 2009; Escombe *et al* 2007) that can match the rate achieved through forced ventilation. However, this results in much higher ventilation rates than that recommended by ASHRAE and CDC. The HVAC system is not able to maintain the room RH with the introduction of outside moisture it is not designed to remove. Difficulty in maintaining thermal comfort conditions by using

only natural ventilation when the outdoor air is hot and humid is acknowledged by Qian *et al* (2010).

There are also questions regarding the location of the facilities to take advantage of natural airflow, the suitable layout of the room that uses natural ventilation and also the required indoor conditions (Yam *et al*, 2011). The authors advocates a simple and cost-effective system of ventilation design that can be incorporated into new and retrofitted hospital general wards to complement available isolation rooms, based on air-ducted exhaust located at the ward ceiling level and higher non-recirculating supply air flow rate of 12 air changes per hour (h^{-1}). The approach was an alternative to a new isolation room design or a full scale refurbishment.

Control methods to improve IAQ and reduce cross-contamination have been included in isolation room design, such as Ultra-Violet Germicidal Irradiation (UVGI) in the HVAC ducting for killing pathogens (Memarzadeh and Jiang, 2000).

The feasibility of using variable-air-volume (VAV) strategy to reduce energy consumption in isolation room was also considered (Kim and Augenbroe, 2009). The authors argued that the selection of a suitable ventilation operation for an isolation room must go beyond taking an operational approach. The organisational behaviour, such as the preferences of the decision makers, needs to be taken into account. The multi-criteria performance assessment was then proposed.

A number of works on the tropical hospitals is worth a special mention. An attempt was made to review the ventilation of multiple wards based on the existing guidelines and codes devised in temperate countries that are used in tropical countries by Yau *et al* (2011). The authors highlighted the existence of a gap in knowledge in ventilation studies between the tropical and the temperate climates. The gap includes

method of appropriate ventilation requirements and engineering controls that are specifically developed for tropical hospitals, with specific attention on multiple-bed wards.

What the studies above have highlighted were the need to have a more comprehensive research on the energy saving measures for the tropical hospitals and a separate body of knowledge of the design requirements tailored specifically for tropical hospitals to achieve. The studies by the authors above have also led the way on the search for an alternative heat recovery device to reduce energy consumption and meet the standards of indoor air quality as well as thermal comfort of patients living in tropical countries, as shown in the extensive studies on the HPHX in operating rooms and an orthopaedic ward.

A study was done regarding a new energy recovery approach for Malaysian hospitals but only for operating rooms, in which a heat pipe heat exchanger (HPHE) system was proposed (Yau, 2006 and 2008). It is therefore critical to consider energy recovery in isolation room since considerable energy is used to cool and dehumidify outside air to maintain strict IAQ and exhaust it entirely. The need is more urgent in the hot and humid climate where the ambient air has much higher moisture content and latent enthalpy. However, the application of HPHX system reviewed was based on the chilled water system while this research attempts to represent the system that is installed in a number of isolation rooms in Malaysian hospitals by considering the DX system. The chilled water system is able to achieve low sensible heat ratio (SHR) of 0.4 (Yau and Ng, 2011) which cannot be matched by the DX coil without a drop in its efficiency.

In Malaysia, the normal design equipment selection for the isolation room HVAC system is a simple re-heat system with no energy recovery mechanism. In view of the research mentioned previously, there is potential for energy reduction by putting energy recovery alone.

In the case of Malaysia hospitals, the traditional design of using full-fresh constant air volume (CAV) for the isolations is still in being practiced but without incorporating any form of energy recovery mechanism. Furthermore, the research reviewed above mostly focuses on the need to control the spread of infection and on the thermal comfort. To name a few examples, Balocco and Lio (2010) studied the aspects of architecture and the ventilation effectiveness of isolation room. From the infection control angle, a method based on difference in pressure between the isolation room and its surroundings was attempted (Adams *et al*, 2011). However, the study that is specific on energy consumption and/or recovery in isolation rooms in the hot and humid climate is almost non-existent.

In the context of ventilation, previous research has not considered an isolation room which has different minimum required air change rate for isolation room of 12 air change per hour (h^{-1}) as opposed to 30 h^{-1} for Operating Theatres (OTs) and 6 h^{-1} for wards. The difference between the isolation room and the wards is that it is required for the room air in the isolation room to be exhausted entirely to the outside environment whereas re-circulation of return air is allowed for the wards. However, the fact that energy saving can be achieved with both OTs and wards imply that the same case is possible for the isolation room.

2.3.3 Measured Performance

Studies on environmental conditions in hospitals in Malaysia are very limited. There is also no known publication on the overall building and HVAC system performance for isolation rooms in Malaysia to measure against the design standards, which makes validation of the design practice difficult. An alternative is by observation using Building Performance Simulation and verification using studies on HVAC systems in tropical climates and publication on other occupied areas in Malaysian hospitals.

Only recently has a study of this nature been conducted, but more of a quantitative survey rather than a verification of design practice. Yau and Chew (2009) conducted a survey on thermal comfort of hospital workers, on four hospitals in Malaysia. They observed that the occupants were operating within temperature range between 20.0°C to 32.2°C, which was higher than the standard comfort criteria set by ASHRAE Standard 55. The indoor RH range recorded in the survey was between 44% and 79%. This observation was higher than 30%-60% range required by ASHRAE Standard (2003). Yau and Chew (2009) proposed that a dedicated standard for tropical hospitals to satisfy the comfort level in the tropics without compromising the health and safety requirements be developed, with a comfort temperature range of between 25.3°C and 28.2°C, based on their findings. However, there is no suggested range of indoor RH and there was no discussion on whether increasing the temperature range would have an impact in energy use. The survey also excluded critical patient areas like isolation rooms.

On the aspect of IAQ in a hospital and its relation to mould growth, a walk-through survey was undertaken by Khew *et al* (2007) on the 700-bed Malaysian hospital. Observations in the library, auditorium and levels 2 and 3 revealed the indoor RH of between 70 and 90% despite the maximum indoor design RH

of 60%. It was also concluded that the air-conditioning operation strategy did not consider low occupancy requirement. This study was limited to the non-critical areas and it can only be assumed that there is potential mould growth problem in the critical areas. It also did not comment on the whether the indoor RH was deliberately set beyond maximum design value as a measure to improve thermal comfort level or as to save energy.

2.3.4 Summary

There is no agreement among the available design standard and guidelines on the indoor conditions for the isolation rooms. Furthermore, there are also no available standards for Malaysian hospitals design and performance. In consequence, the Malaysian hospitals design is not actually tailored to local climate. At the moment, there is no research on isolation room energy performance in Malaysia. The aim of this research is to use the publications available in Malaysia regarding the suggested temperature range and indoor RH and come up with an alternative design of an isolation room for the purpose of the simulation and optimisation.

2.4 Chapter Summary

The literature survey on existing mould growth models was conducted, with the different approaches to mould growth prediction, their benefits and limitations explained in detail. The mould growth model must be able to incorporate temperature, surface RH and time taken for mould species to grow, since the three parameters are interlinked; the temperature and RH range must be relevant to the hot and humid climate, and should be relevant to a range of mould species. In view of the requirements, an approach using Lowest Isopleths for Mould (LIM) developed by Sedlbauer (2001) was selected for this research since it incorporates surface temperature, surface RH, and the spore germination time.

A survey was done on the methods of building optimisation. From the literature survey, most problems have more than one design goal, usually concerning minimising energy cost and maximising thermal comfort. The aim of this research is to find a trade-off between energy use and risk of mould growth, which is not attempted yet. The nature of the problem is multi-objective since there are two design goals that need to be considered. Using a coupled simulation with genetic algorithm (GA) is the most suitable method since a GA is able to handle a large number of candidate solutions from a single simulation (the candidate solutions then forming the trade-off). The building construction, HVAC system and its control strategy were parameters considered to be optimised. With regards to isolation room design, there is no agreement among the available design standard and guidelines. At the moment, there is no research on isolation room energy performance in Malaysia. Therefore, one of the strategies taken in the research is to use the indoor temperature and relative humidity ranges based on studies reviewed in previous sub-sections to help define the scope of optimisation of the HVAC control systems.

Chapter 3 gives a detailed description of two other key components of this research, namely the building performance simulation (BPS) and the optimisation method, with particular attention to solving multi-objective optimisation problems (MOOP).

Chapter 3

Building Performance Simulation (BPS) and Optimisation Method

Chapter 2 gave a literature survey on the mould growth models, building optimisation, the HVAC system and HVAC system operation optimisation, as well as hospital design and performance. This chapter gives an overview on building performance simulation (BPS) and the selection of a suitable BPS for this research. It also gives a brief overview of multi-objective optimisation and as well as selection of a suitable optimisation method. The chapter structure is given in **Figure 3.1**.

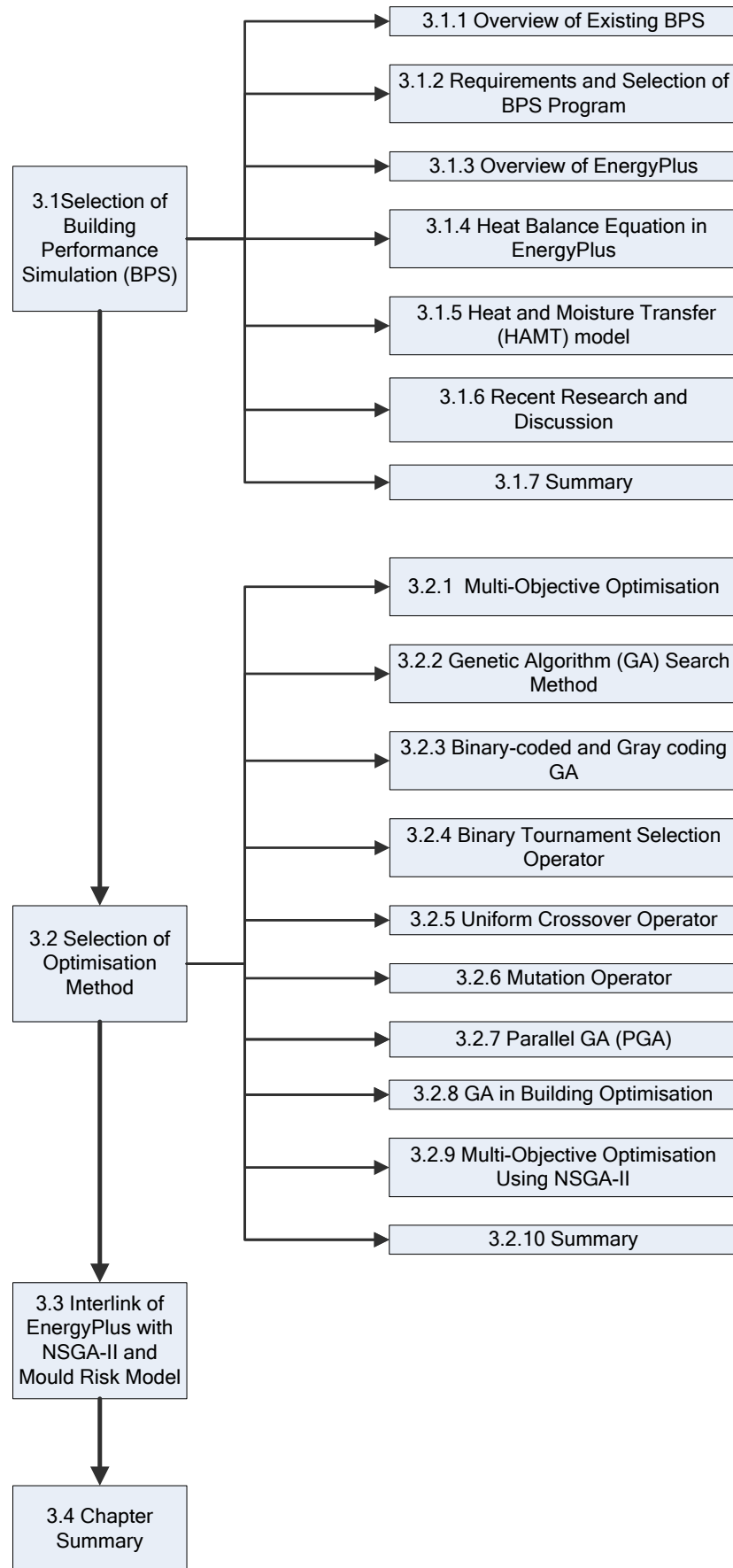


Figure 3.1: Structure of Chapter 3

3.1 Selection of Building Performance Simulation (BPS)

This section gives an overview of the building performance simulation program, as well as the heat and moisture transfer modelling in a building and through building envelope, makes a brief comparison of the existing building performance simulation, and describes, with the justifications, the selected building performance simulation.

3.1.1 Overview of Existing BPS

Existing BPS programs analyse and predict the energy performance of a building based on construction parameters such as the orientation or glazed area, the boundary conditions like the ambient or indoor conditions, and system parameters like the idealised HVAC system. Programs like EnergyPlus, TRNSYS and ESP-r have contrasting capabilities in modelling the heat and mass transfer across and within the building envelope (Crawley *et al*, 2008).

Another physical property considered in the BPS is indoor air humidity which depends on factors such as hygrothermal properties of air and the building materials and their response to moisture transfer across the building envelope. Humidity has an impact on the energy performance of a building and the conditions of the surfaces (Woloszyn and Rode, 2008). To address the issue, a whole-building simulation concept was introduced in which building hygrothermal analysis was incorporated into BPS program (this being known by the generic term called Heat, Air and Moisture model, HAM). The HAM analysis has been developed in recent research to include coupled heat and moisture transfer simulation for air-conditioned buildings in countries with different climates such as Paris and Hong Kong (Qin *et al*, 2009) to investigate the influence of hygroscopic materials on energy performance of buildings. Conducting comprehensive building hygrothermal

analysis requires five categories of knowledge (Straube and Burnett, 2001), as follows:

- a) Geometry of building enclosure such as the building height and its construction details.
- b) Boundary conditions of the interior environment, exterior environment, and between the construction elements.
- c) Material properties and how they respond to parameters such as temperature and moisture content.
- d) Physics, chemistry, thermodynamics, and mathematics of combined heat, air and moisture transport in the building.
- e) Performance thresholds of a material or construction assembly below which the performance will be considered to have failed.

A number of advanced models like WUFI (1995) have been developed to evaluate moisture conditions of the building surfaces. The complexity of the models depends on number of dimensions the models are capable of, whether it is two or three-dimensional, the degree of complexity being linked to accuracy. Since proprietary programs like WUFI are independent and solely handle the hygrothermal performance of a building, they must be coupled with other programs to simulate the wider building performance; this results in an increase in computational time.

An attempt was also made to reduce computational cost in heat and moisture transfer analysis where the full-scale test cycles in a coupled heat and moisture transfer model was shortened from a year to a number of months without compromising the simulation accuracy (Fang *et al*, 2009).

In addition to the whole building approach, alternative is to evaluate energy performance of a building using so called co-

simulation. The aim is to address the issue of limited scope of the modelling library of an individual simulation program. Simulation accuracy is enhanced by enabling combination of component and system models that are available in different simulation programs, as shown by Trcka *et al* (2007) by coupling TRNSYS with EnergyPlus so that the library of HVAC components in TRNSYS can be used together with the library of building models in EnergyPlus.

Currently uncertainty and sensitivity analyses incorporated in simulation programs are limited to uncertainties relating to material properties (Struck *et al*, 2009).

In conceptual design context, it is also expected in the future that BPS can address typical conceptual design issues such as wall-to-window area ratio.

3.1.2 Requirements and Selection of a BPS Program

Selecting a building performance simulation (BPS) program is subject to a few requirements that need to be considered for this research. Firstly, mould growth on internal surfaces of a building is a result from the heat and moisture transfer process across a building envelope. Therefore the dynamic thermal heat transfer, moisture transfer and storage in building materials must be analysed and evaluated by the simulation program.

Secondly, one of the objectives of the research is to minimise HVAC system energy consumption, and to identify a trade-off between the HVAC energy consumption and the risk of mould growth. The simulation program must therefore be able to simulate the impact the HVAC system performance and controls have on the modelled zone and its surface conditions.

Finally, in a real world problem, there are external factors that may influence indoor design conditions. One such factor is the

ingress, or infiltration, of outside air into a room that is air-conditioned continuously and is supposed to be fully sealed. The ingress can occur through user intervention, where occupants have been known to open windows to let in fresh air coming into a patient room as a means of adjusting thermal comfort level, or through a crack or an opening in the building. User behaviour also has an impact on the room condition, surface condition and the HVAC energy consumption, and needs to be taken into consideration in design and simulation.

A number of modelling software tools give results of high accuracy using detailed 3-dimensional (3-D) heat and mass transfer modelling. Proprietary simulation programs provide results with regards to systems operation with modelling flexibility, such as TRNSYS for the HVAC and refrigeration plant, and WUFI[®]2D, which is a dedicated 2-dimensional (2-D) simulation model that evaluates the hygrothermal processes inside the building envelope. However, getting higher accuracy means more complexity of the modelling and results in the simulation being too time consuming. Since WUFI and TRNSYS are specialised software modelling one part of building parameters, for example, building physics or operation, simulating overall building parameters would require coupling with other BPS, a process called co-simulation, to realise the characteristics required in the research. There is a need to strike a balance between reducing the computing time due to complexity and having sufficient accuracy.

An integrated approach that combines the mass and heat balance with the hygrothermal analysis capability, while at the same time fulfils the said requirements is preferred. This provides sufficient accuracy without incurring computational cost associated with the interfacing of two independent BPS

programs. Recent versions of the BPS EnergyPlus (Crawley *et al*, 2001) now include modules for HAM analysis.

3.1.3 Overview of EnergyPlus

EnergyPlus is a modular, structured code building performance simulation software based on features and capabilities of two earlier simulation programs DOE-2 and BLAST, and has input and output of text files (Crawley *et al*, 2001, 2008). Innovative simulation features of EnergyPlus include variable time-step, and user-configurable modular systems that are integrated with heat and mass balance-based zone simulation. Keeping up to date with the movement of integrating hygrothermal analysis of building envelopes into current BPS programs (Woloszyn and Rode, 2008), a 1-dimensional (1-D) heat and moisture transfer algorithm was developed and incorporated, based on the study by Kunzel (1995) on the simultaneous heat and moisture transport through building materials. The description of this new model is described in **section 3.1.5**. EnergyPlus is categorised as a multi-room thermal model, in which multiple rooms or zones are interconnected via heat flow and airflow paths (Megri, 2007).

3.1.4 Heat Balance Equation in EnergyPlus

The underlying building thermal zone calculation method in EnergyPlus is a dynamic-state heat balance model in which room air is modeled as well stirred with uniform temperature throughout (Crawley *et al*, 2001)

The basis for the zone and air system integration is to formulate energy and moisture balances for the zone air and solve the resulting ordinary differential equations (EnergyPlus, 2010). To demonstrate the capability of EnergyPlus in simulating and quantifying heat transfer in a building, the incorporated zone air heat balance algorithm incorporated is described in the following dynamic –state equation expressed in (1)

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i C_p (T_{zi} - T_z) + m_{inf} C_p (T_{\infty} - T_z) + Q_{sys} \quad (1)$$

Where

$$\sum_{i=1}^{N_{sl}} Q_i = \text{sum of the convective internal loads,}$$

$$\sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) = \text{convective heat transfer from the zone surfaces,}$$

$$\sum_{i=1}^{N_{zones}} m_i C_p (T_{zi} - T_z) = \text{heat transfer due to inter-zone air mixing,}$$

$$m_{inf} C_p (T_{\infty} - T_z) = \text{heat transfer due to infiltration of outside air,}$$

$$Q_{sys} = \text{air systems output,}$$

$$C_z \frac{dT_z}{dt} = \text{energy stored in zone air with respect to time}$$

$$C_z = \rho_{air} C_p C_T ;$$

$$\rho_{air} = \text{zone air density,}$$

$C_p =$ zone air specific heat,

$C_p =$ sensible heat capacity multiplier.

If the air capacitance is neglected, the steady-state systems output is expressed as follows:

$$-Q_{sys} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i C_p (T_{zi} - T_z) + m_{inf} C_p (T_{\infty} - T_z) \quad (2)$$

Equation (2) is used to obtain an estimate of the air system energy required to balance the equation with the zone air temperature equal to the set-point temperature.

Q_{sys} , which is the energy provided to a conditioned zone is then formulated as the difference between the supply air enthalpy and the enthalpy of the air leaving the zone, expressed in (3)

$$Q_{sys} = m_{sys} C_p (T_{sup} - T_z) \quad (3)$$

Equation (3) assumes that the zone supply air mass flow rate of air is equivalent to the sum of the air flow rate leaving the zone through the system return air plenum and exhausted entirely from the zone. Both the return and exhaust air streams exit the zone at the zone mean air temperature. Q_{sys} is then simulated to obtain actual system capability and used in the zone temperature update equation (4) to calculate the resulting zone temperature, T_z^t .

$$T_z^t = \frac{\sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_p T_{zi} + m_{inf} C_p T_{\infty} + m_{sys} C_p T_{sup\ ply} - \left(\frac{C_z}{\Delta t}\right) \left(-3T_z^{t-\Delta t} + \frac{3}{2}T_z^{t-2\Delta t} - \frac{1}{3}T_z^{t-3\Delta t}\right)}{\left(\frac{11}{6}\right) \frac{C_z}{\Delta t} + \sum_{i=1}^{N_{surface}} h_i A + \sum_{i=1}^{N_{zones}} m_i C_p + m_{inf} C_p + m_{sys} C} \quad (4)$$

The equation (4) is a dynamic-state third order finite difference approximation to allow for larger time steps in simulation without affecting the stability of the simulation (Taylor *et al*, 1990). Similar to the zone air temperature, the zone air moisture, in terms of humidity ratio is calculated using the sum of latent load components expressed in (5) as follows:

$$\rho_{air} V_z C_W \frac{dW_z}{dt} = \sum_{i=1}^{N_{sl}} kg_{mass\ schedload} + \sum_{i=1}^{N_{surface}} h_i A_i h_{mi} \rho_{air_z} (W_{surfs_i} - W_z^t) + \sum_{i=1}^{N_{zones}} m_i (W_{zi} - W_z^t) + m_{inf} (W_{\infty} - W_z^t) + m_{sys} (W_{sup} - W_z^t) \quad (5)$$

where

$$\sum_{i=1}^{N_{sl}} kg_{mass\ schedload} = \text{internal scheduled latent loads}$$

$$\sum_{i=1}^{N_{surface}} h_i A_i h_{mi} \rho_{air_z} (W_{surfs_i} - W_z^t) = \text{convection to the zone surfaces}$$

$$\sum_{i=1}^{N_{zones}} m_i (W_{zi} - W_z^t) = \text{multi-zone airflow latent loads}$$

$$m_{inf} (W_{\infty} - W_z^t) = \text{infiltration latent loads}$$

$$m_{sys} (W_{sup} - W_z^t) = \text{system latent loads}$$

$$C_W = \text{humidity capacity multiplier}$$

3.1.5 Heat and Moisture Transfer (HAMT) model

EnergyPlus incorporated several heat balance algorithms such as Conduction Transfer Functions (CTF), and Conduction Finite Difference. The moisture transfer modelling was based on the Effective Moisture Penetration Depth (EMPD) algorithm, coupled with CTF. The EMPD algorithm is a simplified, lumped algorithm that simulates surface moisture adsorption and desorption in building materials and assumes that a thin layer of moisture close to the wall surface behaves dynamically and exchanges moisture with the air domain when exposed to cyclic air moisture pulses (Kerestecioglu *et al*, 1989).

The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Programme (ECBCS) Annex 41 (Rode and Woloszyn, 2007) addressed the need for an increased understanding in heat, air and moisture responses by a building. As a result of this newly developed Annex, an enhanced moisture transfer modelling for building envelopes called combined Heat and Moisture Transfer (HAMT) model was integrated into EnergyPlus. The HAMT is a completely coupled, quasi -dynamic model that simulates the movement and storage of heat and moisture in surfaces, based on the study of 1-Dimensional calculation of simultaneous heat and moisture transport in building components by Kunzel (1995). The solution algorithm is able to provide temperature and moisture profiles of surfaces with high surface humidity, the components of which are expressed in equation (6).

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left(k^w \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial T}{\partial x} \right) \quad (6)$$

Where,

$\frac{\partial H}{\partial T} =$ Moisture dependent heat storage capacity
(J/m³°C)

$T =$ Temperature (°C)

$\Delta \tau =$ Time step between calculations (s)

$k^w =$ Moisture dependent thermal conductivity (W/m°C)

$h_v =$ Evaporation enthalpy of water (=2,489,000 J/kg)

$\delta =$ Vapour diffusion coefficient in air (kg/msPa)

$\mu =$ Moisture dependent vapour diffusion resistance factor (-)

$x =$ Distance (m)

The first term from the equation (1), $\frac{\partial H}{\partial T} \frac{\partial T}{\partial \tau}$, describes the heat storage in the material. The second term, $\frac{\partial}{\partial x} \left(k^w \frac{\partial T}{\partial x} \right)$ describes the heat transport, and the third term, $h_v \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial T}{\partial x} \right)$, describes the heat generation.

In the context of moisture transfer through building envelope, the moisture balance equation was represented in equation (2).

$$\frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial \tau} = \frac{\partial}{\partial x} \left(D^w \frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial T}{\partial x} \right) \quad (2)$$

Where

$$\frac{\partial w}{\partial \phi} = \text{Moisture dependent moisture storage capacity (kg/m}^3\text{)}$$

$$D^w = \text{Liquid transport coefficient (m}^2\text{/s)}$$

The first term from the equation (2), $\frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial \tau}$, describes the moisture storage in the material. The second term, $\frac{\partial}{\partial x} \left(D^w \frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial x} \right)$ describes the transport of liquid moisture, and the third term, $\frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial T}{\partial x} \right)$, describes the transport of vapour.

The hygrothermal properties of the building materials required in the HAMT algorithm are porosity, moisture content, sorption isotherm, suction, redistribution, diffusion, liquid transport coefficient, vapour diffusion resistance factor, and thermal conductivity.

The materials database in the HAMT model is limited to six generic building materials provided for in the EnergyPlus Reference Data Sets (Kumaran, 1996), namely concrete, spruce wood, plywood, cellulose and fibreglass insulation, and plasterboard. Since the research is based on the hospitals in Malaysia, it is necessary to include construction materials usually used in hospital buildings in Malaysia. The physical and hygrothermal properties of additional building materials are taken from Kunzel (1995), and the WUFI[®] 5 Light database, which is a 1-Dimensional moisture transport simulation program, Kumaran (2001), and the ISO 10456 Standard (2007),

for the hygrothermal properties of building materials and products.

EnergyPlus uses HAMT model to simulate the movement and storage of heat and moisture is surfaces simultaneously from and to both the internal and external environments. From the simulation input (room temperature and room relative humidity set-points), the HAMT helps to identify wall surfaces with high surface RH based on the moisture content of the construction materials that make up the wall/roof assembly. The surface RH that are obtained as EnergyPlus simulation output is inserted into the mould growth model equation to determine whether the surface conditions pose a risk of mould growth. Further discussion of this is given in **Chapters 4 and 5**.

3.1.6 Recent Research and Discussion

The coupled heat and moisture transfer model approach still finds favour in recent research, such as that by Qin *et al* (2009), where a coupled heat and moisture transfer model was developed to investigate the effect of moisture transfer on indoor air humidity and building energy consumption for hot and humid, as well as for the temperate climate. The system model was implemented in MATLAB-Simulink and validated using a series of published testing tools. The coupled heat and moisture transfer model was further developed by coupling it with the multi-zone indoor airflow to investigate the impact of moisture transfer on indoor air humidity and building energy consumption on hot-humid, dry, and hot-dry climates (Qin *et al*, 2011).

A similar approach was taken by Steeman *et al* (2009) by integrating a 1-Dimensional model for coupled heat and mass transfer (HAM) in porous materials into the building energy performance simulation program TRNSYS in order to simulate the response of a multi-zone building on moisture buffering

effects. This was done by coupling both the heat and mass conservation equations of HAM and TRNSYS.

In this research, the optimisation process requires thousands of simulations to find a solution, and therefore it is necessary to have a compromise between modelling accuracy and computation time. The recent research reinforces the argument that it is more advantageous to take the coupled approach as it provides sufficient accuracy of results with reduced computing cost. Although a 3-dimensional description of the heat and moisture transfer is desirable to provide highly accurate evaluation of building surfaces, the reduced complexity and computation time is the priority in this research. Using EnergyPlus as a one dimensional, steady-state simulation with the integrated HAMT algorithm would be sufficient to simulate the hygrothermal condition of building surfaces. Employing a dedicated moisture modelling program such WUFI-2D along with EnergyPlus simulation would be computationally expensive, without further taking into account the optimisation phase.

3.1.7 Summary

BPS has different capabilities in evaluating energy performance of a building. Apart from the analysis of HVAC systems, more complex parameters such as hygrothermal properties of materials, and user behaviour, are being included to enhance the accuracy. However, increase in the complexity of simulation results in the increase of computing cost. For this research, the simulation process is interfaced with the optimisation process (**section 3.2**) and also the mould growth risk model (**Chapter 4**). Therefore, the BPS must be able to simulate the dynamic indoor conditions, the dynamic heat and moisture transfer and storage across and inside the building envelope, the performance of the HVAC systems and controls in as short computing time as possible. Simultaneously, it must be able to

offer sufficient accuracy for the modelling of the physics and operation of a building to be valid. The requirements listed dictate the choice of BPS. One approach is to use a whole building program that is able to fulfil the said requirements with suitable accuracy. EnergyPlus is an example of the approach with 1-D heat and moisture transfer analysis capability providing sufficient accuracy for modelling the energy performance of the zone and also the conditions of the internal surfaces.

3.2 Selection of the Optimisation Method

The selection of an optimisation algorithm is based on its ability to solve building optimisation problems, and in this research, its potential to identify the trade-off between the design goals, or the objective functions, of minimum HVAC energy use and minimum risk of mould growth. In addition to the two design goals, the algorithm must also compute a number of variables that may affect the extent to which the design goals would be achieved. The algorithm must also be able to be integrated with the selected building performance simulation program, in this case the EnergyPlus that was described in **section 3.1**. This section gives a brief overview on the multi-objective optimisation approach, one which is relevant to the research problem since there is more than one objective to be optimised. A brief description of the genetic algorithm (GA) search method is given. The application of GA in building, HVAC system and HVAC control system optimisation is also discussed. Finally, the overall multi-objective optimisation approach of a Non-dominated Sorting Genetic Algorithm-II (*NSGA-II*) is presented.

3.2.1 Multi-Objective Optimisation (MOOP)

This research aims to investigate the optimum trade-off between energy use and the risk of mould growth, there therefore being two objectives of the optimisation. The focus of

this section is therefore on multi-objective optimisation methods, although single-objective optimisation is also mentioned.

The main aim of a single-objective optimisation is to find a global optimal solution, or the best design solution, resulting in an optimal value for the single objective function, which is either a maximum or a minimum. Therefore, single-objective optimisation only involves decision variable search space in which the goal was always to find the global optimum solution, although the search space may have a number of local optimal solutions (Deb, 2004). However, it is instructive that this is only the case if the solutions are constrained to be in a pre-defined region of the solution space in some way.

Multi-objective optimisation (MOOP), is operated to find a set of solutions that match the two goals shown in **Figure 3.2**; the first goal of the search is to find a set of solutions as close as possible to the Pareto-optimal front, and the second is to find a set of solutions as diverse as possible along that front (Deb, 2004).

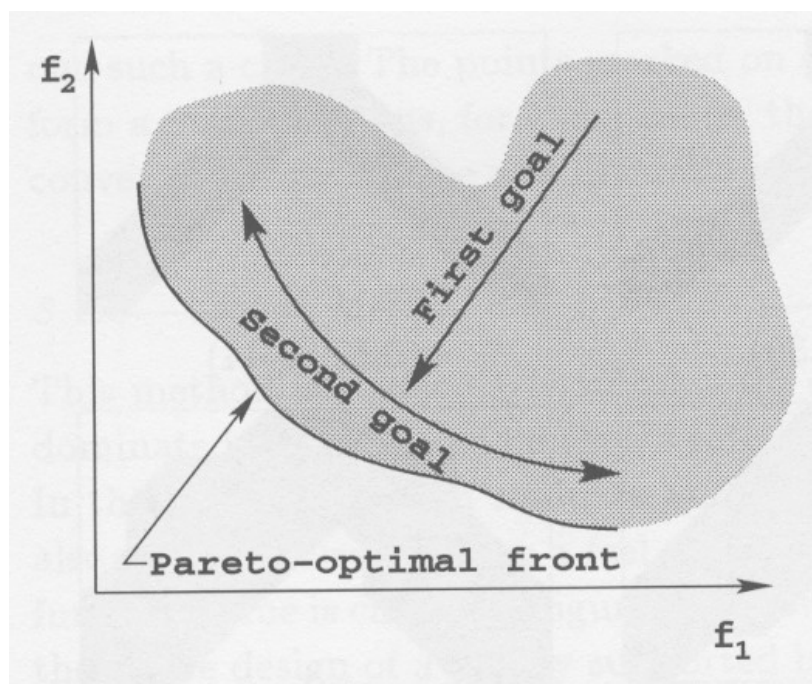


Figure 3.2: Goals of multi-objective optimisation (Deb, 2004)

This second goal is specific to MOOP since a good trade-off with respect to the Pareto optimality defines a set of optimal trade-offs where all objectives are equally important. MOOP improves decision making where the best compromise solution can be chosen based preference information, after the Pareto optimal set is found, *a posteriori*.

In a MOOP problem, there is more than one objective functions to be optimised, each of which has a different individual optimal solution. If there is sufficient difference in the optimal solutions with respect to the objective functions, the objective functions are said to be in conflict with each other. The conflict between objective functions gives rise to a set of optimal solutions in which no one solution can be considered to be better than any other with respect to the objectives. Each element in the Pareto-optimal set constitutes a non-inferior solution to the multi-objective problem (Fonseca and Fleming, 1993). The non-inferior solutions are also termed “non-dominated” solutions. Any attempt to improve their optimality with respect to one or more objectives results in a decrease in optimality with respect to one or more other objectives (De Jong, 2006). For this reason, these solutions are called Pareto optimal solutions and they are all equally optimal.

Multi-objective optimisation problems are generally expressed mathematically as in (3):

$$\begin{aligned}
 & \text{Minimise / Maximise} && f_m(x), && m = 1, 2, \dots, M, \\
 & \text{subject to} && g_j(x) \geq 0, && j = 1, 2, \dots, J, \\
 & && h_k(x) = 0, && k = 1, 2, \dots, K, \\
 & && x_i^{(L)} \leq x_i \leq x_i^{(U)} && i = 1, 2, \dots, n.
 \end{aligned} \tag{3}$$

A solution x is a vector of n decision variables, where $x = (x_1, x_2, \dots, x_n)^T$, g_j is an equality constraint function, h_k is an equality constraint function for the objective functions, while $x_i^{(L)}$ and $x_i^{(U)}$ is called a variable bound where the variable x_i is restricted to take a value within $x_i^{(L)}$ lower bound and $x_i^{(U)}$ upper bound. If a solution x satisfies the constraints and the variable bound, it is known as a *feasible solution*. If it does not, it is known as an *infeasible solution*. A region that constitutes a set of feasible solutions is called a feasible region, or decision variable space, as shown on the left of **Figure 3.3**.

This definition is identical for a single-objective optimisation problem, except that there is only one objective rather than m objectives ($m = 1$). Another difference between single and multi-objective optimisation is that in addition to the decision variable search space for variables x_1, x_2, \dots, x_n , there is a separate multi-dimensional space for the objective function, called object space, denoted by z on the left of **Figure 3.3**. For every feasible solution x , there exists a point in the objective space. More comprehensive explanation on MOOP can be found in the work by Deb (2004).

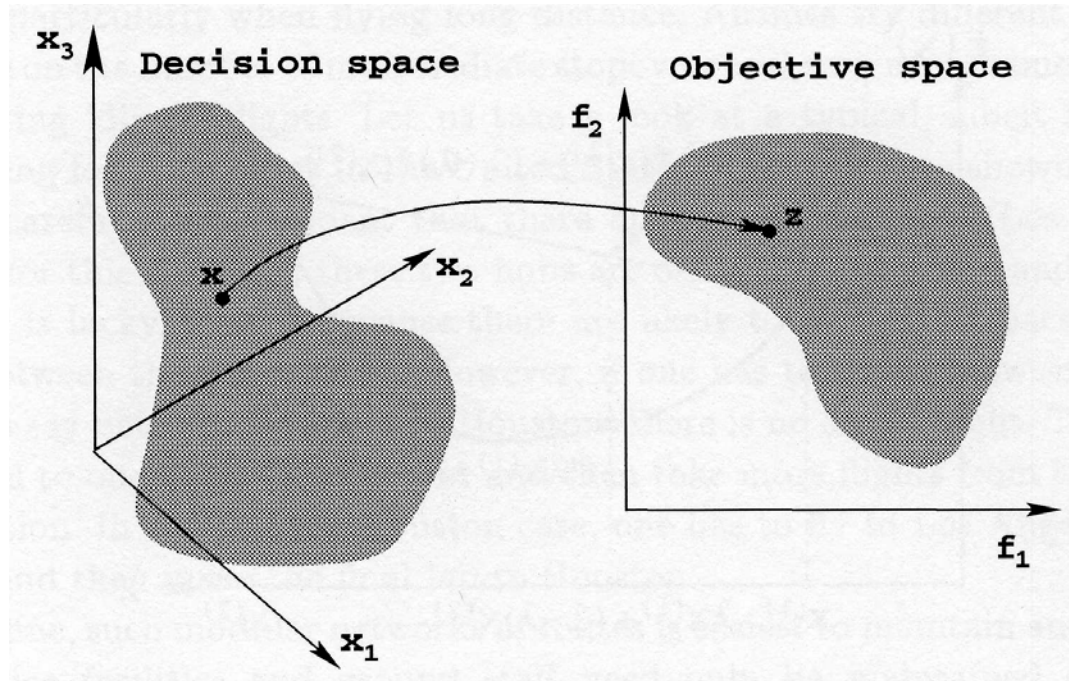


Figure 3.3: Decision variable search space and objective function search space for multi-objective optimisation (Deb, 2004)

It is worth remembering that in this research there are two design goals, namely the minimisation of HVAC energy consumption and the minimisation of the risk of mould growth on the wall surfaces. **Figure 3.4**, illustrates that having both objective functions minimised results in the Pareto-optimal front.

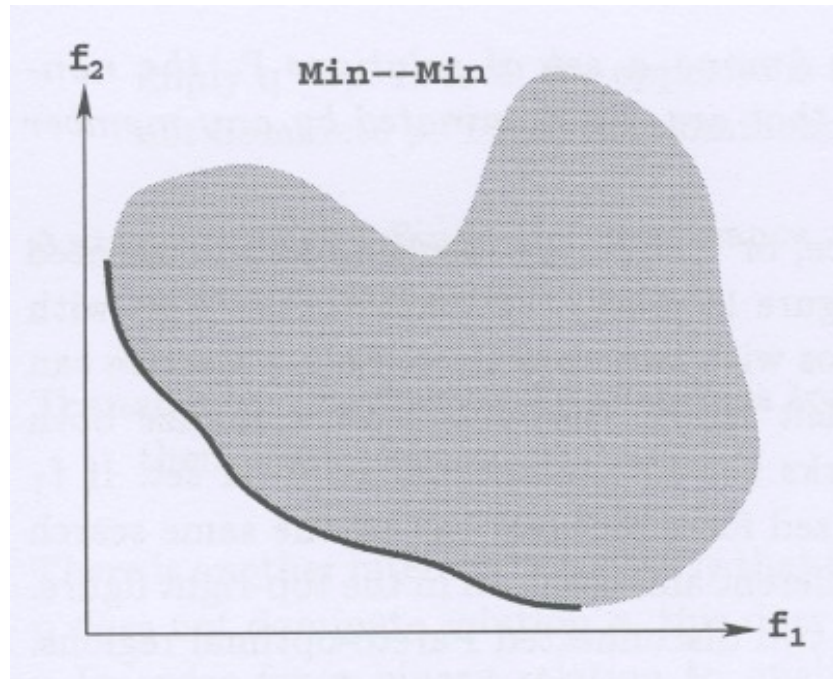


Figure 3.4: Objective space for two minimum objective functions (Deb, 2004)

Building optimisation problems are real world problems, since there is more than one objective to be achieved, such as minimising or maximising total building energy consumption, insulation material cost, or thermal comfort of occupants (Wright *et al*, 2002). Since they are real world problems, there are also design and operating limits that need to be considered pertaining to building construction and control strategy of HVAC system.

The solution of a practical problem may be constrained by a number of restrictions imposed on the decision variable (Fonseca and Fleming, 1998). The design variables, such as the design room temperature, design room relative humidity, and supply air flow rate, are given specific operating range by the standards and the guidelines, either above or below which would have affected thermal comfort, air quality, or plant efficiency. Therefore restrictions, or constraints, are imposed on optimisation variables, guided by the guidelines regarding the indoor environment and HVAC system design to ensure

thermal comfort of occupants; limits taken into account in the research are based on construction and HVAC system.

In context to the construction, the constraints are on the different types of wall assembly and the glazed area, in this case the window height and the range of window widths. On the HVAC system side, limits are imposed on room temperature and relative humidity set-points, and the air change rates into the room. A more detailed description of the variables and the constraints relating to this research can be found in **Chapter 5**.

3.2.2 Genetic Algorithm (GA) Search Method

The optimisation algorithm selected for use in this research must be able to solve building optimisation problems, and have the potential to identify the trade-off between the design goals of minimum energy use and minimum risk of mould growth. The algorithm must also be able to be integrated with the selected performance simulation.

Wetter and Wright (2004) conducted a comparative study between deterministic and probabilistic optimization algorithms for non-smooth simulation-based optimization and indicated that in the solution of building optimization problems, conventional gradient or direct optimisation methods were outperformed by population-based probabilistic search methods such as a Genetic Algorithm. Genetic Algorithms have therefore been selected as the class of optimization method for use in this research.

A GA is a guided, stochastic search technique which is one form of evolutionary algorithm (EA), which is based on the theory of evolution, and were pioneered by Holland (1975) and later popularised by Goldberg (1989). It is an iterative, or repetitive, and random process that operates on a finite set of points (solutions), called a *population*, and with each new population being called a *generation*. The method is based on

the survival of an organism, with the generations of new populations of organism being ensured by incorporating operators for fitness assignment, selection of points for recombination, and mutation of a point, all of which is shown in **Figure 3.5**.

The process involves assigning a “fitness” to each individual solution, the fitness being derived from the design goals and constraints (these having been evaluated from the building performance simulations of the individuals design solutions).

The process of generating a new population of solutions using three main operators, namely selection, crossover and mutation, is briefly described. A new population is constructed by selecting pairs of individuals from the existing population of solutions, the probability of being selected being in some proportion to the fitness of the solution. Two new pairs of solutions are then created by the process of recombination/crossover and mutation. The selection, recombination/crossover, and mutation sequence continues until the new population has been filled with solutions. Convergence of the solutions approaching to global or local optimum is normally controlled by fixing the maximum number of populations generated by the GA. The three main operators are described in more detail in **sections 3.2.3 to 3.2.6**.

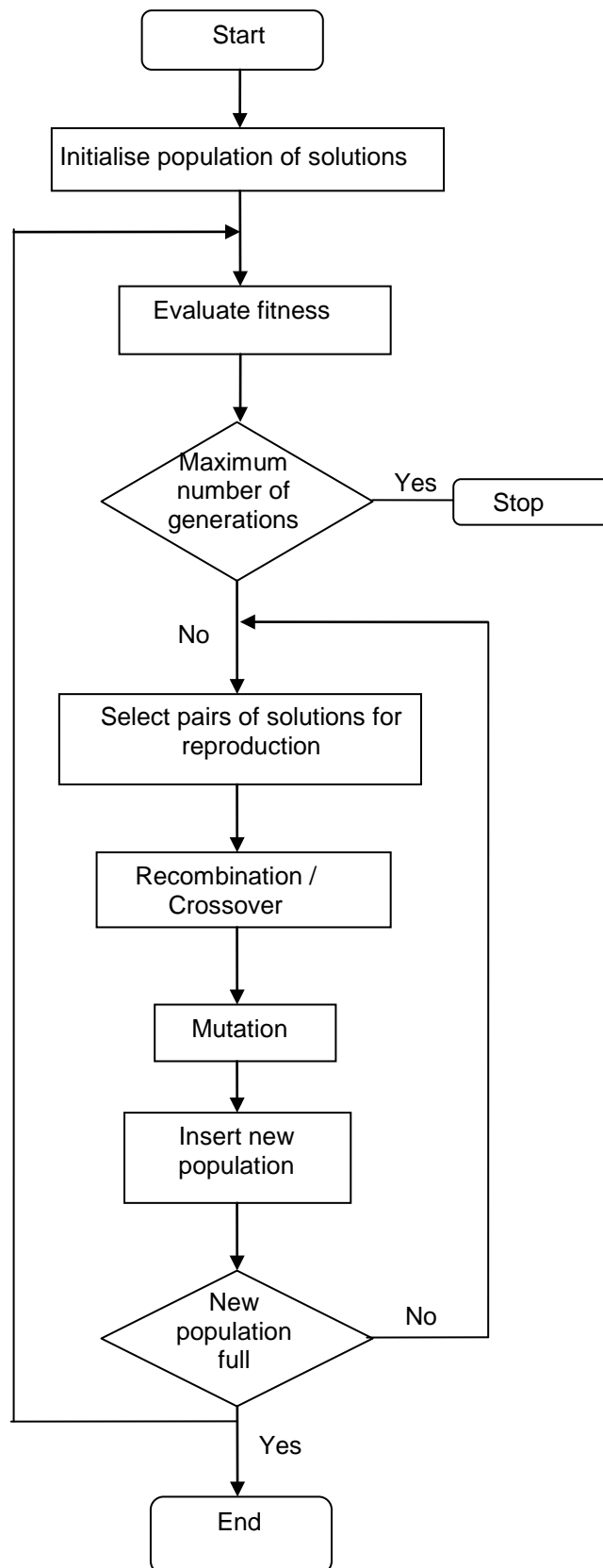


Figure 3.5: GA Operations

The major differences between a GA and other conventional optimisation techniques include (Goldberg, 1989; Deb, 1999):

- a) GA operates with coded versions of the problem parameters rather than parameters themselves. That is, GA works with the coding of solution set and not with the solution itself.
- b) Almost all conventional techniques search from a single point but GA always operate on a whole population of points (solutions).
- c) GA use a fitness function, or objective function information, for evaluation rather than derivatives, or other auxiliary knowledge. As a result, they can be applied to any kind of continuous and discrete optimisation problem.
- d) GA uses probabilistic transition operators, or rules, while conventional methods for continuous optimisation apply deterministic transition operators.
- e) GA can be used in parallel machines since the recombination and mutation processes take place simultaneously with different processors.

One of the characteristics of GA, or EA in general, is it works with a population of solutions, instead of one solution in each iteration, which is a feature of classical direct search or gradient-based method. The elements of directed and stochastic search are combined in the GA, making it more robust than the existing directed search methods. Working with a number of solutions provides the GA with the ability to capture multiple optimal solutions in one single simulation run (Deb, 2004), whereas other methods process a single point in the search space (Michalewicz, 1992).

3.2.3 Binary-coded and Gray coding GA

Rather than operate on the variables directly, GA use an encoding of the variables. Coding variables in a binary string is used in order to have a pseudo-chromosomal representation of a design solution (Deb, 1999), mimicking the chromosomes that makes up a living cell.

The encoding is based on a number of pre-determined 0 or 1 bits to represent a parameter or variable. The number of bits determines the number of possible solutions for that particular parameter. Take for example a five bit string to represent a parameter, the possible number of alternative variable values would then be $2^5 = 32$. A possible solution consists of a number of parameters/variables with different number of bits representing each of them, depending on the nature of the parameter, whether it is discrete or continuous.

Gray coding is a method of coding parameters into bits which has the property that an increase of one step in the parameter value corresponds to a change of a single bit in the code (Wright, 1991), meaning the Gray code redefines the binary numbers so that consecutive numbers have a Hamming distance of one.

Frank Gray (1953) proposed a novel binary coding, as a measure to avoid the error of coding, in order to improve the pulse code communication. By giving an example of the standard binary coding, Gray has shown that by changing a parameter value by a single unit, say from 7 to 8, the corresponding binary value is change from 0111 to 1000, where each of the binary value has been changed. This is due to the fact that the characteristic of the conventional binary number notation is such that a value change of unity is reflected in the simultaneous change in several of the digits. This condition is

known as the "Hamming Cliff" which brings about the difficulty of coding a continuous variable with binary coding.

3.2.4 Binary Tournament Selection Operator

The main objective of a reproduction operator is to identify and select good solutions in a population and make multiple copies of the good solutions to form a mating pool. Because of this, the reproduction operator is also known as selection operator (Deb, 2006). Poor solutions are then eliminated from population, their place taken by the multiple copies of the good solutions, thereby keeping the population size constant (Deb, 1999).

The tournament selection strategy provides higher probability for better candidate solution to be selected by holding tournament among N_{ts} individuals, N_{ts} usually being 2. The winner of the tournament is the one with the highest fitness value of the N_{ts} competitors and the winner is put into the mating pool. The tournament is then repeated until the mating pool is filled. A schematic representation of the workings of the tournament selection is shown in **Figure 3.6**.

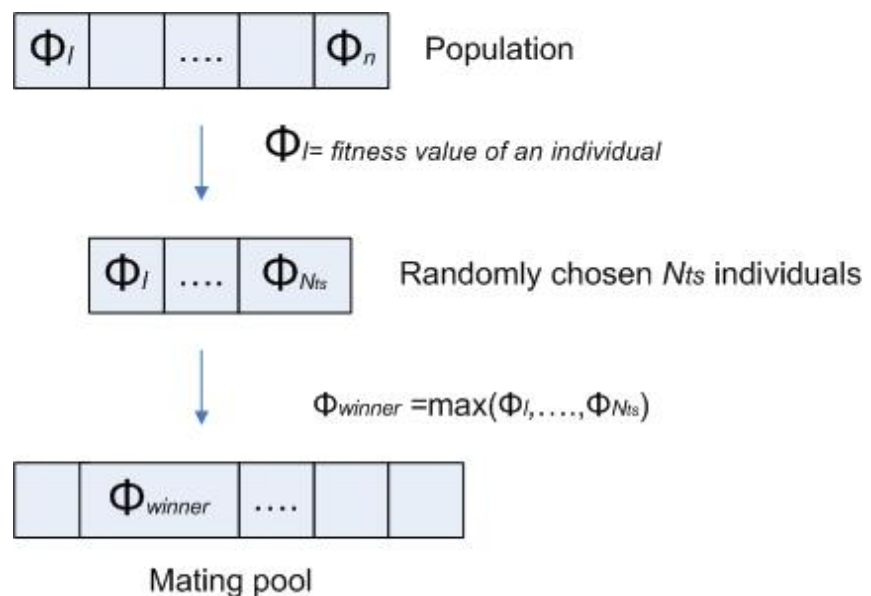


Figure 3.6: Illustrated Principle Workings of Tournament Selection (after Yang and Soh, 1997)

Tournament selection works by first picking N_{ts} individuals (with or without replacement of those individuals) from the population and then selecting the best of the chosen N_{ts} individuals. If performed in a systematic way, this selection scheme can assign exactly N_{ts} copies of the best individual to the mating pool at every generation.

For this research, the *binary tournament selection* operator is used to select the parents ($N_{ts} = 2$). As the name *binary* suggests, two solutions are picked from the population and compared. The better solution is chosen and placed in the mating pool, while the bad one is eliminated. The method is repeated with two other solutions going through the same procedure until a new population in the mating pool is created (Goldberg and Deb, 1991).

3.2.5 Uniform Crossover Operator

In selection phase, good strings (solutions) in a population are probabilistically assigned a larger number of copies and a mating pool is formed. No new strings are formed in this phase. Essentially, the selection operator only selects the best solutions from the population at the expense of the bad ones. As a result, the mating pool, although equal in size to the population, is made up of solutions from only a sub-set of the population, as shown in **Figure 3.7**.

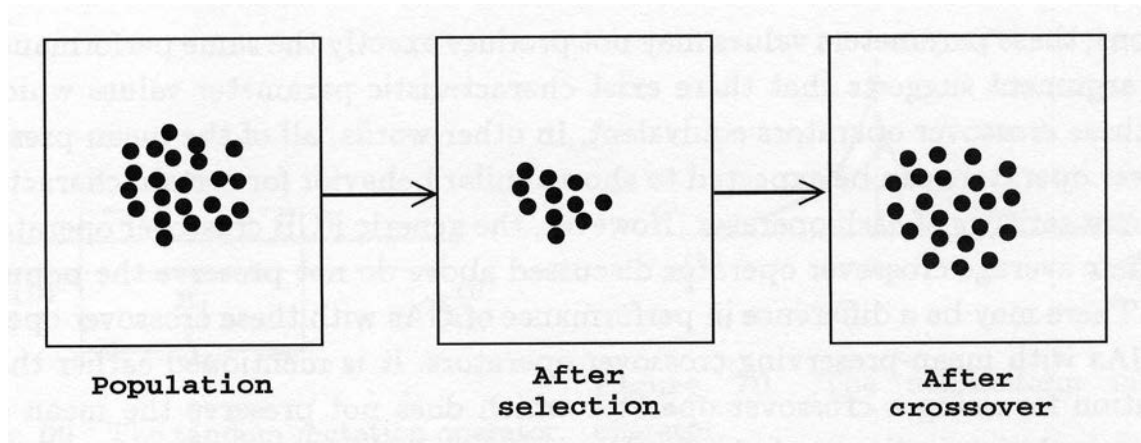


Figure 3.7: Impact of selection and Crossover Operators on Population (after Deb, 2004)

The main reason for employing crossover is to increase the diversity of the population of solutions, since the selection operator is not meant to maintain, or diversify the population of solutions. As **Figure 3.7** showed, the crossover operator restores the diversity of the population by creating offspring from parent solution and inserting the offspring into the population.

Uniform crossover is regarded as a generalised form of single-point crossover but it can also be seen as a form of mutation (mutation being described in **section 3.2.6**). For a single-point crossover, a point is selected at a certain location of bits for each of the two parent solution and the rest of the bits immediately after that point are swapped between the two parents to create a pair of offspring. In the uniform crossover, every bit from the parent chromosome has a potential to be swapped given a certain probability. Usually the probability $p = 0.5$ is used. The graphical representation of the uniform crossover is shown in **Figure 3.8**.

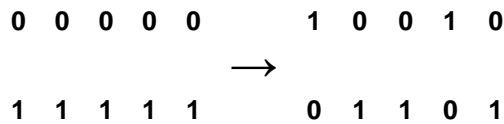


Figure 3.8: Uniform crossover

3.2.6 Mutation Operator

Mutation is another main operator in the GA and one that tends to increase the diversity of the population. It does not “search”, but it does increase the spread of solutions and therefore provides the search with more solutions to consider for use in generating the next population.

In the binary-coded GA, the mutation operator changes the bit value from 1 to 0 or vice versa with a small mutation probability P_m (typically having a value that results in 1 or 2 mutations along the length of each chromosome).

The need for mutation is to create a point in the neighbourhood of the current point, thereby achieving a local search around the current solution. The mutation operator alters a string locally to hopefully create a better string. It is also used to maintain diversity of population. However, this will only be the case for low mutation rates of 1 or 2 bits per chromosome. If the mutation rate is high and many bits are changed, then the solution will move away from the current point. If there is only one bit mutated, then only one variable value will change; therefore one could regard the search as local, even though that particular mutation could result in a big change in the value of a single variable. To illustrate how mutation works, a population of four eight-bit strings is considered based on explanation by Deb (2006).

0	1	1	0	1	0	1	1
0	0	1	1	1	1	0	1
0	0	0	1	0	1	1	0
0	1	1	1	1	1	0	0

All the four strings have a 0 on the first bit position. If the true optimum solution requires 1 in that position, neither reproduction nor crossover is able to change the 0 in that position to 1. That is only with mutation where some probability (N_{P_m}) of turning 0 to 1 is introduced.

3.2.7 Parallel GA (PGA)

The parallelisation of GA depends on how the fitness of a solution is evaluated and the mutation is applied, on whether a single or multiple subpopulation are used, on how individual solutions are exchanged if multiple subpopulations are used, and whether the selection is applied globally or locally. PGA is an effective tool to increase diversity of solutions, apart from reducing the computation cost. Since there is increased diversity, premature convergence due to small population can be avoided.

The type of PGA used in this research that this section is focussed on is the most basic, called the *master-slave parallelisation*, also known as *global parallelisation*, *master-slave model*, or *distributed fitness evaluation* (Nowostawski and Poli, 1999). Master-slave parallelisation uses a single population and the evaluations of individuals and/or the application of genetic operators are performed in parallel. The master stores the population, executes GA operations (selection, recombination and mutation) while several slave processors evaluate the fitness of individual solutions. A schematic of the master-slave parallel GA is shown in **Figure 3.9**. Advantages of master-slave GA include exploring the search space in the same manner as a serial GA and being

easy in its implementation (Cantú-Paz, 1997). The disadvantage of it is the efficiency of the parallel algorithm is reduced as a result of increased communication cost between the master and the slaves as the number of slave processors increased. (Cantú-Paz, 1997; Cantú-Paz and Goldberg, 2000). However, the increased communication time between the master and slave has minimal impact in terms of building optimization as the total computation time is dominated by the time taken to simulate the performance of the building.

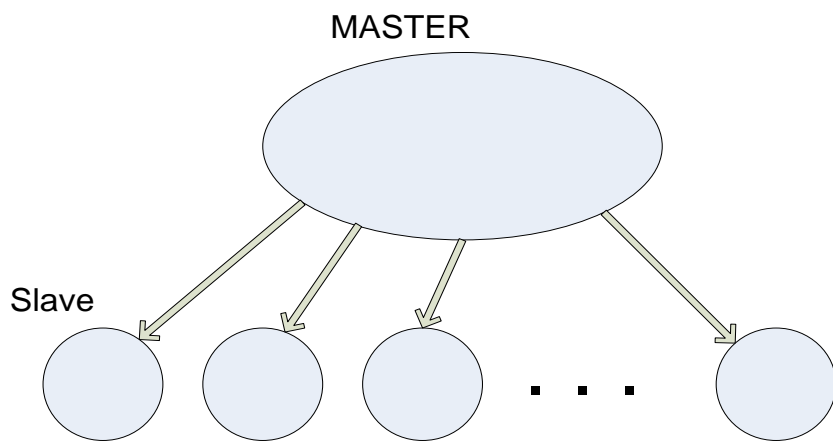


Figure 3.9: Master-slave parallel GA (Cantú-Paz, 1997)

In this research, the optimisation is run on a computer having 8 cores. In order to ensure that the computer had some capacity to perform other functions, the populations of solutions was evaluated using 6 parallel building performance simulations (that is 6 of the 8 cores at once, this allowing 2 cores free for other activity).

3.2.8 GA in Building Optimisation

GA has been widely used in the solution of optimisation problems, be it mathematical or engineering in nature. The effectiveness of GA as an optimisation tool has been compared

against the conventional search methods, such as direct search and Nelder-Mead method, in designing HVAC systems (Wright, 1996), and its advantages of genetic algorithm over other optimisation methods have been extensively discussed (Wetter and Wright, 2004; Caldas and Norford, 2003).

The application of GA to optimise controller parameters for HVAC systems was the subject of a study by Huang and Lam (1997) for automatic tuning of proportional, integral and derivative (PID) controller. This study was an example of simulation program being integrated into the genetic algorithm optimisation program; the dynamic simulation program in this case was HVACSIM+. It was shown that the adaptive tuning controller program based on GA is better in reducing overshoot and settling time (thereby increases stability) than that based on traditional general and random search algorithms such as Ziegler -Nichols method.

In building construction optimisation, GA has been applied in maximising both thermal insulation and thermal inertia of multilayered walls (Sambou *et al*, 2009). Optimising the fenestration, with particular attention to the number of windows and window aspect ratio on a façade has also been attempted (Wright and Mourshed, 2009; Suga *et al*, 2009) as one of the measures to minimise building energy use, where binary encoded GA method was applied on the population of solutions.

GA offers flexibility by way of coupling with building performance simulation like EnergyPlus in an effort to minimise annual energy use of a building (Wright and Alajmi, 2005), minimising either a single, or multiple design goals such as daily energy cost and zone thermal discomfort (Wright *et al*, 2002; Wright and Farmani, 2001; Wright and Loosemore, 2001), and simultaneously optimising building fabric

construction, HVAC system size and plant control strategy which achieved near optimum solutions (Wright and Farmani, 2001; Wright and Loosemore, 2001).

More recent studies on the application of GA in the HVAC systems and system operations optimisation were reviewed in **Chapter 2**, particularly recent researches by Congradac and Kulic (2009) regarding HVAC system optimisation with CO₂ concentration control ; Mossolly *et al* (2009) on the multi-zone buildings using multi-variable control strategy, Palonen *et al* (2009) regarding the newly developed GA based on NSGA-II and Omni-optimizer for optimisation of building envelope and HVAC system parameters, Gacto *et al* (2010) in tuning of fuzzy logic controllers in heating, ventilating and air conditioning systems using SPEA2, and Kusiak *et al* (2011) regarding the optimisation of existing HVAC system using strength pareto evolutionary algorithm with local search (SPEA-LS).

In the context of application of the general application to buildings, Shi (2011) proposed a general methodology in order to perform optimisation of architectural design, which consists of six steps. The first step is to study the background information of the design project, such as volume-to-area ratio, from the optimisation perspective. The second is to clearly and reasonably define the optimisation objectives; clearly in the sense of whether the design problem is single or multi-objective, while reasonably in the sense of whether the objectives can be achieved through sound design, quality construction and proper operation.

This is followed by determining the input and output variables. The input variables are which that can be changed to generate new design solutions. These variables are used as input to the simulation programs to calculate the output variables.

Minimising or maximising the output variables define the optimisation objectives.

Another step is to define the constraints, ranges of the variables and steps, or resolutions. The input variables have a set of range defined by the constraints. The constraints in turn are guided by the design codes and standards as well as the client requirements. There is also a need to achieve a balance in selecting the suitable steps/resolution to reflect the design reality and avoiding too small steps so as to incur high optimisation time.

The next step is to select the appropriate BPS program and the optimisation environment. This is then followed by establishing the workflow. Selection of the appropriate optimisation algorithm; depends on the optimisation objectives and what have been obtained in the previous steps, and finally to perform the optimisation, analysing results and determining the final design.

3.2.9 Multi-Objective Optimisation Using NSGA-II

The Non-Dominated Sorting Genetic Algorithm (NSGA) was proposed by Srinivas and Deb (1994). One of the main evolutionary algorithms developed to solve multi-objective optimisation, one of the characteristics of NSGA being implementing non-dominated solutions concept proposed by Goldberg (1989) and Fonseca and Fleming (1993) as a fitness assignment strategy. It was further replaced with NSGA-II (Deb et al, 2002), where non-dominated solutions are preferred for further generation and a sharing strategy that preserves diversity among the solutions are created. **Figure 3.10** shows the how the NSGA-II is implemented.

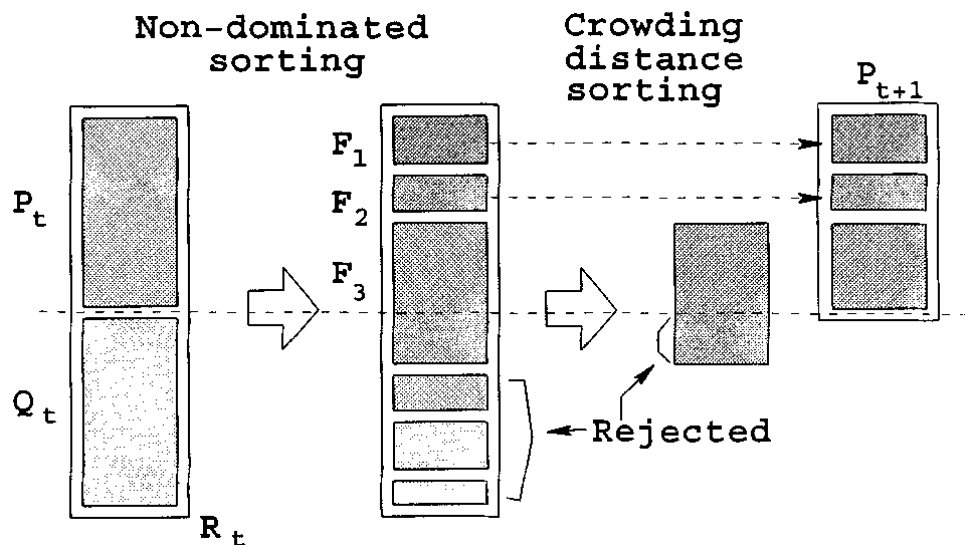


Figure 3.10: NSGA-II procedure (Deb *et al*, 2002)

A few innovations were added in which the computational complexity of non-dominated sorting is reduced by introducing fast non-dominated sorting procedure; introducing elitist-preserving approach into the algorithm to prevent loss of already-found Pareto-optimal solutions from previous generation, also to increase the speed of the GA; and replacing the user-specified sharing perimeter with crowded-comparison approach, or a parameter-less niching operator, in order to maintain a diverse non-dominated set among population members and ensuring uniformly-spread Pareto front. These approaches adopted by NSGA-II were shown more clearly by Salazar *et al* (2006) in **Figure 3.11** showing the two minimised objectives f_1 and f_2 which is more relevant for the research.

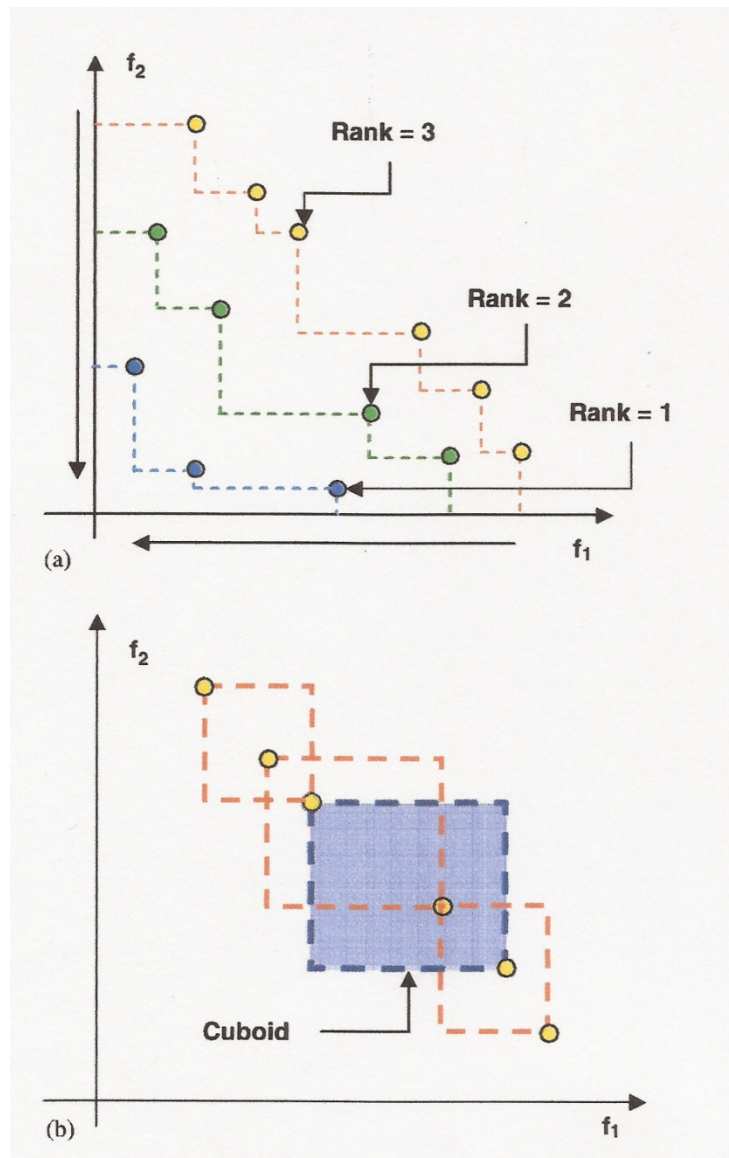


Figure 3.11: Rank (a) and cuboid (b) concepts used by NSGA-II (Salazar et al, 2006)

In the context of ranking as illustrated in **Figure 3.11 (a)**, the front ranking of the populations are based on dominance criteria. Each solution is assigned a non-dominated rank, where a smaller number is assigned to a better non-dominated front, which denotes higher ranking. Therefore, solutions at Rank 1 are preferred to solutions at Rank 2, which in turn are preferred to that at Rank 3. **Figure 3.11 (b)** illustrated a density metric called Crowding Distance, which is an explicit mechanism to preserve diversity of the solutions. For a particular solution of

interest in a particular Pareto front, the density of solutions in its surroundings is estimated by taking average distance of two solutions on its either side along each of the objective, shown by the cuboid. Selection is done on the solutions with a higher rank (Rank 1 > Rank 2 > Rank 3>...). For the solutions that lie in the same rank, the crowding distance is used, where a solution with larger crowding distance than its neighbours is preferred. The Pareto-optimal front that consists of an ideal set of non-dominating solutions has good convergence and good distribution, is illustrated in **Figure 3.12**.

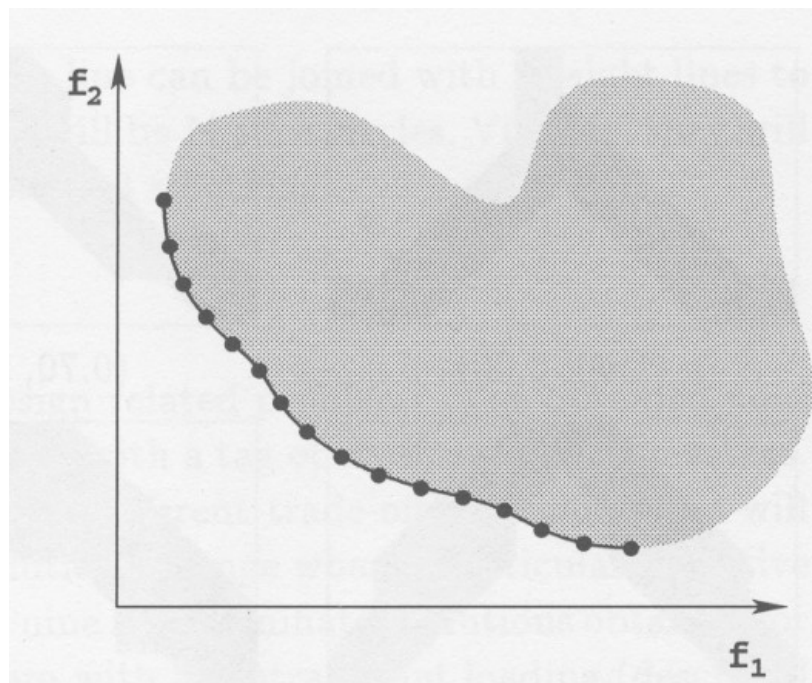


Figure 3.12: Ideal set of non-dominated convergence
(Deb, 2004)

Since NSGA-II was designed for multi-objective optimization but can also be used for single objective ones, application of NSGA-II in building optimisation is numerous. One example of a single objective optimisation application is a study on minimising the difference in investment for building construction (Palonen *et al*, 2009), while researches that use multi-objective optimization include HVAC control system to achieve building energy savings and to control building thermal comfort

(Perfumo *et al*, 2010; Nassif *et al*, 2005). The NSGA-II can also be coupled with advanced neural network (ANN) to reduce building simulation run period in order to reduce building energy consumption and increase thermal comfort of occupants (Magnier and Haghghat, 2009). NSGA-II was also used in solving constrained reliability optimisation problem (Salazar *et al*, 2006).

Another example of the integration of BPS into design optimisation program in architectural design was demonstrated in the study by Shi (2011) in finding the best insulation strategy to minimise the space conditioning load in an office building while at the same time minimising the insulation usage.

A similar effort was made by Fialho *et al* (2011) but in the form a framework tool where the architects optimise the architectural and structural aspects of a building during early stage of design to minimise both the total building energy consumption and the construction costs; the energy consumption was based on the "Total Site Energy" in kWh, while the construction cost was based on the sum of the costs of the insulation materials used, in €/m². This was achieved by combining EnergyPlus with a new multi-objective evolutionary algorithm derived from NSGA-II concept in optimising angle of building and its wall insulation materials. The framework provides assistance to architects to save design time and at the same time explore energy-efficient design solutions.

Another study worthy of note is one by, Chantrelle *et al* (2011) that focused on the renovation of buildings. It is common to optimise the building construction and systems operation with two objective functions. However, the authors developed a new optimisation tool MultiOpt, which is based on NSGA-II and handles four criteria, namely energy consumption, cost, life-cycle environmental impact of building materials and thermal

comfort. The optimised variables were divided into the building envelope group and the shade control group; the building envelope group consisted of types of external wall, roof, ground floor, intermediate floor, partition wall, and window, while the shade control group is the threshold value of the illumination of the façade of the building, and the dead-band associated with the on-off controller. The high diversity of solutions generated from simultaneous optimisation of all the criteria made it difficult to select the most optimum solutions for each criterion. One approach taken by the authors was to retain the "best", or the minimum solution from each objective function, as shown in **Figure 3.13**, since the objective of the optimisation is minimisation.

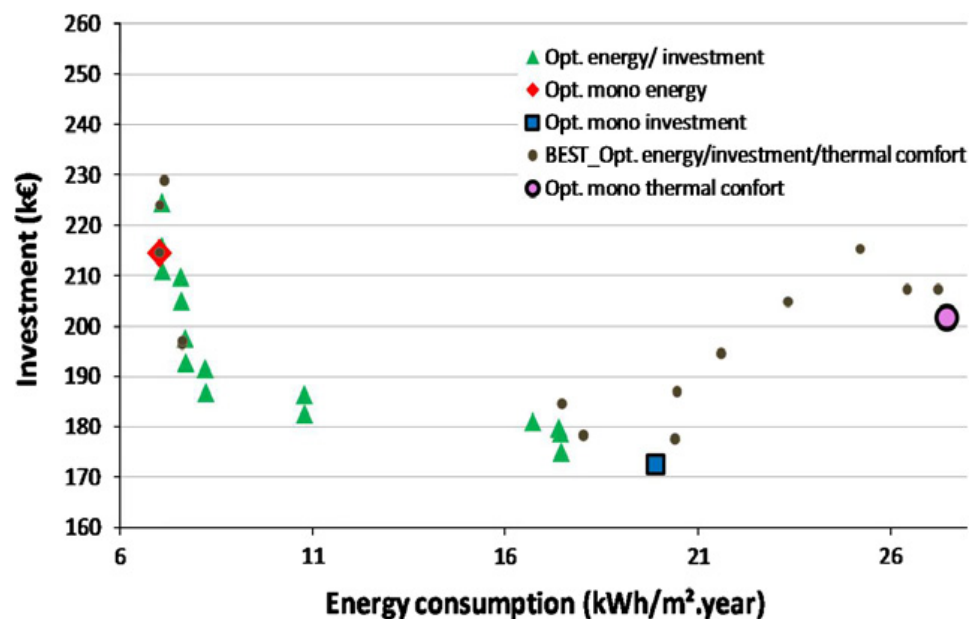


Figure 3.13: Multicriteria optimisation between investment and energy consumption (Chantrelle *et al*, 2011)

It can be seen that in the context of pareto optimality, a better result can be achieved when two objectives are considered simultaneously. Increasing the number of criteria to be optimised means that a number of criteria is treated as a single-

objective problem with only the “best” is selected while other optimal solutions are ignored. There is also a risk of increasing the complexity and computing cost, even though the number of population and the iteration can be low.

3.2.10 Summary

The design goals for this research are based on real world problems which indicate that there is more than just one objective function, or design goal, is considered. Having more than one design goals necessitates the usage of multi-objective optimisation (MOOP) to obtain as large a number of solutions that are as diverse as possible; due to its ability to generate a number of solutions at a single run, this can be achieved using a Genetic Algorithm.

A binary encoding has been used in this research since it allows the optimisation of different variable types and also is able to be associated with crossover and mutation operators. The solutions are encoded into binary strings of zeros (0) and ones (1) for every variable. The binary tournament selection was selected as the reproduction operator. The uniform crossover is an extreme case of multi-point crossover where every bit in the parent solution string has equal probability to be recombined to produce a child solution.

NSGA-II is a widely used GA based on the non-domination sorting of elitist solutions. Recent research on building optimisation revealed the common trend of optimising two objective functions, and increasing the number of objective functions increases the complexity in analysis and selection of optimal solutions.

3.3 Interlink of EnergyPlus with NSGA-II and Mould Risk Model

The point at which the simulation phase interfaces with the mould growth risk analysis stage and the optimisation stage was shown in **Figure 3.14**.

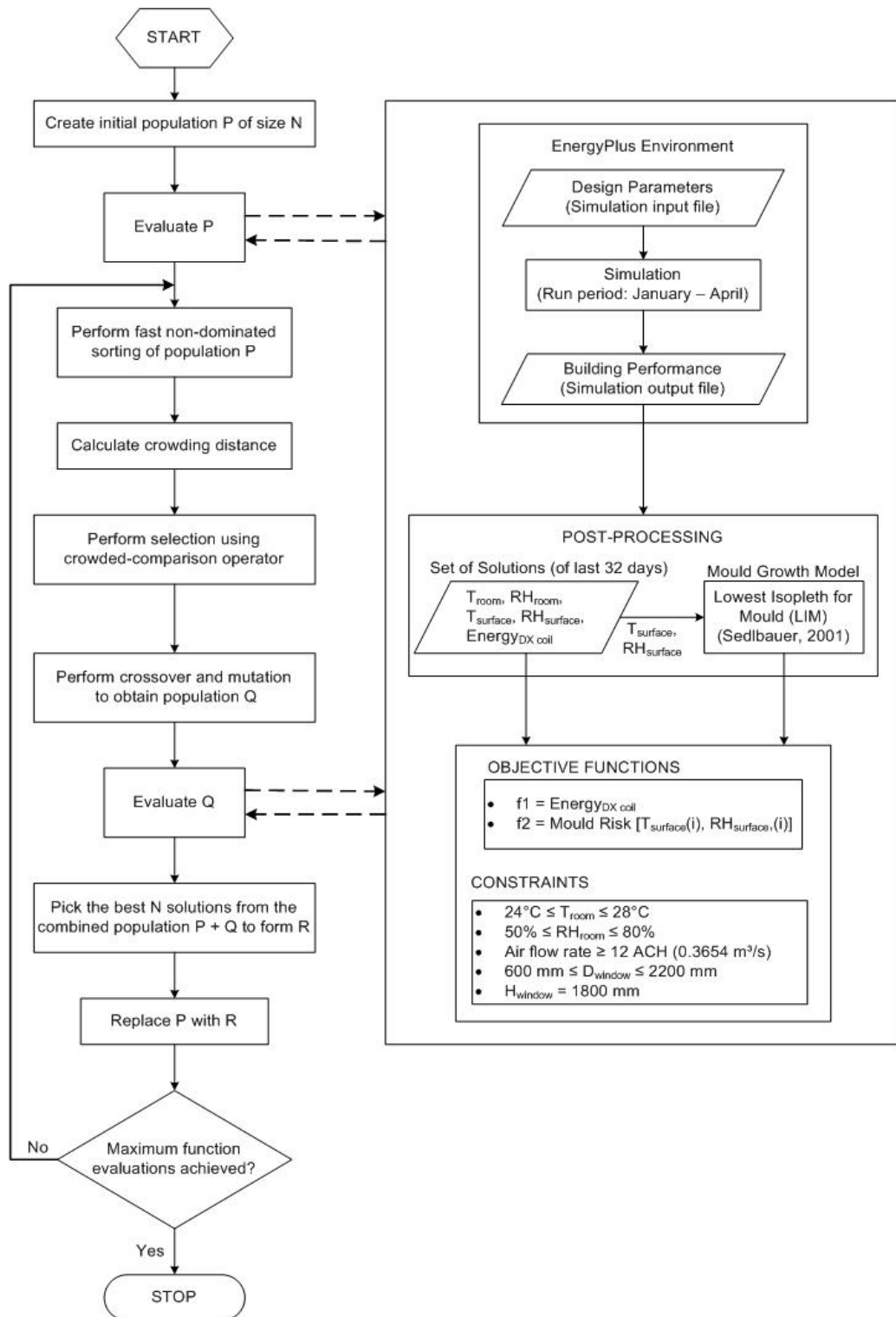


Figure 3.14: Interlink of NSGA-II, EnergyPlus simulation and mould risk model.

The framework shown in **Figure 3.14** is described as follows. Simulation input file contains design parameters defining the zone, among them the building materials used for wall layers with their hygrothermal properties, the room temperature and room relative

humidity (RH_{room}) set-points. The building performance parameters from the simulation output data are room temperature and relative humidity, the room surface temperature and room surface relative humidity ($RH_{surface}$) for walls and the roof, and the DX coil total cooling energy. The parameters were then used during post-processing, where the surface conditions (room surface temperature and room surface relative humidity, $RH_{surface}$) were fed into the extended mould growth model for mould growth risk analysis. The detailed description of the mould growth model is given in **Chapter 4**.

Evaluation of population P consists of treating the solutions as input data for simulation in EnergyPlus. The building performance based on the design parameters is represented by the simulation output file. The next step is to post-process selected data from the simulation output file. The data selected are room indoor temperature, T_{room} , room indoor relative humidity, RH_{room} , room surface temperature, $T_{surface}$, room surface relative humidity, $RH_{surface}$, and total cooling capacity of the HVAC cooling coil, E_{DXcoil} . Evaluation is made on the room indoor conditions to see whether they are maintained. The data used is from the last 32 days of the simulation period, the reason of which is explained in **Chapters 4** and **5**. The wall surface temperature and relative humidity of the last 32 days of simulation period are used to analyse the mould risk using extended mould growth model by Sedlbauer (2001). A more detailed explanation is given on the mould growth risk model in **Chapter 4**.

Analysis with mould growth model is compared against the objective functions and the constraints, of which further explanation can be found in **Chapter 5**. The entire process shown at the right hand side of **Figure 3.14** is the stage where the fitness of population P and the new population Q are evaluated. The population P is then sorted according to the dominance of a solution on the other with respect to the objective function, using a fast non-dominated sorting approach.

Crowding distance, shown as one of the optimisation steps on the left hand side of **Figure 3.14**, is a measure of assessing the density of the feasible solutions surrounding a particular point on a front. It calculates the distance between each solution point. Crowded-comparison operator guides the selection process of ranked non-dominated solutions towards a uniformly spread out Pareto-optimal front, where a solution with lower (better) rank is selected over the other. Alternatively, if both solutions belong to the same front the solution located in a lesser crowded region is preferred. Operators such-as cross-over and mutation are applied on the ranked solutions to create a new population Q .

The number of good solutions in the population P is picked to be combined with solutions Q to form a new population R , and the population R replaces the population P as a current front with respect to the two objective functions. The optimisation process is terminated after the maximum number of function evaluations has been achieved.

It is noted that the range of acceptable comfort for the room relative humidity (RH) is high at the upper end (80%). The reason it is so is because in practice, several areas in hospitals in Malaysia were operated at higher RH than they are designed for. This issue is addressed in further detail in **Chapter 5**.

3.4 Chapter Summary

A detailed explanation of the chosen BPS was given and EnergyPlus was selected based on the measure of the complexity and accuracy of the BPS in evaluating the room indoor and the surface conditions. The feasibility and advantages of using multi-objective optimisation with GA, with particular attention to *NSGA-II* was discussed, and the interface between simulation and *NSGA-II* was presented. The next chapter gives a more detailed description of the selected mould growth risk model and how it is further extended to make it numerically feasible to interface with the simulation and optimisation process.

Chapter 4

Mould Risk Model

Chapter 3 gave an overview on the existing building performance simulation (BPS) programs. The chapter also discussed the requirements of a building performance simulation (BPS) for use in this research and identified EnergyPlus as the suitable whole building simulation program. Similarly, the Non-Dominated Sorting Genetic Algorithm (NSGA-II), was identified as being a suitable algorithm for the simultaneous minimisation of both building energy use and the risk of mould growth. This chapter describes the formulation of the model for predicting the risk of mould growth, this model being derived from the isopleths described by Sedlbauer (2001), these having been identified in **Chapter 2** as the most suitable indicators of mould growth. The chapter structure is given in **Figure 4.1**.

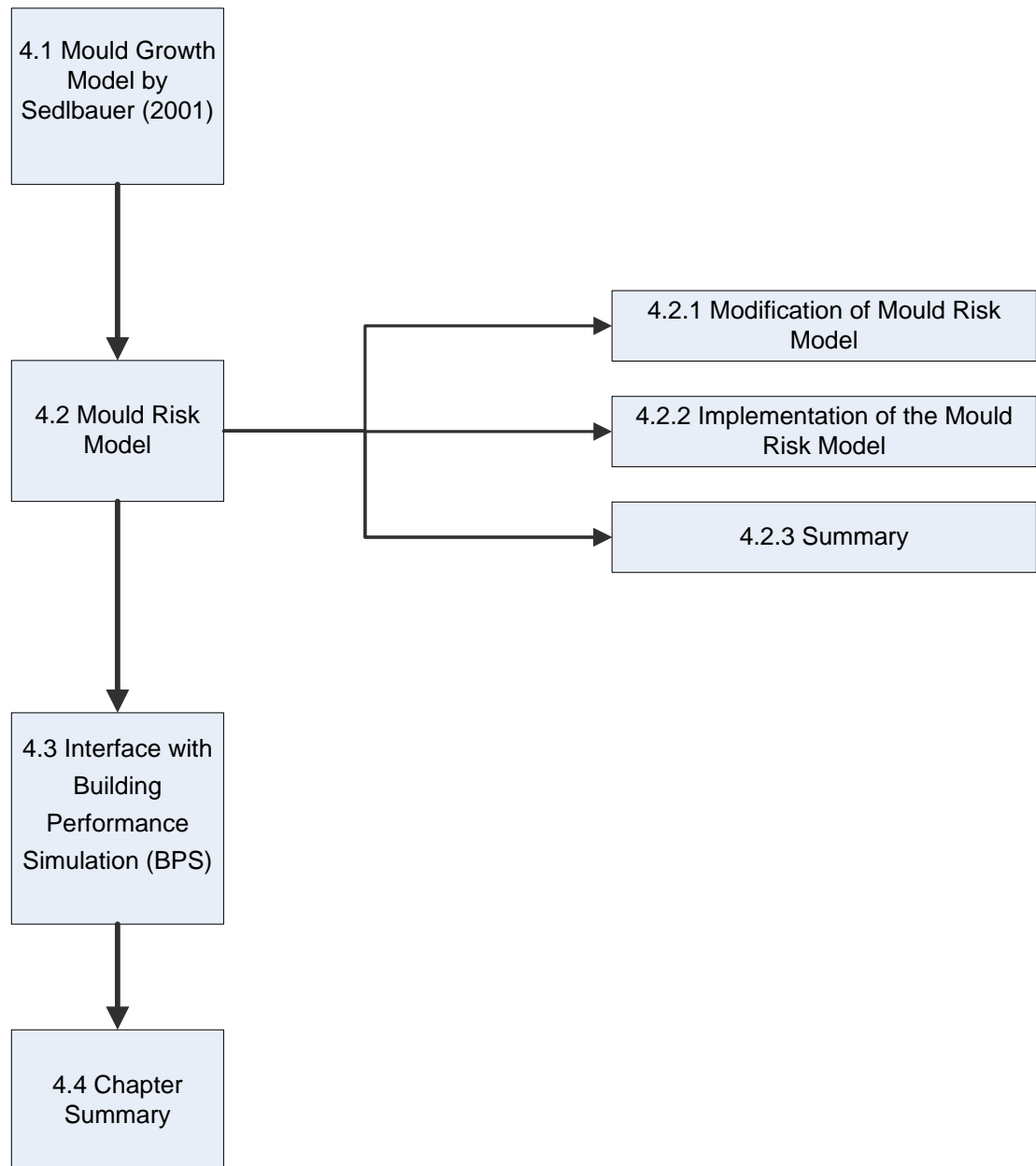


Figure 4.1: Structure of Chapter 4

4.1 Mould Growth Model by Sedlbauer (2001)

The aim of this research is to investigate the trade-off between building energy use and the risk of mould growth on the surfaces of a room. For a given substrate and fungus, the germination time and rate of mould growth is dependent on the time the surface is at a given temperature and relative humidity. Sedlbauer (2001) developed two generalised mould growth limit curves, or isopleths; one based on the hazard classes of fungi species, while the other is based on the substrate, or building materials categories. The available fungi species were divided into hazardous classes, with regards to the hazard they present to humans. The system that is based on hazard classes is further divided into two sets of 'models'; one for hazard class A and the other for classes B and C. [The hazard classes are defined as follows, based on work by Sedlbauer \(2001, 2002\):](#)

- A. Fungus or its metabolic products are highly pathogenic; they should not be allowed to occur in occupied dwellings.
- B. Fungus is a pathogen when people are exposed to it over a long period of time, and it may cause allergic reactions.
- C. Fungus is not dangerous to health; fungal formation may however, cause economic damage.

The selected mould growth curve used in this research is based on the generalised curve for fungi hazard classes B/C; class B is for the fungal species that may cause allergic reactions to humans if exposed for over a long period and class C is for the fungal species that is not dangerous to health, but whose growth may cause economic damage to building structures. The graphical representation of the mould isopleths based on the hazard class is shown in **Figure 4.2**. It is noted that the LIM for hazard class B/C is much lower than that for hazard class A.

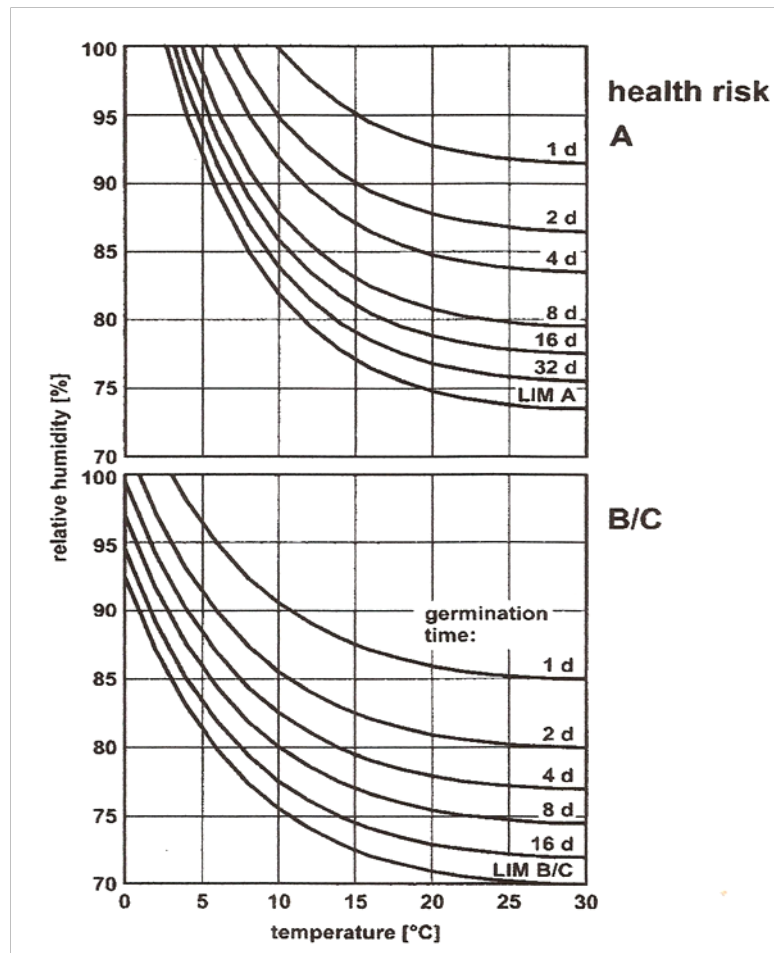


Figure 4.2: Generalised Isoleth system for spore germination, valid for all fungi species or hazardous class A (top) and B/C (below), with “d” denotes days (after Sedlbauer, 2001)

The reason the B/C curves were selected over hazard class A is that because the B/C curves, although they have a lower health risk, they also have lower germination RH/T isopleths, and therefore represent the lower limit of mould growth probably of any species. Isoleth systems for the hazard class B/C (LIM B/C): These systems are based on optimal culture medium substrates. Therefore, they provide the lowest prerequisites for relative humidity and temperature for the growth of fungi. Consequently, they are based on the limits for growth of all species of fungi. This means that growth of hazard class A fungi are also prevented when the boundary conditions exclude the growth of class B/C fungi (Sedlbauer, 2002). The different ranges of surface temperatures and surface relative humidity result in different

responses by the fungi species in terms of germination time and growth rate. The responses form a pattern of growth curves, or isopleths, which are unique to fungi species. The developed Lowest Isopleths for Mould (LIM) on both the systems represent lowest limit below which there is no biological activity evident from the fungi species and also on the building materials.

The isopleths that are based on substrate are divided into two categories; Category I for bio-utilizable substrates and Category II for substrates with porous structures. Building materials that are available to the construction industry are included in these two categories, and are also covered in the selected generalised isopleths of hazard class B/C.

The generalised isopleth based on the building materials since the hazard class LIM covers available fungi species, of which a few are found in the tropical climate, such as *Aspergillus fumigatus* and *Aspergillus versicolor*, both in hazard class A. The *A. fumigatus* is a dominant species found in Malaysia. However, for the purpose of the research, the B/C limit curves were selected due to the lower germination limits. The isopleth system based on substrate categories were less straightforward to select between the two since the construction of isolation room walls consists of building materials that are represented by both Categories I and II. Furthermore, the LIM for the hazard class isopleth system is at the lower position, that is, the germination takes place at lower surface humidities, compared to the substrate category isopleth system. Therefore, the hazard class B/C isopleths system represents a more conservative estimate of the risk of mould growth.

The LIM represents the lowest boundary line for possible fungus activity, taking into account the surface growth conditions for a large number of existing mould species growth, unlike other models, such as by Clarke *et al* (1999), that only considered one fungal species.

The mould risk isopleths for category B/C risk form the basis of the mould risk model used in this research, the risk model being developed specifically for use in the multi-objective optimisation.

4.2 Mould Risk Model

The isopleth curves (**Figure 4.2**) represent the germination times of mould species (time taken for mould to begin growth from spores) for static surface conditions, whereas the building surfaces are subject to dynamically changing indoor relative humidity and indoor temperature. Several approaches to predicting the risk of mould growth for dynamically changing surface conditions have been investigated (Vereecken and Roels, 2012), but all operate in a way that in effect indicate the degree of mould growth or time for germination. In this research, we seek to find the trade-off between the air conditioning systems energy use and the risk of mould growth. Given that some high energy solutions will result in no mould growth, we require a quantifiable measure of the extent to which there is a “risk”, or “no risk”, of mould growth occurring on a wall surface.. The model developed here provides a measure of the “risk” of mould growth for dynamically changing surface conditions, and which spans both the mould growth and no-mould growth region of surface conditions.

4.2.1 Modification of Mould Risk Model

In order to calculate the mould risk, the germination time (time taken for mould to begin growth from spores and develop its own spores), d , as a function of surface temperature (T), and surface relative humidity (ϕ), is required. This has been obtained by applying a curve-fit to data in the range of between 20 and 30 °C extracted from the graphs presented by Sedlbauer (2002), shown in equation (1), and modifying the curves where the axes were changed with surface relative humidity on x-axis and the germination time on y-axis.

$$d(T, \phi) = d_{\min} + (d_{\max} - d_{\min})e^{-\alpha(T, \phi)} \quad (1)$$

where,

$$d_{\min} = \text{minimum germination time in days,}$$

$$d_{\max} = \text{maximum germination time in days.}$$

The minimum germination time d_{\min} is assumed to be 1 day and the d_{\max} is assumed to be 32 days. The assumptions are based on the 30-day simulation period and also that the limit curve of hazard class B/C is assumed to be of 32-day germination time.

The exponential power for the limit curve is expressed as

$$\alpha(T, \phi) = \beta \times \frac{(\phi - \phi_{\min})}{(\phi_{\max} - \phi_{\min})} \quad (2)$$

Where minimum surface relative humidity at a given surface temperature, T , $\phi_{\min}(T)$, is described in quadratic expression as

$$\phi_{\min}(T) = a_0 + a_1T + a_2T^2 \quad (3)$$

While the maximum surface relative humidity at a given T , $\phi_{\max}(T)$ is described in quadratic expression as

$$\phi_{\max}(T) = b_0 + b_1T + b_2T^2; \quad (4)$$

The term ϕ is the simulated surface relative humidity and

$$\beta = 4.6$$

The β represents the measure of steepness, or gradient, of the limit curve, while ϕ_{min} and ϕ_{max} determine the end-points of the limit curve. The exponential power indicates where the surface condition lies on the curve (at a given β) due to the ratio:

$$\frac{(\phi - \phi_{min})}{(\phi_{max} - \phi_{min})}$$

The coefficients (at six decimal places) for equations (3) and (4) are as follows:

$$a_0 = 77.184874; \quad a_1 = -0.466386; \quad a_2 = 0.007563; \\ b_0 = 92.184874; \quad b_1 = -0.466386; \quad b_2 = 0.007563;$$

The coefficients of the curve-fit are valid for surface conditions that lie on or above the limit isopleth, that is, for a surface relative humidity $\phi \geq \phi_{min}(T)$. Note that the best fit was achieved with a germination time associated with the limit isopleth of 29 days, whereas from **Figure 4.2**, intuitively, this might be taken as being equivalent to 32 days; the value of which is not specified by Sedlbauer (2002). Similarly the minimum germination time might be expected to be 1.0, but the best fit to the isopleths was found using a value of 0.8.

The germination time resulting from the model is illustrated in **Figure 4.3**, for the limited surface temperature range between 20 and 30°C. Note that an increasingly negative germination time does not imply less risk, but an increasing risk, since the risk is proportional to the inverse of the germination time.

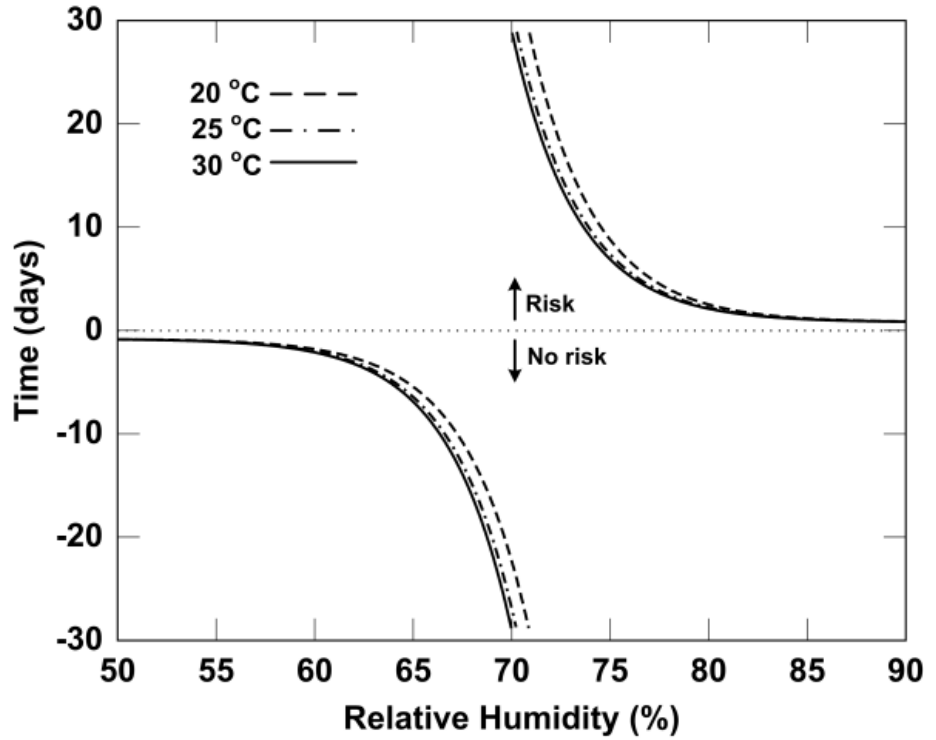


Figure 4.3: Mould Risk Germination Time

Calculation of the “germination” time (risk) for a surface condition which falls *below* the limit isopleth is achieved by increasing the relative humidity by twice the amount that it falls below the limiting humidity, and multiplying the resulting germination time by negative (-) 1, as shown in the second line of the expression (5):

$$d(T, \phi) = \begin{cases} d(T, \phi), & \phi \geq \phi_{\min}(T) \\ -d(T, \phi_b), & \phi < \phi_{\min}(T) \end{cases} \quad (5)$$

where,

$$\phi_b = \phi_{\min}(T) + (\phi_{\min}(T) - \phi) \quad (6)$$

and ϕ is the surface relative humidity, at a given temperature T , that is obtained from the simulation (EnergyPlus simulation output parameter). Increasing the relative humidity in this way

results in the equivalent humidity value lies *above* the limit isopleth.

Two modifications to this model are required for use in this research. First, the isopleth indicates only the conditions under which germination (and mould growth) will occur, and there is no indication of how close surface conditions that lie below the limit isoline are to the limit isoline themselves and to possible mould growth. Since the aim of this research is to find the optimum trade-off between energy use and the risk of mould growth, and that it is feasible for solutions to result in surface conditions that are below the limit isoline, the model needs to predict the degree to which there is no risk of mould growth, as well as there being a risk. The approach adopted in this research is to mirror the germination isopleths about the Limit isoline and to treat conditions below the Limit isoline as having a negative germination time, as shown in **Figure 4.4**.

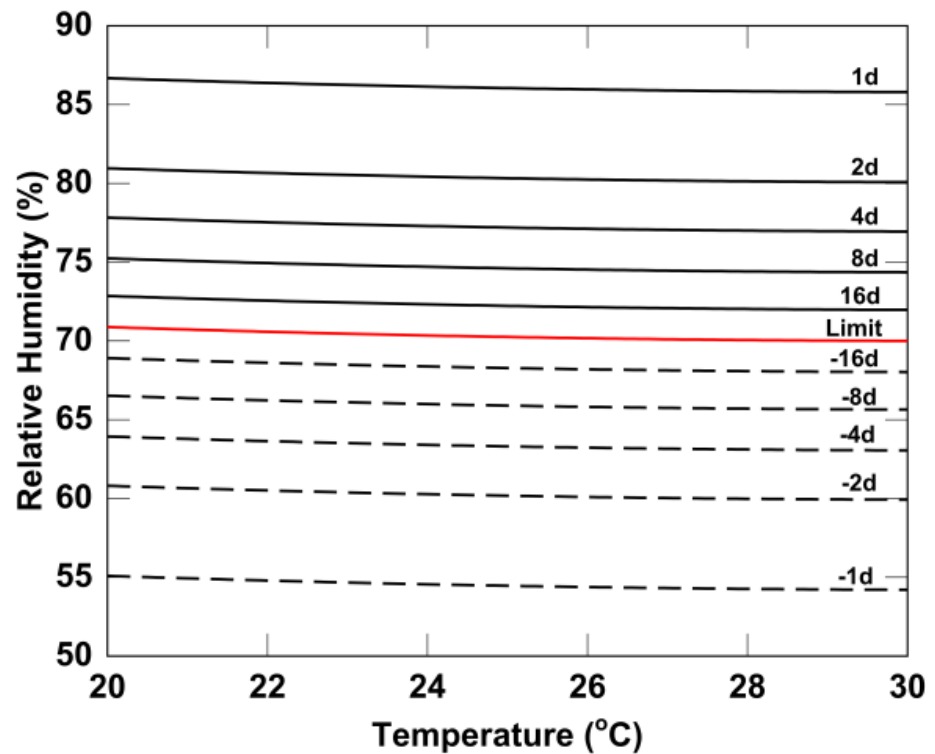


Figure 4.4: Generalised Germination Isopleth System (the dashed lines below limit isoline indicate varying measures of no risk)

While there is no experimental justification for the approach and the fact that it may not be possible to validate the model for conditions under which no growth occurs, the model provides a simple framework in which the degree of no risk (negative germination time) has the same exponential characteristic as the degree of risk (positive germination time). Note also that although the particular isopleths used here are for the risk category B/C, the approach could equally be applied to isopleths representing other categories of mould growth.

The second modification to the model accounts for the fact that the isopleth system represents germination time under static surface temperature and relative humidity, whereas the surface conditions in real buildings are transient. Krus and Sedlbauer (2007) suggested an approach in which the degree of

germination over a given time period (Δt), is equal to $\left(\frac{\Delta t}{d}\right)$

where the time period is in units of days, and d is the corresponding day based on the limit curves from the isopleth system (e.g., 1d, 2d, 4d, etc.) that coincides with surface temperature and surface relative humidity obtained from simulation (for the average surface conditions over the time period). Since the simulation report interval used in this research is 1 hour, the degree of germination for a given hour is

$\frac{1}{(d \times 24)}$. The degree of germination is continuously

integrated until its value is equal to 1.0, at which point germination is deemed to start. This simple approach is limited in that it does not account for the impact of periods of surface drying, but it is sufficient to provide an initial indication of the risk of mould growth, particularly for a tropical climate where the transients in the surface conditions are relatively small.

The integrated degree of germination is used here as a measure of the risk of mould growth, with separate calculations performed for the regions above and below the limit isopleth, as in **Figure 4.3**, represented as r_{growth} and $r_{no\ growth}$ in expressions (7), (8) and (9):

$$r_{growth} = \sum_{i=1}^n \frac{1}{(d_i \times 24)}, \quad \forall(d_i > 0) \quad (7)$$

$$r_{no\ growth} = \sum_{i=1}^n \frac{1}{(d_i \times 24)}, \quad \forall(d_i \leq 0) \quad (8)$$

$$Risk = \begin{cases} r_{growth} & (r_{growth} > 0) \\ r_{no\ growth} & (r_{growth} = 0) \end{cases} \quad (9)$$

where n is the number of hours in the integration. The model equations and mould risk calculation procedure are described in the next section.

Note that the original isopleth curves range in temperature from 0°C to 30°C (**Figure 4.2**), but the modelling here is restricted to the range 20°C to 30°C (**Figure 4.4**), so that it is in line with the valid operating range of the building (and in fact increases the accuracy of the curve-fit for the isopleths).

4.2.2 Implementation of the Mould Risk Model

To demonstrate how the mould growth model is implemented, consider a surface condition in **Figure 4.4**, where the germination time for a surface temperature of 30°C and 80% RH is approximately 2 days, with the result that if the surface is held at these conditions for 30 days. The mould risk then is calculated as being,

$$Risk = \sum_{i=1}^{720} \frac{1 \times 720}{(2 \times 24)} = 15$$

surface temperature and relative humidity where held at 30°C and 60% RH, the risk would be calculated to be

$$Risk = \sum_{i=1}^{720} \frac{1 \times 720}{(-2 \times 24)} = -15$$

The relationship between the risk of mould growth and the surface conditions held constant for a period of 30 days (or 720 hours) is illustrated in **Figure 4.5**, where three sets of curves based on the limited range of between 20 and 30°C were created with the interval of 5°C.

It should be noted that the risk calculations are not statistical or probabilistic measures of mould growth risk. What they provide is an index number in measuring the mould risk (where the greater the index number, the greater the risk, and the more negative the index number implies the less the risk).

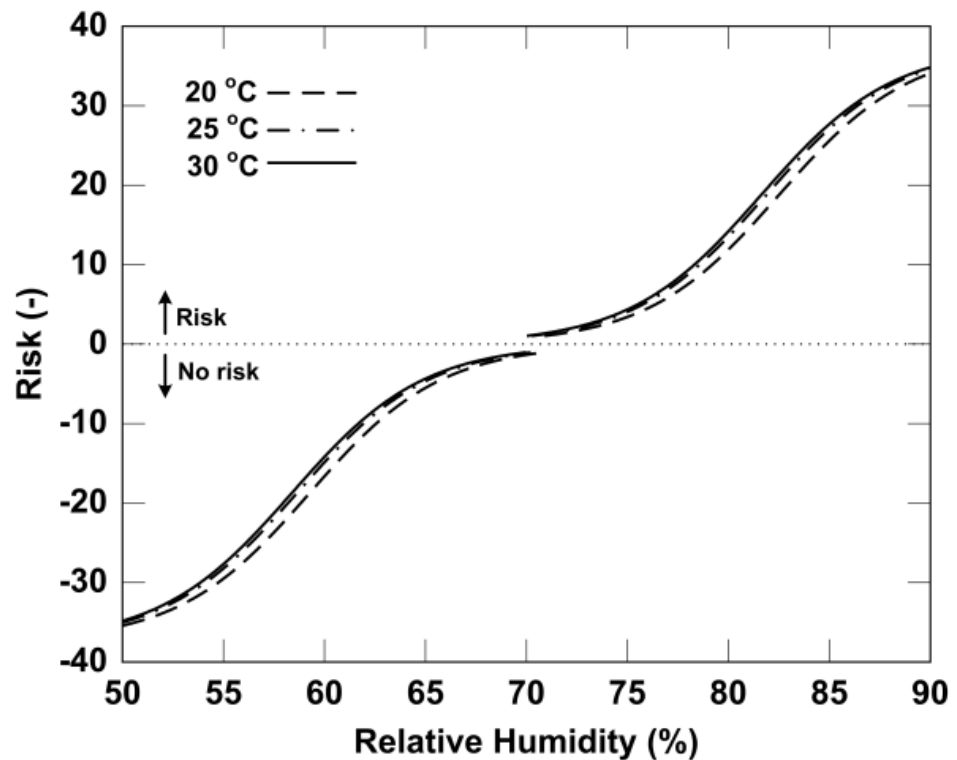


Figure 4.5: Mould Risk for Surface Conditions Held Constant for 30 Days

Three characteristics of the mould risk model are apparent. Firstly, the degree of germination has a normal limit of 1.0 since above this value mould growth is deemed to have started. However, no such cap is applied when the degree of germination is used to represent the risk of mould growth as the measure of risk must vary with all probable surface conditions.

Secondly, it is clear that the risk of mould growth is more sensitive to changes in relative humidity than to changes in temperature. Finally, the risk model is discontinuous about the limit isopleth (Risk = 0). The limit isopleth is associated with a germination time of 29 days as explained previously, and so a surface held at this condition for 30 days would result in a risk value of approximately 1.0, while a condition that lies just below the limit isopleth has a risk value of approximately -1.0.

Since approximately 30 days are required to trigger a risk value of 1.0, the integration is performed for a period of one month. Justification for using a period of only one month is further examined in **Chapter 5**, the justification being driven by the fact that there is very little seasonal variation in ambient conditions in tropical locations, and that there is a need to limit the computation time associated with simulating both the heat and mass transfer performance of the building.

4.2.3 Summary

The risk of mould growth is measured by taking the average of integral risk for one month period. The surface condition is calculated against the isopleths on which the condition lies. The surface temperature and relative humidity from the simulated output data is plotted as hourly values on the isopleth system. The hourly value is calculated as $1/(\text{days corresponding to the isopleth} \times 24 \text{ hours})$. The values resulted from one month period is added to give the total value.

The magnitude of the risk is the distance of the simulated surface RH above the threshold curve at the same surface temperature. If it is positive, that is above the threshold LIM, it is indicative of a probability of risk of mould growth.

A “no risk” condition is given when the surface RH is below the threshold, with the evaluation calculated from using an RH value equal to a value above threshold by an amount equal to the "distance" below the threshold. A no risk condition is given as a negative number.

4.3 Interface with Building Performance Simulation (BPS)

This section gives an explanation of the interface between developed mould growth risk model and the BPS as well as the optimisation tool. As shown in the **Figure 3.15** in **Chapter 3**, the phase at which post-processing begins is when the parameters from the simulation output

files, namely surface temperature and surface relative humidity (RH_{surface}) of the walls and roof, are fed into the extended mould growth risk model and the measure of the risk was calculated between the simulated surface condition and the limit isoline. The measure of mould risk calculated is one of the design goals, apart from the total energy consumption of the HVAC system for the isolation room. The results of the surface conditions are the result from a number of input variables of which are compared to the imposed constraints, to be described in more detail in **Chapter 5**.

4.4 Chapter Summary

An approach for evaluating mould risk has been developed based on an existing mould growth model by Sedlbauer (2001). Two modifications were made in order to predict the degree to which there is a risk of mould growth as well there being a risk, namely by mirroring the germination isopleths about the Limit isoline and treating conditions below the Limit isoline as having a negative germination time, and by taking into account the transient, rather than static surface temperature and relative humidity. The characteristics of the extended mould risk model are that the normal limit of 1.0 for the degree of germination is not applied as the measure of risk varies with all surface conditions, the risk of mould growth is more sensitive to changes in surface relative humidity than the changes in surface temperature, and the risk model is not continuous near the Limit isoline. Chapter 5 consolidates the key components of the research, namely the BPS, the NSGA-II search algorithm and the extended mould growth model, in evaluating a case study based on an actual isolation room as well as alternative design. The chapter also describes in detail the input variables as well as the design constraints for the purpose of optimising the isolation room construction details and its HVAC control strategy.

Chapter 5

A Benchmark Hospital Isolation Zone

Chapter 4 gave a more detailed description of selected mould growth model, of which a literature survey was done on a number of existing mould growth prediction models. A suitable mould growth model was selected and the parameters in the model, namely the surface temperature and surface relative humidity, were formulated for optimisation. The EnergyPlus software and the extended mould growth model were then used to investigate the performances of the isolation room design, its HVAC system as well as its operation. The aims of this chapter are two-fold; firstly, to investigate the reasons why mould growth occurs in hospital buildings with HVAC systems designed according to standard practice by using a base case, and secondly, to define an alternative design to be used in the optimisation study (**Chapter 6**), including the choice of optimisation variables and their values. The structure of this chapter is shown in **Figure 5.1**.

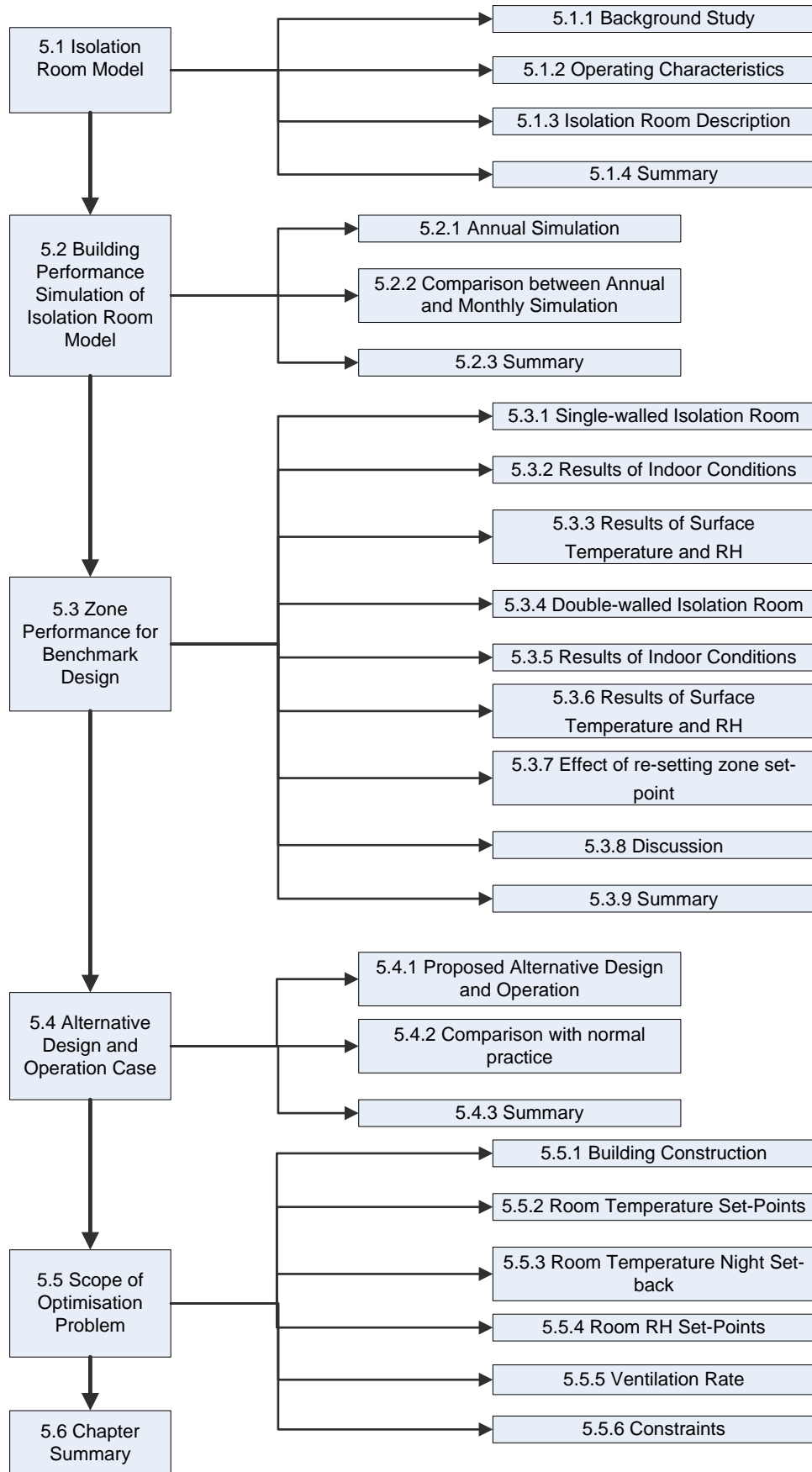


Figure 5.1: Structure of Chapter 5

5.1 Isolation Room Model

This section gives a short background on the existing design practice of isolation rooms in Malaysia. It also describes, and justifies, the example isolation room, including the operating characteristics/parameters investigated, such as the habit of window opening and re-scheduling of room temperature.

5.1.1 Background Study

Isolation room design and ventilation strategies have been the subject of many studies. Early study by Bagshawe *et al* (1978) emphasized the importance of isolating patients as a means of infection control. Phillips *et al* (2004) suggested the need of having an anteroom as a means of barrier protection for the patients against contamination. The sliding door position and human movement in the isolation room do have an impact on air distribution (Shih *et al*, 2007), as well as the positions of the supply air and air extract grilles to ensure smooth air flow in the room (Cheong and Phua, 2006). The Centre for Disease Control and Prevention Guideline (2007) emphasized the minimum air change rate of 12 h^{-1} for new design with no recirculation in order to improve the indoor air quality in the isolation room. There is no mentioned of required design RH in isolation room in the American Institute of Architects Guidelines for Healthcare Facilities (2006). The emphasis is on the indoor air quality; where the air change rate is of critical importance in order to dilute the room air as a mechanism to contain spread of infection.

For the infectious type isolation room for patients with infectious disease such as Tuberculosis or AIDS, the room must be at a negative pressure difference between the room and the surrounding areas. The result is a movement of air from outside area into the room to prevent spreading of disease. Recent studies observed that the higher the air change rate and the negative pressure differential, the higher is the ventilation effectiveness in removing contaminant (Tung *et al*, 2009; Adams *et al*, 2011).

The studies cited were conducted in cold and dry countries. However, there is no study on the influence of design parameters on HVAC energy consumption and wall surface conditions for isolation rooms located in hot and humid countries such as Malaysia. Due to the fact that Malaysia is a hot and humid country with only dry and rainy seasons, the HVAC system operates on cooling mode only.

Currently there is no available standard or guideline on environmental design specifically catered for hospitals in Malaysia, although the design practice for isolation room indoor condition is 24°C/50% RH. There is also no documented evidence pointing to the Ministry Of Health Malaysia using ASHRAE guidelines as part of the design policy.

From the context of ventilation, maintaining the pressure difference, be it negative or positive, is critical for isolation rooms to function properly as designed. Therefore, constant air volume (CAV) system is a standard design feature which maintains that functionality. The variable air volume (VAV) system is discouraged on the grounds that variable air flow rate may alter the designed pressure difference between isolation rooms and surrounding areas, although the VAV does offer reduction in fan energy consumption.

With regards to the equipment selection, the advantages the direct expansion (DX) type HVAC system have over the chilled water system (CHWS) are lower installation cost, less degree of complexity and more independent use by building users. These are more apparent for upgrading works, or when a new building is added to existing health-care facility. Incorporating new CHWS into an existing one to cater for additional load incurs the risk of disrupting the system flow and decreasing its efficiency.

Another feature of a typical isolation room in Malaysian hospitals is the absence of heat recovery mechanism, such as desiccant wheel, to remove moisture and heat from outside air. The concern about potential cross-contamination due to contact between return air and

the incoming fresh air has resulted in this mechanism not being considered in HVAC system design.

5.1.2 Operating Characteristics

In addition to the design practice using guidelines that suit different climates, attention was given to the operating characteristics of the building that may contribute to whether its performance matches the design intent.

The opening of windows is one of the measures to introduce fresh air into a zone. Opening windows to introduce natural ventilation in wards as a measure of infection control is gaining momentum (Qian *et al*, 2010), as awareness on energy consumption among hospital designers and staff increases, and as a response to climate change (Lomas and Ji, 2009). However, the HVAC system for the isolation room uses 100% outdoor air and the room is required to be fully sealed to prevent infiltration of outdoor air other than that which goes through the cooling coil, and also to avoid upsetting the pressure difference between the isolation room and the surroundings. Therefore opening windows is regarded as unwanted infiltration and is discouraged due to its impact on difference in air pressure in relation to adjacent areas (Tang *et al*, 2006), and the possibility of microbes entering from outside environment, as mentioned by Beggs *et al* (2008) . However, personal experience has encountered building users resort to opening window in rooms that were meant to be fully sealed, as a result of differing perceptions in thermal comfort among occupants. This type of uncertainty is difficult to be quantified accurately and often not taken into consideration in detailed heat load calculation.

5.1.3 Isolation Room Description

An upgraded isolation room for the Intensive Care Unit suite in Kuala Lumpur General Hospital was used as a design base case for this research. The room was an airborne infection isolation (AII) type room, which operates at a lower pressure than the outside environment to avoid the spread of contaminated into the room. To achieve negative pressure, the exhaust air flow rate is 10 percent higher than the supply air flow rate. The indoor design condition follows the guideline from ASHRAE, where the design room temperature of 24°C and the design room relative humidity (RH_{room}) of 50% were used. The total ventilation rate of the room of at least 12 air changes per hour (h^{-1}) follows the guideline of the Centre for Disease Control and Prevention (2005) where 100% outdoor air is cooled, dehumidified and supplied into the room and exhausted entirely to the outdoors. These design criteria are applied for isolation room in new health-care buildings as well as in existing health-care settings.

The base case includes an anteroom which is part of a requirement in isolation room design. The anteroom functions as a containment barrier between the isolation room and other areas. In this research the anteroom was assumed to have the same indoor conditions as the isolation room. The occupancy for the room was fixed at one patient at all times. The light heat gain was set at 10 W/m², and the equipment heat gain at 2.5 W/m². The room was located next to a patient ward that was naturally ventilated. The occupancy for the ward was fixed with 4 people. The internal heat gain was equal to that in the isolation room. The graphical representation of the two zones was shown in **Figure 5.2**.

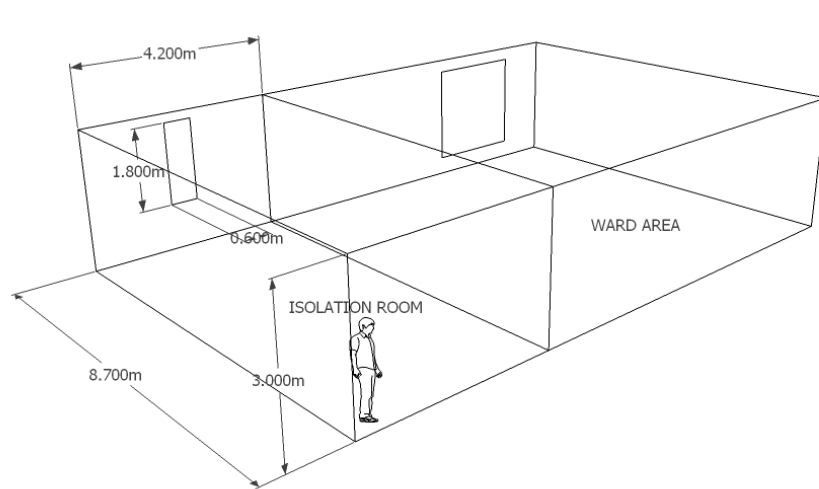


Figure 5.2: Schematic view of Isolation Room and Ward

The west and north walls were defined as the external walls, exposed to the sun. The south wall was defined as unexposed to sun and wind, assuming that the outer surface of the wall was exposed to an area which was either running on 8 hours of air-conditioning or was naturally ventilated.

The roof was assumed to be unexposed and functioned as the floor slab for a zone above which was not simulated. The condition the roof was exposed and was assumed to be non-conditioned. The construction of roof layer consisted of aerated autoclaved concrete at the outer layer, followed by the water vapour, sprayed polyurethane, air layer, and interior gypsum ceiling board. The air layer represented the void through which the air-conditioning ducting was passed.

The east wall of the isolation room was an internal wall that separated the isolation room and ward. To balance the mass flow into and out of the room, infiltration was assumed to be coming from the naturally-ventilated ward.

The indoor conditions of the room were set at a temperature of 24°C and 50% RH_{room} with the ventilation rate set at 12 h⁻¹. The room air exhausted directly to the outdoors with no re-circulation (ASHRAE, 2008). The mass flow rate of outdoor air which was treated and supplied throughout the system was kept constant.

The HVAC system selected in the simulation was a Direct Expansion (DX) type. It comprised of a blow-through supply fan, a cooling coil and a heating coil to provide cooling, dehumidifying and re-heating for the 100% outside air and was simulated to operate continuously (24 hours) to maintain the indoor conditions. The heat and moisture transfer across the zone envelope was assumed to be 1-dimensional and in steady-state form and no energy loss occurred within the HVAC system.

The re-setting of the room temperature set-point to a fixed range was also simulated, based on the study on thermal comfort of hospital workers in Malaysia by Yau and Chew (2009). In this study, the authors conducted a field survey to investigate the temperature range for thermal comfort in three public hospitals and a private hospital in Malaysia. The influence of room temperature on the room relative humidity (RH_{room}) and the energy consumption of the HVAC system was also investigated. The study observed that there are variable ranges of space average dry bulb temperature in the four hospitals where the surveys were conducted. There are three ranges for the public hospitals (20.0°C to 30.0°C, 20.9°C to 24.6°C, and 23.9°C to 32.2°C) while the range for the private hospital is between 19.0°C and 24.0°C. Adding up all the temperature ranges resulted in the very large range of between 19.0°C and 32.2°C, whereas the design room temperature range for Intensive Care Unit recommended by ASHRAE (2003) is between 21.0°C and 24.0°C. Therefore, to simulate the re-setting the temperature set-point by occupants, the amended temperature set-points of 19.0°C was selected

The simulation output data that were used for comparison with the design room condition were room temperature and room relative humidity (RH_{room}). The surface condition data that were part of the EnergyPlus output data, namely the internal wall surface temperature and internal wall surface relative humidity ($RH_{surface}$), were calculated using the HAMT modelling. The surface data were used in the modified mould growth model (described in **Chapter 4**) for mould growth risk analysis. The mould growth risk analysis was conducted as a form of validation of the design practice. The surface relative humidity is defined as the moisture content at the wall surface at a given surface temperature divided by the saturated moisture content at the same surface temperature. For the sake of clarification, the HVAC system will control the room relative humidity (RH_{room}). The room condition, together with moisture level at the wall surface, dictates the surface relative humidity ($RH_{surface}$) of the wall. The RH_{room} and the $RH_{surface}$ are not equal in value, with $RH_{surface}$ generally being lower because the surface temperature is lower.

5.1.4 Summary

The background study of isolation room design was conducted where it was observed that the design was based on standards and/or guidelines that are not suitable for hot and humid climate. An airborne infection isolation room based on an actual upgraded room was selected as a base case with the design conditions of 24°C and 50% RH and the ventilation rate of 12 h⁻¹. The design practice is evaluated for its performance in the next section.

5.2 Building Performance Simulation of Isolation Room Model

The previous section described the design practice of isolation room in Malaysia, including the operating characteristics or parameters, such as the habit of window opening and re-schedule for room temperature, that impact on the performance of isolation rooms in real condition. The section also described an example isolation room based on the normal practice in Malaysia. This section gives an explanation on annual simulation and

provides justification for shortening the simulation run period in order to reduce the computing time.

5.2.1 Annual Simulation

The annual run period was initially used in the simulation, starting from 1 January to 31 December. The time taken to simulate the conditions in the isolation room for that period was almost 30 minutes, which was considered high computing cost. A number of reasons can be accounted for the long simulation period. Firstly, the simulation was run for one year. Secondly, the HAMT algorithm in EnergyPlus calculates the surface conditions using the coupled heat and moisture conditions across the wall assembly instead of heat transfer only. Thirdly, construction details, such as the number of building materials that form the building fabric, and the properties of each building material have substantial influence on the simulation time.

In the context of building performance simulation, there was an opportunity to reduce the computing time. This is due to the fact that Malaysia lies slightly above the equator, thus having a consistent hot and humid climate. Unlike countries that have annual four seasons which may be necessary to record the climatic changes for a full year, Malaysia only have dry and rainy seasons. The diurnal outdoor temperature difference does not vary significantly and outdoor temperature, as well as the outdoor relative humidity, is constant for the whole year, as were shown in **Figures 5.3** and **5.4**. Due to these flat climatic conditions, the building performance can be evaluated for one month instead of twelve months.

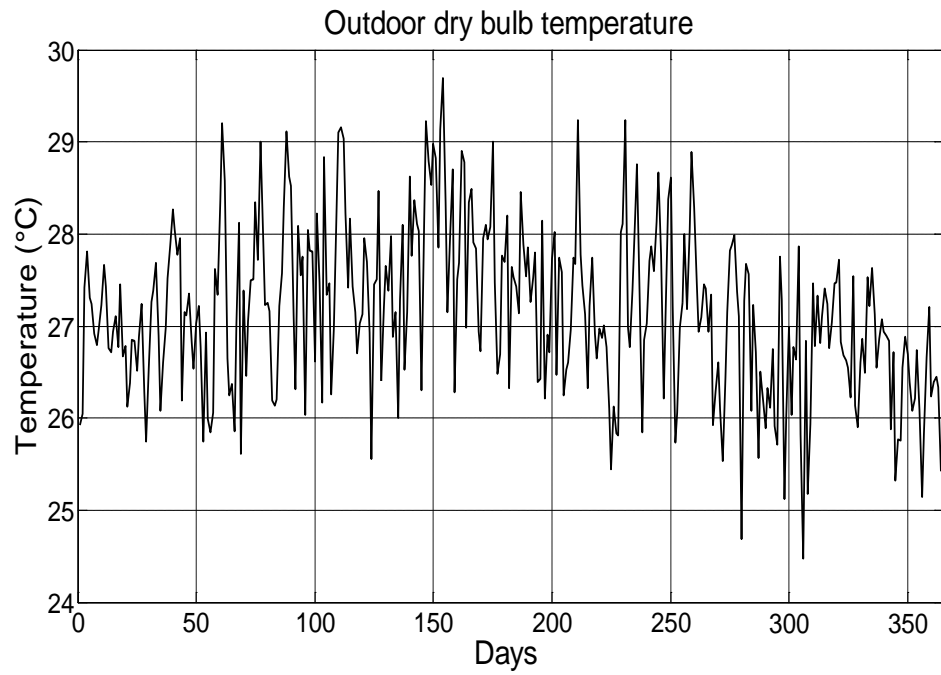


Figure 5.3: Annual outdoor dry bulb temperature for Kuala Lumpur.

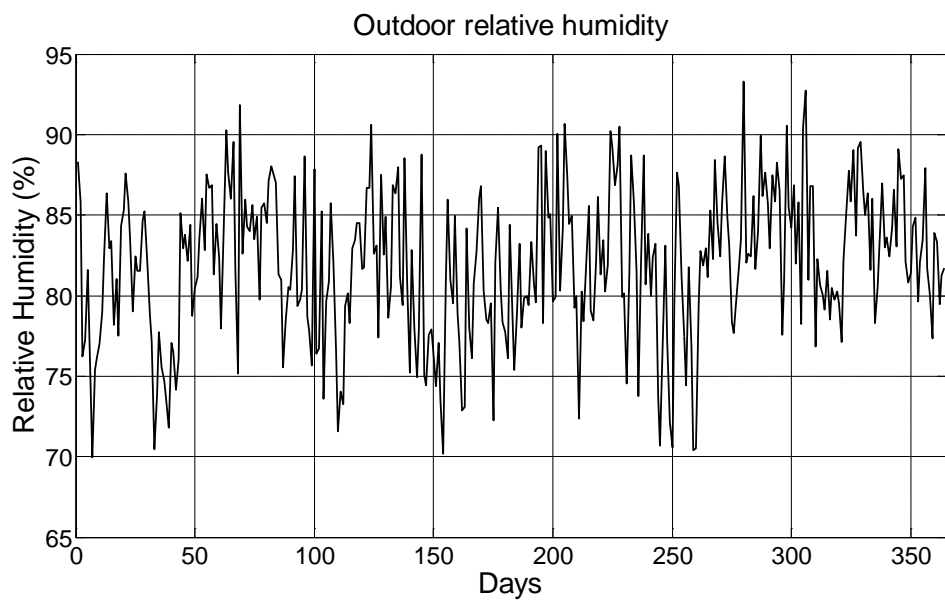


Figure 5.4: Annual outdoor relative humidity for Kuala Lumpur.

5.2.2 Comparison between Annual and Monthly Simulation

One way to confirm whether a one month simulation was more suitable was by comparing the surface temperature and relative humidity data points from a random monthly simulation with the corresponding month from an annual simulation. This was to verify whether the results were identical. Hourly data for outdoor conditions and external wall surface from March, June, September, and December were selected for comparison. The results were shown in **Figures 5.5, 5.6, 5.7 and 5.8.**

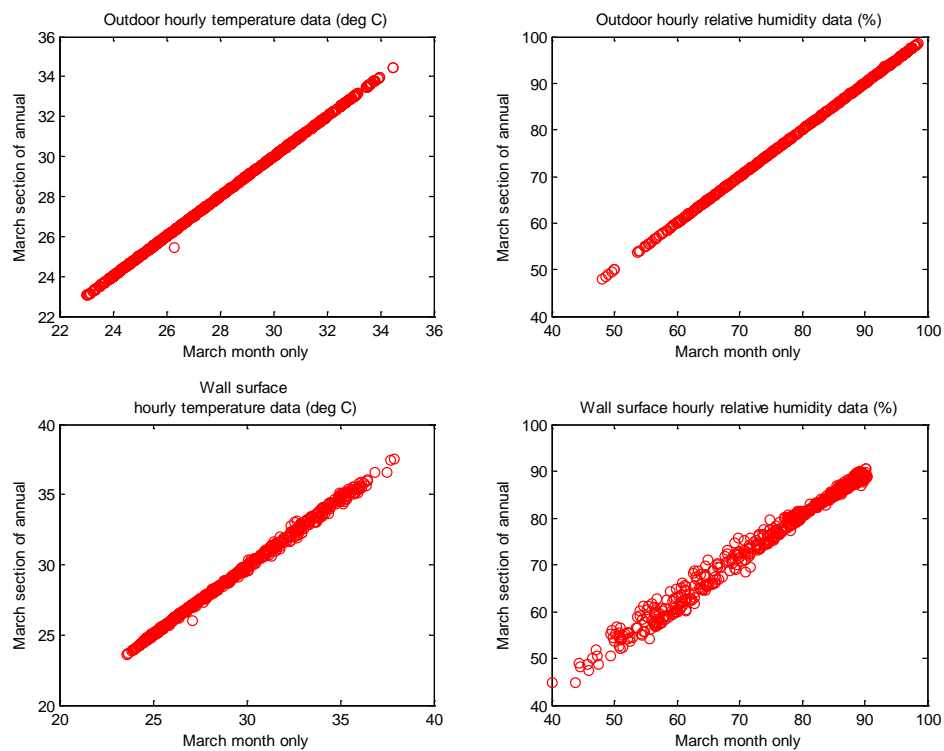


Figure 5.5: March hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions.

It is noted that there is spread in the linear plots for the wall surface conditions. The moisture and heat storage capabilities of building materials may have some influence on the time constant in the heat and moisture transfer. Therefore, simulated conditions for one month did not seem to represent that of the whole year since the monthly surface conditions had different time constant from that of corresponding monthly sections of the annual simulation.

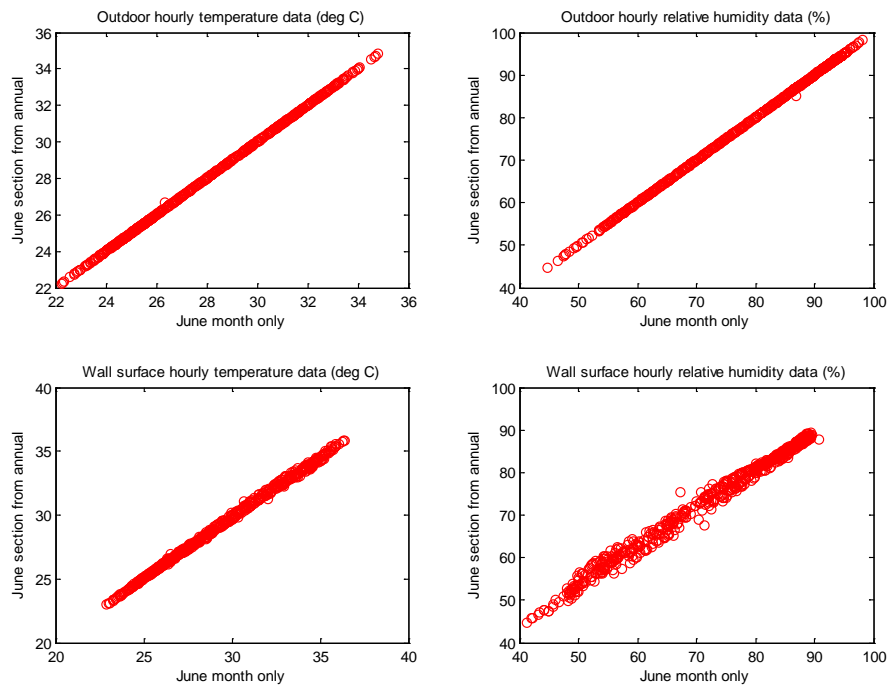


Figure 5.6: June hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions.

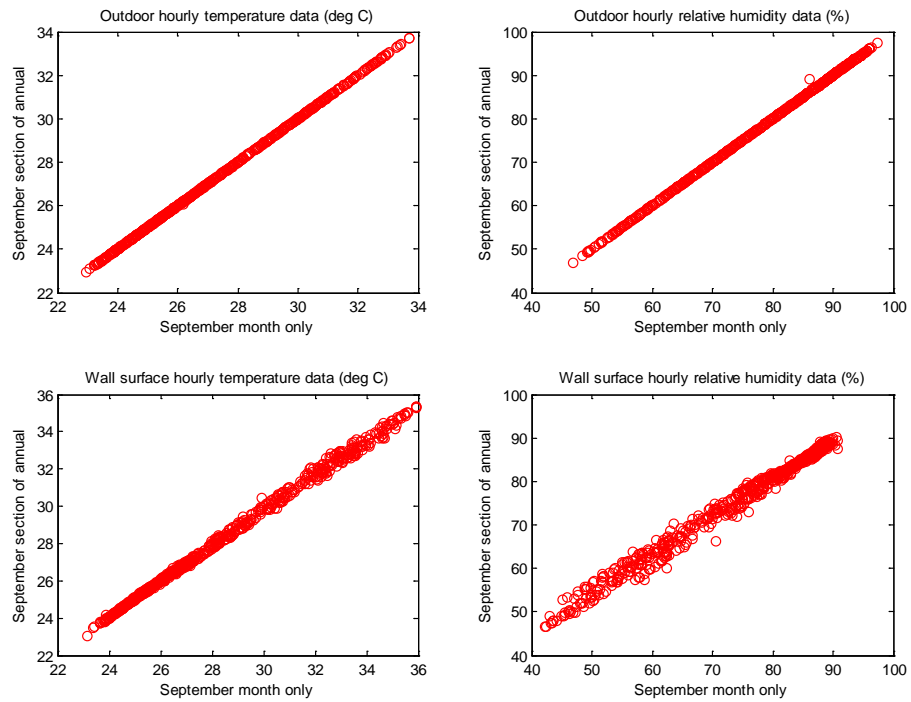


Figure 5.7: September hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions.

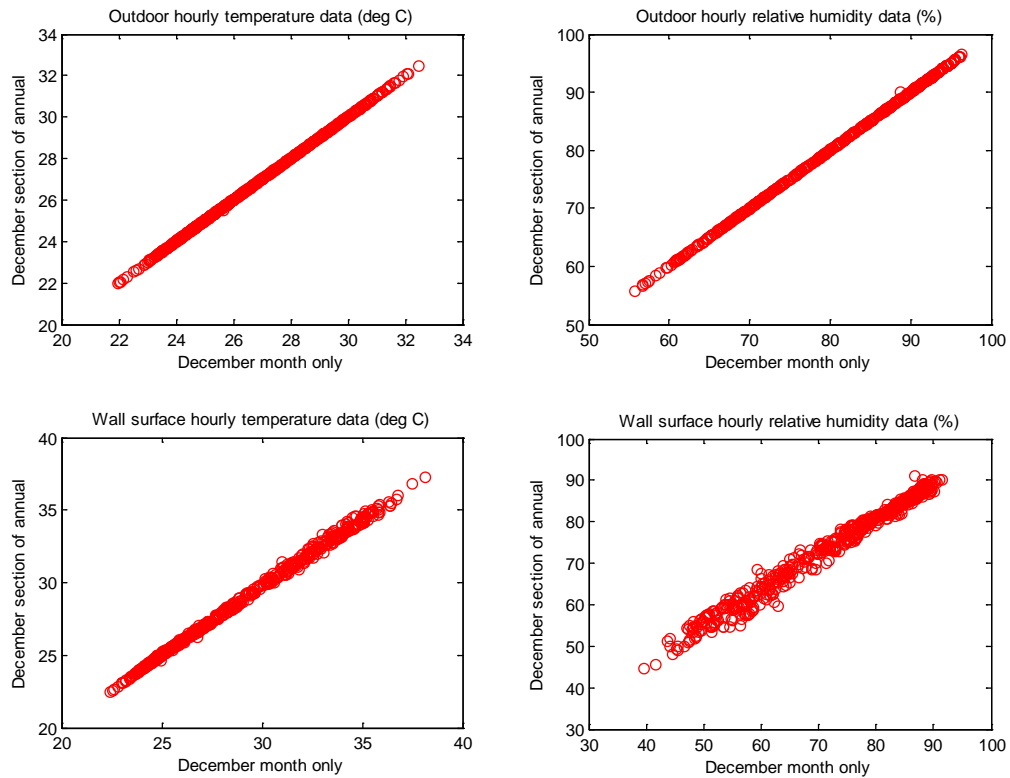


Figure 5.8: December hourly data comparison between monthly (x-axis) and annual simulation (y-axis) for outdoor and external wall surface conditions.

The initial impression from the results was the conditions were almost identical to each other. However, closer observation revealed presence of an outlier for the outdoor conditions, which was due to the difference in outdoor temperature and relative humidity on the first hour of the first day of the month. Further investigation revealed that the anomalies consistently occurred on the first hour of the first day for all the selected months.

Looking at the results for the external wall surface, the data points did not match. The errors seem to be present during the whole month. As explained earlier, a possible explanation could be that the moisture and heat storage capabilities of building materials may have some influence on the time constant in the heat and moisture transfer. The information on the time constant that would have been

captured in an annual simulation might have been lost from the monthly simulation. Therefore, simulated conditions for one month did not seem to represent that of the whole year since the monthly surface conditions had different time constant from that of corresponding monthly sections of the annual simulation.

A compromise was reached where the objective was to run an annual simulation for all the surfaces and to observe the point at which the surfaces reached stable condition. The results were shown in **Figures 5.9**, and **5.10**.

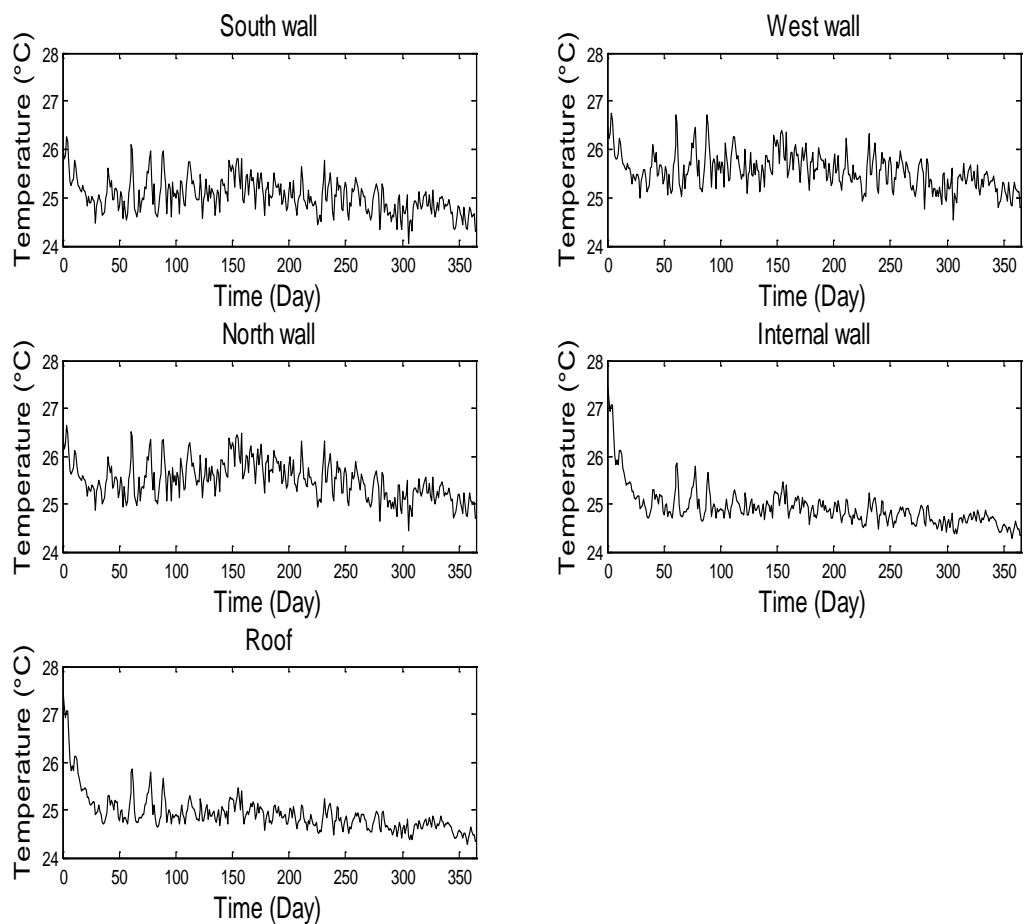


Figure 5.9: Annual surface temperature for single-walled Isolation Room.

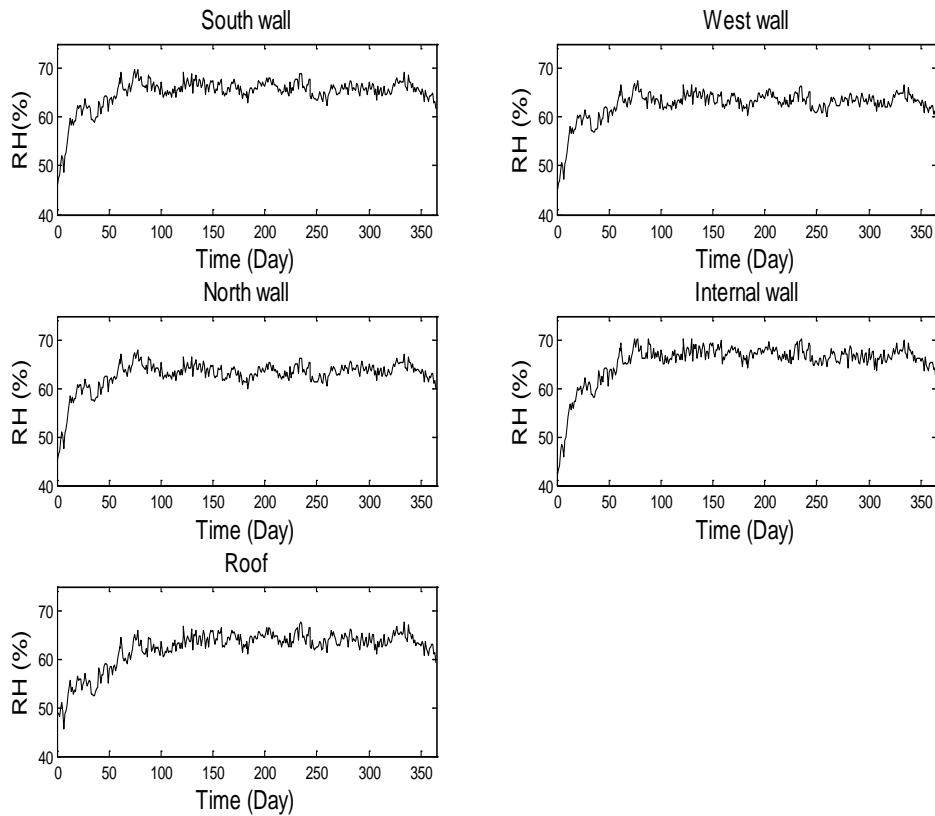


Figure 5.10: Annual surface relative humidity (RH_{surface}) for single-walled Isolation Room.

From the annual simulation results for all the surfaces, it was observed that the surfaces took a very long time to achieve stability until after about 100 days of operation, which was in early April. Therefore, between reducing computing time and selecting the period of which conditions most represent that for the whole year due to the time-constant of the building construction, the simulation must be run for 4 months, with the performances assessment being based on the last month.

5.2.3 Summary

Justification on using shorter periods rather than annual simulation was given on the grounds that the outside conditions in the hot and humid climate are constant at any month. It was observed that the building reached stability after 100 days of operation. It was

suggested that the simulation is run for over 4 months with the analysis being done on the final month.

5.3 Zone Performance for Benchmark Design

In this section, the performance of the benchmark case that represents normal design practice is evaluated based on the simulation output and the surface conditions were analysed using the extended mould growth model by Sedlbauer (2001). The simulation also includes parameters like infiltration and window openings by occupants.

5.3.1 Single-walled Isolation Room

A single wall construction is based on an upgraded isolation room for the Intensive Care Unit (ICU) suite in Kuala Lumpur General Hospital. The wall construction starting from outside layer to inside layer were 20 mm cement plaster, 110 mm thick brick wall, and 20 mm cement plaster, shown in **Figure 5.11**. Properties of building materials were obtained from generic materials database in the HAMT algorithm in EnergyPlus. However, the materials in the database were limited to six and more materials were obtained from the WUFI material database and from the study by Kunzel (1995). The mould growth risk analysis is then conducted using internal wall surface temperature and surface relative humidity (RH_{surface}).

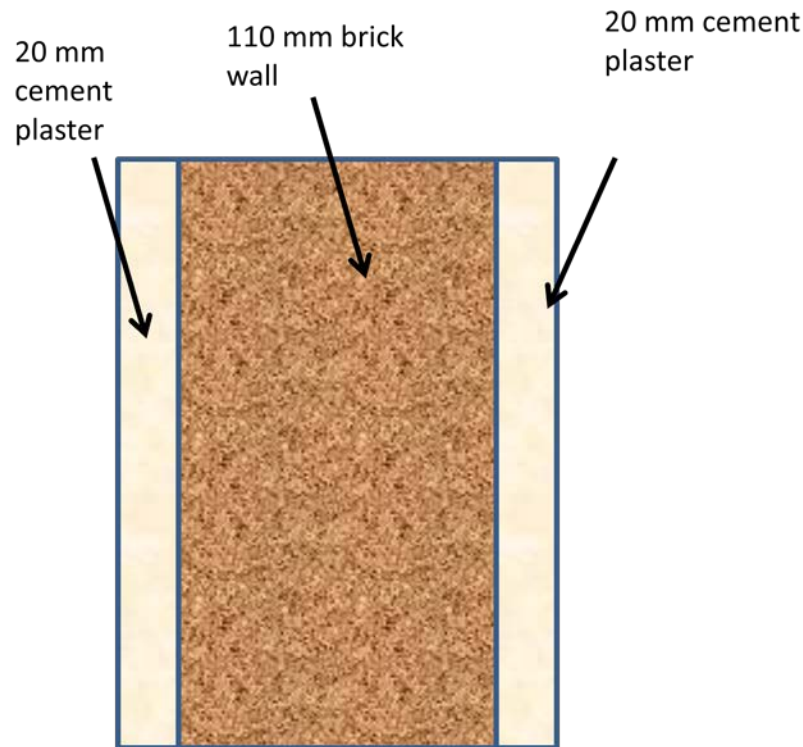


Figure 5.11: A single wall construction for benchmark design.

As a means of validating the normal design practice of isolation rooms in hot and humid climate like Malaysia, simulation runs are performed to evaluate the performance of a benchmark isolation room design. It is also important to include parameters in order to mimic as closely as possible the actual operation. The parameters include infiltration and user behaviour, specifically window opening. In the context of infiltration, it is assumed that there are small cracks in the building structures, such as cracks between window sill and the wall, or the structural openings like gaps between doors and the floorings. The infiltration used in this research is not calculated in full detail but is based on estimate with the air flow rate set at 0.6 h^{-1} (CIBSE Guide A, 2006).

Personal observation notes that occupant behaviour does have an influence on the indoor condition, and it needs to be included in the simulation. The opening of windows by occupants is simulated using the schedule during which the window of the isolation room is open for a number of hours in a day. It is difficult to quantify the behaviour

to a schedule, but the study by Kubota *et al* (2009) could be used a guide, in which residential occupant open windows from 10.00 a.m. to 6.00 p.m. for daytime ventilation. The amount of air going into the room through the window is represented by the opening area of the window (1.08 m²) and it is assumed to be fully opened from 10.00 a.m. to 6.00 p.m.

5.3.2 Results of Indoor Conditions

The results for the room temperature, room relative humidity (RH_{room}) and the DX cooling coil total cooling energy were shown in **Figure 5.12**.

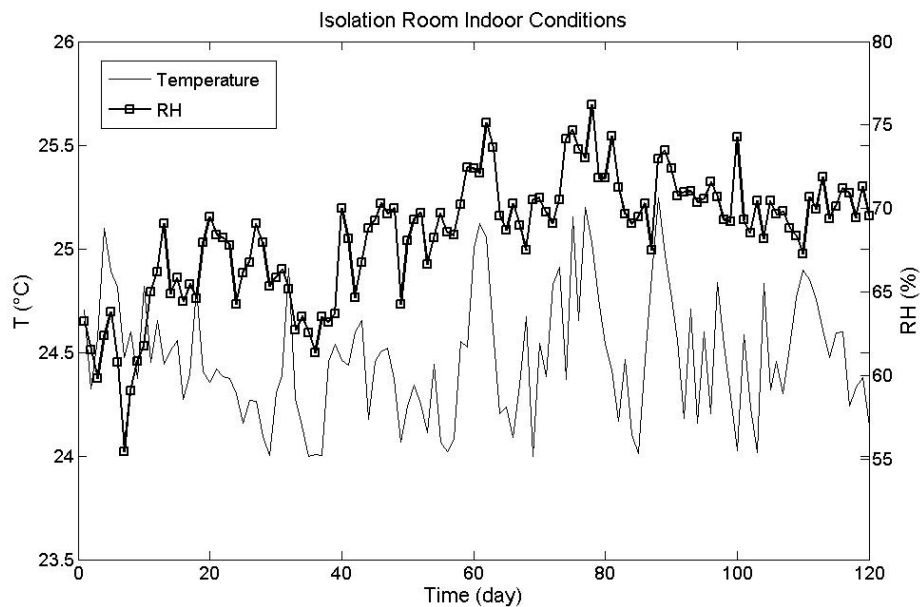


Figure 5.12: Indoor conditions for Benchmark design

The result in **Figure 5.12** showed that the HVAC system was able to maintain the room temperature within the maximum of 1°C. However, it was observed that there was a lack of ‘anti-phase’ relationship between the room temperature and RH_{room}. An explanation regarding this is that as time progressed, the moisture content inside the room increased. The walls of the isolation room have become charged with moisture and there was less potential for moisture coming out of the room air and going into the wall surface. As a result, the DX system was struggling to cope with maintaining

the room RH and room temperature. The system was not able to maintain the RH_{room} at design level of 50%, with a few occasions approaching 75%. The RH_{room} being above 70% may indicate a risk of mould growth on wall surfaces. The total cooling coil energy profile is shown in **Figure 5.13**, where the system is cooling and dehumidifying the supply air at maximum load.

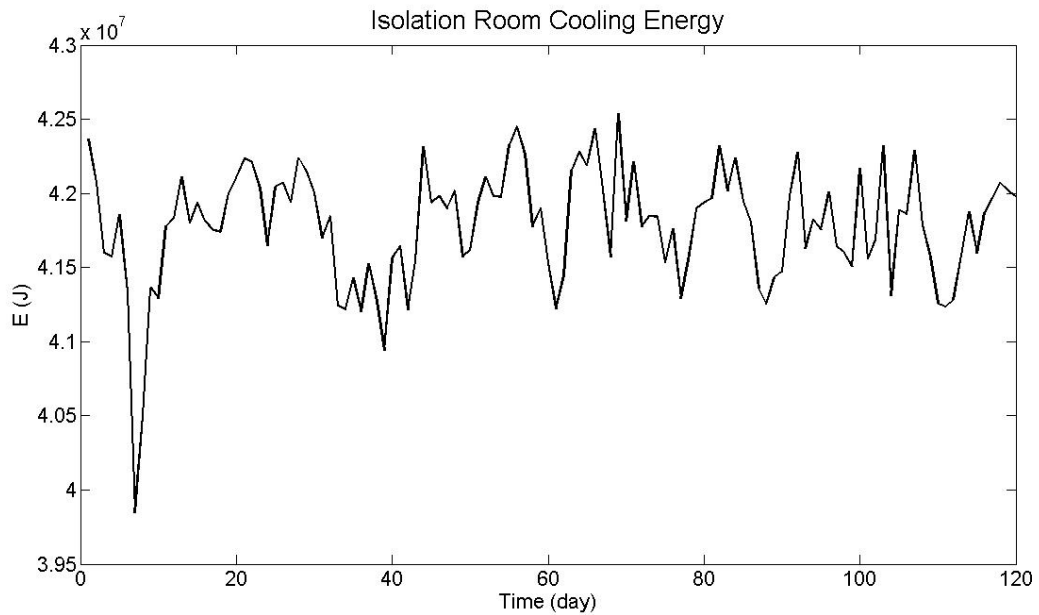


Figure 5.13: HVAC energy use for Single-Walled Isolation Room with conventional HVAC system

5.3.3 Results of Surface Temperature and RH_{surface}

To assess the probability of mould growth, the wall surfaces and the roof conditions were simulated and the results were shown in **Figures 5.14**, and **5.15**.

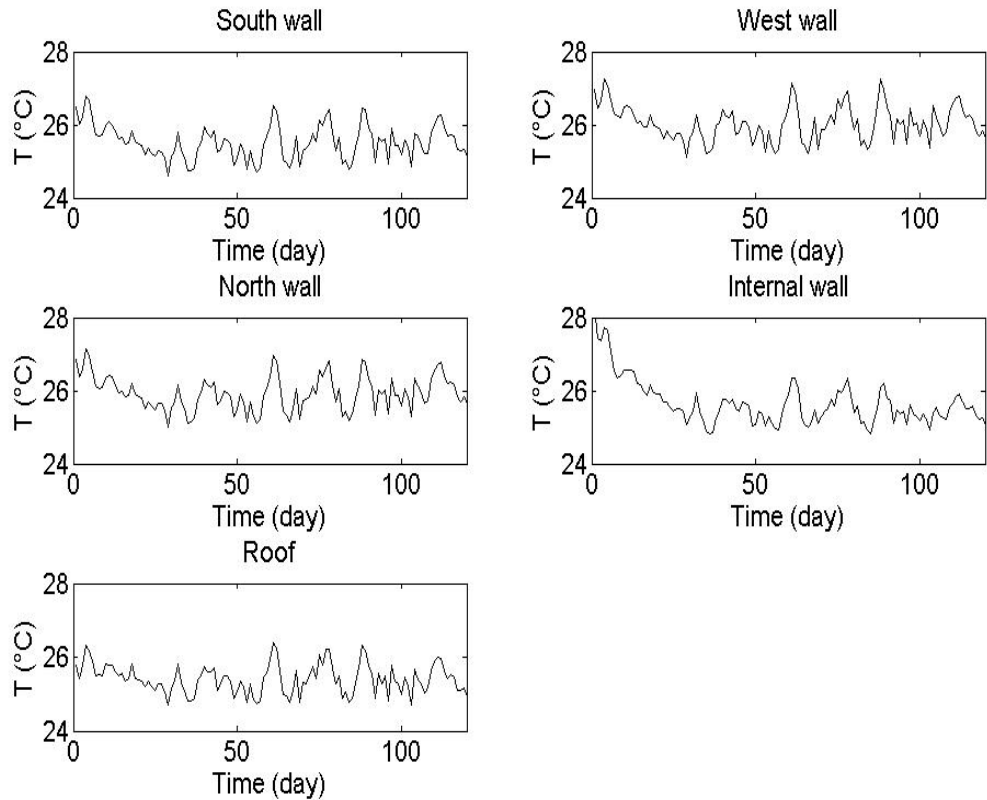


Figure 5.14: Wall surface temperatures for Benchmark design

The wall and roof internal surface temperatures were found to be slightly higher than the room temperature but the concern is on the surface RH_{surface} which is in the region of 70% and slightly above for a considerable time period; the consequence of high RH_{room} and the indoor moisture being absorbed by the internal surfaces.

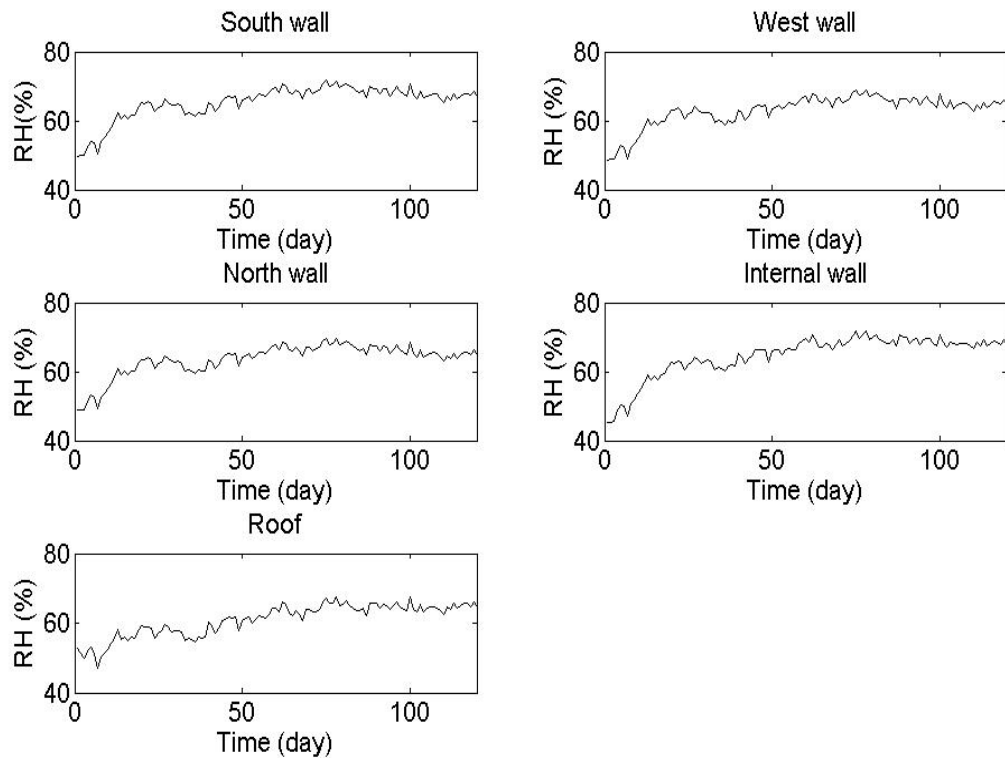


Figure 5.15: Wall surface relative humidity (RH_{surface}) for Benchmark design

To determine the measure of the risk of mould growth on any surface, the analysis was done on the wall and roof surfaces on the last month of the simulated period. The positive number indicates the surface condition being above the Lowest Isopleth for Mould (LIM) which may incur the risk of mould growth, while the negative sign indicates no likelihood of mould growth occurring. The results were as shown in **Table 5.1**.

Table 5.1: Measure of risk of mould growth on all surfaces for Benchmark Design

Wall				Roof
South	West	North	East (Internal)	
1.11	0.37	0.42	1.45	0.30

As a reminder, the measure of the mould growth risk is calculated by using the expressions (1), (2) and (3) in **Chapter 4**,

$$r_{growth} = \sum_{i=1}^n \frac{1}{(d_i \times 24)}, \quad \forall (d_i > 0) \quad (1)$$

$$r_{no\ growth} = \sum_{i=1}^n \frac{1}{(d_i \times 24)}, \quad \forall (d_i \leq 0) \quad (2)$$

$$Risk = \begin{cases} r_{growth} & (r_{growth} > 0) \\ r_{no\ growth} & (r_{growth} = 0) \end{cases} \quad (3)$$

Where n is 720 hours, corresponding to the 4 months simulation run period, and d_i is the time period for the mould growth limit curve. Taking the east (internal) wall as an example to illustrate the workings of the extended mould growth model, the measure of mould risk for the single-walled isolation room is calculated into the time taken for as,

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 1.45$$

and,

$$\frac{1}{d} \times 30 = 1.45$$

$$\therefore d = 20.7 \text{ days}$$

The results in **Table 5.1** have shown that all the surfaces registered positive figures, meaning the surface conditions simulated are above the threshold mould growth limit curve. The higher the positive figures are, the less time it takes for the mould to grow on the surfaces. Since the limit isoline corresponds to the 30-day spore germination time, it is therefore, suggested that there is a measure of risk of mould growth on the surfaces, within that time period.

5.3.4 Double-walled Isolation Room

As a matter of comparison, the normal design practice with a double wall construction is simulated. This construction was based on an Accident and Emergency Block in Banting Hospital, located approximately 60 km from the capital of Kuala Lumpur. For the wall assembly, the layers from outside started with 20 mm cement plaster, followed with 110 mm thick brick wall, 25 mm fire proof PU foam, 110 mm brick wall, and 20 mm cement plaster, shown in **Figure 5.16**.

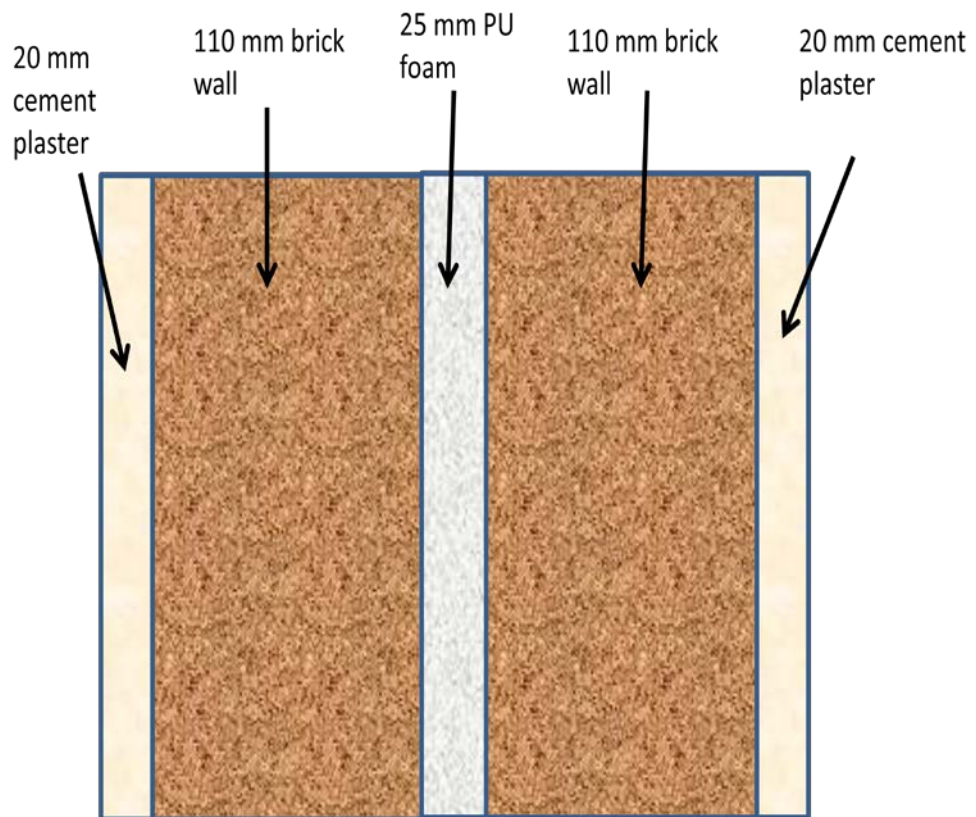


Figure 5.16: A double wall construction for benchmark design

The HVAC system is similar to the benchmark design, where 100% outside air is cooled and dehumidified to condition the isolation room and then is entirely exhausted to the outside environment. The room design condition was set at 24°C and 50% RH_{room} and no heat recovery is installed in the system.

5.3.5 Results of Indoor Conditions

The results for the room temperature, room relative humidity and the DX cooling coil total cooling energy after simulation were shown in **Figures 5.17**.

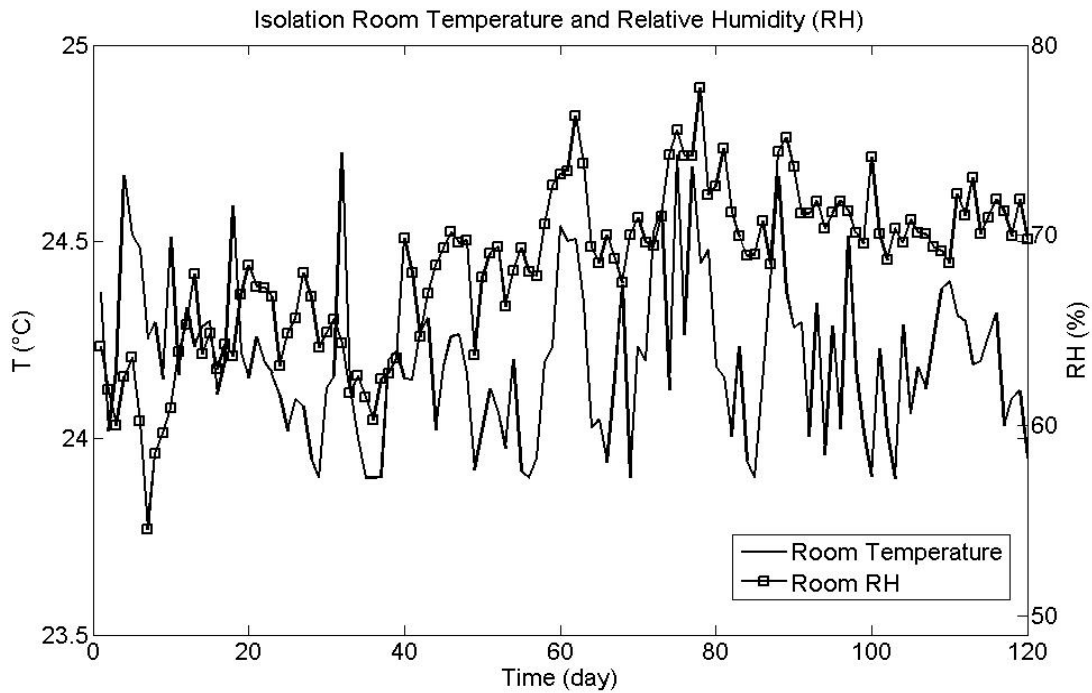


Figure 5.17: Room Conditions for Double-Walled Isolation Room

As with the benchmark design, the simulation results showed that the HVAC system was not able to maintain the design room relative humidity at 50%, with the room temperature maintained slightly higher than 24°C. The cooling coil energy was similar to that of the benchmark design, indicating it was operating at maximum capacity and still not sufficient to remove moisture from outside air continuously, as is shown in **Figure 5.18**.

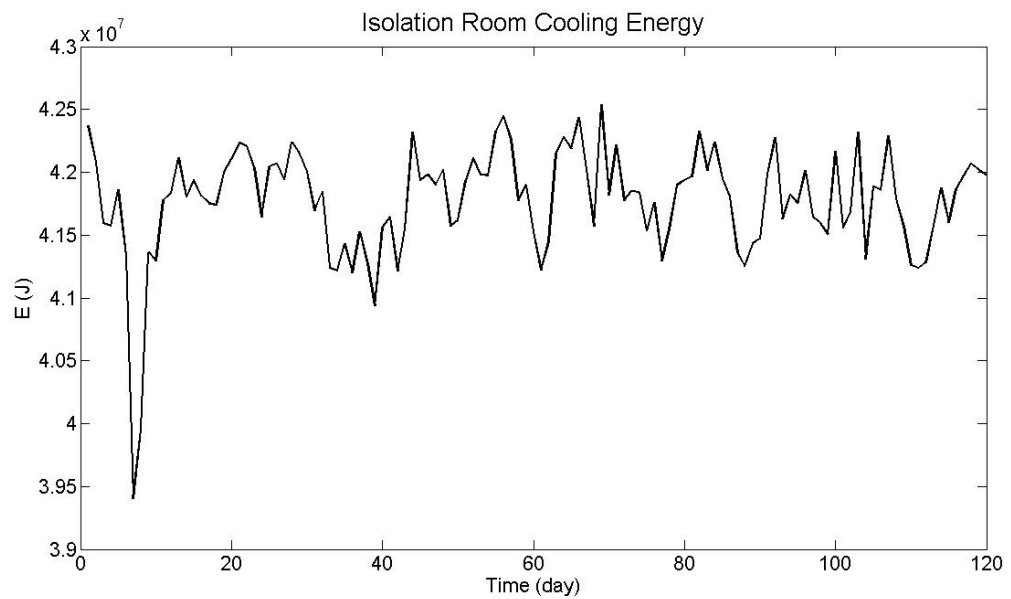


Figure 5.18: HVAC energy use for Double-Walled Isolation Room with conventional HVAC system

5.3.6 Results of Surface Temperature and RH_{surface}

To assess the measure of risk of mould growth, the wall surfaces and the roof conditions were simulated and the results were shown in **Figures 5.19**, and **5.20**.

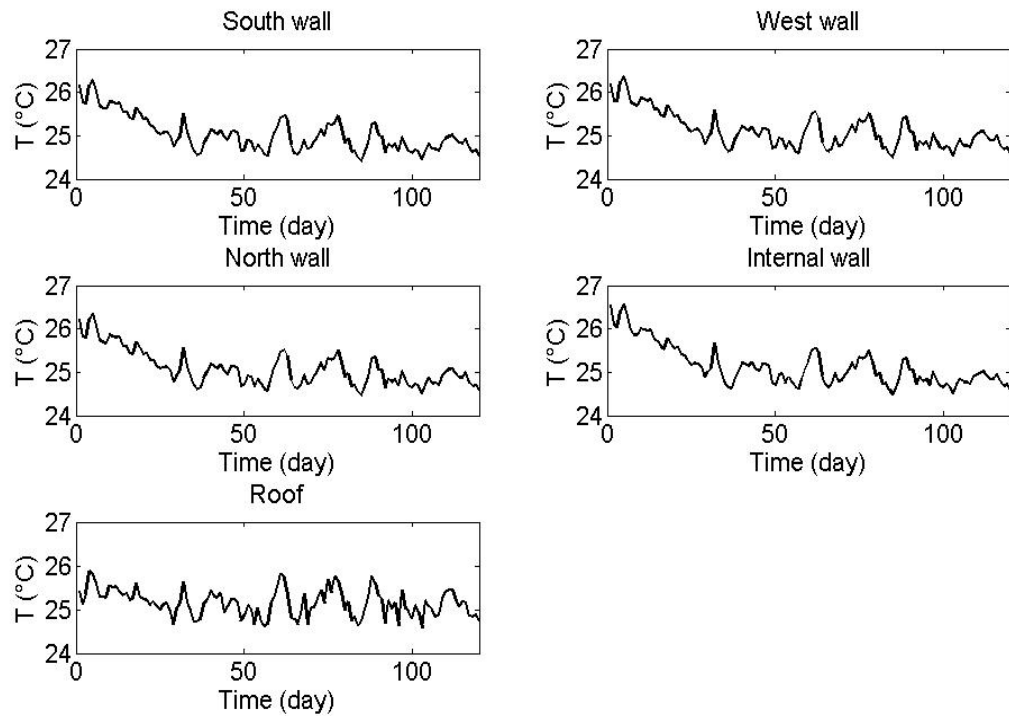


Figure 5.19: Wall surface temperatures for Double-Walled Isolation Room

As can be seen in **Figure 5.19**, the wall surface conditions started to stabilise after approximately 50 days of operation. However, the internal surface temperatures were only slightly higher than the room temperature. The surface RH results for the double-walled construction were shown in **Figure 5.20**.

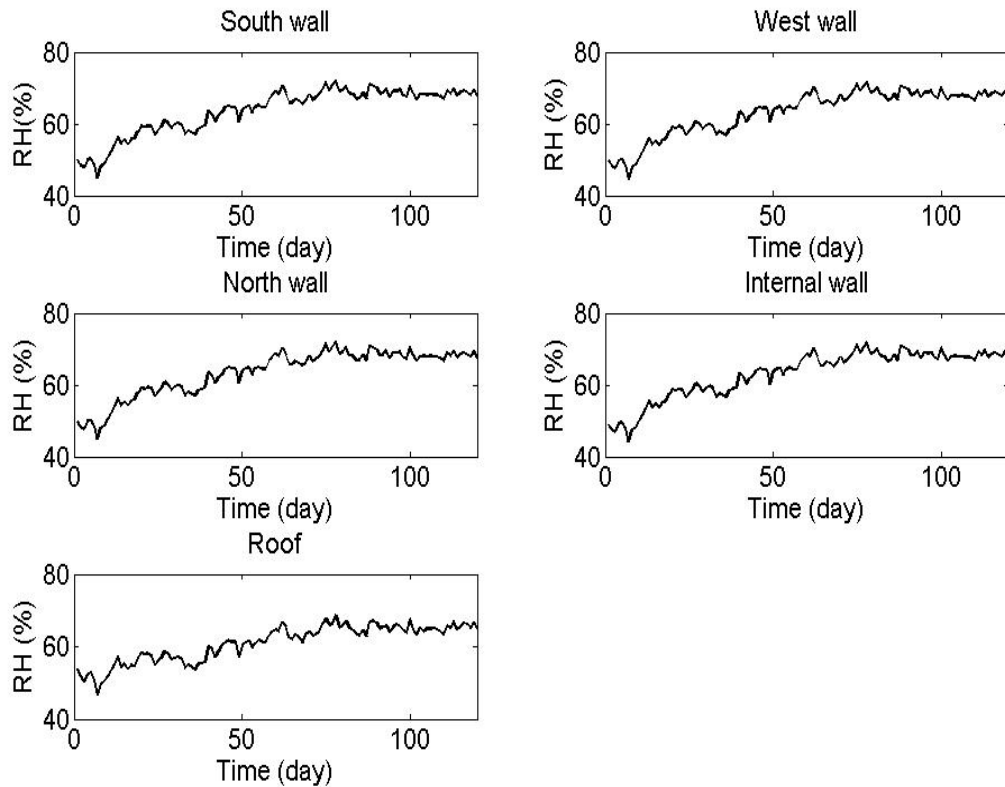


Figure 5.20: Wall surface relative humidity for double-walled Isolation Room

The results have shown that due to the HVAC system being unable to maintain control on the room RH which resulted in very high RH_{room} , The internal wall surfaces were also affected where very high $RH_{surface}$ were detected that may result in high likelihood of mould growing on the surface.

As with the analysis on the benchmark design, the mould growth risk analysis was done on the wall and roof surfaces on the last month of the simulated period. The results were as shown in **Table 5.2**.

Table 5.2: Measure of risk of mould growth on all surfaces for Double-walled Isolation Room

Wall				Roof
South	West	North	East (Internal)	
1.54	1.38	1.44	1.51	0.42

As with the single-walled version, the east wall is again taken as an example for the purpose of consistency. The measure of mould risk for the double-walled isolation room is calculated into the time taken as

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 1.51$$

and,

$$\frac{1}{d} \times 30 = 1.51$$

$$\therefore d = 19.9 \text{ days}$$

The results from **Figure 5.18** and **Table 5.2** have shown that all the surfaces registered high RH_{surface} and the mould risk are positive figures, indicating the simulated surface conditions were above the threshold mould growth limit curve. Since the limit curve corresponds to the 30-day spore germination time, it is therefore, suggested that there is a risk of mould growth on the surfaces, within that period.

Comparing the results for single wall construction (**Table 5.1**) against a double wall construction (**Table 5.2**) has shown that the risks of mould growth have risen for all the walls of the double-walled isolation room, with risks risen substantially for the walls on the west side (1.38 against 0.37) and north side (1.44 against 0.42). One explanation is the higher moisture diffusion inside the double wall, in terms of the ability of the construction layer to retain moisture at a

given time period, that may give rise to interstitial condensation. It also suggests due to the thickness of the double wall, the time taken for the double wall to dry up is more than 30 days.

5.3.7 Effect of re-setting zone set-point

In addition to opening windows to let fresh air into the room, occupants have been known to alter the temperature set-points to suit their thermal comfort level. More often the occupants change the temperature than the RH settings, since they were not as receptive to RH as to temperature (Skoog, 2004) and especially for the system that offers individual control, only the room temperature set-points are available for manipulation.

The effect of re-setting the room set-points on indoor conditions was simulated in EnergyPlus by amending the room temperature schedule in the input object. The set-point was reduced from 24°C to 19°C, based on the survey findings by Yau and Chew (2009) on thermal comfort of hospital staff in Malaysia. The impact of set-point change is investigated on both single-and double-walled isolation room with the conventional HVAC system. The room design condition was maintained at 24°C and 50% RH_{room}. The simulation results for the single-walled isolation room are shown in **Figures 5.21, 5.22, and 5.23**.

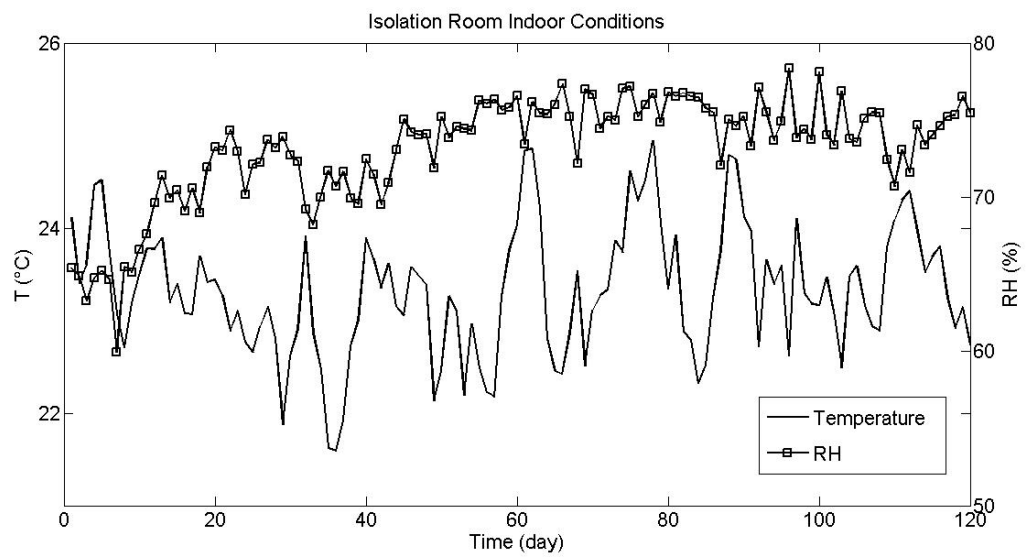


Figure 5.21: Indoor conditions for Single-Walled Isolation Room at 19°C set-point

The conventional system was found to be unable to maintain the indoor design conditions where the room RH fluctuated between 70 and 80% RH. Surface temperature profile for the single-walled case is shown in **Figure 5.20**.

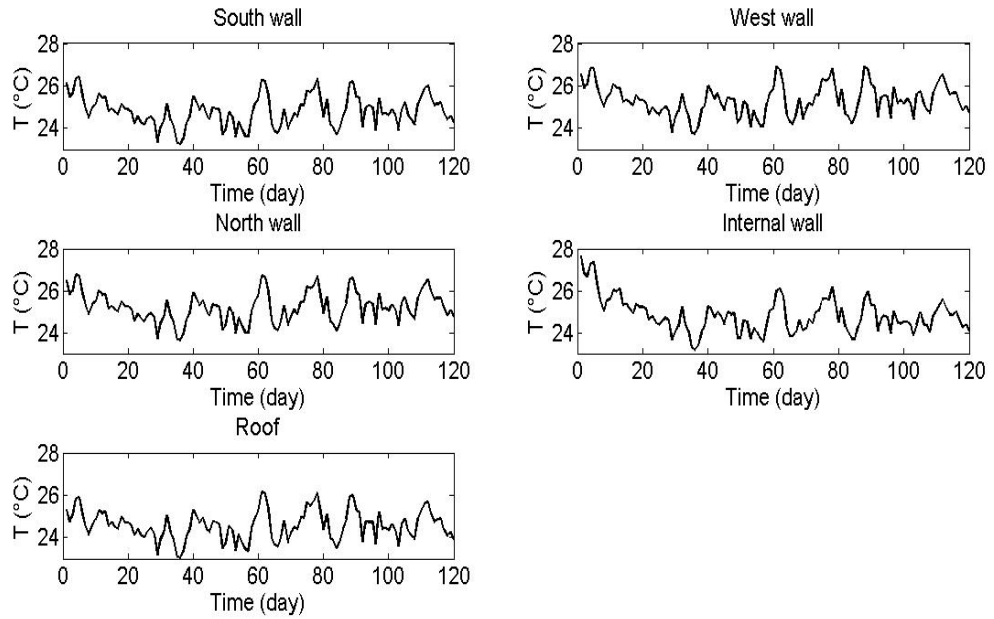


Figure 5.22: Surface temperature profiles for Single-Walled Isolation Room at 19°C set-point

The surface relative humidity profiles for the single-walled case are shown in **Figure 5.23**. The results for all internal surfaces implied the ‘wet’ conditions that may incur the risk of mould growth.

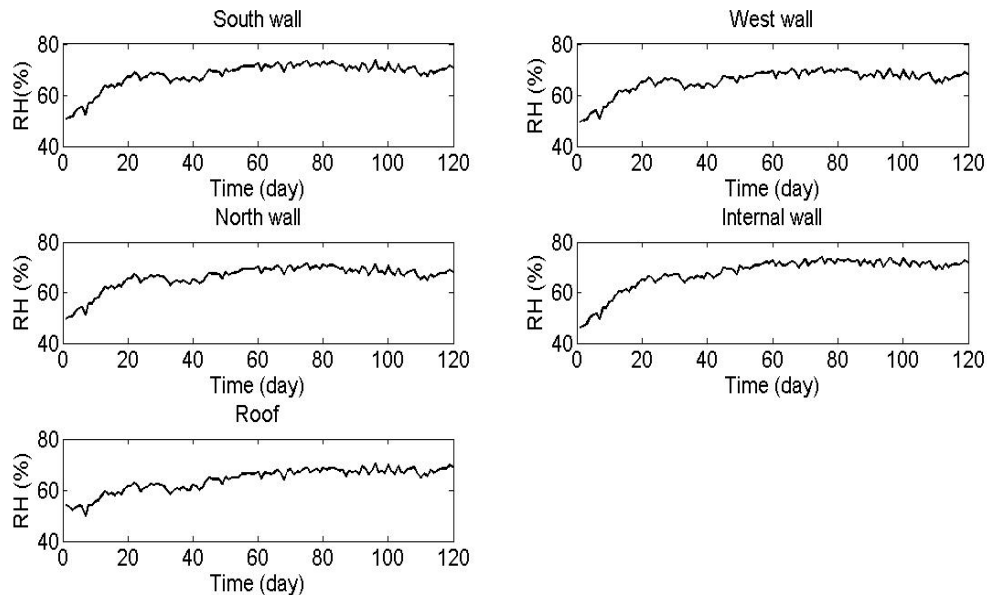


Figure 5.23: Surface relative humidity profiles for Single-Walled Isolation Room at 19°C set-point

The same mode of investigation is done on the double-walled isolation room with the conventional system to assess its performance. The indoor conditions profile for the double-walled isolation room is shown in **Figure 5.24**.

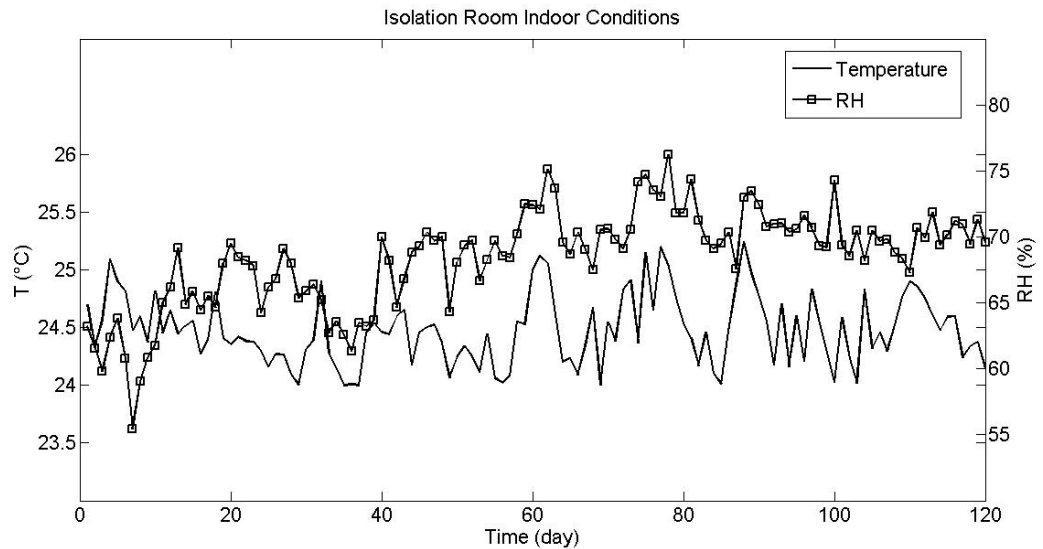


Figure 5.24: Indoor conditions of Double-Walled Isolation Room at 19°C set-point

The indoor conditions were substantially affected when the temperature set-point was reduced below the normal design practice of 24°C. The RH_{room} could not be maintained at 50%. This implied that the cooling coil is already operating at the maximum capacity in cooling and dehumidifying, as shown in **Figure 5.25**. There is also a possibility that the efficiency of the cooling coil has dropped and is not able to remove the moisture from the supply air.

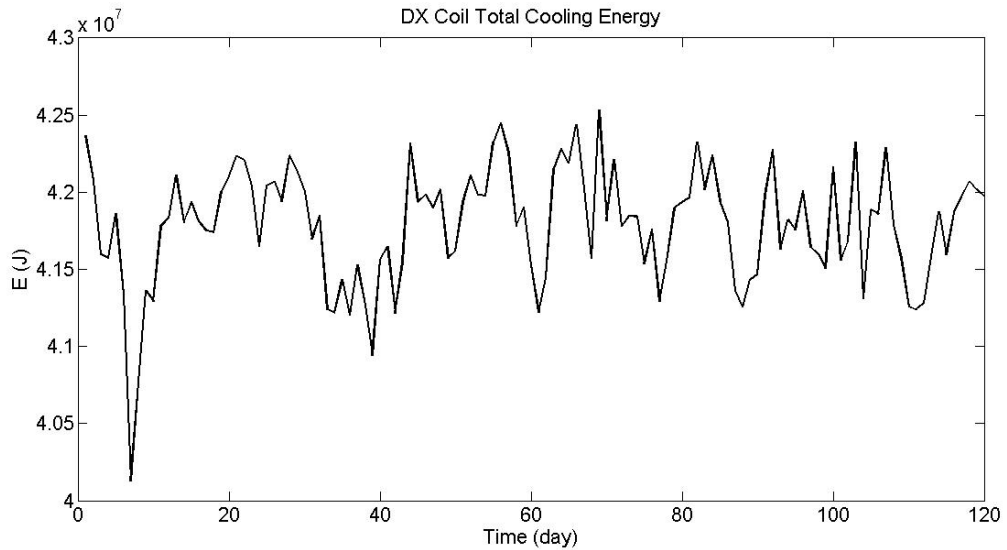


Figure 5.25: HVAC energy consumption for Double-Walled Isolation Room at 19°C set-point

The surface conditions of all the internal walls and roof are shown in **Figures 5.26 and 5.27**.

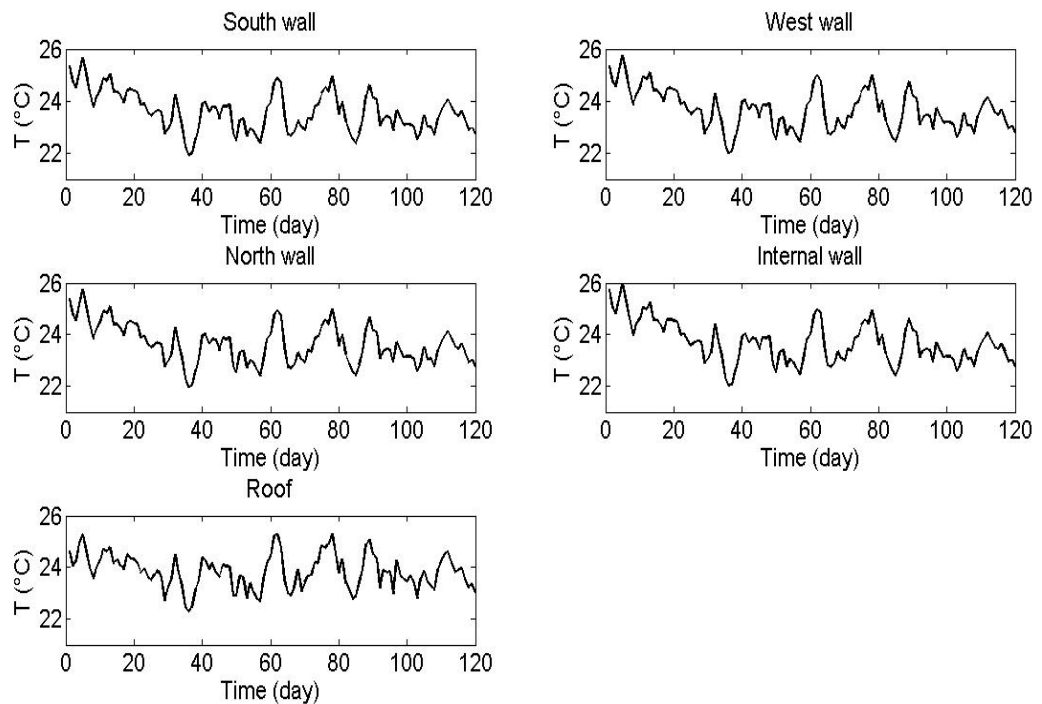


Figure 5.26: Surface Temperature for Double-Walled Isolation Room at 19°C Set-Point

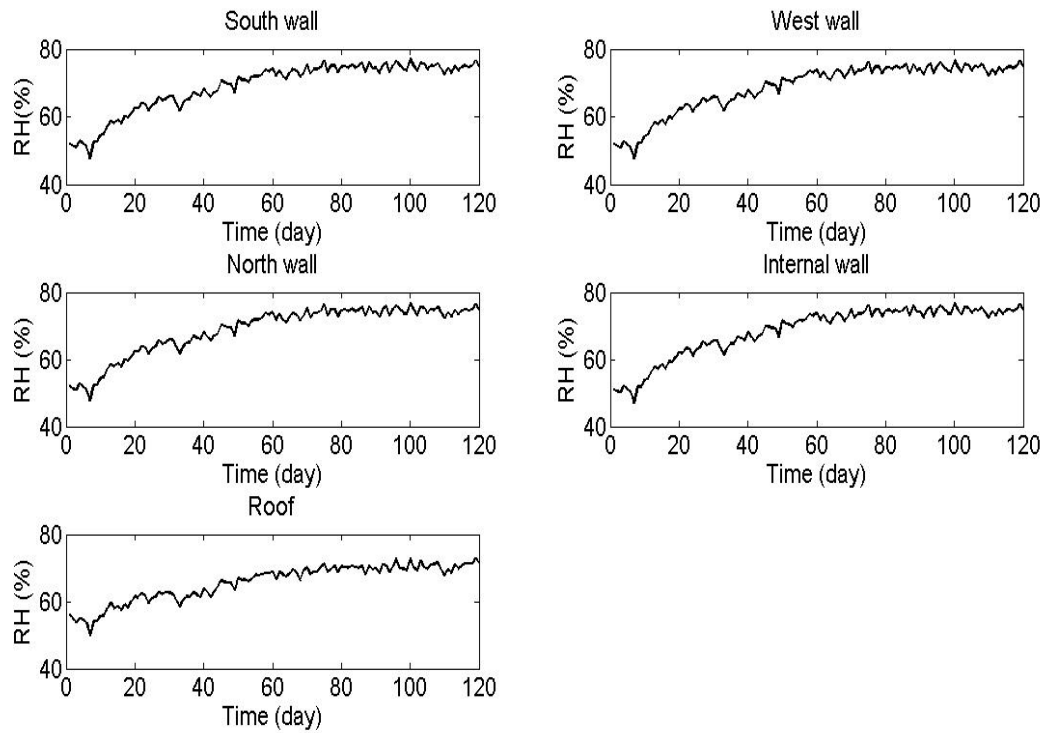


Figure 5.27: Surface Relative Humidity for Double-Walled Isolation Room at 19°C Set-Point

The results indicated that re-setting the room temperature set-point lower than the design temperature without manipulation of RH_{room} set-point resulted in both the room temperature and the room RH going above the design limit.

The mould growth risk analysis was then conducted to verify whether high surface RH on the walls and roof would lead to mould growth over time. The comparison of results is shown in **Table 5.3**.

Table 5.3: Comparisons of the measure of mould growth risk on internal surfaces for Single-Walled and Double-Walled Isolation Room at 19°C set-point.

Wall Type	Orientation				Roof
	South	West	North	East (Internal)	
Single	2.27	0.94	1.03	3.23	0.82
Double	6.69	6.20	6.40	6.58	1.83

To explain the comparison, it is important to remember that the index number has a normal limit of 1.0 since above this value mould growth is deemed to have started. In this case however, no such limit applies when the index number is used to represent the risk of mould growth since the measure of risk must vary with all the surface conditions. The results implied that the internal surfaces were getting damper with the lowering of the room temperature set-points. The time taken for mould to grow on the east side of the single-walled surface is calculated as,

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 3.23$$

and,

$$\frac{1}{d} \times 30 = 3.23$$

$$\therefore d = 9.3 \text{ days}$$

Whereas, the time taken for mould to grow on the east side of the double-walled surface is calculated as,

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 6.58$$

and,

$$\frac{1}{d} \times 30 = 6.58$$

$$\therefore d = 4.5 \text{ days}$$

The inference that can be taken from the comparison was that the bigger the measure of risk is (values getting bigger than 1.0), the further up the surface conditions lie above the limit isoline. This means the germination time (time taken for the mould to begin growth from spores and develops its own spores) is also shorter.

The mould growth analysis showed that risks of mould growth occurring were higher with the reduction of zone set-points. One probable explanation was that at the 19°C room set-point, the cooling coil surface temperature was reduced to the point below the dew-point of the supply air. This may result in the cooling coil freezes. Therefore, the moisture contained in the outside air that was supposed to be removed was passed through the freezing cooling coil into the room. The moisture is in turn absorbed by the porous wall surface and induces germination of ubiquitous mould spores.

5.3.8 Discussion

The normal design practice following the design standards and guidelines should result in the room design condition maintained correctly and, in achieving that, mould growth on wall surface is unlikely to occur. However, the simulation results suggested that the design objective was not met, which could be attributed to a number of factors.

One factor to consider was the references used in the design itself. The guidelines, such as the ASHRAE Guideline used for heat load calculation and equipment selection, were created mainly for the western countries that have seasonal climates. The temperature variations and especially ambient relative humidity are substantially different compared to tropical countries like Malaysia.

Another factor is the differences between what was calculated manually and what was calculated in EnergyPlus. In the manual heat load calculation, the total DX cooling capacity for the isolation room was 12,661.9 Watt (3.6 Refrigeration Ton) and the heating capacity was 570 Watt. The calculated air flow rate was 0.2005163 m³/s (424.87 cubic feet per minute (cfm)). The flow rate per watt of rated cooling capacity was 1.5836×10^{-5} m³/s/Watt (118.02 cfm/ton).

However, these calculated figures could not be verified using EnergyPlus, where the usage of the figures has resulted in errors before the simulation started. This is due to the fact that the

calculated figure flow rate per watt of rated cooling capacity was outside what is permissible for DX system in EnergyPlus.

In the EnergyPlus, the permissible rated volumetric air flow was between $4.027 \times 10^5 \text{ m}^3/\text{s}$ and $6.041 \times 10^5 \text{ m}^3/\text{s}$ per Watt of rated total cooling capacity (300 – 450 cfm/ton). The rated conditions are considered to be air entering the cooling coil at 26.7°C dry bulb/19.4°C wet bulb and air entering the outdoor condenser coil at 35°C drybulb/23.9°C wet bulb.

This range is effective on the assumption that the recirculation of air is taking place. If a user defines the constant air flow rate to be at 12 h^{-1} , the EnergyPlus adjusts the total cooling capacity and the sensible heat ratio in order to place the air flow rate per total cooling capacity within the specified range. An error will be given if the flow rate per total cooling calculated is out of this range. This leads to the suggestion that the air flow must be increased, or the cooling capacity must be reduced for the simulation to run successfully.

The specified operating range was based on studies on the impact of low evaporator air flow rate on the direct expansion (DX) cooling coil performance. Studies by Parker et al (1997) and Palani *et al* (1992) have shown that cooling capacity and latent capacity dropped rapidly when the evaporator flow rate was reduced below 200 cfm/ton. This leads to coil icing and shortened compressor life. The effective range of the flow rate per rated cooling for DX system in the EnergyPlus is between 300 cfm/ton to 450 cfm/ton. However, the resultant flow rate per rated cooling based on manual heat load calculation for typical design practice was 118.02 cfm/ton, which was substantially below the effective operating range of a DX cooling coil.

Another explanation is the differences between manual heat load calculation and the parameters defined in EnergyPlus before simulations are run. Taking into consideration the solar heat gain and transmission heat gain through window glass, roof, external walls as well as transmission heat gain through surfaces inside the

building zone such as wall partition or ceiling. The heat load component is calculated from the square area of the surfaces with the temperature difference between outside air and the design room air, multiplying with the specific load factors (storage load factors for walls, window shade factor) and transmission coefficients. Various weights of the construction material lead to selection of different load factors. There is no component of this type in EnergyPlus.

Outdoor design condition selected for the normal practice in Malaysia is based on a maximum design day with 35°C dry bulb temperature and 60% relative humidity. The room design condition of 24°C temperature and 50% relative humidity is based on the ASHRAE Guidelines for healthcare facilities. The heat load calculation selects the maximum value of the day and not the average values that are representative Malaysian climate.

The heat load calculation does not take into account the conditions at night-time and assumes that the ambient condition is constant throughout the day. The latent load that comes from infiltration from doors, windows and/or surface cracks was not considered in the heat load calculation. The need for the indoor condition to be continuously maintained at 24°C room temperature, and 50% RH at very high outside air flow rate of 12 h⁻¹ without considering the high outdoor humidity which is characteristic of a hot and humid climate, meant the DX cooling coil was unable to entirely remove moisture from the outdoor air.

A question arises from the fact that the time taken for mould to grow on the internal surface for double wall construction is slightly shorter than that for the single wall construction. A possible scenario is the moisture transfer across the double wall takes longer. There is time delay across the internal brick wall and the insulation. This scenario is more obvious in double-walled compared with single-walled construction. The interstitial condensation occurs inside the double wall as a consequence of extra number of construction layers.

The internal surfaces for both the single- and double-walled constructions have inadequate drying time since the surface RH was above the limit of 70% for most of the time. The consequence of not putting vapour barrier at the outermost layer of wall assembly resulted in the ingress of high moisture content from outside environment through the building envelope-either condensed inside the wall assembly or absorbed by the internal wallpaper.

The element of user behaviour in the form of scheduled opened windows was introduced into the simulation as a means to reflect the real world situation and assess its impact on the performance of the isolation room, particularly the reliability of the HVAC system in maintaining the indoor design conditions-the results have shown for both the single- and double-walled isolation room that the conventional system was not able to maintain the room RH even though operating at maximum capacity.

Another telling feature of isolation room HVAC system design is the absence of energy recovery mechanism, with particular reference to the latent heat exchanger. This mechanism, particularly desiccant thermal wheel, is widely used in the operating theatre where this area requires very high air change rate of up to 30 h^{-1} , in which the high amount of moisture from the outside air is absorbed by the desiccant wheel then transferred into the exhaust air path to be taken out into the outside environment. This requirement is all the more critical in the hot and humid climate like Malaysia where the ambient conditions are more extreme compared to countries in temperate climate. Therefore, it is significant to note that the latent heat recovery is not considered in the heat load calculation and the equipment selection for isolation room HVAC system design.

Studies conducted in hospitals in Malaysia has shown that design criteria do not take into account local condition, and the building operation that is not in accordance with what has been designed for, can have a negative effect on a building. Thermal comfort study of

hospital workers by Yau and Chew (2009) gives a range of suitable comfort temperature that is higher than required in ASHRAE Standard 55. The study covered 4 hospitals in Malaysia and various departments. The suggestion from the study was that there is a need for a standard for tropical hospitals to satisfy the comfort level in the tropics without compromising the health and safety requirements. The overall RH observed in the survey was between 44% and 79% compared to between 30% to 60% as required by ASHRAE Standard (2003).

With respect to the impact of building operation on indoor environment, a study was undertaken by Khew *et al* (2007) regarding the mould growth issue in a 700-bed Malaysian hospital. Observations from walk-through exercise in the library, auditorium and the levels 2 and 3 have revealed the relative humidity (RH_{room}) in the mentioned areas was between 70 to 90% when the maximum design RH_{room} should have been 60%. This was due to the air-conditioning system operation not tailored to low occupancy requirement.

There is no documented observation or published study with regards to the environmental conditions of isolation rooms in Malaysia, or their performance, which makes validation of design practice difficult. Therefore, inference has to be made from simulation output and available publication regarding the HVAC system in tropical climates and studies on healthcare facilities in Malaysia. The inference is that DX coil performance in design practice will drop to a stage that may lead to the freezing of the coils and the shortening of compressor life. Since infiltration was not taken into account in the manual heat load calculation and the heat recovery mechanism excluded in the equipment selection stage, the implication was the room design RH was not maintained and may result in a probable risk of mould growth.

5.3.9 Summary

The simulation results for the benchmark case and the double-walled isolation room have shown that the room design condition based on normal practice was unable to maintain control on the zone conditions as expected. Furthermore, there were risks of mould growth occurring on the wall surfaces based on the mould growth risk analysis. The DX HVAC system cannot maintain the room condition with limited range of air flow rate per cooling capacity, below which will result in the deteriorating cooling coil efficiency. This problem was made worse by not adding heat recovery to improve the moisture removal from the outside air, and exacerbated by uncertainty elements such as infiltration due to structural defect or by user behaviour such as opening windows. The next section suggests an alternative to the benchmark design as a reference for simulation and optimisation.

5.4 Alternative Design and Operation Case

The results from section 5.2 have shown that the normal design practice of isolation room HVAC system design in the hot and humid climate, using standards or guidelines more suitable to cold and dry climates, was not able to achieve the indoor conditions it was designed for. In this section, an alternative design and operation that acts as a starting point to the optimisation process is proposed, with its performance simulated and compared against the conventional system.

5.4.1 Proposed Alternative Design and Operation

Following the inability of the conventional construction and HVAC system design to maintain the required indoor condition and to be energy-efficient, it is necessary to arrive at a solution that takes into account the harsh climatic condition and also able to fulfil the design objectives, namely reducing energy use and minimising the risk of mould growth. The proposed alternative design therefore is different from the normal practice with a number of attributes incorporated.

An enthalpy heat recovery mechanism is added to the HVAC system to maintain the design room relative humidity (RH_{room}). The feasibility of coupling the direct expansion air dehumidification system with heat recovery device is proven based on recent studies by Zhang (2006). Liang *et al* (2010) modelled and experimentally validated an independent DX-type system equipped with membrane –based total heat recovery used to provide fresh air ventilation for control of epidemic respiratory disease like Swine flu in hot and humid climate. Comparison was made between the novel system and a conventional DX system. The result revealed that the coefficient of performance for the novel system was 2.2 times higher than that of the conventional one.

The latent heat recovery is selected due to its ability to remove moisture and suitable in hot and humid climate more than the sensible heat recovery (Mandegari and Pahlavanzadeh, 2009). One advantage of using this device is the reduction in overall thermal load and downsizing of cooling capacity (Nobrega and Brum, 2009). With regards to latent effectiveness, different types give different figures, such as 0.85 for desiccant wheel, and 0.72 for membrane type heat exchanger (Zhang, 2006).

Initial examination of the alternative design and operation was performed to evaluate its performance in maintaining the room design condition set at 24°C and 50% RH_{room} , and the DX coil cooling capacity. The latent heat recovery effectiveness of 0.72 is also incorporated. The simulation was run for four months in order to stabilise the indoor conditions. The results were shown in **Figure 5.28**.

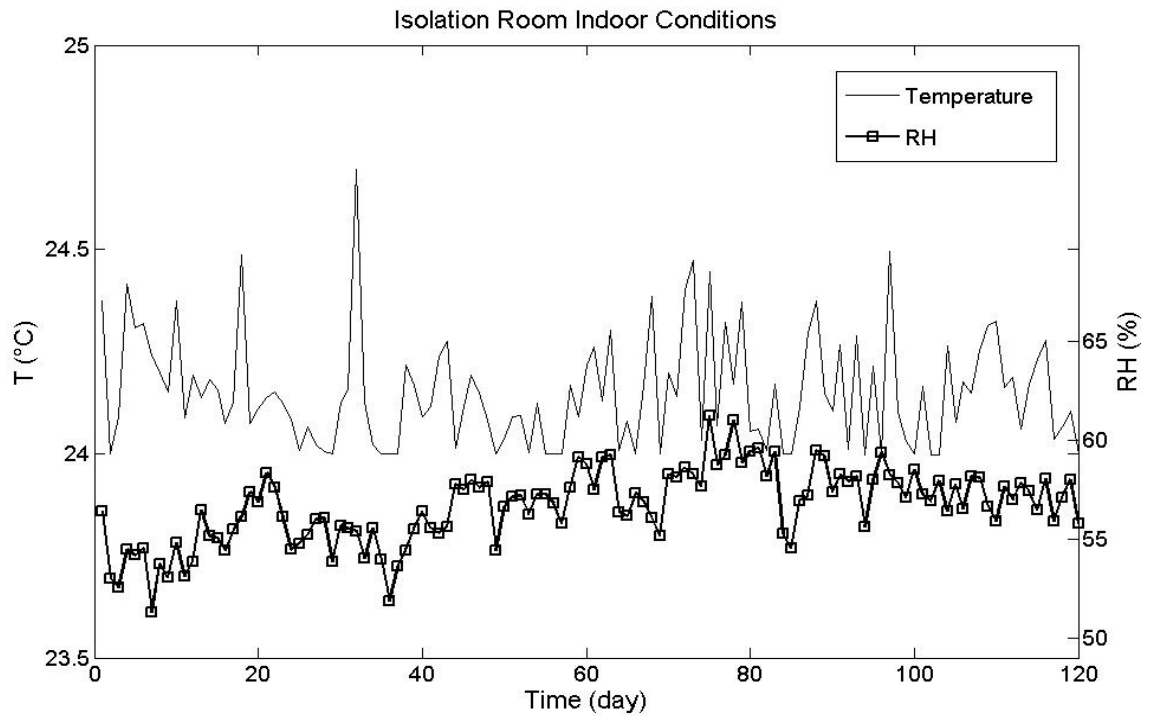


Figure 5.28: Indoor Conditions for Alternative design

The results indicated that incorporating heat recovery mechanism, in this case the latent heat recovery, has improved the room temperature and room relative humidity to design conditions. The DX coil total cooling energy was reduced substantially with less moisture to remove from the outside air by the cooling coil.

The annual simulation results of the surface temperature and relative humidity for inside surfaces of the south wall, west wall, north wall, the internal wall, and the roof of the alternative case are shown in **Figures 5.29** and **5.30**.

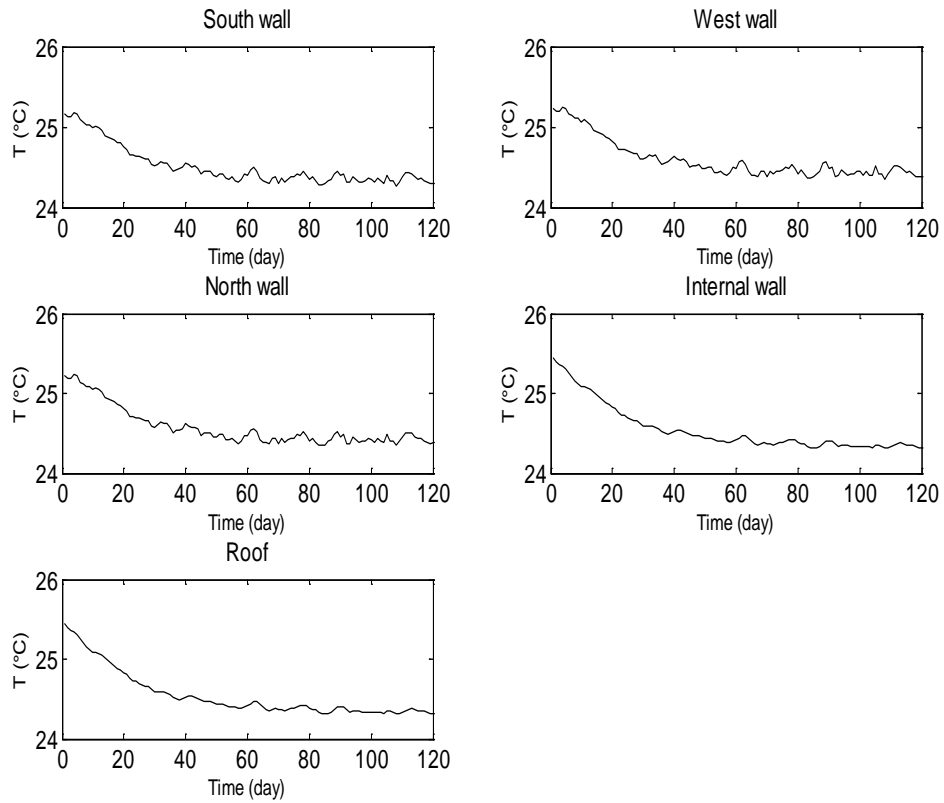


Figure 5.29: Surface temperature for alternative design

The surface room temperature was gradually decreasing towards 24°C and the surface relative humidity was gradually increasing until it achieved stability at below 50%. Based on the results for all the internal surfaces, an inference can be made that mould growth is unlikely to occur.

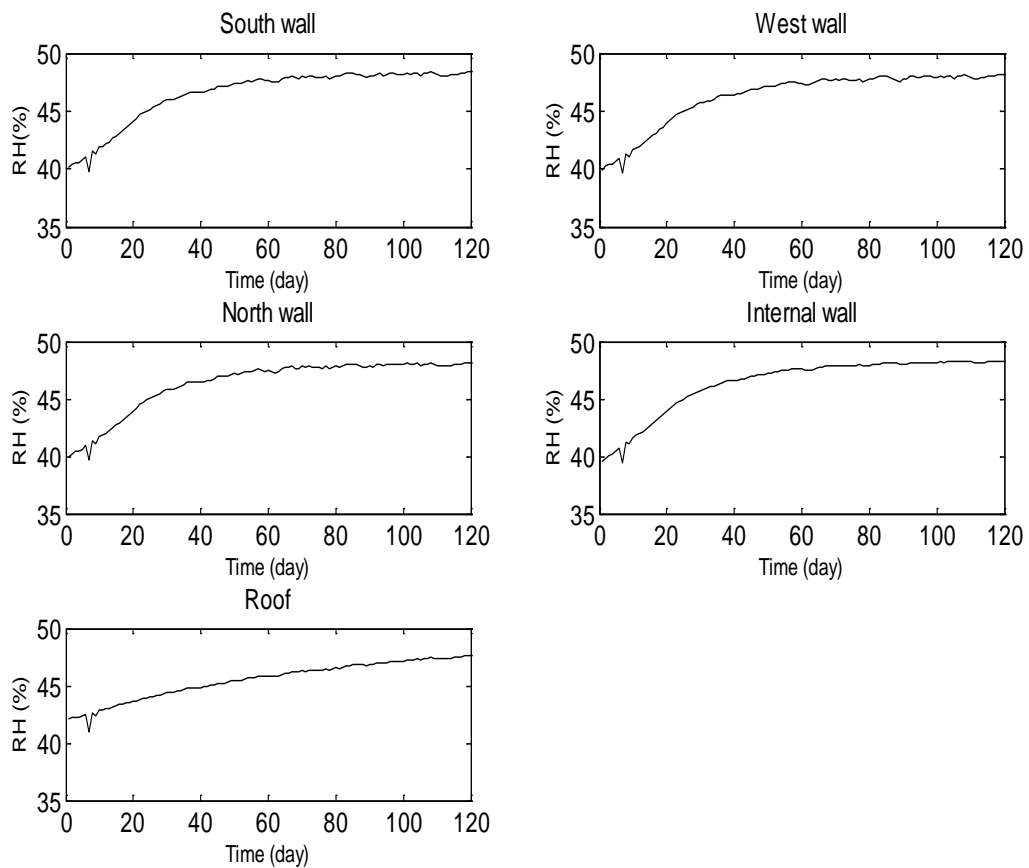


Figure 5.30: Surface relative humidity for alternative design

5.4.2 Comparison with normal practice

The performance of the alternative case with regards to the indoor conditions is further compared with the single-walled without heat recovery (Case Study 1) and the double-walled versions without heat recovery (Case Study 2) and the results are shown in **Figures 5.31** and **5.32**. The application of enthalpy heat exchanger has resulted in the indoor conditions being maintained at approximate level of design limit.

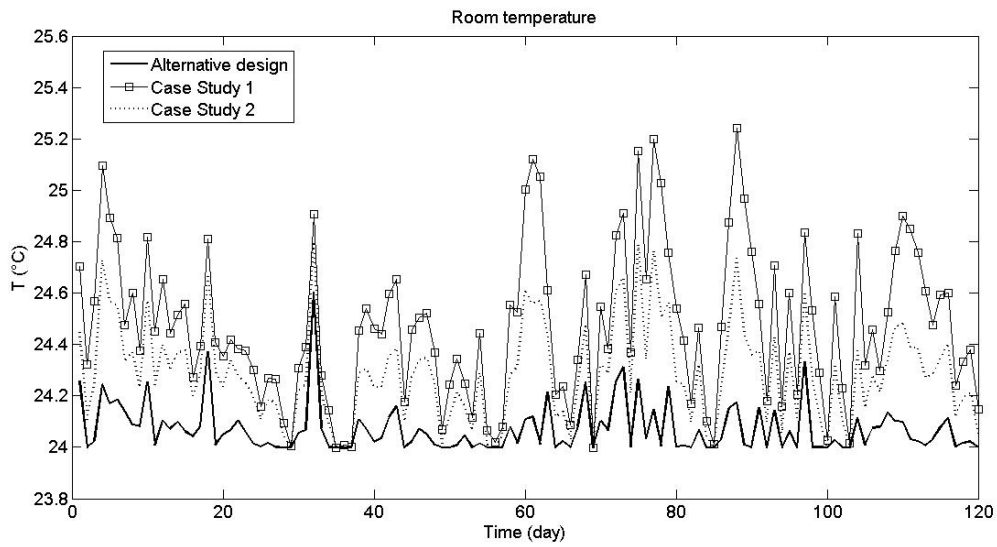


Figure 5.31: Room temperature profiles three versions of Isolation Room

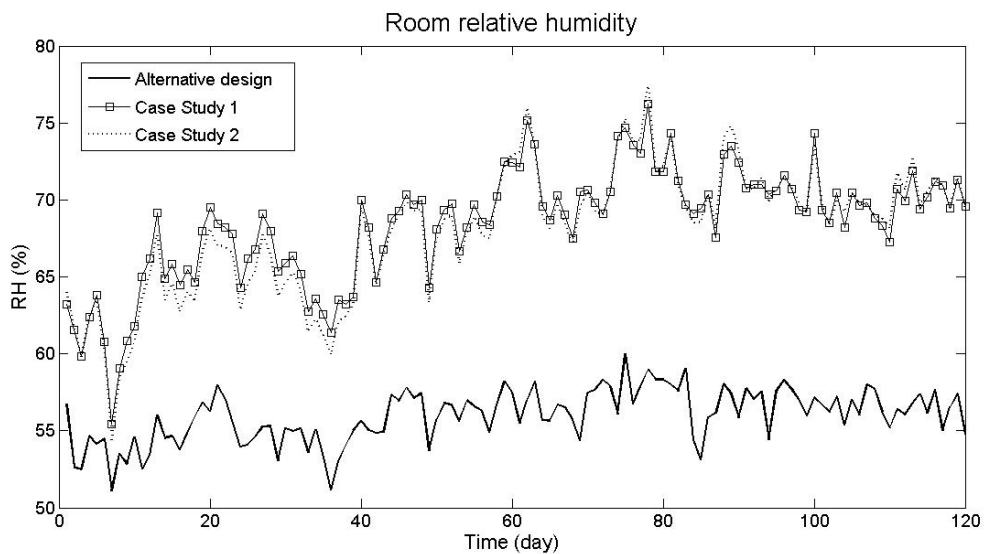


Figure 5.32: Room relative humidity profiles for three versions of Isolation Room

The performance in terms of the cooling energy for both HVAC system coupled with enthalpy heat exchanger and the conventional system are compared and the results are shown in **Figure 5.33**.

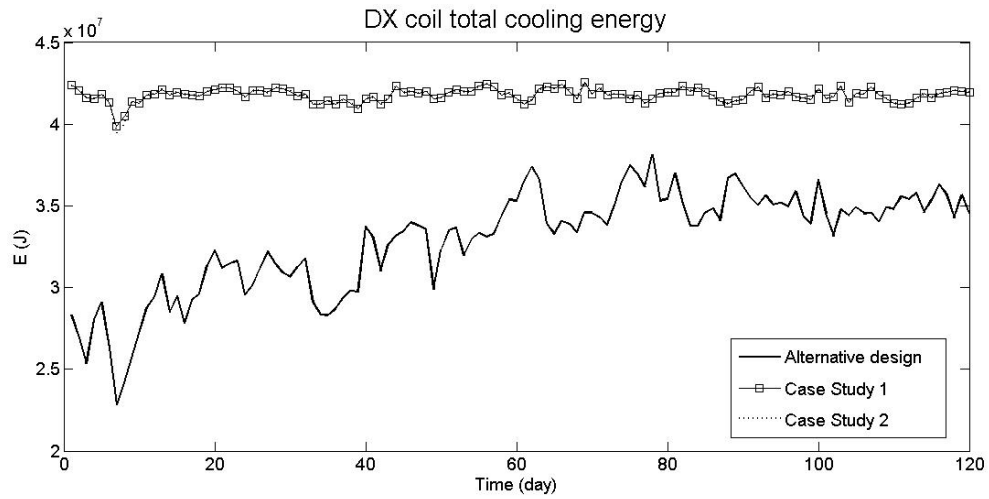


Figure 5.33: HVAC total cooling energy profiles for the alternative design and the normal practice

Comparison between the alternative case and the two versions of isolation room operating at normal design practice showed the impact of incorporating the latent heat recovery into the HVAC DX system where the room conditions were maintained at design limit at lower cooling coil energy consumption. The HVAC system for the alternative case was shown to be operating at a lower energy usage compared to the Case Studies 1 and 2 that were operating on conventional systems without heat recovery.

As was shown in **Figure 5.33**, the conventional system was operating at maximum capacity with respect to the fluctuating indoor conditions. Even when the conventional system was operating at maximum limit, the room relative humidity is still much higher than the design limit. The reason for this inability to control relative humidity was given in the sub-section 5.3.6.

The effect of using the alternative case in minimising the risk of mould growth on the internal surfaces against the normal practice is shown in **Table 5.4**.

Table 5.4: Comparison of the measure of mould growth risk for alternative case and normal practice

Wall Type	Orientation				Roof
	South	West	North	East (Internal)	
Single-Walled	2.27	0.94	1.03	3.23	0.82
Double-Walled	6.69	6.20	6.40	6.58	1.83
Alternative	0.05	0.04	0.04	0.05	0.03

Taking the east (internal) wall again as an example, the measure of mould risk for the single-walled isolation room is calculated as,

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 3.23$$

and,

$$\frac{1}{d} \times 30 = 3.23$$

$$\therefore d = 9 \text{ days}$$

Referring back to the mould growth limit curves by Sedlbauer (2001), it can be implied that for the single-walled isolation room operating at 24°C/50% RH_{room} on conventional HVAC system for a period of 30 days, there is a measure of risk that it would take 9 days for the mould spores to germinate on the east wall. The east wall for the double-walled isolation room fared worse where the risk for mould growth to occur is much higher, by which the time taken would be:

$$\frac{1}{d} \times \left(\frac{720}{24} \right) = 6.58$$

and,

$$\frac{1}{d} \times 30 = 6.58$$

$$\therefore d = 4.6 \text{ days}$$

The application of the vapour barrier on the outermost layer of the wall construction for the alternative case prevented the moisture ingress from the outside environment, where the probability of mould growth is much reduced for the alternative case, even though there is a minute measure of risk as was shown in **Table 5.4**. However, the measure of risk on the east wall for the alternative case is close to zero, meaning which the surface condition lies approximately on the limit isoline and it would take about 29 days for mould growth to occur, since the limit isoline is associated with germination time of 29 days, as shown in **Chapter 4**.

In the context of building construction, it has been shown that there is a measure of risk of mould growth on the internal surfaces regardless of the type of construction. Therefore, there is a need to prevent high moisture content from the hot and humid climate from entering the building early on. One of the solutions is to apply vapour barrier inside the wall.

To illustrate the effect of having this barrier further, the performance of the double-walled isolation room without the vapour barrier, as well as the alternative case are simulated in EnergyPlus and the surface conditions are evaluated. Both versions of isolation room are installed with DX type HVAC system coupled with enthalpy heat exchanger. The results have shown that the application of enthalpy recovery can be used as a technical remedy to the energy use and humidity control issues in the isolation rooms. By drying the air using a regenerative device, this results to the lowering of room relative

humidity, which in turn contributes to the reduction in the measure of infection risk.

On the wall construction side, the alternative case isolation room has the vapour barrier applied on the outermost layer of all its external walls. The results for comparison purposes are shown in **Table 5.5**.

Table 5.5: Impact of putting vapour barrier on the measure of risk of mould growth for double-walled and alternative case

Wall Type	Orientation				Roof
	South	West	North	East (Internal)	
Double-Walled without vapour barrier (with heat recovery)	0.08	0.06	0.06	0.08	0.001
Alternative case	0.05	0.04	0.04	0.05	0.03

Having vapour barrier installed pushes the measure of mould growth risk slightly further down by preventing moisture ingress through the building envelope. This result is further justification of having a double wall envelope with vapour barrier as one of the input variables for optimisation.

5.4.3 Summary

The alternative design was proposed as a starting point of the optimisation process. The differences between the alternative design and the normal design practice are that the vapour barrier was incorporated in the construction and the enthalpy heat exchange was incorporated into the HVAC system. The alternative design was simulated and the performance in terms of the ability of its HVAC system to maintain the indoor conditions and the total cooling energy was evaluated and compared with the normal practice. It was found that the alternative design performed better than conventional design in that the indoor relative humidity was maintained and there was a reduction in the total cooling coil energy. The measure of risk of

mould growth on the internal surfaces was reduced where the time taken for mould to grow is much longer within the simulated time period. The next section explains the scope of the optimisation problem by discussing the appropriate input variables as well as defining the constraints.

5.5 Scope of Optimisation Problem

After the new base case was selected and analysed, the next step was to define the scopes for optimisation. This includes selecting the suitable variables to be searched with the justification for the choice of the variable, and the range of each variable.

For the purpose of this research, the implementation of the optimisation uses an existing code that is based on the NSGA-II operation in order to create the number of optimal solutions.

The optimisation needs to be performed on the elements of building design and operation that affect the building energy use and risk of mould growth. These elements were the construction materials, the HVAC system type and the system operating strategy (as represented by the control set-points). The variables selected then were the wall assembly, design room temperature, design room relative humidity, and the ventilation rate.

5.5.1 Building Construction

In the context of building design, the variable selected for optimisation is the different options of wall assembly. The reason for having more than one type of building assembly was to provide an opportunity to evaluate the performance of wall assemblies in new, as well as upgraded, buildings.

Wall Type 1 is a single wall type from which the benchmark case is based on. The Wall Type 2 construction is based on the construction of a newly built Accident and Emergency Block at Banting Hospital which is located about 62 km from Kuala Lumpur. Wall Type 3 is a construction based on the new Public Works Department Guideline

on Prevention of Mould (2009). **Table 5.6** shows the construction details of the wall assemblies.

The wall is assumed to be painted and the thickness of wall paint is negligible. Red brick is a material normally used in the Malaysian construction industry. Properties of cement plaster was derived from ISO/FDIS 10456: 2007(E) *Building materials and products — Hygrothermal properties — Tabulated design values and procedures for determining declared and design thermal values*. However, the properties only covered density, design thermal conductivity, specific heat capacity, and water vapour resistance factor. There was only one hygrothermal property that was available for emulsion paint and gloss paint and cannot be used to represent the PU paint.

For optimisation purpose, the wall types 1, 2 and 3 are assigned index values of 0, 1 and 2, respectively, and the construction details for each wall assembly are shown in **Table 5.6**.

Table 5.6: Construction details for wall assembly

Envelope Layer	Wall		
	Type 1	Type 2	Type 3
Outside layer	Cement (2 mm)	Cement (2 mm)	Wall sealer
Layer 2	Red brick (110 mm)	Red brick (110 mm)	Cement (2 mm)
Layer 3	Cement (2 mm)	Polyurethane foam insulation (25 mm)	Red brick (110 mm)
Layer 4		Red brick (110 mm)	Polyurethane foam insulation (25 mm)
Layer 5		Cement (2 mm)	Red brick (110 mm)
Layer 6			Cement plaster (2 mm)
Index Number	0	1	2

The construction details for roof, floor and the window are shown in **Table 5.7**. The roof Type 1 construction is based on the normal practice while the Type 2 construction is based on the new Public Works Department Guideline on Prevention of Mould (2009). The floor and window constructions were maintained during the optimisation process.

Table 5.7: Construction details for roof, floor and window

Envelope Layer	Roof		Floor	Window
	Type 1	Type2		
Outside Layer	Concrete (100 mm)	Autoclaved aerated concrete (100 mm)	Sprayed polyurethane (50 mm)	Low tint glass (6 mm)
Layer 2	Air Layer (50 mm)	Water vapour retarder (10mm)	Water vapour retarder (10 mm)	Air (13 mm)
Layer 3	Interior gypsum board (12 mm)	Sprayed polyurethane (50 mm)	Concrete (100 mm)	Low tint glass (6 mm)
Layer 4		Air Layer (50 mm)		
Layer 5		Interior gypsum board (12 mm)		
Index Number	0	1		

Another input variable to be optimised is the window dimensions. It is to investigate the influence the orientation and dimensions of windows have on the cooling energy of an HVAC system due to the amount of daylight and the solar heat gain entering the room, as well as on the likelihood of mould growth on the surfaces facing the window area that are exposed to sunlight. The orientation of the window is maintained at the North orientation and its height is maintained at 1800 mm. The widths are varied and the corresponding assigned index number for the width differences are shown in **Table 5.8**.

Table 5.8: Window dimensions and corresponding index number for alternative design

Width, W (mm)	Width difference (mm)	Index
600	0	0
1000	400	1
1150	550	2
1300	700	3
1600	1000	4

The details of the optimised variables relating to the building construction is summarised in **Table 5.9**.

Table 5.9: Summary of optimised building construction variables

Variable	Index Number
Wall Type	
1	0
2	1
3	2
Roof Type	
1	0
2	1
Window Width Difference (mm)	
0	0
400	1
550	2
700	3
1000	4

5.5.2 Room Temperature Set-Points

A study on thermal comfort of occupants in Malaysian hospitals was done by Yau and Chew (2009). From a field survey on the hospital workers at four hospitals in Malaysia, a new defined comfort temperature for Malaysian hospitals was developed, which is between 25.2 and 28.3°C. There is no specific guideline that set design criteria for Malaysian hospitals, hence the reference to the Malaysian Code of Practice MS 1525:2007 which is catered for non-residential buildings. Reference also was made from the ASHRAE Standard 170-2008 Standards for Health-Care Facilities for recommended temperature range. Comparison between the three sources was shown in **Table 5.10**.

Table 5.10: Indoor design condition used as the basis for optimisation of temperature set-points

Reference	Temperature range (°C)
Malaysian Code of Practice MS 1525 (2007)	23 - 26°C
ASHRAE Standard 170 (2008) Standards for Health-Care Facilities	21 - 24°C
Yau and Chew (2009)	25.2 - 28.3°C

From the comparison, it was observed that the temperature range in Malaysia is above the range recommended by the ASHRAE Standard, suggesting that the occupants in Malaysia can tolerate higher comfort level. By combining the ranges from the sources shown and taking into account the normal design practice, a new range of temperature is selected. The lower bound of the range is

24°C and the upper bound of the range is 28°C with the resolution of 0.5°C.

The temperature range reflects the realistic situation in which the occupants in hot and humid climate such as Malaysia are tolerant to higher thermal comfort range. There is potential for energy saving, where the temperature difference between the inside zone and the outdoor is less than that in the colder and dryer climate. At the same time, it overlaps with the recommended range from the Malaysian Code of Practice MS 1525 (2007) and with the upper limit range of the ASHRAE Standard 170 (2008).

5.5.3 Room Temperature Night Set-back

Another variable that is looked into is the room temperature night set-back where there is opportunity to reduce the energy use by increasing the room set-point above the 24°C, rather than maintaining the design temperature continuously. The range for night setback starts from 8.00 at night time since the solar heat gain is absent until 9.00 in the next morning before working hours. The maximum temperature for night setback never goes above the upper bound of 28°C, since this is the upper bound of the room temperature set-point.

For the purpose of optimisation, the night set-back range is represented in fraction form where the lower bound of 24°C is 0 and the upper bound of 28°C is 1 with the resolution at 0.1. To illustrate how this works, the figure of 0.5 indicates the night temperature set-point being at the mid-point between 24°C and 28°C, which is 26°C.

5.5.4 Room RH Set-Points

As previously mentioned in **Chapter 3**, there are several areas in hospitals in Malaysia were operated at higher RH than they are designed for. In selecting a suitable range of room RH, the range of possibilities based on the existing studies and guidelines were looked into. Again, referring the previous study on Malaysian

hospitals by Yau and Chew (2009), the total RH range measured in the hospitals was between 44% and 79%. However, unlike temperature, a new RH range for Malaysian hospitals was not developed based on what was measured in the survey.

The comfort RH range as recommended in the Malaysian Code of Practice MS 1525:2007 was from 55 to 70%. However, this code of practice applies to the design of new non-residential buildings which are generic, and does not include health-care facilities. The indoor RH being consistently above 70% may result in mould growth on the inside wall surface (Public Works Department Malaysia, 2009). The guideline and the standards developed in Malaysia were based from that developed in the western countries. The ASHRAE Standard 170-2008 Standards for Health-Care Facilities recommended the RH of less than 60%, and the British Standard 5250 (2002) makes assumption that the indoor RH being consistently above 70% may result in mould growth on the inside wall surface.

As described previously, there is no local guideline available in Malaysia for recommended indoor RH for isolation room. The references were usually taken from ASHRAE or CDC. In order to introduce a measure of complexity to the optimisation, it is suggested that the RH_{room} range be extended to obtain a higher number of possible solution. Selection of the room RH range must also take into account its effect on the performance of the design system in eliminating contagion. It is normal practice for an isolation room to be equipped with Ultra-Violet Germicide Irradiation (UVGI) for that purpose.

A number of studies on the influence of RH_{room} on the effectiveness of UVGI have been conducted on various numbers of micro-organisms. Kowalski *et al* (2003) suggested the RH may be less than 65% based on existing research even though the limit value is not specific to any micro-organism. Xu *et al* (2005) stated that the

RHroom should be around 50% since the performance of UVGI in inactivating bacteria degraded significantly as RHroom increases from 50% to 75-90%. Lin and Li (2002) observed the different levels of susceptibilities for bacterial and fungal bio-aerosols between 50% and 80% room RH. However, for maximum effectiveness of UVGI performance, the room RH should be maintained at the range between 40% and 60%. For viruses, the susceptibility factor is higher at 55% room RH than at 85% (Tseng and Li, 2005).

It was also suggested that the RH indicated from their study that the investigated RH range of 50 to 83% does not affect the UV inactivation rate of bacterial spores (Ke *et al*, 2009). Ko *et al* (2000) emphasized the importance of keeping the indoor RH below 75% for optimal performance of UVGI. It should be noted that the research was based on the simulated high humidity condition in the experimental chamber that is analogous to tropical climate.

Since ambient RH has always been higher in the tropical climates, the required low RH for effective upper room UVGI in the tropical climate is always higher than that recommended in the studies conducted in the colder and drier climate. Wang *et al* (2009) consolidated all the relevant studies with respect to the factors influencing effectiveness of UVGI and noted that there is no clearly defined RH range within which the UVGI operates optimally to inactivate all types of micro-organisms. They also observed that the inactivation performance in previous studies was derived in controlled experiments.

All the studies have shown that there are varied susceptibility levels among different types of micro-organisms to UV in different RH range. Studies on UVGI recommended the RH range between 50% and 60%. Therefore, other sources on design criteria for other non-residential buildings were consulted. To achieve thermal comfort, the design criteria set by the Malaysian Code of Practice (2007) for the room RH is between 55% and 70%. The guideline by the Public

Works Department Malaysia (2009) and the BS 5250 (2002) suggest the RH threshold of 70% in a room. But this figure applies for general buildings. Having the RH above that threshold value for a time period may initiate mould growth, although no specific time frame has been given by both guidelines.

Flexibility in terms of a longer RH range may result in a reduction in occupant comfort level but the number of probable solutions in terms of energy consumption and mould growth risk would be greater. Therefore, instead of selecting 55% to 70% RH range which is the thermal comfort range and the threshold limit set by PWD Guideline and the British Standards, the new selected room RH range for optimisation was between 50% and 80% with the interval of 0.5%.

5.5.5 Ventilation Rate

Memarzadeh and Jiang (2000) indicated that, in relation to the effectiveness of UVGI, the best ventilation rate was 10-12 h⁻¹ for the winter season and 6 h⁻¹ for the summer season. Rydock *et al* (2004) stated 15 h⁻¹ as representative of best practice for patient room in Nordic hospitals. Tung *et al* (2009) used 12 and 24 h⁻¹ combined with different pressure differentials to evaluate the ventilation effectiveness of an isolation room, though no explanation was given as to why 24 h⁻¹ was selected. Bannister *et al* (2009) recommended a minimum air change rate of 12 h⁻¹ in the framework for the design and operation of high-level isolation units in Europe, which was in agreement with the level stated by the Center for Disease Control and Prevention (CDC, 2005). However, CDC also gave flexibility for the isolation rooms in existing health-care settings, where the minimum air change rate should be at least 6 h⁻¹.

The recommendation of high ventilation rate is driven by the need to maintain high indoor air quality (IAQ) in the isolation room so as to avoid cross-contamination, rather than reducing HVAC energy consumption. It is noted that the researches were based on the cold climates which require low energy to increase the ventilation rate.

However, maintaining 12 h^{-1} rate using 100 % fresh air in hot and humid climate already requires substantial HVAC energy consumption. Increasing the flow rate to 15 or 24 h^{-1} would result in not only the increase in energy use, but also the moisture intake into the room. A suggestion in order to reduce energy use and maintaining the ventilation rate is by re-circulating a percentage of room air back into the supply air path, without the overall air change rate dropping below the minimum of 12 h^{-1} .

The various number of references cited discrete values of recommended air exchange rates. Suggested optimised range for the air flow rate is between $0.36 \text{ m}^3/\text{s}$ (12 h^{-1}) and $0.72 \text{ m}^3/\text{s}$ (24 h^{-1}) with the resolution of $0.01 \text{ m}^3/\text{s}$. The selection is aimed to offer a higher number of probable solutions from optimisation, and to evaluate performance of the alternative system in terms of its ability to maintain the indoor air condition at very high ventilation rate.

5.5.6 Constraints

To recap, the two objective functions defined in this research are the minimisation of the HVAC energy consumption and minimisation of mould growth risk. The objective functions were subject to the constraints that have been defined. The optimisation can only be successful if the conditions were satisfied.

For this research, the variables used for optimisation were imposed as constraints; in this case the range for room design temperature, room design relative humidity and the air exchange rate were imposed as inequality constraints, as shown in **Table 5.11**.

Table 5.11: Constraints for alternative design

No.	Parameter (Unit)	Constraint
1	Room temperature (C)	$24 \leq T_{room} \leq 28$
2	Room relative humidity (%)	$50 \leq RH_{room} \leq 80$
3	Air change rate (h^{-1})	$ACH \geq 12$
4	Window dimension (mm)	$Height = 1800$ $600 \leq Width \leq 2600$

The details of the optimised variables relating to the HVAC control strategy is summarised in **Table 5.12**.

Table 5.12: Summary of optimised HVAC control strategy variables

Variable	Unit	Range		Resolution
		Lower Bound	Upper Bound	
Temperature Set-Point	°C	24	28	0.5
Night Setback	Fraction	0.0	1.0	0.1
RH Set-Point	%	50	80	0.5
Air Flow Rate	m^3/s	0.36	0.72	0.01

5.6 Chapter Summary

A background study on the design of isolation rooms from existing literature was done that indicated no available design guideline catered for Malaysian climate. The simulation run period using the hot and humid climate was evaluated and it was suggested that the shorter period was more suitable than running annual simulation since the climate is constant throughout the year and it takes four months for the zone envelope to stabilise. The performance of the normal design practice was investigated and the surface conditions were analysed for any probable risk of mould growth.

Preliminary results indicated that a full-fresh air system with no recirculation limits the extent to which the system can control the room humidity, which resulted in the internal surface conditions susceptible to mould growth. The inclusion of latent heat recovery was observed to be providing good control, and robustness, of the HVAC operation. The alternative design was defined as new base case to be used in optimisation study, in which the latent heat recovery was included in the HVAC system. The variables selected for optimisation were room temperature set-points, room relative humidity set-points, wall and roof assemblies, window dimensions and air exchange rate. The optimisation process, the results from that process, mould growth analysis and simulation were discussed in the following **Chapter 6**.

Chapter 6

Results and Analysis

Chapter 5 gave a detailed description on the selection and justification of using alternative design for the simulation, mould risk analysis and optimisation process. The chapter also listed the number of variables to be optimised and justification of the ranges selected for each of the variables. The constraints within which the optimisation process must be undertaken have been listed. This chapter analyses the results from the simulation, mould risk analyses, as well as the optimisation of isolation room alternative design. Analyses are made with regards to the possibility of a trade-off between two conflicting design goals, namely minimising HVAC energy use and minimising the risk of mould growth on indoor surfaces.

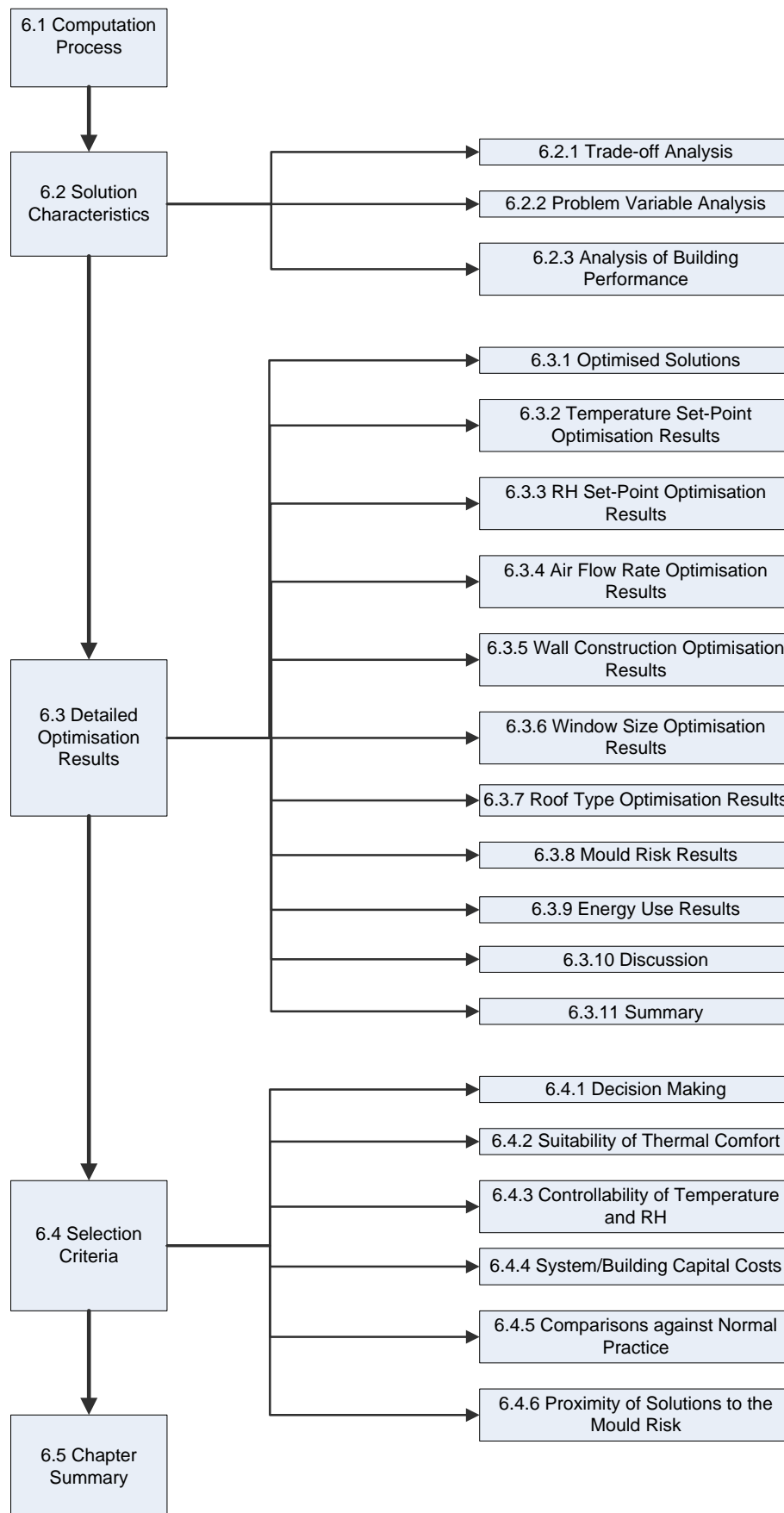


Figure 6.1: Structure of Chapter 6

6.1 Computation process

The simulation and optimisation process was done using the Quad core personal computer which has the Intel Core i7-960 processor with a speed of 3.2 Gigahertz. The random access memory (RAM) used is the DDR3 type with a capacity of 8 Gigabyte memory and the speed of 1333 Megahertz. The processor has 4 core and 8 threads, meaning that it is possible to run 8 simulations in parallel. A single optimisation ran at approximately 72 hours.

6.2 Solution Characteristics

Multi-objective optimization is intended to provide information on the trade-off between two or more conflicting goals (in this case, between HVAC system energy use and the risk of mould growth). Since the trade-off is represented by a set of equally optimum solutions, selection of a single solution for construction requires a structured approach to decision making. Decision-making is synonymous with the analysis of the solution characteristics; therefore for clarity the solution characteristics are discussed in advance of the decision making.

There are three elements in the analysis of the solutions; the first element is the analysis of the trade-off between system energy use and the risk of mould growth, the second element is the analysis of the variation in the problem variables, and the final element is the analysis of building performance through derived quantities. The following subsection discusses those elements in more detail.

6.2.1 Trade-off Analysis

Table 6.1 gives the Pareto optimum objective function and problem variable values, with the trade-off between energy use and the risk of mould growth also being illustrated in **Figure 6.2**. The energy use ranges from the lowest value to the highest by a factor of over 3.8; the majority of solutions are associated with no mould growth, although the lowest energy use solutions

have a risk of mould growth. The highest mould risk values fall below the germination limit of 1.0. However, since the integration period for the risk assessment is only 30 days, any positive risk value is likely to result mould germination if the similar surface conditions prevail over a longer period (which they are expected to, since tropical locations experience a small annual and diurnal variation in climatic conditions).

Table 6.1: Energy Use, Risk of Mould Growth and Problem Variables

System Energy Use (kWh)	Mould Risk (-)	Daytime Temperature Setpoint (°C)	Night Temperature Setpoint (°C)	Relative Humidity Setpoint (%)	Supply Air Flow Rate (m ³ /s)	Outdoor Air Flow Rate (m ³ /s)	External Wall Type (-)	Internal Wall Type (-)	Ceiling Type (-)	Window to Wall Ratio (%)
6374	0.9	28.0	28.0	80	80	0.36	3	3	3	1
6374	0.9	28.0	28.0	80	80	0.36	3	3	3	1
7149	0.7	28.0	28.0	80	80	0.44	3	3	3	1
8972	0.0	28.0	28.0	70	70	0.48	3	3	3	1
9147	-3.0	28.0	28.0	70	70	0.36	3	3	3	1
10208	-3.7	28.0	28.0	70	70	0.48	3	3	3	2
11205	-4.5	28.0	28.0	70	70	0.60	3	3	3	2
12181	-5.3	28.0	28.0	70	70	0.72	3	3	3	2
12876	-6.8	28.0	28.0	65	65	0.40	3	3	3	2
14638	-7.4	28.0	28.0	65	65	0.72	3	3	3	2
14638	-7.4	28.0	28.0	65	65	0.72	3	3	3	2
17421	-16.5	28.0	28.0	60	60	0.36	3	3	3	2
19166	-16.6	28.0	28.0	60	60	0.41	3	3	3	2
20034	-16.9	28.0	28.0	60	60	0.48	3	3	3	2
22298	-17.7	27.5	27.6	60	60	0.82	3	3	3	2
23329	-26.9	28.0	28.0	55	55	0.36	3	3	3	2
26140	-27.8	28.0	28.0	55	55	0.44	3	3	3	1
28078	-28.1	28.0	28.0	55	55	0.47	3	3	3	2
29285	-29.1	28.0	28.0	55	55	0.60	3	3	3	2
29477	-31.9	28.0	28.0	50	50	0.36	3	3	3	2
31361	-32.2	28.0	28.0	50	50	0.39	3	3	3	1
32625	-32.2	28.0	28.0	50	50	0.39	3	3	3	2
33610	-32.9	28.0	28.0	50	50	0.44	3	3	3	1
35660	-33.4	28.0	28.0	50	50	0.49	3	3	3	1
35660	-33.4	28.0	28.0	50	50	0.49	3	3	3	1
37594	-33.9	28.0	28.0	50	50	0.55	3	3	3	1
40784	-34.4	28.0	28.0	50	50	0.64	3	3	3	1
42358	-34.8	28.0	28.0	50	50	0.71	3	3	3	2
42602	-34.8	28.0	28.0	50	50	0.72	3	3	3	2
42602	-34.8	28.0	28.0	50	50	0.72	3	3	3	2

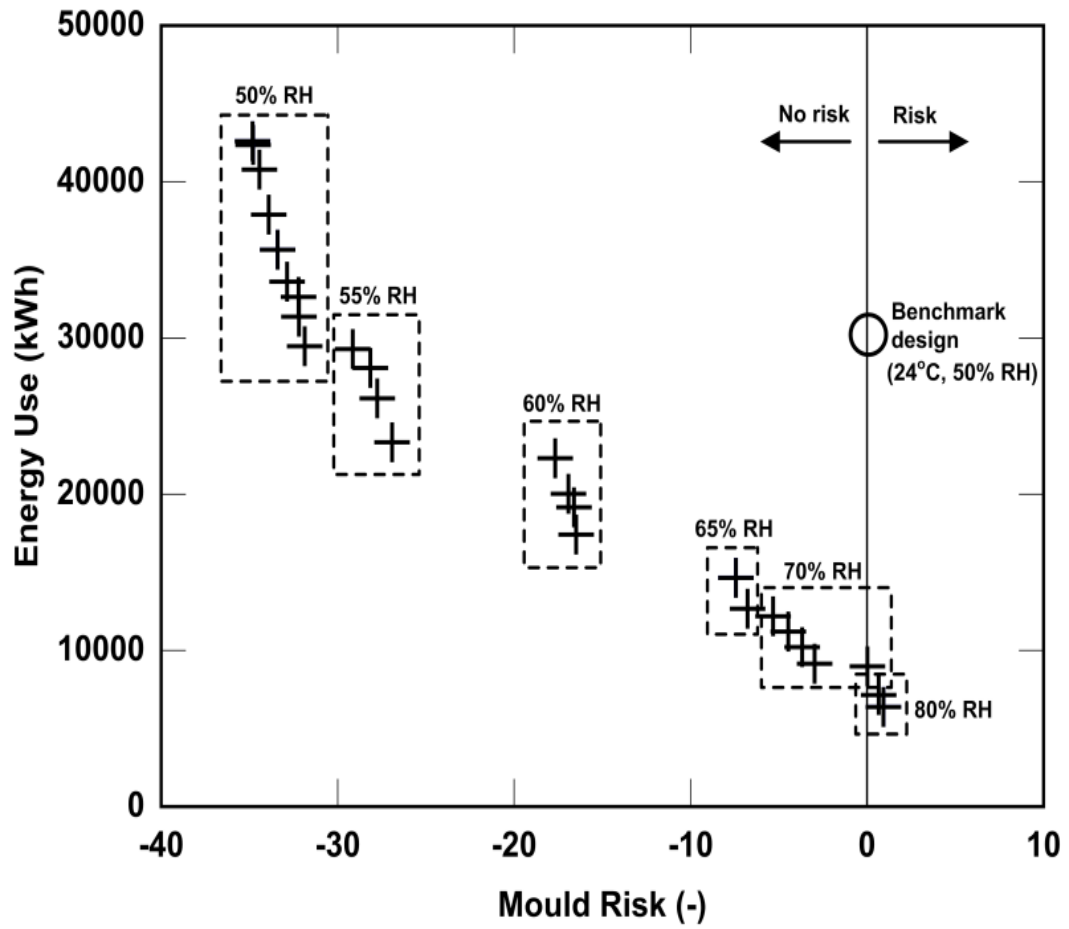


Figure 6.2: Trade-off between Energy Use and Risk of Mould Growth (with the boxed values being grouped on the Zone Relative Humidity Set-point)

The solid line represents the surface held at a constant 28°C, this being the predominant value of the zone temperature set-point along the trade-off (refer to **Table 6.1**).

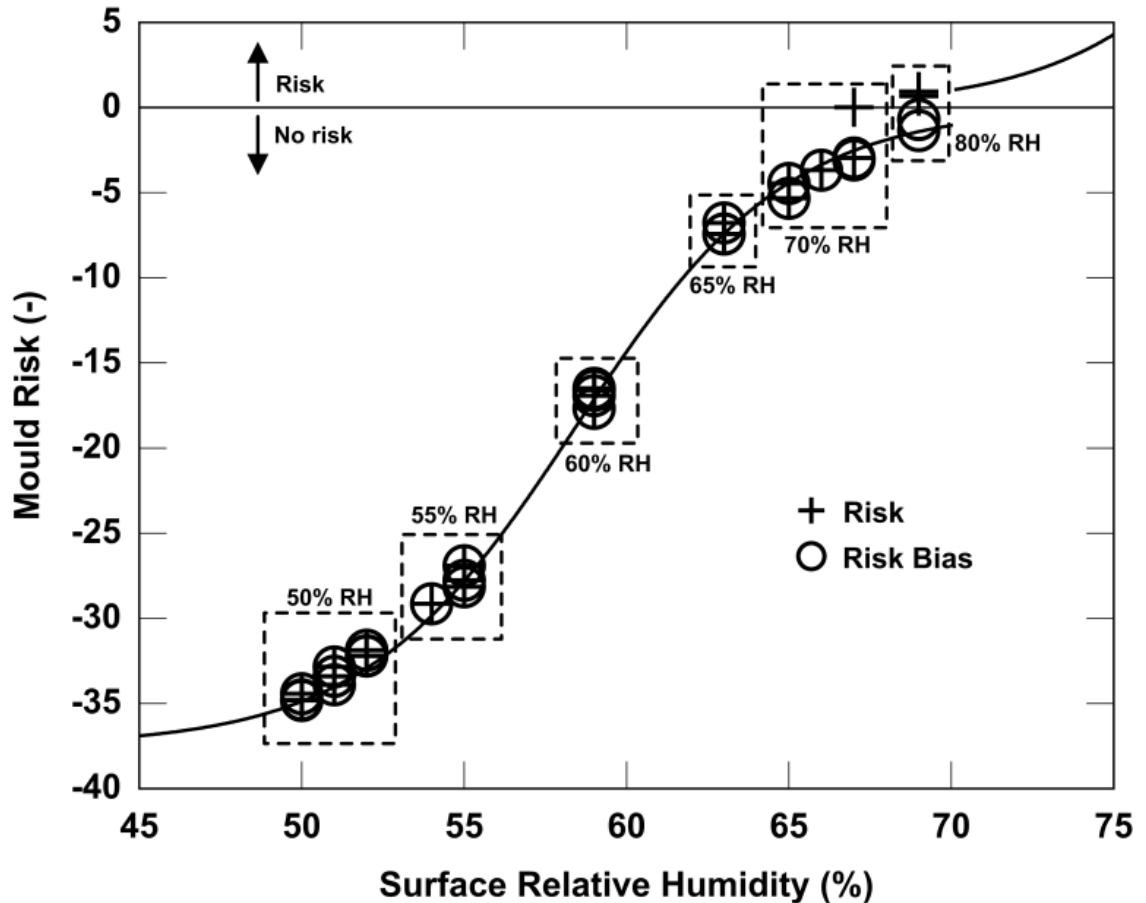


Figure 6.3: Mould Risk and Surface Relative Humidity (with the boxed values being grouped on the Zone Relative Humidity Setpoint)

Two sets of results are illustrated in the **Figure 6.3**; the risk values calculated according to equations (1) and (2) described in **Chapter 4**, and the bias in the risk (this being calculated by integrating all hourly risk values regardless of whether they are positive or negative). A coincident value for the risk and its bias indicates that the surface conditions consistently result in the same level of risk over the 30 day integration period. This is the case for the majority of solutions, except those for which the risk value is positive; the difference in the risk and risk bias values for these solutions indicates that the positive risk results from only a subset of the integrated risk values, and that the average surface conditions do not contribute to mould growth.

6.2.2 Problem Variable Analysis

The results in **Table 6.1** indicated that there are three broad categories of variable:

- a) variables that have a constant value along the trade-off;
- b) variables that drive the trade-off; and
- c) variables that have an uncertain relationship with the trade-off.

The variables having a constant value along the trade-off are; the day-and night-setback zone temperature set-points, the outdoor air flow rate, and the type of wall construction. The day-time zone temperature set-point is almost constant across the trade-off with a value of 28.0°C, this corresponding to the upper bound for the variable. Since the day-time temperature lies on the upper-bound of the variable, there was no scope for night set-back (night set-back in cooling operation corresponding to an increase in the zone temperature).

It is conceivable that the zone set-point temperature should vary along the trade-off as reducing the zone temperature will increase the cooling energy while reducing the risk of mould growth (as a lower zone temperature will result in a lower surface temperature). However, as was shown in **Chapter 4** (refer to **Figure 4.6**), the sensitivity of mould growth to surface temperature is significantly lower than for the surface relative humidity. A reduction in zone temperature also increases the load on the HVAC system and therefore the risk that it is unable to maintain the zone humidity, and therefore that the risk of mould growth can be increased rather than reduced. This has been confirmed by re-optimizing the design with the upper bound on the zone temperature set-point reset to 26.0°C; **Figure 6.4** illustrates that all 26.0°C solutions are all dominated by the 28.0°C solutions. **Figure 6.1** also indicates that the base

case solution, which has lower zone set-point temperature of 24.0°C, is also dominated by all solutions on the trade-off.

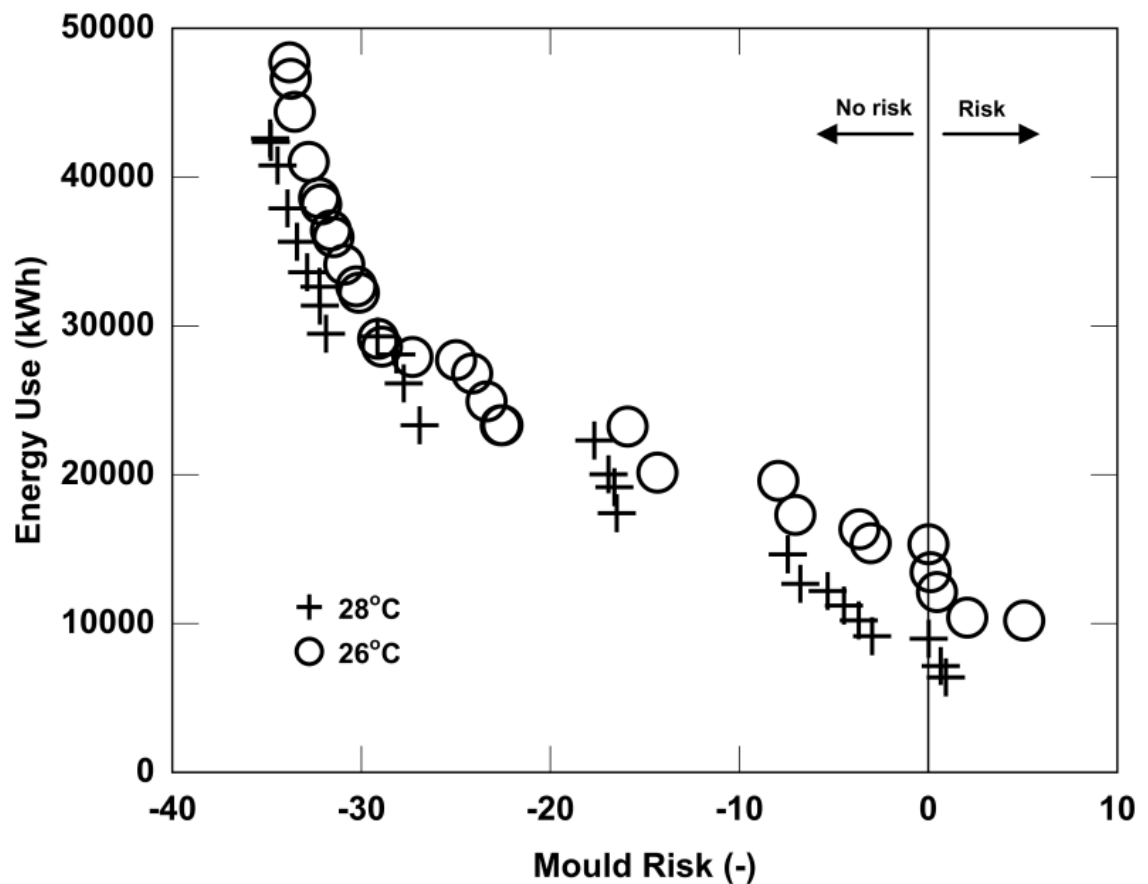


Figure 6.4: Trade-off for Different Zone Temperature Set-point Upper Bounds

It might be expected that the outdoor air flow rate would be constant along the trade-off as increasing the outdoor air flow rate will increase the energy use due to the cooling and dehumidification load without there being any direct reduction in the risk of mould growth.

Both the internal partition wall (between the ward and isolation room), and the external walls, have a constant Type 3 construction along the trade-off. There are three (3) possible wall construction, with Type 1 being of thermally lighter weight and less insulated construction than both of Types 2 and 3 (**Table 5.6**). The difference between Type 2 and 3 constructions

is that the Type 3 construction having a surface treatment to reduce vapour transfer, this appearing to have a significant impact on the performance of the fabric (although the extent to which it has an impact is not investigated further here).

The variables that have an ordered change in value along the trade-off are the zone relative humidity set-point, and the supply air flow rate, and as such, these variables can be considered to be the main drivers for the trade-off. It is not surprising that the zone relative humidity set-point is the main driver for the trade-off as it has a significant impact on both system energy use and the risk of mould growth. For a given zone relative humidity set-point, the supply air flow rate drives the trade-off by helping to maintain the zone relative humidity (for a fixed outdoor air flow rate, increasing the supply air flow rate will increase the proportion of re-circulated air, and as such help provide more stable room conditions). **Table 6.1** indicates that the primary driver for the trade-off is the zone relative humidity set-point, with the supply air flow rate having a secondary effect on the trade-off.

The variables for that have an irregular variation in value along the trade-off are the ceiling construction type and the window to wall ratio. Two alternative ceiling types are possible (**Table 5.7**), the difference between Type 1 and 2 being in the outer (upper) layers of the construction. Since the first two layers of construction closest to the conditioned zone are identical for both construction types, and that the ceiling is modelled as an adiabatic surface, it is probable that there is insufficient difference in the thermal performance of the two constructions to form a distinct relationship between the ceiling type and the trade-off characteristic (although this requires further work to confirm this is the case).

The window-to-wall ratio has an irregular value for low energy use solutions, but becomes constant at the upper bound for the higher energy use solutions. The reasons for this characteristic are not clear and require further work (especially as to how the larger window area is associated with a low risk of mould growth).

6.2.3 Analysis of Building Performance

The analysis of the building performance is concerned with the extent to which the HVAC system maintains the zone temperature and humidity, and the resultant impact of this on the risk of mould growth and energy use. For all solutions along the trade-off, the HVAC system maintained the zone conditions to within 0.1°C.

However, the bias errors in the zone relative humidity set-point given in **Table 6.2** indicate that this was not the case for the zone relative humidity. For relative humidity set-points above 60%, the zone relative humidity is generally below the set-point, this possibly indicating that the natural upper limit of zone relative humidity is approximately 70% RH (with the zone maintained at 28°C). As the zone relative humidity set-point is reduced below 60%, the HVAC system is progressively less able to maintain the zone relative humidity, the highest bias error being 6% above the set-point of 50% RH; this is largely due to the natural dehumidification performance limit of a cooling coil.

The control error in relative humidity is however reduced as the supply air flow rate (and degree of air re-circulation) is increased. Inevitably, the surface temperature and humidity follow the zone temperature and humidity, with the control error in relative humidity having a particular impact on the surface relative humidity and the risk of mould growth (note that all surfaces have very similar average temperature and relative

humidity, the standard deviation in average temperature and humidity being less than 0.1°C and 1% RH).

As is expected, **Table 6.2** indicates that the HVAC system energy use is driven by the relative humidity set-point and the supply air flow rate. Since it would appear that the natural limit of zone relative humidity is approximately 70%, there is very little, or no re-heat energy for this or higher relative humidity set-points.

Table 6.2: Energy Use, Risk of Mould Growth and Building Performance Metrics

System Energy Use (kWh)	Mould Risk (-)	Relative Humidity Setpoint (%)	Supply Air Flow Rate (m ³ /s)	Zone Relative Humidity Bias Error (°C)	Average Surface Temperature (°C)	Average Surface Relative Humidity (%)	Fan Energy Use (kWh)	Re-Heat Energy Use (kWh)	Cooling Energy Use (kWh)
6374	0.9	80	0.36	-11	28.1	69.4	1255	0	5120
6374	0.9	80	0.36	-11	28.1	69.4	1255	0	5120
7149	0.7	80	0.44	-11	28.1	68.7	1533	0	5615
8972	0.0	70	0.48	-3	28.1	67.1	1673	445	6854
9147	-3.0	70	0.36	-3	28.2	66.4	1255	272	7620
10208	-3.7	70	0.48	-3	28.3	65.6	1673	231	8304
11205	-4.5	70	0.60	-4	28.3	64.9	2091	202	8912
12181	-5.3	70	0.72	-4	28.3	64.2	2509	177	9495
12676	-6.8	65	0.40	-1	28.3	63.0	1394	1375	9907
14638	-7.4	65	0.72	-1	28.2	62.7	2509	1095	11034
14638	-7.4	65	0.72	-1	28.2	62.7	2509	1095	11034
17421	-16.5	60	0.36	1	28.2	58.9	1255	3301	12865
19166	-16.6	60	0.41	1	28.2	58.9	1429	4046	13691
20034	-16.9	60	0.48	0	28.2	58.8	1673	4159	14202
22298	-17.7	60	0.62	0	27.8	58.5	2161	4046	16091
23329	-26.9	55	0.36	3	28.2	54.9	1255	5687	16487
26140	-27.8	55	0.44	2	28.1	54.8	1533	6893	17714
28078	-28.1	55	0.47	2	28.2	54.5	1638	7397	19043
29285	-29.1	55	0.60	1	28.2	54.0	2091	7318	19876
29477	-31.9	50	0.36	6	28.2	51.4	1255	8082	20141
31361	-32.2	50	0.39	5	28.1	51.4	1359	9144	20858
39625	-32.2	50	0.39	5	28.2	51.3	1359	9497	21769
39610	-32.9	50	0.44	4	28.1	51.0	1533	9960	22117
35660	-33.4	50	0.49	4	28.1	50.7	1708	10692	23261
35660	-33.4	50	0.49	4	28.1	50.7	1708	10692	23261
37894	-33.9	50	0.55	3	28.1	50.4	1917	11473	24504
40784	-34.4	50	0.64	2	28.1	50.0	2230	12449	26105
42358	-34.8	50	0.71	1	28.2	49.5	2474	12540	27344
42602	-34.8	50	0.72	1	28.2	49.5	2509	12615	27478
42602	-34.8	50	0.72	1	28.2	49.5	2509	12615	27478

6.3 Detailed Optimisation Results

This section offers a more detailed description of the optimised results in a step-by-step manner and discusses the impact of optimising HVAC control strategy on the trade-off between low energy use and low mould risk. Comparison is also made between the solutions and the benchmark design.

6.3.1 Optimised Solutions

Convergence was achieved after 3,780 function evaluations and 125 population generations when the optimisation process was terminated. The results shown in **Figure 6.5** compared the generations of solutions before the convergence. Comparison revealed that convergence was already achieved at 50 generations since there was overlapping with the 100th generation of solutions.

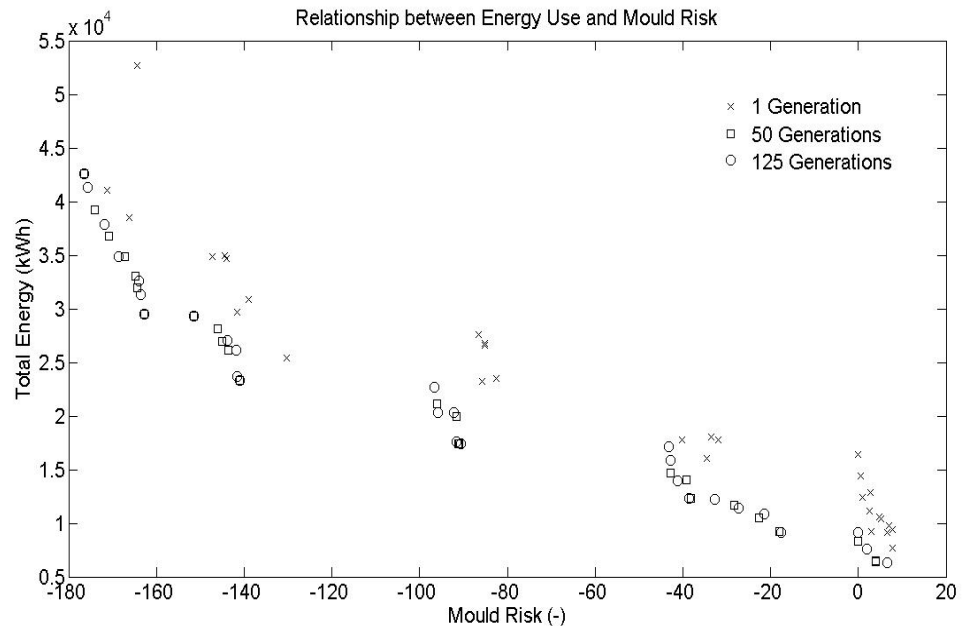


Figure 6.5: Trade-Off between Energy Use and Mould Risk

Figure 6.6 shows all the non-dominated solutions obtained after 125 generations using NSGA-II, where three discontinuous regions in the Pareto-optimal front were observed and they were numbered for easy reference during analysis. There are actually 30 solutions available. However, both solutions 1 and 28 have 2 identical solutions overlapping. It is of notable interest to observe the absence of equal spread along the front with breaks between the solutions at 12 and 13, and between solutions 17 and 18, as well as a smaller break between solutions 25 and 26.

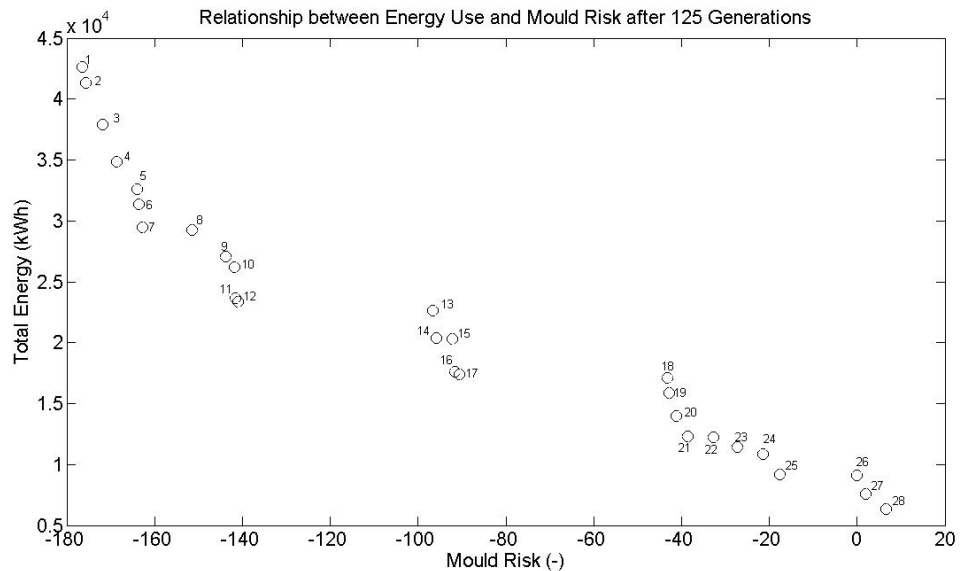


Figure 6.6: Optimised Solutions after 125 Generations

The total energy for the HVAC system after 30-day simulation was expressed as

$$E_{Total} = E_{Fan} + E_{Re-Heat} + E_{DXCoil} \quad (1)$$

where

$$E_{Total} = \text{Total Energy in kWh}$$

$$E_{Fan} = \text{Fan Energy in kWh}$$

$$E_{\text{Re-Heat}} = \text{Re-Heat Energy in kWh}$$

$$E_{\text{DXCoil}} = \text{DX Coil Cooling Energy in kWh}$$

The calculation of the mould risk was based from the expression (2),

$$\text{risk} = \frac{\text{Time Interval}}{\text{days} \times 24} \quad (2)$$

where

Time Interval = the last 30 days of the simulated 4-month period (hours)

Days = germination time in days (the time between the mould spores begins growth and develop its own spores)

The full description of the risk model was given in **Chapter 4**. The corresponding energy use and mould risk as well as the set-points for the optimised solutions and the benchmark design are shown in **Table 6.3**.

Table 6.3: Corresponding objective functions and set-points for the optimised solutions and the benchmark design

Solution	E_{Total} (kWh)	Mould Risk	Cooling Set-Point (°C)	RH Set-Point (%)
1	42602	-176.39	28	50
2	41306	-175.56	28	50
3	37887	-171.81	28	50
4	34858	-168.52	28	50
5	32625	-164.03	28	50
6	31362	-163.65	28	50
7	29477	-162.74	28	50
8	29285	-151.55	28	55
9	27082	-143.73	28	55
10	26166	-141.79	28	55
11	23678	-141.57	28	55
12	23329	-140.94	28	55
13	22655	-96.69	27.5	60
14	20358	-95.73	28	60
15	20344	-92.24	28	60
16	17612	-91.66	28	60
17	17419	-90.58	28	60
18	17118	-43.19	27	65
19	15863	-42.76	27.5	65
20	13977	-41.13	28	65
21	12318	-38.50	28	65
22	12260	-32.76	28	65
23	11454	-27.20	28	70
24	10844	-21.51	28	70
25	9147	-17.51	28	70
26	9127	0.01	28	70
27	7611	2.02	28	80
28	6332	6.54	28	80

6.3.2 Temperature Set-Point Optimisation Results

The room temperature set-point was one of the variables to be optimised. The range was set between 24°C and 28°C, which also functioned as an imposed constraint. The 28°C set-point was taken as the upper bound of the range based on the

28.3°C upper limit of comfort temperature range for hospitals proposed by Yau and Chew (2009). 24°C was selected since it was the requirement by ASHRAE and was the norm for isolation room HVAC system design in the Malaysia. It was observed that the highest ranking Pareto optimal solutions operate at the room temperature set-point of 28°C which is higher than the recommended 24°C by the ASHRAE Standard (2008).

To illustrate the difference in how much energy was used to maintain the set-points, the simulations were run for both 24°C and 50% RH, which is the base case design and 28°C and 50% RH and the total energy (heating and cooling) in kWh for the last month was taken. The results were shown in **Figures 6.7** and **6.8**.

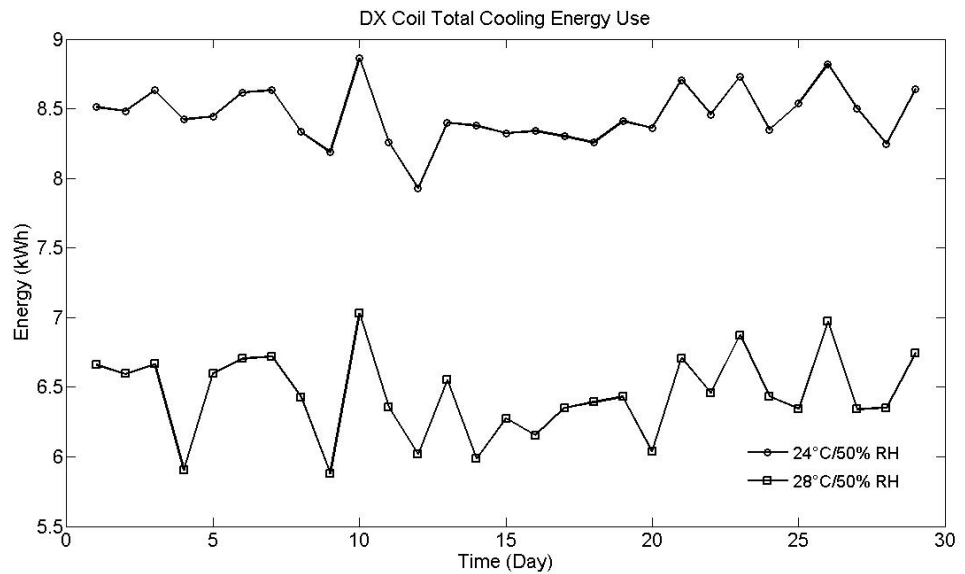


Figure 6.7: Comparison in cooling energy between 24°C /50% RH and 28°C/50% RH set-points

The results showed that less energy was required by the DX cooling coil to cool and dehumidify the outside air to meet the 28°C room temperature set-point compared to that required for the 24°C set-point.

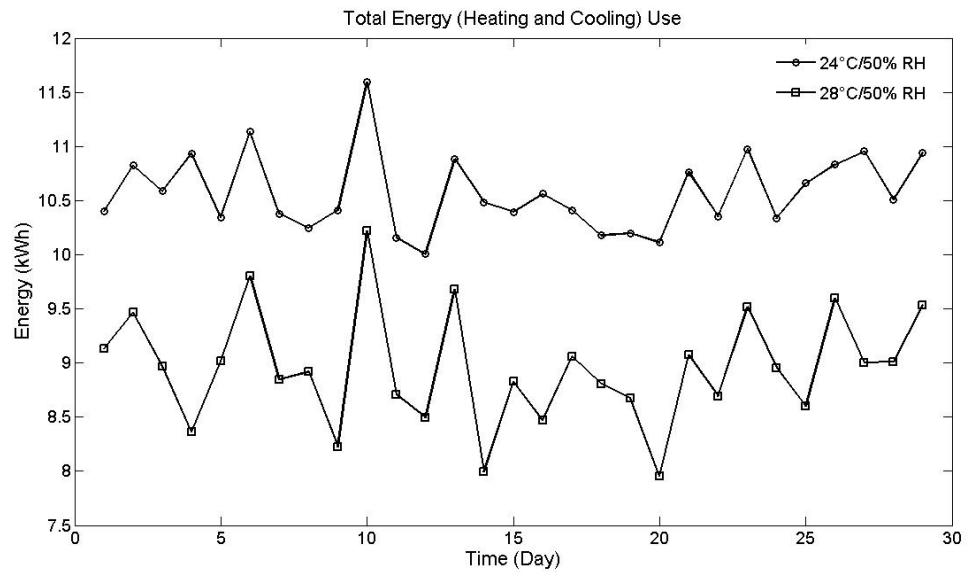


Figure 6.8: Total Energy Use between 24°C/50% RH and 28°C/50% RH set-points

The ability of the system to maintain the zone temperature and RH set-point conditions is measured by its error control, or bias. Analyses were made on the daytime bias set-point error as an indication of the reliability of the system to maintain the design conditions. The day-time bias error is justified since it is the harshest condition and the highest cooling load occurs during the day-time.

The bias error for temperature set-point was evaluated using the average of differences between the actual zone conditions and the room set-points, numerically expressed as

$$Error_{T_{bias}} = \frac{\sum_{i=1}^n (T_{Zone} - T_{SP})}{n} \quad (4)$$

where

$$Error_{T_{bias}} = \text{Daytime Bias Temperature Set-Point Error (}^{\circ}\text{C)}$$

T_{Zone} = Actual Zone Temperature

T_{SP} = Temperature Set-Point

n = Number of Evaluations

The results for the set-point errors were shown in **Table 6.4**.

Table 6.4: Daytime Bias Set-Point Error

Solution	RH Set-Point (%)	$Error_{Tbias}$ (°C)	$Error_{RHbias}$ (%)
1	50	0.0	1
2	50	0.0	2
3	50	0.0	3
4	50	0.0	4
5	50	0.0	5
6	50	0.0	5
7	50	0.0	6
8	55	0.0	1
9	55	0.0	2
10	55	0.0	2
11	55	0.0	3
12	55	0.0	3
13	60	0.0	0
14	60	0.0	0
15	60	0.0	0
16	60	0.0	1
17	60	0.0	1
18	65	0.0	-1
19	65	0.0	-1
20	65	0.0	-1
21	65	0.0	0
22	65	0.0	0
23	70	0.0	-4
24	70	0.0	-4
25	70	0.0	-3
26	70	0.0	-3
27	80	0.0	-11
28	80	0.0	-10
Benchmark	50	0.6	15

The results indicated that there was no bias error for the room temperature set-point, meaning the system was able to maintain constant room temperature at 28°C.

6.3.3 RH Set-Point Optimisation Results

From the results shown in **Table 6.4**, it was observed that mould risk were present at the 80% RH set-point with 70% is the upper RH limit. As RH set-points decreases, the HVAC system total energy consumption increases in order to cool and dehumidify the supply air. At the same time, the risk of mould growth also decreases since the internal wall and roof surfaces getting drier as a result of less moisture content absorbed by the surfaces from the indoor environment. The results suggest that low energy and low mould risk are driven by the room relative humidity set-point, and it appears that the 70% is the natural limit of maximum humidity for a temperature set-point of 28°C. This is in agreement with the recommendation by Public Works Malaysia Guidelines on the Prevention of Mould Growth in Buildings (2009), and the British Standards 5250 (2002).

The re-heating of the outside air was not needed at the 80% room humidity. There was no necessity for the cooling coil to overcool and dehumidify the outside air as it would have at the 50% RH. Therefore, a point at which overcooling may result in the cooling coil freezing was not reached. The implications are that (i) heater is not necessary if the HVAC system is to operate at 80% RH set-point and the heating cost is virtually eliminated, and (ii) the size of the DX cooling coil is reduced. However there is real risk of mould growth on the surface as shown by the results, due to the cooling coil removing less moisture from the outside air than it should, as a result of the HVAC system operating at partial-load.

The bias error for RH set-point was evaluated using the average of differences between the actual zone conditions and the room set-points, numerically expressed as

$$Error_{RHbias} = \frac{\sum_{i=1}^n (RH_{Zone} - RH_{SP})}{n} \quad (5)$$

where,

$Error_{RHbias}$ = Daytime Bias RH Set-Point Error (%)

RH_{Zone} = Actual Zone Relative Humidity

RH_{SP} = Relative Humidity Set-Point

n = Number of Evaluations

of which data was shown in **Table 6.4**, and given a graphical representation in **Figure 6.9**. There was overlapping of the figures, making them appear fewer than they actually are.

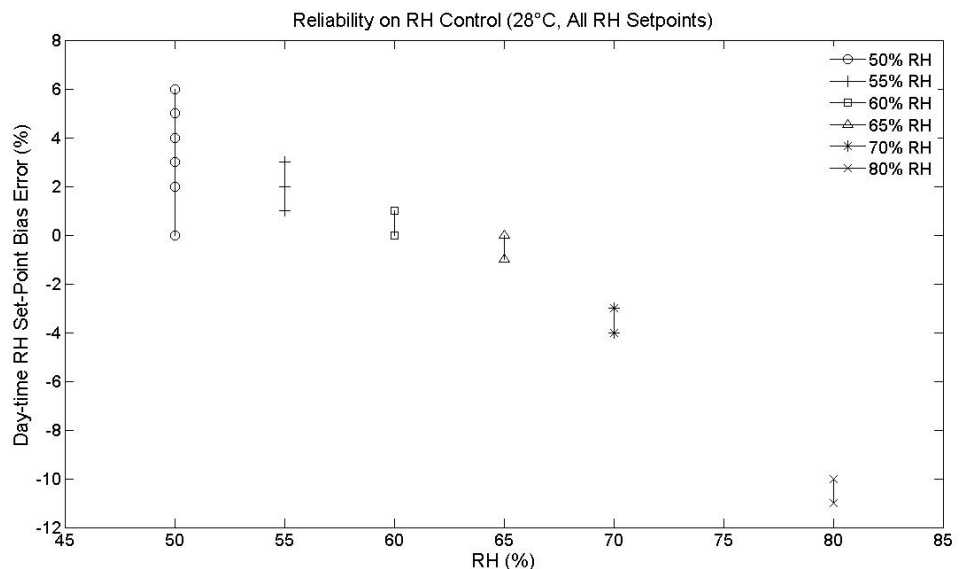


Figure 6.9: Bias RH Set-Point Error

There were substantial bias set-point errors on the room RH. At 80% set-point, there was indication that the system was actually operating between 69% and 70% RH. At 70% RH set-point, the system actually operates at between 66% and 67%. The zero bias errors for solutions at 60% and 65% suggest the maximum controllability of the system at those set-points. At 55% set-point, the HVAC system was starting to be struggling to maintain control on the room RH. The situation was getting worse at 50% RH set-point, when the bias error was observed to be at the highest of 6% and only reduced to 1% at the expense of very high HVAC energy use. Comparing the bias errors of the optimised solutions with the base case, the latter was observed to be having the highest margin, indicating that the HVAC system was not able to maintain control on the room RH at 50% set-point. The optimised HVAC system operated towards the more controllable range of 60 to 65% room RH.

The parameter is another indicator that the RH being the main driving factor on the balance between low energy use and the low mould risk. The error margin for the base case also suggests that the system was not able to maintain control on room RH and was operating above the design limit.

6.3.4 Air Flow Rate Optimisation Results

The results of the total energy and mould risk in relation to air flow rate were shown in **Table 6.5**. The range was set between $0.36 \text{ m}^3/\text{s}$ (12 h^{-1}) and $0.72 \text{ m}^3/\text{s}$ (24 h^{-1}), which also functioned as the constraint. The $0.36 \text{ m}^3/\text{s}$ figure was taken as the lower bound of the range based on the requirement by the ASHRAE and CDC Guidelines for design of new isolation room to prevent cross contamination, and must not fall beyond this rate.

It is also important to recall that the optimisation and the simulation also took into account the parameters of infiltration that is set to be constantly present at 0.6 h^{-1} and the opening of

windows set between 10.00 a.m. and 6.00 p.m. Even though the parameters were estimation and they were not calculated in detail, it was sufficient in order to mimic as closely as possible the actual operations of an isolation room.

Table 6.5: Air flow rate and energy use for optimised solutions and the benchmark design

Solution	Supply Air Flow Rate (m ³ /s)	Outdoor Air Flow Rate Fraction (m ³ /s)	E_{Fan} (kWh)	$E_{Re-Heat}$ (kWh)	E_{DXCoil} (kWh)
1	0.72	0.36	2509	12615	27478
2	0.67	0.36	2335	12226	26745
3	0.55	0.36	1917	11483	24487
4	0.47	0.36	1638	10419	22801
5	0.39	0.36	1359	9497	21769
6	0.39	0.36	1359	9171	20832
7	0.36	0.36	1255	8082	20141
8	0.6	0.36	2091	7318	19876
9	0.43	0.36	1498	7162	18422
10	0.4	0.36	1394	6877	17895
11	0.37	0.36	1289	5717	16672
12	0.36	0.36	1255	5587	16487
13	0.72	0.36	2509	3972	16174
14	0.6	0.36	2091	3700	14568
15	0.51	0.36	1777	4186	14381
16	0.37	0.36	1289	3324	12999
17	0.36	0.36	1255	3316	12849
18	0.72	0.36	2509	1632	12977
19	0.72	0.36	2509	1341	12013
20	0.6	0.36	2091	1229	10658
21	0.36	0.36	1255	1368	9696
22	0.36	0.36	1255	1979	9027
23	0.63	0.36	2195	195	9064
24	0.71	0.36	2474	233	8136
25	0.36	0.36	1255	272	7620
26	0.51	0.36	1777	421	6929
27	0.48	0.36	1673	0	5938
28	0.36	0.36	1255	0	5077
Benchmark	0.37	0.37	1289	6193	23592

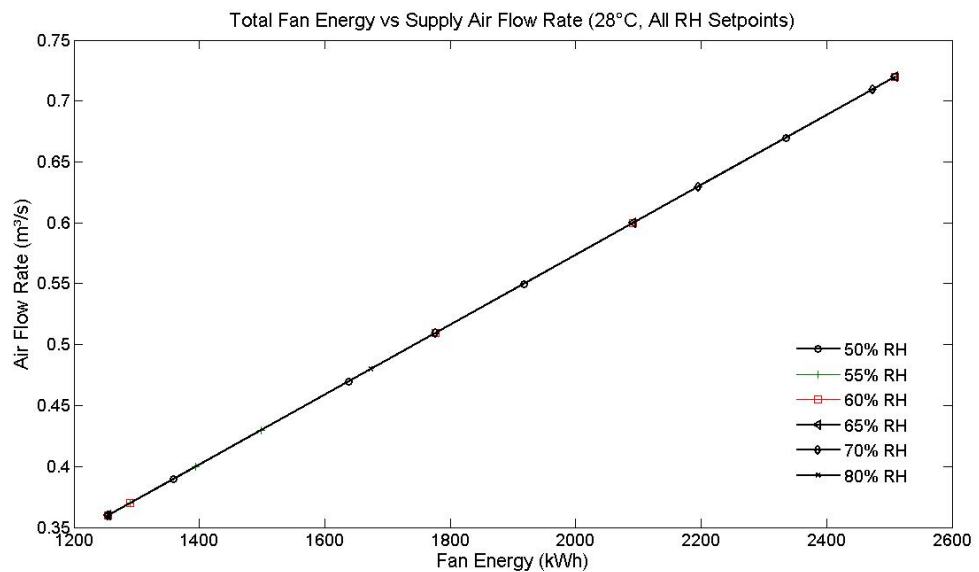


Figure 6.10: Relationship between Supply Air Flow Rate and Fan Energy

The data is shown in a graphical form in **Figure 6.10**. The supply air flow rate was found to be directly proportional to the fan energy for all the RH set-points. The case is true for the total energy is considered, as in **Figure 6.11**, and it appears that the balance was achieved at the 60% RH set-point. However, increasing ventilation rate was having little impact on the mould risk on the internal surface, shown in **Figure 6.12**, where only slight reduction of the risk metric for substantial energy expense. Given any combination of the temperature and RH, the air flow rate is a key driver to the energy consumption. Therefore, application-wise, there was no incentive to increase the ventilation rate, even though re-circulation was applied and increased, as it means installing bigger fan, thereby increasing fan energy cost to the system.

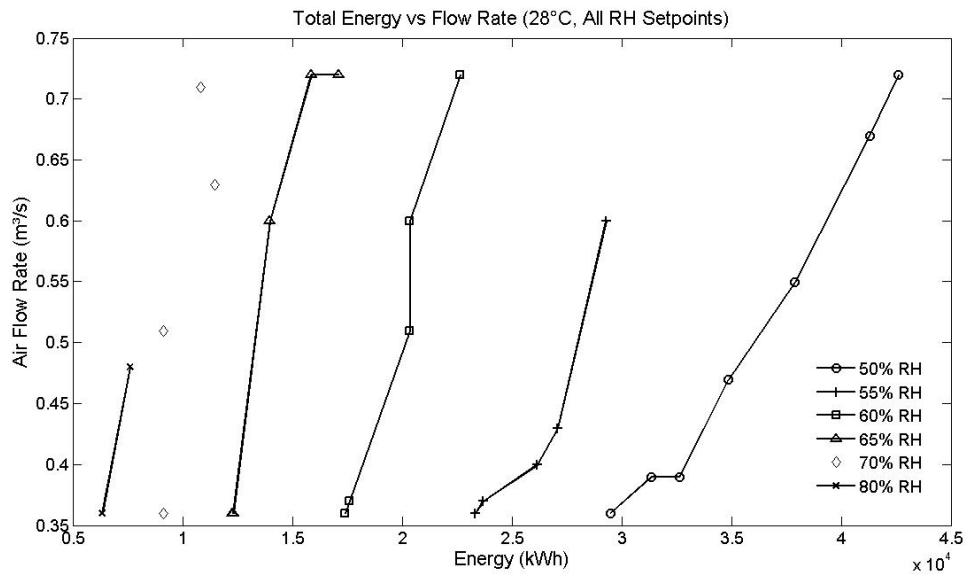


Figure 6.11: Relationship between Total Energy Use and the Supply Air Flow Rate

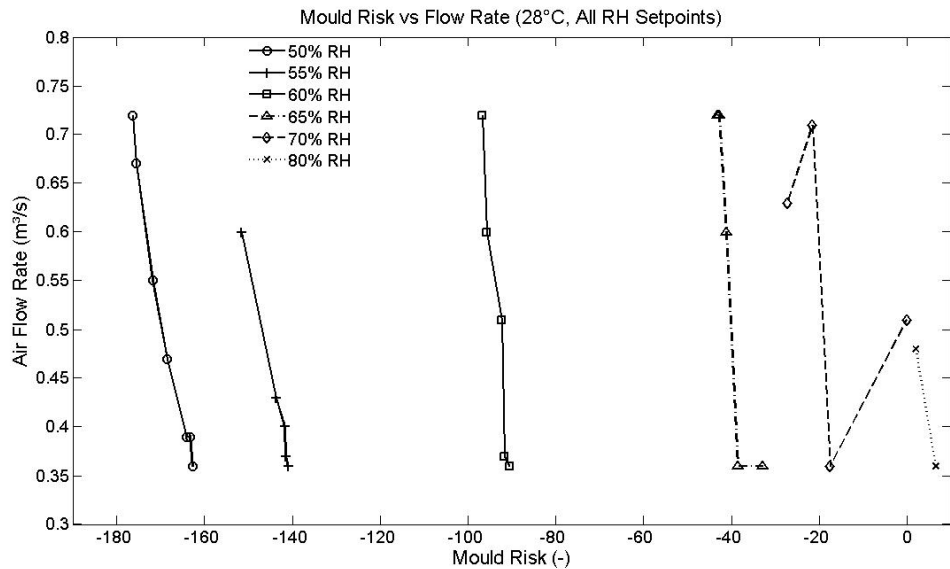


Figure 6.12: Relationship between Mould Risk and Supply Air Flow Rate

An anomaly that occurs at 70% RH set-point, represented by two parallel lines, is worth further scrutiny. Even though the fan energy increases with higher supply air flow rate from 0.36 to 0.71 m³/s, it does not match with the fluctuating re-heat energy

and cooling energy. The set of data was then re-arranged to investigate whether a pattern is present, as shown in **Table 6.6**.

Table 6.6: Data for 70% RH set-points

Flow Rate (m ³ /s)	Mould Risk (-)	Fan Energy (kWh)	Re-heat Energy (kWh)	Cooling Energy (kWh)	Bias RH Set-point Error (%)	Actual RH (%)
0.36	-17.51	1255	272	7620	-3	67
0.51	0.01	1777	421	6929	-3	67
0.63	-27.20	2195	195	9064	-4	66
0.71	-21.51	2474	233	8136	-4	66

The flow rate was divided in relation to the bias error, according to the actual room RH the system was running at. The solutions were found to be operating at two conditions of 66% and 67% RH, therefore analysis was done within those two separate conditions. It indicated a trend of increasing fan energy and re-heat energy costs as higher volume of air was cooled and dehumidified. The higher risk mould growth was the result of less energy used by the cooling coil in removing the moisture from the supply air. The moisture then entered the zone to be absorbed by the internal surfaces. Exactly why the cooling energy is lower than it was expected to be when the supply air flow rate gets higher is a subject for further investigation.

6.3.5 Wall Construction Optimisation Results

There were three (3) types of wall construction considered. Wall Type 1 is a single brick wall with cement plastered on the external whereas Types 2 and 3 are double-walled. Further description of the wall assemblies were given in **Chapter 5**. For optimisation purposes, the wall types were categorised as

discrete variables and were assigned identifiers 0, 1 and 2, respectively, and the result shown in **Table 6.7**.

Table 6.7: Wall Construction Optimisation Results

Solution	Total Energy (kWh)	Mould Risk	External Wall Type	Internal Wall Type
1	42602	-176.39	2	2
2	41306	-175.56	2	2
3	37887	-171.81	2	2
4	34858	-168.52	2	2
5	32625	-164.03	2	2
6	31362	-163.65	2	2
7	29477	-162.74	2	2
8	29285	-151.55	2	2
9	27082	-143.73	2	2
10	26166	-141.79	2	2
11	23678	-141.57	2	2
12	23329	-140.94	2	2
13	22655	-96.69	2	2
14	20358	-95.73	2	2
15	20344	-92.24	2	2
16	17612	-91.66	2	2
17	17419	-90.58	2	2
18	17118	-43.19	2	2
19	15863	-42.76	2	2
20	13977	-41.13	2	2
21	12318	-38.50	2	2
22	12260	-32.76	2	2
23	11454	-27.20	2	2
24	10844	-21.51	2	2
25	9147	-17.51	2	2
26	9127	0.01	2	2
27	7611	2.02	2	2
28	6332	6.54	1	2

The results has shown that Wall Type 3, which consists of double brick wall with polyurethane (PU) as insulation and the water vapour retarder at the outermost layer, contributes to the lowest energy use and lowest risk of mould growth compared to wall Types 1 and 2. The PU insulation between the double-brick

wall prevents heat transfer across the wall assembly from the outside environment into the isolation room. Since the climate is hot and humid, the application of the water vapour retarder prevents the transfer of moisture from the outside environment across the wall assembly, which would have increased the moisture content of the internal wall surfaces and increased the HVAC system energy consumption in removing moisture other than that is designed for. The selected wall construction is in agreement with the recommendation by the Public Works Department Malaysia Design Guideline (2009).

Likewise for the internal wall, the wall type that performs best is the wall Type 3. The internal wall divided the isolation room and the ward, which is non-conditioned. Therefore, there is a difference in moisture content between the two zones. Having the water vapour retarder at the outermost layer prevents moisture transfer across the wall assembly from the ward into the isolation room.

6.3.6 Window Size Optimisation Results

Recalling the window dimension optimisation in **Chapter 5**, the height of the window was made constant at 1.8 metres while the width of the window was optimised by selecting five (5) width differences. The smallest window width is 0.6 metre (width difference = 0 m) followed by 1.0 m (width difference = 0.4 m), 1.15 m (width difference = 0.55 m), 1.3 m (width difference = 0.7 m) and the biggest window width is 1.6 metre (width difference = 1.0 m). The window width differences were assigned as discrete variables with identifiers 0, 1, 2, 3 and 4, respectively. The relative impact of the window area on both the total energy consumption and the mould risk are shown in **Table 6.8**.

Table 6.8: Window Size Optimisation Results

Solution	Total Energy (kWh)	Mould Risk	Window Width Difference
1	42602	-176.39	4
2	41306	-175.56	2
3	37887	-171.81	3
4	34858	-168.52	3
5	32625	-164.03	4
6	31362	-163.65	1
7	29477	-162.74	4
8	29285	-151.55	4
9	27082	-143.73	0
10	26166	-141.79	0
11	23678	-141.57	2
12	23329	-140.94	4
13	22655	-96.69	4
14	20358	-95.73	4
15	20344	-92.24	4
16	17612	-91.66	4
17	17419	-90.58	0
18	17118	-43.19	4
19	15863	-42.76	4
20	13977	-41.13	3
21	12318	-38.50	4
22	12260	-32.76	3
23	11454	-27.20	4
24	10844	-21.51	4
25	9147	-17.51	0
26	9127	0.01	2
27	7611	2.02	3
28	6332	6.54	0

The data in Table 6.6 was given graphical representation in **Figures 6.13 and 6.14.**

the energy use and the risk of mould growth are insensitive to the changes in the window area. The impact of the window area on energy use is considered miniscule during night-time since the major heat components, such as the solar heat gain, are absent. An explanation to this insensitivity is the orientation of the window which is on the North wall. The solar intensity at the north orientation is less compared to that on the east and west. Thus, the solar heat gain and conduction heat gain components through the window at the north orientation is also less compared to, say, the west orientation. However, since the location of the window is not optimised, the impact of window location on the balance between low energy use and low mould risk is also a subject for further investigation.

6.3.7 Roof Type Optimisation Results

In this research, only two types of roof were considered. It was observed that that the roof Type 2, which consists of Autoclaved Aerated Concrete (AAC), water vapour retarder, sprayed PU, 50 mm of air layer and interior gypsum board, performs better than roof Type 1 which only consists of concrete, air layer and interior gypsum board. The roof construction represents an exposed roof, or it can also represent the ceiling of the isolation room, above which there is an assumed non-conditioned area. For optimisation purposes, the roof types were categorised as discrete variables and were assigned identifiers 0 and 1, respectively.

The results in **Table 6.9** suggested that, similar to the walls, the application of the vapour retarder and the sprayed PU prevents the heat and moisture transfer across the roof assembly from outside environment or non-conditioned area into the isolation room. This type of construction is also in agreement with the recommendation by the Public Works Department Malaysia Design Guideline (2009).

Table 6.9: Roof Construction Optimisation Results

Solution	Total Energy (kWh)	Mould Risk	Roof Type
1	42602	-176.39	1
2	41306	-175.56	1
3	37887	-171.81	0
4	34858	-168.52	0
5	32625	-164.03	1
6	31362	-163.65	0
7	29477	-162.74	1
8	29285	-151.55	1
9	27082	-143.73	1
10	26166	-141.79	1
11	23678	-141.57	1
12	23329	-140.94	1
13	22655	-96.69	1
14	20358	-95.73	1
15	20344	-92.24	1
16	17612	-91.66	1
17	17419	-90.58	1
18	17118	-43.19	1
19	15863	-42.76	1
20	13977	-41.13	1
21	12318	-38.50	1
22	12260	-32.76	0
23	11454	-27.20	1
24	10844	-21.51	0
25	9147	-17.51	1
26	9127	0.01	0
27	7611	2.02	0
28	6332	6.54	0

6.3.8 Mould Risk Results

The total mould risk on the surfaces, the extent of which the risk magnitude lies above or below the threshold growth limit curve is shown in **Table 6.10**.

Table 6.10: Mould risk components of the optimised solutions

Solution	Mould Risk	South Wall Risk	West Wall Risk	North Wall Risk	Internal Wall Risk	Roof Risk
1	-176.39	-35.1	-35.3	-35.2	-35.1	-35.6
2	-175.56	-34.9	-35.1	-35.1	-35.0	-35.5
3	-171.81	-34.2	-34.4	-34.4	-34.3	-34.5
4	-168.52	-33.6	-33.8	-33.7	-33.6	-33.9
5	-164.03	-32.6	-32.9	-32.8	-32.7	-33.1
6	-163.65	-32.6	-32.8	-32.8	-32.6	-32.9
7	-162.74	-32.3	-32.5	-32.4	-32.3	-33.2
8	-151.55	-29.8	-30.3	-30.1	-29.9	-31.5
9	-143.73	-28.3	-28.8	-28.7	-28.4	-29.6
10	-141.79	-27.9	-28.4	-28.3	-28.0	-29.2
11	-141.57	-27.7	-28.2	-28.1	-27.8	-29.7
12	-140.94	-27.6	-28.1	-28.0	-27.7	-29.6
13	-96.69	-18.3	-19.1	-18.9	-18.5	-21.9
14	-95.73	-18.1	-19.0	-18.8	-18.3	-21.5
15	-92.24	-17.7	-18.5	-18.3	-17.8	-19.9
16	-91.66	-17.3	-18.1	-17.9	-17.5	-20.8
17	-90.58	-17.1	-17.9	-17.8	-17.3	-20.6
18	-43.19	-7.8	-8.3	-8.2	-8.1	-10.8
19	-42.76	-7.7	-8.3	-8.1	-7.9	-10.8
20	-41.13	-7.4	-8.0	-7.8	-7.5	-10.4
21	-38.50	-6.9	-7.5	-7.3	-7.0	-9.7
22	-32.76	-6.3	-6.8	-6.7	-6.4	-6.6
23	-27.20	-4.8	-5.2	-5.1	-4.9	-7.2
24	-21.51	-4.0	-4.3	-4.2	-4.0	-4.9
25	-17.51	-3.0	-3.3	-3.3	-3.1	-4.8
26	0.01	-2.8	-3.0	-3.0	-2.8	0.0
27	2.02	0.4	0.3	0.3	0.4	0.5
28	6.54	1.5	1.3	1.3	1.1	1.2
Benchmark	0.09	0.0	0.0	0.0	0.0	-27.6

To recall the developed mould growth risk model based on that by Sedlbauer (2001), the minimum mould growth threshold limit curve corresponds to the generalized Lowest Isoleth for Mould, below which there is no biological activity takes place on a building surface. The duration for the threshold limit curve is approximately 32 days, after which mould spore germination

occurs. The maximum mould growth threshold limit curve corresponds to the 1-day limit curve, above which the spore germination takes place less than 1 day.

Any surface condition that lie between these two curves were calculated for its mould risk and the duration for mould spore germination using the expression of **risk = time interval /days x 24**, where the time interval, that is the last month of the simulation run period, which is 30 days calculated in hours and days representing the period after which the mould spores would have germinated.

Taking the mould risk of 2.02 at 28°C/80% RH set-point as an example, the duration after which mould growth takes place is $1/\text{days} \times 720/24 = 2.02$, $\text{days} = (30/2.02) = 14.8$ days. This is equivalent to a 15-day period after which until 32 days, the mould growth has already occurred on any of the internal wall surface.

Conversely, if the mould risk is computed as a negative, it indicates the magnitude above the 1-day limit curve and is added to the distance between the minimum and maximum threshold curves. The total distance will be that below the minimum threshold curve. Therefore, the solution at 28°C/50% RH set-point having the mould risk of -176.39 has the metric of $-176.39/30 = -5.9$ days

A few solutions present mould risks. It was observed that the total mould risks were highest at the room conditions of 28°C/80% RH with the magnitudes of 2.02 and 6.54, with mould risks occurred at all the wall surfaces and the internal roof surface. At 70% RH set-point, the magnitude of the total mould risk was 0.01 as shown in the shaded area, indicating that the system was operating on the threshold limit. There was a likelihood that mould would grow on the roof surface after 32 days.

The small difference between outdoor RH and the indoor RH resulted in low cooling and dehumidification as well as no re-heating but the implication was that moisture was not sufficiently removed by the cooling coil as a result of complying with the high set-points. As the RH set-points were decreased, the mould risks for all the internal surfaces were also reduced, meaning the further down the conditions from the mould growth limit curve, the more reliable the system is in maintaining control of the conditions.

The result for the benchmark design is worth mentioning as it showed the total mould risk magnitude of 0.09. There was likelihood of mould growing on all internal surfaces except the roof, meaning the zone conditions were actually maintained at the threshold limit curve, rather than at the design set-points.

6.3.9 Energy Use Results

The results of the energy components of the HVAC system with respect to the optimised solutions are shown in **Table 6.11**.

Table 6.11: Energy Components of the Optimised Solutions

Solution	E_{Total} (kWh)	E_{Fan} (kWh)	$E_{Re-Heat}$ (kWh)	E_{DXCoil} (kWh)
1	42602	2509	12615	27478
2	41306	2335	12226	26745
3	37887	1917	11483	24487
4	34858	1638	10419	22801
5	32625	1359	9497	21769
6	31362	1359	9171	20832
7	29477	1255	8082	20141
8	29285	2091	7318	19876
9	27082	1498	7162	18422
10	26166	1394	6877	17895
11	23678	1289	5717	16672
12	23329	1255	5587	16487
13	22655	2509	3972	16174
14	20358	2091	3700	14568
15	20344	1777	4186	14381
16	17612	1289	3324	12999
17	17419	1255	3316	12849
18	17118	2509	1632	12977
19	15863	2509	1341	12013
20	13977	2091	1229	10658
21	12318	1255	1368	9696
22	12260	1255	1979	9027
23	11454	2195	195	9064
24	10844	2474	233	8136
25	9147	1255	272	7620
26	9127	1777	421	6929
27	7611	1673	0	5938
28	6332	1255	0	5077
Benchmark	31074	1289	6193	23592

At the 80% RH set-point, the total energy use was the minimum which comprised of only fan and DX coil cooling energy without re-heat, as shown in the shaded area. Since the RH was at 80%, substantial cooling was not required to dehumidify the outdoor air and no heating of the supply air is required.

Decreasing the zone RH set-points from 80% to 50% resulted in decreased mould risk. However, the penalty was the increase in re-heating energy since the cooling and dehumidifying process to achieve low room RH results in the air being overcooled towards the dew-point of the supply air. The implication is the freezing of the cooling coil of the DX system. There was a need to re-heat the overcooled air towards the room design temperature and RH.

Comparing the base case with the rest of the optimised solutions revealed that there was considerable cooling and re-heat energy use by the HVAC system to meet the 24°C/50% set-point.

6.3.10 Discussion

The presence of a number of Pareto optimal solutions has an advantage in providing building designers and owners with a decision making tool for design based on the priorities between two design goals. A decision can be made on whether to design with efficient building energy performance in mind and accept a compromise on the likelihood of mould growth on internal wall surfaces or to have a mould-free isolation room as the design objective and there is no constraint on the energy cost.

The optimal solutions in **Figure 6.15** were divided and grouped into design set-points. Of particular interest is the position of the base case solution as a reference point that lies above the Pareto front, indicating that in terms of the design objectives, it is dominated by all but a couple of the Pareto optimal solutions.

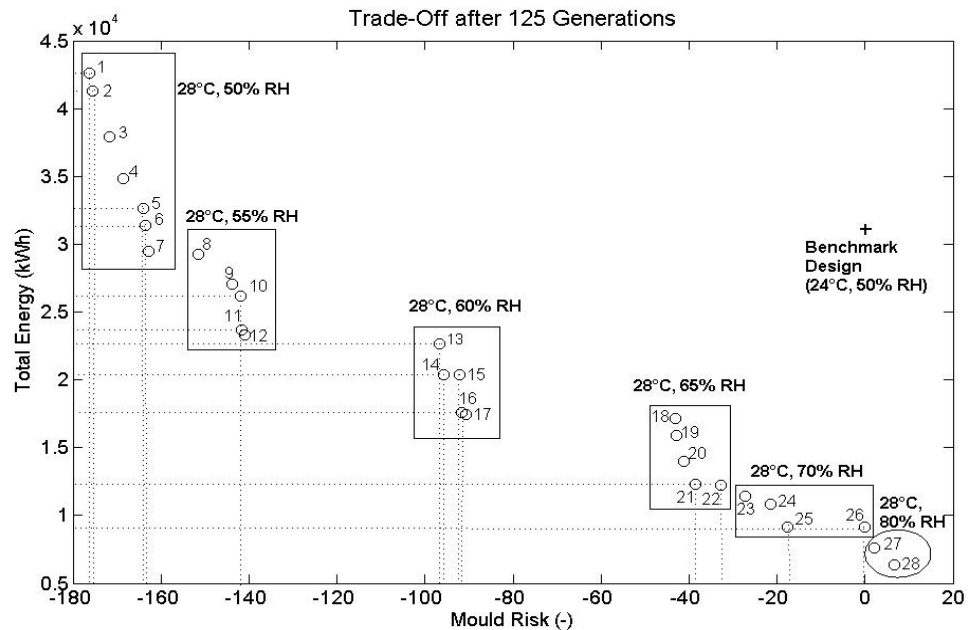


Figure 6.15: Pareto optimal solutions based on room set-points

Taking the room design conditions of 28°C/50% as an example, the points 1 to 7 represented solutions with different values for the same optimised variables; for the same design condition, a number of options are available. For these range of solutions, the total mould risks have very large negative number, meaning the zone conditions were operating far below the threshold mould growth limit curve. Therefore, there is likelihood that it would take more than 32 days for mould growth to occur on the internal surfaces. As the solutions move from 1 to 7, the total energy consumption required to maintain the zone condition decreases while at the same time the mould risks gradually increases.

The case is also true for other solutions in respective RH set-points until the design condition of 28°C/70% RH. The solution 26 at has the mould risk magnitude of 0.01, indicating that zone conditions are very slightly above the threshold mould growth limit curve. It suggests that 70% is the upper RH limit. At the end of the Pareto front in the ellipse, the solutions at 28°C/80%

RH operate at beyond the upper RH limit and the mould risks were present. Solution 28 provided the lowest total energy use but also the highest risks of mould growth.

The results of the base case has shown that operating at 24°C/50% RH incurred high energy consumption but the risk of mould growth was present at 0.09. It can be concluded at this point that the normal design practice was not optimum since it incurred high energy cost yet still there was a possibility of mould growth.

To illustrate, a number of solutions of interest in **Figure 6.14** were selected and compared. The differences in energy use and the magnitude of mould risks for these selected solutions were shown in **Table 6.12**.

Table 6.12: Differences in total energy and mould risk for neighbouring solutions

Solutions	ΔE (kWh)	Δ Mould Risk (-)
1 & 2	1296	0.83
5 & 6	1263	0.38
10 & 11	2488	0.22
13 & 14	2297	0.96
14 & 15	14	3.49
15 & 16	2732	0.58
21 & 22	58	5.74
25 & 26	20	17.5

Comparing solutions at point 1 or 2 revealed that they do not dominate each other since solution 1 has higher energy consumption while solution 2 has worse mould risk; in essence, both solutions have one design goal better off and one design goal worse off. Selecting 2 over 1 would result in 1296 kWh less energy used but an increase in magnitude of mould risk of

0.83. In this case, however, both the solutions have operating conditions at a considerable distance below the threshold mould growth limit curve, and thus the mould risk is regarded as a “second order” problem. If efficient building energy performance is preferred to indoor air quality with an acceptable miniscule increase in mould growth risk, then solution 2 is preferred. The case is similar for comparisons between points 5 and 6, 10 and 11, 13 and 14, and between 15 and 16. Comparisons between 14 and 15, as well as 21 and 22, were interesting since the difference in total energy consumed is only 14 kWh. However, the difference in magnitude of the mould risk is considerable, even though the solutions lie much further below the threshold limit. It does suggest that if the priority is to lower the risk as much as possible without incurring substantial energy cost, then the solutions 14 and 21 are preferred.

Solutions 25 and 26 are solutions where the zone conditions operate near and on the threshold limit above which mould would grow on internal surfaces. Selecting point 26 results in the likelihood of mould growth in 32 days but increasing the HVAC system energy by 20 kWh eliminates that risk. Therefore selecting solution 25 is a sounder step.

6.3.11 Summary

It was observed that the highest ranking Pareto optimal solutions operate at the room temperature set-point of 28°C which is higher than the recommended 24°C by the ASHRAE Standard (2008). The results suggest that low energy and low mould risk are driven by the room relative humidity set-point, and it was observed that the mould risk was detected on the threshold limit at 70% RH set-point, indicating 70% as the upper RH limit. The air flow rate is another driving factor for the total energy where the gradual increase in the ventilation rate, contributed to the increase in the fan energy.

The results from the construction optimisation showed that Wall Type 3, which consists of double brick wall with polyurethane (PU) as insulation and the water vapour retarder at the outermost layer, contributes to the lowest energy use and lowest risk of mould growth compared to wall Types 1 and 2. Having the water vapour retarder at the outermost layer prevents moisture transfer across the wall assembly from the outside environment as well as the non-conditioned ward into the isolation room. The roof Type 2, which consists of Autoclaved Aerated Concrete (AAC), water vapour retarder, sprayed PU, 50 mm of air layer and interior gypsum board, performs better where the application of the vapour retarder and the sprayed PU prevents the heat and moisture transfer across the roof assembly. It was also found that the energy use and the risk of mould growth is insensitive to the changes in window size.

Analyses were made on the daytime bias set-point error as an indication of the reliability of the system to maintain the design conditions. There was no bias error detected for the room temperature set-point, indicating the system was able to maintain control on room temperature at 28°C. The zero bias errors for solutions at 60% and 65% RH set-points suggest the limit of system control for the RH set-point is between 60% and 65%. The RH bias set-point error is another indicator that the RH set-point is the main driving factor to the balance between low energy use and the low mould risk. The base case was shown to be having the largest daytime bias RH set-point compared to other optimised solutions with 15%, meaning the isolation room was actually operating at 65% RH. This result suggests that the base case HVAC system was not able to maintain control on room RH and was operating above the design limit.

6.4 Selection Criteria

Based on the results analysed, it is now possible to use those results to form a set of criteria from which the selection can be made on a single most optimum solution, or a set of plausible solutions. The criteria for selection are as discussed in the following sub-sections.

6.4.1 Decision Making

Multi-objective optimization has the advantage that the Pareto set of solutions can be analysed to obtain an understanding of the problem characteristics. However, it has the possible disadvantage that a single solution must eventually be selected for construction. The decision as to which solution is selected is made from an understanding of the problem characteristics, as well as preferences not directly included in the optimisation (these often being of a subjective).

Given that there is only marginal risk of mould growth, it would be tempting to select a low energy use solution (perhaps even for a relative humidity set-point at or above the natural limit of 70% RH). However, given the uncertainty the quality of final construction it is likely that as the system performance deteriorated with age, that mould growth would occur. Conversely, there appears to be little reason to select a very high energy (low relative humidity) solution as mid-energy solutions are also associated with a low risk of mould growth.

Table 6.2 indicated that the best control of humidity is achieved for a relative humidity setpoint of 60%RH. **Figure 6.3** also indicated that the solutions for 60% RH are isolated in term of their position on the risk characteristic, and are in a region away from the point of inflection after which the risk tends towards mould growth. Given the preference (if possible), to use a 100% outdoor air a flow rate of 0.36 m³/s is also be selected here as being the choice for construction.

Table 6.13: Optimised and Base Case Designs

Design Parameter	Unit	Optimised Design	Base Case Design
Temperature set-point	(°C)	28.0	24.0
Night setback temperature set-point	(°C)	28.0	28.0
Relative humidity set-point	(%)	60	50
Wall construction type	(-)	Type 3	Type 1
Ceiling construction type	(-)	Type 2	Type 1
Window area	(%)	20.0	9.0
Energy Use	(kWh)	17421	30313
Mould Risk	(-)	-16.5	0.05
Temperature control error bias	(°C)	0	1
Relative humidity control error bias	(%)	1	15

The single solution for construction is given in **Table 6.13**, together with the standard benchmark design solution. Not only does the optimised solution have a 43% lower energy use, but it is associated with a significantly lower risk of mould growth. The optimised solution is also able to maintain control of both the zone temperature and relative humidity, whereas this is not the case for the base case design. This result suggests that the reason that mould growth occurs for the standard design is that the system is unable to maintain control of the zone relative humidity (the higher zone humidity leading to mould growth).

6.4.2 Suitability for Thermal Comfort

Although all solutions are considered acceptable since they are a result of the specified variable range-with respect to the balance between thermal comfort and energy efficiency, the room temperature set-point of 28°C is on the upper limit of the

range that is where the energy consumption is the least. Although thermal comfort is not the objective of this research, the results are in agreement with the proposed thermal comfort range of 25.2 to 28.3°C for tropical hospitals by Yau and Chew (2009).

6.4.3 Controllability of Temperature and RH

It is critically important for the isolation room temperature and relative humidity to be consistently maintained to ensure the indoor air quality is maintained. Therefore, HVAC system must be ensured that performs as designed and control is maintained on the room conditions so as not result in the deteriorating of the indoor air quality. The results have shown that the HVAC system was struggling to maintain the normal design room RH at 50%, with the bias error of up to 6% and also struggling to maintain control at the maximum room RH range. The converging patterns of the bias error at both sides of the Pareto solutions suggest that the HVAC system performs most optimum at the conditions between 60 and 65% RH where it has full control.

6.4.4 System / Building Capital Costs

One feasible strategy to reduce the HVAC system capital cost is to operate at high room set-points with reduced re-heater size, or possibly eliminating its use in the HVAC system. The implication is the reduced or nil use of re-heat energy as were shown by the solutions at 28°C/70% or 28°C/80% set-points. Caution should be taken, however, that 70% is the upper RH limit permissible. Going higher than the limit means operating in conditions within the mould growth threshold curve that suggest presence of mould growth on internal surfaces.

6.4.5 Comparisons against Normal Practice

The existing guidelines required that 100% fresh air is required for the purpose of ventilating the isolation room and entirely exhausting the room air to outside environment. The minimum ventilation rate is 12 h^{-1} ($0.36 \text{ m}^3/\text{s}$) and the indoor design condition of $24^\circ\text{C}/50\% \text{ RH}$ to be maintained continuously. The normal design practice of the isolation room in hot and humid countries like Malaysia was based on these requirements that are suited for temperate countries. However, as was shown in previous results, the base case solution incurred very high energy use and still not able to maintain the room RH with the bias error of 15%, indicating that in the context of energy reduction and minimising mould risk, the base case solution is not a feasible option. On the other hand, the Pareto solutions have shown that saving energy and minimum mould risk can be achieved when operating at higher room set-points. These results can be used as comparison against what has been used as normal practice in HVAC system design for isolation room.

The optimisation results have shown that increasing the ventilation rate also increases the total energy. Re-circulation is possible as a strategy to minimise the mould risk without the reducing the outside air flow rate. However, the reduction of mould risk is very small for the given range. More importantly, the supply air flow rate is directly proportional to the fan energy cost. Therefore, there is not much incentive in operating at higher ventilation rates.

6.4.6 Proximity of Solutions to the Mould Risk

Another important criterium is the proximity of the solutions to the positive and negative mould risks. As was shown in the results, operating at very high set-points carry the risk of mould growing on the surface since there is moisture entering into the zone as a result of high RH set-point. The risk is taken as the

product of the fraction of an hour multiplied with 1/days, in this case the 'days' refer to the day curve with the number of days taken for mould to grow. Taking an example of the solution at 28°C/80% RH with the mould risk index of 6.54, it is equivalent to $30 \text{ days}/6.54 = 4.58 \text{ days}$. This was translated to the 4 day growth limit curve. Mould growth may not necessarily occur after four successive days of surface exposure, but it would already have taken place within 30 days of operation. On the other hand, solutions at 28°C/50% RH have the mould risk of - 176.39, much beyond the minimum threshold curve of 32 days. The risk of mould growth is much remote the lower the room set-points are.

6.5 Chapter Summary

This chapter analysed the results from the simulation, mould risk analyses, as well as the optimisation of isolation room alternative design. The analyses have shown that through optimisation, a Pareto front existed indicating a balance between low HVAC energy use and low mould risk. The HVAC system was shown to be able to provide control on the room conditions of 28°C and the RH set-point between 60% and 65%. However, the upper RH limit of 70% was observed, and there was mould risk present at the design conditions of 28°C/80% RH. The results indicated that RH set-point is the main driving factor. Another driving factor was the air flow rate where increasing the amount of supply air increases the fan energy. The results also have shown that the benchmark design based on normal practice was not suitable for the hot and humid climate since high energy consumption was incurred but the HVAC system was not able to control the room condition that resulted in a likelihood of mould growth. The next chapter revisits the aims and objectives of the research and compare them with the results analysed, discusses the limitations and offers a few recommendations for further research.

Chapter 7

Conclusion and Recommendation

The previous chapter analysed the results from the simulation, mould risk analyses, as well as the optimisation of isolation room alternative design. Analyses were made with regards to the possibility of a trade-off between two conflicting design goals, namely minimising HVAC energy use and minimising the risk of mould growth on indoor surfaces. This chapter takes a look back at the aims and objectives of the research and compare them with the results analysed, and in the process attempts to answer a few issues raised. It also discusses the limitations and offers a few recommendations for further research. The chapter ends with concluding remarks. The overall structure of this chapter is shown in **Figure 7.1**.

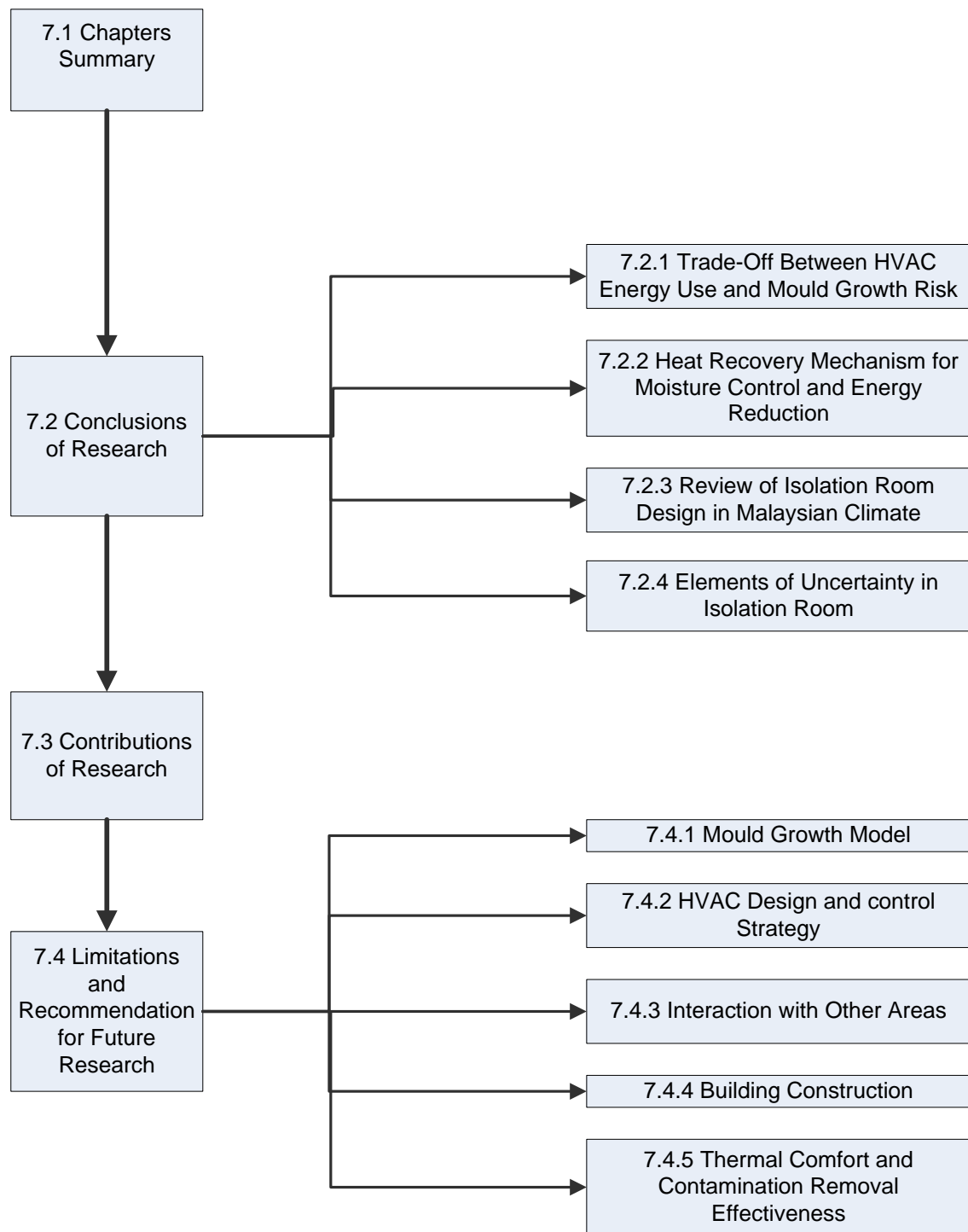


Figure 7.1: Structure of Chapter 7

7.1 Chapters Summary

Chapter 1 gave a background on the design and operation of isolation rooms for hospital buildings located in hot and humid climates, where the normal practice of was the continuous operation of the HVAC system in order to maintain indoor air quality. The room design parameters are 24°C and 50% RH which were based on the design standards and guidelines applicable for temperate countries such as the United Kingdom. The implication was that these rooms have HVAC system operating at high energy consumption, resulting in high carbon emissions. Apart from the HVAC system design, climate has large influence on the choice of construction materials for a building. There was a need, to minimise the high energy use of the HVAC systems that serve the critical areas in tropical hospitals, and at the same time minimising the risk of mould growing in these areas which may be detrimental to the health of occupants. The chapter also describes the aim of the research, which is to investigate the minimisation of both the energy use and risk of mould growth in hospital buildings located in a tropical climate such as Malaysia, while identifying the relationship between these two criteria- through the use of model-based optimisation.

Chapter 2 discussed the factors leading to mould growth in buildings and the extent to which the "risk" of mould growth in buildings, and procedures for predicting the risk, were studied in existing literature. An overview of existing modelling approaches available in predicting mould growth was given in a literature survey, revealing several approaches in evaluating mould growth risk, such as applying a threshold value to surface relative humidity, or devising a mould index based on visual observation. In the context of the research, it was required that the mould growth model be able to (i) incorporate temperature, surface RH and time taken for mould species to grow, since the three parameters interlink, (ii) the surface temperature and surface RH ranges be suitable to the hot and humid climate, and (iii) be able to take into account all the mould species that thrive in that climate. The approach using Lowest

Isopleths for Mould (LIM) developed by Sedlbauer (2001) was selected since it fulfilled the requirements.

The development of building optimisation, specifically building construction, HVAC system, and HVAC system operation was also covered. Current design practice for hospital design in Malaysia and the comparison with measured performance in available literature were discussed –It was observed that there was no consensus among the international design standard and guidelines with regards to the indoor conditions for the isolation rooms. Furthermore, there is neither available standard for design and performance of Malaysian hospitals, nor is there specific researches done on isolation room energy performance in Malaysia. In consequence, the isolation rooms in Malaysian hospitals are designed using available guidelines and standards that are not actually taking into account the local climate. Current research on isolation room design were mostly focused on improving the effectiveness of ventilation in preventing cross-contamination and increasing thermal comfort of occupants.

Chapter 3 gave a background study on the performance of Building Performance Simulation (BPS) programs and selected the BPS based on its ability to (i) analyse and evaluate the dynamic thermal heat transfer, moisture transfer and storage in building materials, (ii) to simulate the impact the HVAC system performance and controls have on the modelled zone and its surface conditions, and (iii) able to take into account the uncertain parameters such as infiltration. An integrated approach, that is the whole building simulation, was used in which it combines the mass and heat balance with hygrothermal analysis. This approach gives sufficient accuracy with lower computing cost, particularly processing time, compared to the combination of two (2) independent simulation programs, or co-simulation. The EnergyPlus program was selected for the research due to its features that met the required abilities.

Multi-objective optimisation problem has two goals; the first was to find a set of solutions as close as possible to the Pareto-optimal front, while the second was to find a set of solutions as diverse as possible. Since the research uses a real-world problem as a base case, and real world problems usually have more than one objective functions, multi-objective optimisation approach was selected. The genetic algorithm (GA) search method was selected due to its ability to capture a number of solutions on a single run of simulation. In order to create a more diverse population of solutions, the genetic algorithm operators, such as the tournament selection, uniform crossover and the mutation operators are used. The NSGA-II, which was a variant of GA, was selected because of its fast sorting and good archiving of non-dominated solutions. The interfacing between the NSGA-II and the simulation output from EnergyPlus was given further description.

Chapter 4 gave a further explanation on the selected mould growth model by Sedlbauer (2001), a brief description of which was given in **Chapter 2**. The selected generalised mould growth limit curve was based on the selected mould hazard class B/C, and termed as Lowest Isoleth for Mould (LIM), below which there is no biological activity taking place. The LIM was re-created using exponential curve-fit to represent the threshold curve above which there is high likelihood of mould growth. The surface temperature range of interest was limited to between 20 and 30°C to take into account the corresponding actual operating room temperature range in tropical hospitals. Four months of simulation period was run, from which the risk of mould growth was calculated using the data on the last month.

Two modifications were made in order to predict the degree to which there is a risk of mould growth as well there being a risk, namely (i) by mirroring the germination isopleths about the Limit isoline and treating conditions below the Limit isoline as having a negative germination time, and (ii) by taking into account the transient, rather than static, surface temperature and relative humidity.

The characteristics of the extended mould risk model were also described, namely (i) that the normal limit for the degree of germination (denoted as 1.0) is not applied since the measure of risk varies with all surface conditions, (ii) the risk of mould growth is more sensitive to changes in surface relative humidity than the changes in surface temperature, and (iii) the risk model is not continuous near the Limit isoline. The model was then interfaced with the EnergyPlus where the data from simulation output was fed into the model for mould risk analysis.

Chapter 5 described in full detail the performance of a base case isolation room, based on the normal design practice. In the context of simulation period, the justification of using monthly period rather than the annual period was given. The Malaysian climate is constantly hot and humid throughout the year; therefore, monthly simulation sufficiently represents the climate and also reduces simulation time. Another observation was that the zone envelope tends to stabilise after the first four months. Thus, instead of running simulation a full year simulation, a compromise was made to run the simulation for four months and the zone analysis was done using the final month. The EnergyPlus program explained in **Chapter 3** and the extended mould growth model described in **Chapter 4** were then incorporated to evaluate the performance of the base case design, the HVAC system and its operation to investigate the mould growth risks on the surfaces in the isolation room, and the energy consumption of its HVAC systems designed according to standard practice. Uncertainty parameters were included in deterministic manner to assess their impact on the building performance, such as scheduled window opening for a few hours during day-time and fixing the outdoor infiltration at 0.5 h^{-1} to be constantly available during operation. Comparison was also made between different construction types. Results have shown that the indoor conditions based on normal design practice were not ably maintained by the HVAC system where the room RH was found to be above 70% for most of the four-month simulated

period. There was implication that mould growth on internal surfaces is likely to occur.

An alternative design was proposed, its performance was simulated and mould growth risk on the surfaces was analysed. Heat recovery, initially not considered in the base case, was incorporated into the HVAC system. The problem variables were also defined, namely the room temperature set-point range (between 24 and 28°C), RH set-point range (between 50 and 80%), and the air flow rate (between 0.36 and 0.72 m³/s). The construction parameters defined for optimisation were wall types, glazing area, and ceiling type.

Chapter 6 analysed the results from the simulation, mould risk analyses, and the optimisation of isolation room alternative design. There are three elements in the analysis of the solutions; the first element is the analysis of the trade-off between system energy use and the risk of mould growth; the second element is the analysis of the variation in the problem variables; and the final element is the analysis of building performance through derived quantities.

7.2 Conclusions of Research

To recap, the aim of this research is to investigate a relationship between minimising energy use and minimising mould growth risk in tropical hospitals using simulation and optimisation, with special attention to the isolation rooms in Malaysian hospitals. This section gives a conclusion on the results and analyses from the simulation and optimisation of the alternative design in Chapter 6 and compares them against that aim.

7.2.1 Trade-Off between HVAC Energy Use and Mould Growth Risk

The results in **Chapter 6** have shown that a trade-off exists between the low energy use of the HVAC system and the low mould risk.

The comparison between the optimised solutions and the standard benchmark design solution has shown that, not only do

the optimised solutions have lower energy use, they are also associated with a significantly lower risk of mould growth. The optimised solution is also able to maintain control of both the zone temperature and relative humidity, whereas this is not the case for the benchmark design. This result suggests that the reason that mould growth occurs for the standard design is that the system is unable to maintain control of the zone relative humidity (the higher zone humidity leading to mould growth). The results also indicated that the room upper RH limit is 70% and suggests that RH was the main driver to the energy use.

The measure of reliability for the HVAC system on the room condition was measured by its ability to maintain control of the room design set-points. The RH bias set-point error is another indicator that the RH set-point is the main driving factor to the balance between low energy use and the low mould risk. The optimisation results indicated that the best control of humidity is achieved for a relative humidity set-point of 60%RH. It is also indicated that the solutions for 60% RH are isolated in term of their position on the risk characteristic, and are in a region away from the point of inflection after which the risk tends towards mould growth.

The air flow rate was another factor influencing the relationship between low energy use and low mould risk. Given the preference, a 100% outdoor air flow rate of $0.36\text{m}^3/\text{s}$ is recommended as the choice for construction.

A double brick wall with polyurethane (PU) as insulation and the water vapour retarder at the outermost layer is recommended since it contributed to the lowest energy use and lowest risk of mould growth. Having water vapour retarder at the outermost layer prevents moisture transfer across the wall assembly from the outside environment as well as the non-conditioned ward into the isolation room.

For roof construction, a layer consists of Autoclaved Aerated Concrete (AAC), water vapour retarder, sprayed PU, 50 mm of air layer and interior gypsum board is recommended since the vapour retarder and the sprayed PU prevents the heat and moisture transfer.

7.2.2 Heat Recovery Mechanism for Moisture Control and Energy Reduction

Present design practice of the isolation room in Malaysia follows strictly the standards and/or guidelines, such as those by ASHRAE, which are more applicable in the temperate countries. In order to validate the design practice, the performance of a single-zone isolation room based on actual construction in Malaysian hospitals was simulated using EnergyPlus. The HVAC system in the simulation was based on the actual DX system installed in the isolation rooms in the hospitals in Malaysia. Simulation results suggest that there was small deviation for room temperature from design room temperature of 24°C but there was big deviation for room relative humidity (RH_{room}) from the 50% design room RH. The research has shown that the current design practice does not work.

The total energy results suggest that the inclusion of enthalpy heat recovery in the HVAC system is an influential factor in maintaining room RH, where moisture was removed more successfully rather than relying on the DX cooling coil alone to do the job. This results in the energy consumption of the DX cooling coil being reduced compared to the base case, which represents the normal practice in Malaysia. It may be possible to predict the problems encountered regarding the moisture content in the room that may lead to probable mould growth on wall surfaces, and also the high energy consumption due to continuous nature of operation and not employing energy-saving measures. Therefore, enthalpy heat

recovery is a crucial component in controlling the mould risk and minimising HVAC energy use.

7.2.3 Review of Isolation Room Design in Malaysian Climate

HVAC design reliability issue of maintaining indoor condition set-points with respect to energy usage needs to be tackled. That being the case, in the context of energy use, it is sufficient to use the recommended temperature range of 25 to 28°C as a base for review.

In the context of building design and construction, a holistic approach should be taken. Building envelope needs to be designed with more thought on the climate and must not be independent of the required active HVAC system, the design of which is dependent on available guidelines only

The research has pointed out that there is a need to revise the current design limit for the isolation room in Malaysia and introduce a new room design conditions that take into account the aspects of energy consumption and mould risk. Simulation and optimisation results as well as mould risk analysis have shown that the normal design condition of 24°C and 50% RH incurred high energy consumption but cannot maintain room RH, the result of which the mould risk was evident.

7.2.4 Elements of Uncertainty in Isolation Room

The uncertainty elements, such as user behaviour that results from different thermal comfort levels between individuals, are ever present. Different types of response, such as opening windows and/or changing the room temperature setting, do affect indoor conditions. Simulation results showed that user behaviour does have an impact on the moisture behaviour in the room. One example is introducing ambient air with very high moisture content which results in increased room RH, since this moisture is uncontrolled. Hence it is not removed by the cooling coil. Ingress

of outside air with high moisture content contributes to moisture build-up in the room and this moisture is eventually absorbed by the wall surfaces or furniture, providing suitable medium for spore germination. Even if the isolation room is designed to be fully sealed, it is often advisable for the building operators and owners to ensure that open-able windows must be fully closed to prevent moisture ingress.

7.3 Contributions of Research

Relating to the aims of this research, a number of contributions of this research is discussed. Firstly, the presence of a Pareto front in the objective function search space suggests that a trade-off exists between minimising energy use and minimising risk of mould growth. Pareto optimal solutions act as the base to assist decision making with regards to designing isolation rooms. The model-based optimisation serves as a decision making tool that provides opportunity for designers and building owners to prioritise the design options; either opting for energy efficient system with a compromise on small magnitude of risk of mould growth, or making indoor air quality top priority while at the same time incurring high energy cost in meeting that priority.

Secondly, the research has shown that the normal design conditions of 24°C and 50% RH used in isolation room design for hot and humid climate incurred high energy cost for the HVAC system and failed to maintain control on the zone conditions which leads to the likelihood of mould growth on wall surfaces. The absence of heat recovery in the HVAC system exacerbated the problem. The optimisation results showed that less energy use and lower mould growth risk could be achieved if the design conditions are higher; in this case at 28°C room temperature and between 60 and 65% RH set-point where the HVAC system maintains zero set-point error. Therefore, a new design guideline for isolation room HVAC in hot and humid climate is recommended that takes into account the energy recovery mechanism such as regenerative device for indoor air drying.

The third contribution is the interfacing between three main components that form the model-based optimisation to determine the trade-off between the two design goals, namely (i) the whole building performance simulation program (EnergyPlus), (ii) the extended mould growth risk model, and (iii) the constrained multi-objective optimisation using NSGA-II as the search method. The whole building simulation program gives sufficient accuracy with shortened computing time. The mould growth model was modified so that the surface parameters were used to analyse the data from the EnergyPlus simulation output file for mould growth risk. The constrained multi-objective optimisation using NSGA-II generated a number of optimum solutions with reduced searching time since the genetic algorithm is suitable for parallel computing. Thus, a simple decision-making framework for design that comprises simulation, optimisation and mould growth modelling is recommended.

The originality of the research was in the application of optimisation methods to investigate that relationship and the new knowledge was focused on the required modelling or analysis of components together with the trade-off between energy use and mould growth. The approach serves as decision making tool for the design of energy-efficient buildings in hot-humid climates, particularly specialized units requiring continuous operation.

7.4 Limitations and Recommendation for Further Research

This section lists down a number of limitations not covered in the research and offers recommendations for future work.

7.4.1 Mould Growth Model

The extended mould growth model is deterministic in nature, in which no uncertainty element was included, such as risk of any condensation that is taking place in the corners of the internal walls, or thermal bridges. The considerable magnitude of mould risk below the threshold curve does not indicate the amount of

time needed for the mould to grow, even though the conditions below LIM denote the absence of biological growth.

It is also recommended in the future study that the robustness of the developed mould growth model is ensured through validation.

7.4.2 HVAC Design and Control Strategy

The HVAC topology used in this research was an all-air system, specifically DX type with re-heat and the latent heat recovery incorporated. The all-water system, such as the chilled water system (CHWS) was not considered. Therefore the extent to which the CHWS system incorporated with heat recovery system is able to maintain control on the indoor conditions is not known. The consideration of the all-water system is recommended in the future work.

The reliability of the HVAC system was analysed using the daytime bias set-point. Due to the constraint of time, the night-time bias set-point was excluded. It is suggested that this parameter is included in the future study to further investigate the ability of the system to maintain control on the room RH set-point during night-time operation.

The air distribution and the velocity of the supply air across the surface of the isolation room walls are not considered in this research and need to be addressed with regards to their impact on the movement of mould spores and the settling of the spores inside the room. The use of computational fluid dynamics (CFD) is recommended in addressing the issues.

To address the issue of infection risk in the isolation room as a result of application of energy recovery mechanism, it is recommended in the future practice to employ a regenerative device in the DX-type HVAC as a means for internal air drying.

7.4.3 Interaction with Other Areas

The research was limited to a single zone area and one of the walls was shared with a naturally-ventilated ward. However the ward was not of interest at this point; only indoor surfaces were under analysis while outdoor surfaces were not included. Thus, no surface analyses were conducted for the outer walls, even though the assumptions were made that the walls are external. Multi-zone areas to be recommended to evaluate the difference are rooms that are naturally ventilated, such as ward, or intermittently conditioned, such as 8-hour air-conditioned room, which are connected to the isolation room that may have different indoor conditions. A more accurate lay-out is also preferable.

Relationship with the other rooms, such as ante-room, designed to act as barrier between isolation room and other areas next to the isolation suite was not looked into in this research.

7.4.4 Building Construction

A flat roof was used for the modelling and the construction details followed real world example. However, due to limited time, the pitch roof construction is not taken into consideration and it is therefore recommended for inclusion in future research.

The ingress of outside air due to cracks in building structure was represented as infiltration made constantly present. However, the calculation of infiltration rate was based on air change method, which was an estimate for design purpose, so as to indicate its impact on room indoor conditions.

7.4.5 Thermal Comfort and Contamination Removal Effectiveness

The occupants in tropical countries give different responses to the changes in room indoor conditions compared to people in temperate countries. It has become a subject of a number of researches in relation to thermal comfort and user behaviour in

buildings. The occupants in tropical climate can respond to higher room temperature range than that recommended by ASHRAE and CIBSE Guide.

The research investigates the trade-off between energy use and risk of mould growth and the results suggest higher optimum temperature set-points. For the sake of comparison, a comfort temperature range for hospital buildings proposed by Yau and Chew (2009) was between 25.2 and 28.3°C. Even though the results do agree with the proposed range, how the trade-off directly affects the thermal comfort of isolation room occupants and the effectiveness of the HVAC system to remove contaminants from the system is a subject for further investigation.

REFERENCE

ABUKU, M., JANSSEN, H. and ROELS, S., 2009. Impact of wind-driven rain on historic brick wall buildings in a moderately cold and humid climate: Numerical analyses of mould growth risk, indoor climate and energy consumption. *Energy and Buildings*, **41**(1), pp. 101-110.

ADAMS, N.J., JOHNSON, D.L. and LYNCH, R.A., 2011. The effect of pressure differential and care provider movement on airborne infectious isolation room containment effectiveness. *American Journal of Infection Control*, **39**(2), pp. 91-97.

ADAMSKI, M., 2007. Optimization of the form of building on an oval base. *Building and Environment*, **42**(4), pp. 1632-1643.

ADAN, O.C.G., 1994. *Fungal disfigurement of interior finishes*, University of Eindhoven, Eindhoven, The Netherlands.

AIA, 2006. *Guidelines for Design and Construction of Hospitals and Health Care Facilities*. 2nd edn. Washington, D.C.: The American Institute of Architects Press.

AIBINU, A.M., SALAMI, M.J.E., SHAFIE, A., ALI, M. and BAMGBOPA, I.A., 2009. Assessment of Mould Growth on Building Materials using Spatial and Frequency Domain Analysis Techniques. *International Journal of Computer Science and Network Security*, **9**(7), pp. 154-167.

AJIBOLA, K., 1993. Energy Optimization in a warm humid climate - a case study of some health facilities in Ife-Ife, Nigeria. *Renewable Energy*, **3**(1), pp. 39-44.

AL-HOMOUD, M.S., 1997. Optimum Thermal Design of Office Building. *International Journal of Energy Research*, **21**, pp. 941-957.

ANDERSON, B. R., CHAPMAN P. F., CUTLAND N. G., DICKSON C. HENDERSON G., HENDERSON J. H., ILES P. J., KOSMINA L., and SHORROCK L. D. 2001. BREDEM-12 Model Description, BRE. Garston, UK.

ASHRAE, 2011. *Addenda a to Standard 160-2009 -- Criteria for Moisture-Control Design Analysis in Buildings*. Atlanta, GA 30329, USA: ASHRAE.

ASHRAE, 2008. *ASHRAE Standard 170-2008 -- Ventilation of Health Care Facilities*. 1 edn. Atlanta, GA 30329, USA: ASHRAE.

ASHRAE, 2003. *ASHRAE Handbook Fundamentals SI Edition*. Atlanta, GA 30329, USA: ASHRAE.

BAGSHAW, K.D., BLOWERS, R. and LIDWELL, O.M., 1978. Isolating patients in hospital to control infection. *British Medical Journal*, **2**, pp. 744-748.

BALOCCO, C. and LIO, P., 2010. Modelling infection spreading control in a hospital isolation room. *Journal of Biomedical Science and Engineering*, **3**, pp. 653-663.

BANNISTER, B., PURO, V., FUSCO, F.M., HEPTONSTALL, J. and IPPOLITO, G., 2009. Framework for the design and operation of high-level isolation units: consensus of the European Network of Infectious Diseases. *The Lancet Infectious Diseases*, **9**(1), pp. 45-56.

BECKER, R., 1984. Condensation and Mould Growth in Dwellings-Parametric and Field Study. *Building and Environment*, **4**, pp. 243-250.

BEGGS, C.B., KERR, K.G., NOAKES, C.J., HATHWAY, E.A. and SLEIGH, P.A., 2008. The ventilation of multiple-bed hospital wards: Review and analysis. *American Journal of Infection Control*, **36**(4), pp. 250-259.

BLOCK, S.S., 1953. Humidity Requirements for Mould Growth. *Applied Microbiology*, **1**(6), pp. 287-293.

BRITISH STANDARDS INSTITUTION, 2002. *British Standard BS 5250: 2002 Code of practice for control of condensation in buildings*. 1 edn. London: British Standards Institution.

CALDAS, L.G. and NORFORD, L.K., 2003. Genetic Algorithms for Optimization of Building Envelopes and the Design and Control of HVAC Systems. *Journal of Solar Energy Engineering*, **125**, pp. 343-351.

CANTÚ-PAZ, E. and GOLDBERG, D.E., 2000. Efficient parallel genetic algorithms: Theory and practice. *Computer Methods in Applied Mechanics and Engineering*, **186** (2-4) , pp. 221-238.

CANTÚ-PAZ, E., 1997. Designing Efficient Master-Slave Parallel Genetic Algorithms. *IlligAL Report No. 97004*, Illinois Genetic Algorithms Laboratory, USA.

CENTERS FOR DISEASE CONTROL AND PREVENTION, 2005. *Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Settings, 2005*. Atlanta, GA 30333: Centers for Disease Control and Prevention.

CHANG, J.S., FOARDE, K.K. and VANOSDELL, D.W., 1995. Growth evaluation of fungi (*Penicillium* and *Aspergillus* spp.) on ceiling tiles. *Atmospheric Environment*, **29**(17), pp. 2331-2337.

CHANTRELLE , F. P., LAHMIDI, H., KEILHOLZ, W., EL MANKIBI, M., and MICHEL, P., 2011. Development of a multicriteria tool for optimizing the renovation of buildings. *Applied Energy*, **88**, pp. 1386-1394.

CHEONG, K.W.D. and PHUA, S.Y., 2006. Development of ventilation design strategy for effective removal of pollutant in the isolation room of a hospital *Building and Environment*, **41**(9), pp. 1161-1170.

CIBSE Guide A: Environmental Design, 2006 (7th Edition), The Chartered Institution of Building Services Engineers, London.

CLARKE, J.A., JOHNSTONE, C.M., KELLY, N.J., MCLEAN, R.C., ANDERSON, J.A., ROWAN, N.J. and SMITH, J.E., 1999. A technique for the prediction of the conditions leading to mould growth in buildings. *Building and Environment*, **34**, pp. 515-521.

CLARKE, J. A., 1985. *Energy Simulation in Building Design*, Butterworth-Heinemann, Oxford.

CONGRADAC, V. and KULIC, F., 2009. HVAC system optimization with CO₂ concentration control using genetic algorithms. *Energy and Buildings*, **41**(5), pp. 571-577.

CRAWLEY, D. B., LAWRIE, L. K., WINKELMANN, F. C., BUHL, W.F., HUANG, Y. J., PEDERSEN, C.O., STRAND, R. K., LIESEN, R. J., FISHER, D. E., WITTE, M. J., and GLAZER, J. 2001. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, **33**(4), pp. 319-331.

CRAWLEY, D.B., HAND, J.W., KUMMERT, M. and GRIFFITH, B.T., 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, **43**(4), pp. 661-673.

DAOU, K., WANG, R.Z. and XIA, Z.Z., 2006. Desiccant cooling air conditioning: a review. *Renewable & Sustainable Energy Reviews*, **10**(2), pp. 55-77.

DE JONG, K.A., 2006. *Evolutionary Computation: A Unified Approach*. Cambridge, Massachusetts, USA: MIT Press.

DEB, K., 2004. *Multi-Objective Optimization using Evolutionary Algorithms*. 1 edn. West Sussex, England: John Wiley & sons, Ltd.

DEB, K., 1999. An Introduction to genetic algorithm. *Sadhana*, **24**(4 & 5), pp. 293-315.

DEB, K., PRATAP, A., AGARWAL, S. and MERAYIVAN, T., 2002. A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. *IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION*, **6**(2), pp. 182-197.

DIKAKI, C., GRIGOROUDIS, E. and KOLOKOTSA, D., 2008. Towards a multi-objective optimization approach for improving energy efficiency in buildings. *Energy and Buildings*, **40**, pp. 1747-1754.

DJURIC, N., NOVKOVIC, V., HOLST, J. and MITROVIC, Z., 2007. Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools. *Energy and Buildings*, **39**, pp. 471-477.

D'ORAZIO, M., PALLADINI, M., AQUILANTI, L. and CLEMENTI, F., 2009. Experimental evaluation of the growth rate of mould on finishes for indoor housing environments: Effects of the 2002/91/EC directive. *Building and Environment*, **44**(8), pp. 1668-1674.

DOS SANTOS, G.H., MENDES, N. and PHILIPPI, C.P., 2009. A building corner model for hygrothermal performance and mould growth risk analysis. *International Journal of Heat Mass Transfer*, **52**(21-22), pp. 4862-4872.

EMMERICH, M.T.M., HOPFE, C.J., MARIJT, R., HENSEN, J., STRUCK, C. and STOELINGA, P., 2008. Evaluating optimization methodologies for future integration in building performance tools, *Proceedings of the 8th Int. Conf. on Adaptive Computing in Design and Manufacture (ACDM)*, 29 April - 1 May 2008.

ESCOMBE, A.R., OESER, C.C., GILMAN, R.H., NAVINCOPA, M., TICONA, E., PAN, W., MARTINEZ, C., CHACALTANA, J., RODRIGUEZ, R., MOORE, D.A.J., FRIEDLAND, J.S. and EVANS, C.A., 2007. Natural Ventilation for the Prevention of Airborne Contagion. *PLoS Med*, **4**(2), pp. e68.

EZEONU, I.M., NOBLE, J.A., SIMMONS, R.B., PRICE, D.L., CROW, S.A. and AHEARN, D.G., 1994. Effect of Relative Humidity on Fungal

Colonization of Fiberglass Insulation. *Applied and Environmental Microbiology*, **60**(6), pp. 2149-2151.

FANG, X., ATHIENITIS, A.K. and FAZIO, P.P., 2009. Methodologies for shortening test period of coupled heat-moisture transfer in building envelopes. *Applied Thermal Engineering*, **29**(4), pp. 787-792.

FIALHO, A., HAMADI, Y. and SCHOENAUER, M., 2011. Optimizing Architectural and Structural Aspects of Buildings towards Higher Energy Efficiency, *GECCO 2011 Workshop on GreenIT Evolutionary Computation (2011)*, July 12–16 2011, Association for Computing Machinery.

FLANAGAN, R. and JEWELL, C., 2003. The risk of mould damage over the whole life of a building. *RICS Foundation*, Downloaded from http://www.rics.org/NR/rdonlyres/FEBC03F8-A55E-4272-ABC8-FE312517ED38/o/mould_14022004.pdf.

FONG, K.F., HANBY, V.I. and CHOW, T.T., 2008. A Robust Evolutionary Algorithm for HVAC Engineering Optimization. *HVAC & R Research*, **14**(5), pp. 683-705.

FONSECA, C.M. and FLEMING, P.J., 1993. Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization, S. FORREST, ed. In: *Proceedings of the 5th International Conference on Genetic Algorithms*, 17-21 July 1993 1993, Morgan Kaufmann Publishers Inc., pp. 416.

GACTO, M.J., ALCALA, R. and HERRERA, F., 2010. A multi-objective evolutionary algorithm for an effective tuning of fuzzy logic controllers in heating, ventilating and air conditioning systems. *Applied Intelligence*, **36**(2), pp. 330-347.

GOLDBERG, D.E., 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*. 1 edn. Addison-Wesley Publishing Company, Inc.

GRANT, C., HUNTER, C.A., FLANAGAN, B. and BRAVERY, A.F., 1989. The Moisture Requirements of Moulds Isolated from Domestic Dwellings. *International Biodeterioration*, **25**(4), pp. 259-284.

GRAY, F., 1953. Pulse Code Communication. *Patent US2,632,058*, United States Patent Office.

HENS, H.L.S.C., 1999. Fungal Defacement in Buildings: A Performance Related Approach. *HVAC & R Research*, **5**(3), pp. 265-280.

HOLLAND, J.H., 1975. *Adaptation in natural and artificial systems*. Cambridge, MA, USA: MIT Press.

HOLST, J.N., 2003. Using whole building simulation models and optimizing procedures to optimize building envelope design with respect to energy consumption and indoor environment, *Eighth International IBPSA Conference 2003*, IBPSA, pp. 507.

HORNER, W. E., 2006, Managing building-related *Aspergillus* exposure. *Medical Mycology*, **44**, pp. S33-S38.

HUANG, W. and LAM, H.N., 1997. Using genetic algorithms to optimize controller parameters for HVAC systems. *Energy and Buildings*, **26**(3), pp. 277-282.

HUH, J.H. and BRANDEMUEHL, M.J., 2008. Optimization of air-conditioning system operating strategies for hot and humid climates. *Energy and Buildings*, **40**(7), pp. 1202-1213.

HUKKA, A. and VIITANEN, H.A., 1999. A mathematical model of mould growth on wooden material. *Wood Science and Technology*, **33**, pp. 475-485.

INTERNATIONAL ENERGY AGENCY, 1990. *IEA ANNEX 14: Condensation and Energy Volume 2 (Guidelines & Practice)*. Belgium: International Energy Agency.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2007. *ISO 10456: 2007 Building materials and products -- Hygrothermal properties -- Tabulated design values and procedures for determining declared and design thermal values*. 3 edn. International Organization for Standardization.

JOHANSSON, S., WADSO, L. and SANDIN, K., 2010. Estimation of mould growth levels on rendered facades based on surface RH and surface temperatures measurements. *Building and Environment*, **45**(5), pp. 1153-1160.

JUROVICS, S.A., 1978. Optimization Applied to the Design of an Energy-Efficient Building. *IBM Journal of Research and Development*, **22**(4), pp. 378-385.

KE, Q.S., CRAIK, S.A., EL-DIN, M.G. and BOLTON, J.R., 2009. Development of a Protocol for the Determination of the Ultraviolet Sensitivity of Microorganisms Suspended in Air . *Aerosol Science and Technology*, **43**(4), pp. 284-289.

KERESTECIOGLU, A., SWAMI, M. and KAMEL, A., 1989, "Theoretical and Computational Investigation of Simultaneous Heat and Moisture Transfer in Buildings: Effective Penetration Depth Theory." ASHRAE Winter Meeting, Atlanta, GA.

KIM, S.H. and AUGENBROE, G., 2009. Ventilation Operation in Hospital Isolation Room: A Multi-criterion Assessment Considering Organizational Behaviour, IBPSA, ed. In: *Building Simulation 2009: Eleventh International IBPSA Conference*, July 27-30 2009, IBPSA, pp. 1322.

KLAMER, M.:M., E. and HUSEMOEN, T., 2004. Fungal growth on different insulation materials exposed to different moisture regimes. *International Biodeterioration & Biodegradation*, **54**(4), pp. 277-282.

KO, G.K., FIRST, M.W. and BURGE, H. A., 2000. Influence of relative humidity on particle size and UV sensitivity of *Serratia marcescens* and

Mycobacterium bovis BCG aerosols . *Tubercle and Lung Disease*, **80**(4/5), pp. 217-228.

KOSAR, D., 2006. Dehumidification System Enhancements. *ASHRAE Journal*, **48**(2), pp. 48-58.

KOWALSKI, W.J., BAHNFLETH, W.P. and ROSENBERGER, J.L., 2003. Dimensional Analysis of UVGI Air Disinfection Systems. *HVAC & R Research*, **9**(3), pp. 347-363.

KRUS, M. and SEDLBAUER, K., 2007. A New Model for Prediction and its Application in Practice, *6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings - IAQVEC 2007* , Oct. 28 - 31 2007, INIVE.

KUBOTA, T., TOE, H.C. and AHMAD, S., 2009. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and Buildings*, **41**(8), pp. 829-839.

KUMARAN, K., 2001. Hygrothermal properties of building materials. In: H.R. TRECHSEL, ed, *Moisture analysis and condensation control*. 1 edn. Pennsylvania, USA: American Society for Testing and Materials (ASTM), pp. 29-65.

KUMARAN, K. 1996. IEA ANNEX 24, Final Report, Volume 3.

KUNZEL, H.M., 1995. *Simultaneous heat and Moisture Transport in Building Components*. Stuttgart: Fraunhofer IRB Verlag Stuttgart.

KUSIAK, A., TANG, F. and XU, G., 2011. Multi-objective optimization of HVAC system with an evolutionary computation algorithm. *Energy*, **36**(5), pp. 2440-2449.

LI, Y., LEUNG, G.M., TANG, J.W., YANG, X., CHAO, C.Y.H., LIN, J.Z., LU, J.W., NIELSEN, P.V., NIU, J., QIAN, H., SLEIGH, A.C., SU, H.-J., SUNDELL, J., WONG, T.W. and YUEN, P.L., 2007. Role of ventilation in

airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. *Indoor Air*, **17**(1), pp. 2-18.

LIAN, K.S., L., INANGDA, N. and RAMLY, A., 2007. Sources of indoor air quality problem in a new hospital in Malaysia. In: *6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings – IAQVEC 2007, October 28 - 31, Sendai, Japan*. Downloaded from http://www.inive.org/members_area/medias/pdf/Inive/IAQVEC2007/Lian.pdf.

LIANG, C.H., ZHANG , L.Z. and PEI, L.X., 2010. Independent air dehumidification with membrane-based total heat recovery: Modeling and experimental validation *International Journal of Refrigeration*, **33**(2), pp. 398-408.

LIM, G., TAN, T.K. and TOH, A., 1989. The fungal problem in buildings in the humid tropics. *International Biodeterioration*, **25**(1-3), pp. 27-37.

LIN, C.-Y. and LI, C.-S., 2002. Control effectiveness of ultraviolet germicidal irradiation on bioaerosols *Aerosol Science and Technology*, **36**(4), pp. 474-478.

LOMAS, K.J. and JI, Y., 2009. Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy and Buildings*, **41**(6), pp. 629-653.

MAGNIER, L. and HAGHIGHAT, F., 2010. Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network. *Building and Environment*, **45**(3), pp. 739-746.

MALAYSIAN STANDARDS, Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings (First Revision), Department of Standards Malaysia, 2007, MS 1525:2007.

MANDEGARI, M.A. and PAHLAVANZADEH, H., 2009. Introduction of a new definition for effectiveness of desiccant wheels *Energy*, **34**(6), pp. 797-803.

MEGRI, A.C., 2007. Building Load and Energy Simulation Programs and the Design Process. *The International Journal of Ventilation*, **6**(2), pp. 177-192.

MEMARZADEH, F. and JIANG, J., 2000. Methodology for Minimizing Risk from Airborne Organisms in Hospital Isolation Rooms, *ASHRAE Transactions: Symposia*, June 2000, pp. 733.

MENDEZ, C., SAN JOSE, J.F., VILLAFRUELA, J.M. and CASTRO, F., 2008. Optimization of a hospital room by means of CFD for more efficient ventilation. *Energy and Buildings*, **40**(5), pp. 849-854.

MICHALEWICZ, Z., 1996. *Genetic Algorithms + Data Structures = Evolution Programs*. 3rd edn. Berlin, Germany: Springer-Verlag.

MOON, H.J. and AUGENBROE, G., 2004. Towards A Practical Mould Growth Risk Indicator. *Building Service Engineering Research and Technology*, **25**(4), pp. 317-326.

MOSSOLLY, M., GHALI, K. and GHADDAR, N., 2009. Optimal control strategy for a multi-zone air conditioning system using a genetic algorithm. *Energy*, **34**(1), pp. 58-66.

NASSIF, N., KAJL, S. and SABOURIN, R., 2005. Optimization of HVAC Control System Strategy Using Two-Objective Genetic Algorithm. *HVAC & R Research*, **11**(3), pp. 459-486.

NATIONAL HEALTH SERVICE, 1994. *Health Technical Memorandum 2025. Design considerations: ventilation in health care premises*. 1 edn., HMSO, London

NOBREGA, C.E.L. and BRUM, N.C.L., 2009. Modeling and simulation of heat and enthalpy recovery wheels *Energy*, **34**(12), pp. 2063-2068.

NOWOSTAWSKI, M. and POLI, R., 1999. Parallel Genetic Algorithm Taxonomy, *Third International Conference on Knowledge-Based Intelligence Information Engineering Systems*, 31 August-1 September 1999, pp. 88.

ORESZCZYN, T. and PRETLOVE, S.E.C., 1999. Condensation Targeter II: Modelling surface relative humidity to predict mould growth in dwellings. *Building Service Engineering Research and Technology*, **20**(3), pp. 143-153.

PALANI, M., O'NEAL, D. and HABERL, J., 1992. The Effect of Reduced Evaporator Air Flow on the Performance of a Residential Central Air Conditioner, *Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates*, 13-14 May 1992, pp. 20.

PALONEN, M., HASAN, A. and SIREN, K., 2009. A Genetic Algorithm for Optimization of Building Envelopes and HVAC System Parameters, IBPSA, ed. In: *Building Simulation 2009 Eleventh International IBPSA Conference*, 27-30 July, 2009 2009, IBPSA, pp. 159.

PARKER, D., SHERWIN, J., RAUSTADT, R. and SHIREY, D., 1997. Impact of Evaporator Coil Air Flow in Residential Air Conditioning Systems. *ASHRAE Transactions*, **103**(2), pp. 395-405.

PASANEN, A., -L, JUUTINEN, T., JANTUNEN, M.J. and KALLIOKOSKI, P., 1992. Occurrence and moisture requirements of microbial growth in building materials. *International Biodeterioration & Biodegradation*, **30**(4), pp. 273-283.

PASANEN, A., KASANEN, J., RAUTIALA, S., IKAHEIMO, M., RANTAMAKI, J., KAARIAINEN, H. and KALLIOSKOSKI, P., 2000. Fungal growth and survival in building materials under fluctuating moisture and temperature conditions. *International Biodeterioration & Biodegradation*, **46**, pp. 117-127.

PERFUMO, C., WARD, J.K. and BRASLAVSKY, J.H., 2010. Reducing energy use and operational cost of air conditioning systems with multi-objective evolutionary algorithms, IEEE, ed. In: *2010 IEEE Congress on Evolutionary Computation*, 18-23 July 2010 2010, Institute of Electrical and Electronic Engineers, pp. 1.

PHILLIPS, D.A., SINCLAIR, R.J. and SCHUYLER, G.D., 2004. Isolation Room Ventilation Design Case Studies, *IAQ Conference 2004* 2004, ASHRAE.

PUBLIC WORKS DEPARTMENT MALAYSIA, 2009. *Guidelines on the Prevention of Mould Growth in Buildings*. 1 edn. Kuala Lumpur Malaysia: Public Works Department Malaysia.

QIAN, H., LI, Y., SETO, W.H., CHING, P., CHING, W.H. and SUN, H.Q., 2010. Natural ventilation for reducing airborne infection in hospitals. *Building and Environment*, **45**(3), pp. 559-565.

QIN, M., WALTON, G., BELARBI, R. and ALLARD, F. 2011. Simulation of whole building coupled hygrothermal-airflow transfer in different climates. *Energy Conversion and Management*, **52** (2) , pp. 1470-1478.

QIN, M., BELARBI, R., AIT-MOKHTAR, A. and ALLARD, F., 2009. simulation of coupled heat and moisture transfer in air-conditioned buildings. *Automation in Construction*, **18**(5), pp. 624-631.

RADHI, H., 2008. A systematic methodology for optimising the energy performance of buildings in Bahrain. *Energy and Buildings*, **40**(7), pp. 1297-1303.

REN, M.J. and WRIGHT, J.A., 1997. Predictive optimal control of fabric thermal storage systems, *International IBPSA Conference 1997*, IBPSA.

RODE,C. and WOLOSZYN, M., 2007. Whole-Building Hygrothermal Modeling in IEA Annex 41, OAK RIDGE NATIONAL LABORATORY (ORNL), ed. In: *Thermal Performance of the Exterior Envelopes of Whole Buildings*, December 2-7 2007, Oak Ridge National Laboratory (ORNL).

ROMERO, D., RINCON, J. and ALMAO, N., 2001. Optimization of the Thermal Behaviour of Tropical Buildings, *Building Simulation 2001: Seventh International IBPSA Conference*, August 13 - 15 2001, IBPSA, pp. 1079.

RYDOCK, J.P., EIAN, P.K., LINDQVIST, C., WELLING, I. and LINGAAS, E., 2004. *Best Practice in Design and Testing of Isolation Rooms in Nordic Hospitals*. Oslo, Norway: Nordic Innovation Centre.

SALAZAR, D., ROCCO, C.M. and GALVAN, B.J., 2006. Optimization of constrained multiple-objective reliability problems using evolutionary algorithms. *Reliability Engineering & System Safety*, **91**(9), pp. 1057-1070.

SAMBOU, V., LARTIGUE, B., MONCHOUX, F. and ADJ, M., 2009. Thermal optimization of multilayered walls using genetic algorithms. *Energy and Buildings*, **41**(10), pp. 1031-1036.

SEDLBAUER, K., 2002. Prediction of Mould Growth by Hygrothermal Calculation. *Journal of Building Physics*, **25**(4), pp. 321-336.

SEDLBAUER, K., 2001. *Prediction of mould fungus formation on the surface of and inside building components*, Fraunhofer Institute for Building Physics.

SEKHAR, S.C., 2007. A Review of Ventilation and Air-Conditioning Technologies for Energy-Efficient Healthy Buildings in the Tropics. *ASHRAE Transactions*, **113**(1), pp. 426-434.

SHI, X., 2011. Design optimization of insulation usage and space conditioning load using energy simulation and genetic algorithm. *Energy*, **36**(3), pp. 1659-1667.

SHIH, Y.C., CHIU, C.C. and WANG, O., 2007. Dynamic airflow simulation within an isolation room. *Building and Environment*, **42**(9), pp. 3194-3209.

SKOOG, J., 2006. Relative Air Humidity in Hospital Wards – User Perception and Technical Consequences. *Indoor and Built Environment*, **15**(1), pp. 93-97.

SRINIVAS, N. and DEB, K., 1994. Multiobjective Optimization Using Nondominated Sorting in Genetic Algorithms. *Evolutionary Computation*, **2**(3), pp. 221-248.

STEEMAN, H.-., BELLEGHEM, M. VAN, JANSSENS, A. and PAEPE, M.D., 2009. Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage. *Building and Environment*, **44**(10), pp. 2176-2184.

STEEMAN, M., JANSSENS, A., STEEMAN, H.J., VAN BELLEGHEM, M. and DE PAEPE, M., 2010. On coupling 1D non-isothermal heat and mass transfer in porous materials with a multizone building energy simulation model. *Building and Environment*, **45**(4), pp. 865-877.

STRAUBE, J., 1999. Moisture Fundamentals and Mould, *OBEC Seminar*, November 17 1999, Ontario Building Envelope Council.

STRAUBE, J. and BURNETT, E., 2001. Overview of Hygrothermal (HAM) Analysis Methods (Chapter 5), In: *Manual on Moisture Analysis in Buildings, Manual 40*, American Society for Testing and Materials (ASTM), pp. 81-89.

STRUCK, C., HENSEN, J. and KOTEK, P., 2009. On the Application of Uncertainty and Sensitivity Analysis with Abstract Building Performance Simulation Tools. *Journal of Building Physics*, **33**(1), pp. 5-27.

SUGA, K., KATO, S. and HIYAMA, K., 2009. Structural analysis of Pareto-optimal solution sets for multi-objective optimization: an application to outer window design problems using Multiple Objective Genetic Algorithms. *Building and Environment*, .

TANG, J.W., LI, Y., EAMES, I., CHAN, P.K.S. and RIDGWAY, G.L., 2006. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. *Journal of Hospital Infection*, **64**(2), pp. 100-114.

TAYLOR, R. D., PEDERSEN, C.O. and LAWRIE, L., 2007. Simultaneous simulation of buildings and mechanical systems in heat balance based energy analysis programs, *Proceedings of the 3rd International Conference on System Simulation in Buildings*, December 3-5 1990, Leige, Belgium.

TENWOLDE, A., 2008. ASHRAE Standard 160P-Criteria for Moisture Control Design Analysis in Buildings. *ASHRAE Transaction*, **114**(1), pp 167-169.

TRCKA, M., WETTER, M. and HENSEN, J., 2007. Comparison of Co-Simulation Approaches for Building and HVAC/R System Simulation, *Building Simulation 2007: 10th International Building Performance Simulation Association Conference*, September 3-6 2007, IBPSA, pp. 1418.

TSENG, C.C. and LI, C.S., 2005. Inactivation of Virus-Containing Aerosols by Ultraviolet Germicidal Irradiation. *Aerosol Science and Technology*, **39**(12), pp. 1136-1142.

TUHUS-DUBROW, D. and KRARTI, M., 2010. Genetic-algorithm based approach to optimize building envelope design for residential buildings *Building and Environment*, **45**(7), pp. 1574-1581.

TUNG, Y., HU, S., TSAI, T. and CHANG, I., 2009. An experimental study on ventilation efficiency of isolation room *Building and Environment*, **44**(2), pp. 271-279.

US DEPARTMENT OF ENERGY, EnergyPlus Engineering Reference. The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory, 2010.

VAN LOO, J.M., ROBBINS, C.A., SWENSON, L. and KELMAN, B.J., 2004. Growth of Mold on Fiberglass Insulation Building materials - A Review of the Literature. *Journal of Occupational and Environmental Hygiene*, **1**(6), pp. 349-354.

VERECKEN, E. and ROELS, S., 2012. Review of mould prediction models and their influence on mould risk evaluation, *Building and Environment*, **51**, pp. 296-310.

VIITANEN, H. and SALONVAARA, M., 2001. Failure Criteria. In: H.R. TRECHSEL, ed, *Moisture Analysis and Condensation Control in Building Envelopes MNL 40*. 1 edn. Pennsylvania, USA: American Society for Testing and Materials, pp. 66-80.

WANG, B., MORTAZAVI, R. and HAGHIGHAT, F., 2009. Evaluation of Modeling and Measurement Techniques of Ultraviolet Germicidal Irradiation

Effectiveness-Towards the Design of Immune Buildings. *Indoor and Built Environment*, **18**(2), pp. 101-112.

WANG, W., RIVARD, H. and ZMEUREANU, R., 2006. Floor shape optimization for green building design. *Advanced Engineering Informatics*, **20**(4), pp. 363-378.

WETTER, M. and WRIGHT, J.A., 2004. A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. *Building and Environment*, **39**(8), pp. 989-999.

Wetter, Michael. 2001, August. "GenOpt – A Generic Optimization Program." Edited by R. Lamberts, C. O. R. Negrão, and J. Hensen, *Proc. of the 7-th IBPSA Conference*, Volume I. Rio de Janeiro, Brazil, pp. 601–608.

WILKINS, K., LARSEN, K. and SIMKUS, M., 2000. Volatile metabolites from mold growth on building materials and synthetic media. *Chemosphere*, **41**(3), pp. 437-446.

WOLOSZYN, M., KALAMEES, T., ABADIE, M.O., STEEMAN, M. and KALAGISIDIS, A.S., 2009. The effect of combining a relative-humidity sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. *Building and Environment*, **44**(3), pp. 515-524.

WOLOSZYN, M. and RODE, C., 2008. Tools for Performance Simulation of Heat, Air and Moisture Conditions of Whole Buildings. *Building Simulation*, **1**(1), pp. 5-24.

WRIGHT, J.A. and MOURSHED, M.M., 2009. Geometric optimization of fenestration, *Building Simulation 2009: Eleventh International IBPSA Conference*, 27-30 July, 2009, IBPSA, pp. 920-927.

WRIGHT, J.A. and ALAJMI, A., 2005. The robustness of genetic algorithms in solving unconstrained building optimization problems, *Ninth International IBPSA Conference 2005*, IBPSA, pp. 1361-1368.

WRIGHT, J.A., LOOSEMORE, H.A. and FARMANI, R., 2002. Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy and Buildings*, **34**(9), pp. 959-972.

WRIGHT, J.A. and FARMANI, R., 2001. The simultaneous optimization of building fabric construction, HVAC system size, and the plant control strategy, *Seventh International IBPSA Conference 2001*, IBPSA, pp. 865-872.

WRIGHT, J.A. and LOOSEMORE, H., 2001. The multi-criterion optimization of building thermal design and control, *Seventh International IBPSA Conference 2001*, IBPSA, pp. 873-880.

WRIGHT, J.A., 1996. HVAC optimization studies: Sizing by genetic algorithm. *Building Service Engineering Research and Technology*, **17**(1), pp. 7-14.

XU, P., KUJUNDZIC, E., PECCIA, J., SCHAFER, M.J., MOSS, G., HERNANDEZ, M. and MILLER, S.L., 2005. Impact of Environmental Factors on Efficacy of Upper-Room Air Ultraviolet Germicidal Irradiation for Inactivating Airborne Mycobacteria. *Environmental Science & Technology*, **39**(24), pp. 9656-9664.

YAM, R., YUEN, P.L., YUNG, R. and CHOY, T., 2011. Rethinking hospital general ward ventilation design using computational fluid dynamics. *Journal of Hospital Infection*, **77**(1), pp. 31-36.

YANG, J., and SOH, C.K. 1997. Structural optimization by genetic algorithms with tournament selection *Journal of Computing in Civil Engineering*, **11** (3), pp. 195-200.

YAU, Y.H., 2008. The use of a double heat pipe exchanger system for reducing energy consumption of treating ventilation air in an operating theatre - A full year energy consumption model simulation. *Energy and Buildings*, **40**(5), pp. 917-925.

YAU, Y.H., 2006. Using heat pipe heat exchangers for reducing energy consumption of treating ventilation air in an operating theatre in a tropical climate: a simplified model. *Building Service Engineering Research and Technology*, **27**(4), pp. 297-310.

YAU, Y.H., CHANDRASEGARAN, D. and BADARUDIN, A., 2011. The ventilation of multiple-bed hospital wards in the tropics: A review . *Building and Environment*, **46**(5), pp. 1125-1132.

YAU, Y.H. and CHEW, B.T., 2009. Thermal comfort study of hospital workers in Malaysia. *Indoor Air*, **19**(6), pp. 500-510.

YIK, F.W.H. and POWELL, G., 2003. Review of Isolation Ward Ventilation Design and Evaluation by Simulation. *Indoor and Built Environment*, **12**(1-2), pp. 73-79.

ZHANG , L.Z., 2006. Energy performance of independent air dehumidification systems with energy recovery measures. *Energy*, **31**(8-9), pp. 1228-1242.

ZITZLER, E., DEB, K. and THIELE, L. (2000). Comparison of multiobjective evolutionary algorithms: Empirical results. *Evolutionary Computation* **8**(2), pp. 173–195.

ZNOUDA, E., MORCOS, N.G. and ALOUANE, A.H., 2007. Optimization of Mediterranean building design using genetic algorithms. *Energy and Buildings*, **39**, pp. 148-153.

BIBLIOGRAPHY

AFONSO, C.F.A., 2006. Recent advances in building air conditioning systems. *Applied Thermal Engineering*, **26**, pp. 1961-1971.

AL-ASSADI, S.A.K., PATEL, R.V., ZAHEER-UDDIN, M., VERMA, M.S. and BREITINGER, J., 2004. Robust decentralized control of HVAC systems using H-performance measures. *Journal of the Franklin Institute*, **341**(7), pp. 543-567.

ALCALA, R., CASILLAS, J., CORDON, O., GONZALEZ, A. and HERRERA, F., 2005. A genetic rule weighting and selection process for fuzzy control of heating, ventilating and air conditioning systems. *Engineering Application of Artificial Intelligence*, **18**, pp. 279-296.

AL-HOMOUD, M.S., 2009. Envelope Thermal Design optimization of Buildings with Intermittent Occupancy. *Journal of Building Physics*, **33**(1), pp. 65-82.

AL-HOMOUD, M.S., 2005. Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, **40**, pp. 353-366.

AL-HOMOUD, M.S., 2005. A Systematic Approach for the Thermal Design Optimization of Building Envelopes. *Journal of Building Physics*, **29**(2), pp. 95-119.

ASHRAE, 2010. *ASHRAE Standard 55-2010 -- Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA 30329, USA: ASHRAE.

BELLIA, L. and MINICHELLO, F., 2003. A simple evaluator of building envelope moisture condensation according to an European Standard. *Building and Environment*, **38**, pp. 457-468.

BS EN ISO 13788:2002 Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface

humidity and interstitial condensation - Calculation methods. 2002. Standards Policy and Strategy Committee.

BUSWELL, R.A. and WRIGHT, J. A., 2004. Uncertainty in model-based condition monitoring. *Building Service Engineering Research Technology*, **25**(1), pp. 65-75

CHAN, A.L.S., HANBY, V.I. and CHOW, T.T., 2007. Optimization of distribution piping network in district cooling system using genetic algorithm with local search. *Energy Conversion & Management*, **48**, pp. 2622-2629.

CHOW, D. H. C. and LEVERMORE, G. J., 2007. New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models. *Building Service Engineering Research Technology*, **28**(3), pp. 237-248.

DEB, K. and GUPTA, H., 2006. Introducing Robustness in Multi-Objective Optimization. *Evolutionary Computation*, **14**(4), pp. 463-494.

DOS SANTOS, G.H. and MENDES, N., 2009. Combined Heat, Air and Moisture (HAM) Transfer Model for Porous Building Materials. *Journal of Building Physics*, **32**(3), pp. 203-220.

FARMANI, R. and WRIGHT, J.A., 2003. Self-Adaptive Fitness Formulation for Constrained Optimization. *IEEE Transactions on Evolutionary Computation*, **7**(5), pp. 445-455.

FONG, K.F., HANBY, V.I. and CHOW, T.T., 2006. HVAC system optimization for energy management by evolutionary programming. *Energy and Buildings*, **38**, pp. 220-231.

HOES, P., HENSEN, J.L.M., LOOMANS, M.G.L.C., DE VRIES, B. and BOURGEOIS, D., 2009. User behavior in whole building simulation. *Energy and Buildings*, **41**, pp. 295-302.

HOLM, A. and SEDLBAUER, K., 2003. The Hygrothermal Behaviour of Rooms: Combining Thermal Building Simulation and Hygrothermal Envelope

Calculation, *Building Simulation 2003: Eighth International IBPSA Conference*, August 11-14, 2003 2003, IBPSA.

ISAKSSON, T., THELANDERSSON, S., ERKSTRAND-TOBIN, A. and JOHANSSON, P., 2010. Critical conditions for onset of mould growth under varying climate conditions. *Building and Environment*, **45**(7), pp. 1712-1721.

KERESTECIOGLU, A. and GU, L., 1990. Theoretical and computational investigation of simultaneous heat and moisture transfer in buildings:"evaporation and condensation" theory. *ASHRAE Transactions*, **96**(1), pp. 455-464.

KRUS, M., SEDLBAUER, K., ZILLIG, W. and KUNZEL, H.M., 2001. A New Model for Mould Prediction and its Application on a Test Roof, *II International Scientific Conference on "The Current Problems of Building-Physics in the Rural Buildings 2001*.

KUMAR, R., SINHA, A.R., SINGH, B.K. and MODHUKALYA, U., 2008. A design optimization tool of earth-to-air heat exchanger using a genetic algorithm. *Renewable Energy*, **33**(10), pp. 2282-2288.

LEE, J.H., 2007. Optimization of indoor climate conditioning with passive and active methods using GA and CFD. *Building and Environment*, **42**(9), pp. 3333-3340.

LI, Q., RAO, J. and FAZIO, P., 2009. Development of HAM tool for building envelope analysis. *Building and Environment*, **44**(5), pp. 1065-1073.

LIAN, K.S., INANGDA, P.S.N. and RAMLY, A., 2007. Sources of indoor air quality problem in a new hospital in Malaysia, *6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings - IAQVEC 2007*, Oct. 28 - 31 2007, INIVE.

MACDONALD, I.A. and CLARKE, J.A., 2007. Applying uncertainty considerations to energy conservation equations. *Energy and Buildings*, **39**(9), pp. 1019-1026.

MOON, H.J., 2005. *Assessing Mold Risks in Buildings under Uncertainty*, PhD Thesis, Georgia Institute of Technology, USA.

MOON, H.J. and AUGENBROE, G., 2008. Empowerment of decision-makers in mould remediation. *Building Research & Information*, **36**(5), pp. 486-498.

MOON, H.J. and AUGENBROE, G., 2005. A Mixed Simulation Approach to Analyze Mold Growth Under Uncertainty, *Building Simulation 2005: Ninth International IBPSA Conference*, August 15-18 2005, IBPSA, pp. 785.

MUI, K. W., WONG, L. T. and YAW, L. W., 2007. An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates. *Applied Energy*, **84**(1), pp. 89-98.

MUMOVIC, D., RIDLEY, I., ORESZCZYN, T. and DAVIES, M., 2006. Condensation risk: comparison of steady-state and transient methods. *Building Service Engineering Research and Technology*, **27**(3), pp. 219-232.

MUMOVIC, D., DAVIES, M., RIDLEY, I., ORESZCZYN, T., BELL, M., SMITH, M., and MILES-SHENTON, D., 2005. An Evaluation of the Hygrothermal Performance of 'Standard' and 'As Built' Construction Details Using Steady-State and Transient Modelling, *Building Simulation 2005: Ninth International IBPSA Conference*, August 15 - 18, 2005, IBPSA.

NASSIF, N., KAJL, S. and SABOURIN, R., 2004. Two-objective on-line optimization of supervisory control strategy. *Building Service Engineering Research and Technology*, **25**(3), pp. 241-251.

NASSIF, N., KAJL, S. and SABOURIN, R., 2004. Evolutionary Algorithms for Multi-Objective Optimization in HVAC System Control Strategy, *Fuzzy Information, 2004. Processing NAFIPS '04. IEEE Annual Meeting of the 2004*, IEEE, pp. 51.

NATIONAL HEALTH SERVICE, 1994. *Health Technical Memorandum 2025. Design considerations: ventilation in health care premises*. 1 edn. London: NationalHealthServices Estates.

NIA, F.E., VAN PAASSEN, D. and SAIDI, M.H., 2006. Modeling and simulation of desiccant wheel for air conditioning. *Energy and Buildings*, **38**, pp. 1230-1239.

OOKA, R. and KOMAMURA, K., 2009. Optimal design method for building energy systems using genetic algorithms. *Building and Environment*, **44**(7), pp. 1538-1544.

PERDELLI, F., CRISTINA, M.L., SARTINI, M., SPAGNOLO, A.M., DALLERA, M., OTTRIA, G., LOMBARDI, R., GRIMALDI, M. and ORLANDO, P., 2006. Fungal Contamination in Hospital Environments. *Infection Control and Hospital Epidemiology*, **27**(1), pp. 44-47.

ROWAN, N.J., JOHNSTONE, C.M., MCLEAN, R.C., ANDERSON, J.G. and CLARKE, J.A., 1999. Prediction of Toxigenic Fungal Growth in Buildings by Using a Novel Modelling System. *Applied and Environmental Microbiology*, **65**(11), pp. 4814-4821.

SALMINEN, K., PEUHKURI, R., LAHDESMAKI, K., VIITANEN, H., VINHA, J., PAAJANEN, L., IITTI, H., OJANEN, T. and STRANDER, T., 2007. *Mould growth in building materials in laboratory and field experiments*. Leuven, Belgium: International Energy Agency.

SEKHAR, S.C., 2005. Space temperature difference, cooling coil and fan - energy and indoor air quality issues revisited. *Energy and Buildings*, **37**, pp. 49-54.

SEKHAR, S.C., 1995. Higher space temperatures and better thermal comfort - a tropical analysis. *Energy and Buildings*, **23**, pp. 63-70.

SEKHAR, S.C. and TAN, L.T., 2009. Optimization of cooling coil performance during operation stages for improved humidity control. *Energy and Buildings*, **41**(2), pp. 229-233.

SIRIM BERHAD, 2007. *MS 1525: 2007 Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings (First Revision)*. Shah Alam, Malaysia: SIRIM Berhad.

SIVANANDAM, S.N. and DEEPA, S.N., 2008. *Introduction to Genetic Algorithms*. 1 edn. Berlin: Springer.

SMITH, S.L. and HILL, S.T., 1982. Influence of temperature and water activity on germination and growth of *Aspergillus restrictus* and *Aspergillus versicolor*. *Transactions of British Mycological Research*, **79**(3), pp. 558-560.

VIITANEN, H., VINHA, J., SALMINEN, K., OJANEN, T., PEUHKURI, R., PAAJANEN, L. and LAHDESMAKI, K., 2010. Moisture and Bio-deterioration Risk of Building materials and Structures. *Journal of Building Physics*, **33**(3), pp. 201-224.

WANG, W., RIVARD, H. and ZMEUREANU, R., 2005. An object-oriented framework for simulation-based green building design optimization with genetic algorithms. *Advanced Engineering Informatics*, **19**, pp. 5-23.

WRIGHT, J.A. and ZHANG, Y., 2008. Evolutionary Synthesis of HVAC System Configuration: Experimental Results. *HVAC & R Research*, **14**(1), pp. 57-72.

WRIGHT, J.A. and ZHANG, Y., 2008. The Minimum Capacity of HVAC Secondary Systems (with Capacity Reduction by Interzonal Airflow) (RP-1049). *HVAC & R Research*, **14**(3), pp. 397-415.

WRIGHT, J.A. and ZHANG, Y., 2005. An "ageing" operator and its use in the highly constrained topological optimization of HVAC system design, *Genetic And Evolutionary Computation Conference 2005*, Association for Computing Machinery, pp. 2075.

WRIGHT, J.A., ZHANG, Y., ANGELOV, P., HANBY, V. and BUSWELL, R., 2008. Evolutionary Synthesis of HVAC System Configurations: Algorithm Development (RP-1049). *HVAC & R Research*, **14**(1), pp. 33-55.

YAU, Y.H. and NG, W. K. 2011. A comparison study on energy savings and fungus growth control using heat recovery devices in a modern tropical operating theatre. *Energy Conversion and management*, **52**, pp. 1850-1860.

YAU, Y.H., 2010. Analyses of heat recovery devices in the HVAC system in an operating theatre in the tropics. *Building Services Engineering Research and Technology*, **31**(4), pp. 341-355.

YAU, Y.H., 2007. Application of a heat pipe heat exchanger to dehumidification enhancement in a HVAC system for tropical climates-a baseline performance characteristics study. *International Journal of Thermal Sciences*, **46**, pp. 164-171.

YAU, Y.H., 2007. Experimental thermal performance study of an inclined heat pipe heat exchanger operating in high humid tropical HVAC systems. *International Journal of Refrigeration*, **30**, pp. 1143-1152.

YAU, Y.H., 2006. Analysis of enthalpy with/without a heat pipe heat exchanger in a tropical air conditioning system. *International Journal of Energy Research*, **30**, pp. 1251-1263.

YOSHINO, H., MITAMURA, T. and HASEGAWA, K., 2009. Moisture buffering and effect of ventilation rate and volume rate of hygrothermal materials in a single room under steady state exterior conditions. *Building and Environment*, **44**(7), pp. 1418-1425.