ANIDOLIC DAYLIGHTING SYSTEM FOR EFFICIENT DAYLIGHTING IN DEEP PLAN OFFICE BUILDING IN THE TROPICS

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I would like to dedicate this thesis to my beloved mother and siblings.

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ABSTRACT

Daylight is a natural resource for space illumination. Providing more available daylight in buildings is highly desirable, not only for energy efficiency but also to enhance the occupants' performance and well-being. Daylight through window is common solution to lit the indoor space, but only provides limited depth of room space. Anidolic Daylighting System (ADS) is one particularly promising technology to be used for transferring daylight into deeper interior spaces. This research determines the ADS variables that are applicable under tropical climate according to modified duct shapes, duct width, duct length and distributor configuration. Experimental scale model and Integrated Environmental Solutions <Virtual Environment> (IES<VE>) computer simulation were employed in conducting the research. Physical scale model (1:10) was used to validate the simulation tool and to determine the appropriate orientation. Subsequently, the ADS was simulated in different variables of duct shapes, duct width, duct length and distributor configuration in open plan office. The analysis of results for daylight quantity was done based on absolute Work Plan Illuminance (WPI), daylight factor and daylight ratio, as well as WPI uniformity for daylight quality.The results illustrated that the ADS performed well for all orientations, but its performance in the South orientation was better than other orientations. It was shown that the developed ADS by rectangular duct shape and three meter duct width can transfer daylight as deep as 12.5m and 20m from window wall in overcast and intermediate sky conditions respectively. Moreover, the results demonstrated that effective daylighting depth could be supported with acceptable performance by developed ADS until 12.5m in both quality and quantity under intermediate sky. The new findings give insights for architects, engineers and built environment scientists to reach the complete potential of ADS in visual comfort as well as energy saving.

ABSTRAK

Cahaya siang adalah sumber semulajadi untuk pencahayaan. Penggunaannya di dalam bangunan adalah sangat dikehendaki, bukan hanya untuk penjimatan tenaga, tetapi juga untuk meningkatkan prestasi dan kesejahteraan penghuni. Keadah lazim cahaya siang melalui tingkap boleh memberikan pencahayaan yang mencukupi, walaubagaimanapun ia hanya memberi pencahayaan di sekitar kawasan tingkap yang berhampiran sahaja. Sistem Pencahayaan Siang Hari Anidolic (ADS) adalah salah satu teknologi berpotensi besar terutamanya untuk memindahkan cahaya ke dalam ruang dalaman yang lebih dalam. Kajian ini menentukan pembolehubah sistem ADS yang sesuai digunakan diiklim tropikal mengikut bentuk, lebar, dan panjang saluran yang diubahsuai dan konfigurasi pengagihan. Model skala fizikal dan Integrated Environmental Solutions <Virtual Environment> (IES<VE>) simulasi komputer digunakan dalam menjalani kajian ini. Model skala fizikal (1:10) digunakan untuk mengesahkan program simulasi dan menentukan orientasi yang sesuai. Seterusnya, simulasi sistem ADS digunakan di dalam pelbagai pembolehubah pada panjang, lebar dan bentuk saluran dan juga konfigurasi pengagihan di dalam pelan pejabat. Penemuan analisis bagi kuantiti cahaya siang diguna pakai berdasarkan pencahayaan tempat kerja mutlak, factor dan purata cahaya siang, dan juga keseragaman pencahayaan tempat kerja bagi kualiti cahaya siang. Keputusan menunjukkan, ADS menghasilkan petunjuk yang baik untuk semua orientasi, tetapi pelaksanaan sistem ini dalam orientasi Selatan adalah lebih baik daripada orientasi lain. Selian itu, ia menunjukkan bahawa sistem tersebut mampu memindahkan cahaya siang sedalam kira-kira 12.5m dan 20m walaupun dalam keadaan langit mendung dan sederhana menggunakan bentuk saluran segi empat tepat dan saluran selebar tiga meter. Penemuan baru ini memberi pendedahan kepada arkitek, jurutera dan ahli sains alam bina untuk mencapai potensi yang lengkap daripada ADS dalam penjimatan tenaga, dan juga keselesaan penglihatan.

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LIST OF SYMBOLS

A	-	Area
CC	-	Cloud Cover in Oktas
Cd	-	Candela
CR	-	Cloud Ratio
C_V	-	Cloud Cover Ration on Illuminance
d	-	Depth
E_b	-	Direct Illuminance
E_d	-	Diffuse Illuminance
E	-	Illuminance
E_e	-	External Illuminance
E_G	-	Global Illuminance
E_g	-	Ground Reflected Illuminance
Ei	-	Interior Illuminance
E_{in}	-	Average Internal Illuminance
Ev	-	Vertical Illuminance
E_n	-	Test Point
f(x)	-	Indicatrix Function
hr	-	Hour
I	-	Irradiance
I_d	-	Diffuse Irradiance
I_G	-	Global Irradiance
I_V	-	Luminous Intensity
K_G	-	Global Luminous Efficacy
l	-	Length
L	-	Luminance

n	-	Daily Sunshine Duration
NI	-	Nebulosity Index
no	-	Maximum possible sunshine duration
S	-	Relative Sunshine Duration
T_d	-	Light Transmittance of Glass
W	-	Width
Z	-	Zenith Angle of a sky Element
Zs	-	Zenith Angle of the Sun
Φ	-	Luminous Flux

LIST OF ABBREVIATIONS

2-D	-	Two dimensional
3-D	-	Three dimensional
ADS	-	Anidolic Daylighting System
AIC	-	Anidolic Integrated Ceiling
ASEAN	-	Association of South East Asian Nations
ASHRAE	-	American Society of Healthing, Refrigerating and Air conditioning engineers
CIBSE	-	Chartered Institution of Building Services Engineers
CIE	-	International commission of Illumination
CPC	-	Compound Parabolic Collector
DF	-	Daylight Factor
DR	-	Daylight Ratio
DS	-	Daylighting System
EXP		Experimental
FAB	-	Faculty of Built Environment
GBI	-	Green Building Index
IEQ	-	Indoor Environmental Quality
IES<VE>	-	Integrated Environmental Solution <virtual environment>
IES	-	Illumination Engineering Society
IRIF	-	Illuminance Ratio Improvement Factor
IT	-	Information Technology
IR	-	Infrared
JB	-	Johor Bahru
LCP	-	Laser Cut Panel
LEO	-	Low Energy Office
Min	-	Minimum

MS	-	Malaysian standard
NI	-	Nebulosity Index
N,S,E,W	-	North, South, East & West
PV	-	Photovoltaic
PTMZEO	-	Pusat Tenaga Selangor Zero Energy Office
RE	-	Renewable Energy
RGB	-	Red, Green and blue
RP	-	Reference Point
SC	-	Sky Component
SI	-	International System
SIM	-	Simulation
SR	-	Sky Ratio
UTM	-	Universiti Teknologi Malaysia
UV	-	Ultraviolet
VLT	-	Visible Light Transmittance
VSD	-	Visual Sky Dome
VT	-	Visible Transmittance
WFR	-	Window-to-floor Ratio
WPI	-	Work Plane Illuminance
WWR	-	Window-to-wall Ratio
ZEB	-	Zero Energy Building
HVAC	-	heating, ventilation, and air conditioning

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CHAPTER I

INTRODUCTION

2.1 Introduction

Daylighting has been an integral part of the Architecture studies. Light illuminate and serves a lot of purpose in a building; hence daylighting is one of the conditions taken into consideration during building design processes. In order to create quality of life in the living environment, architects must design structures that have illumination by the daylighting in spaces that is natural light. Therefore, natural daylighting is essential in building because visual perception and lifestyle of people influenced by daylight which in turn affects their behaviour, working pattern, emotion and so on. Moreover, daylight plays an imperative role in achieving sustainable and healthy living environment.

Furthermore, sustainable energy consumption in a building has become relevant, and there has been an increased interest in saving energy over the last couple of decades. This quest together with growing concern for the environment has spurred the growth of daylight technology in the field of Sustainable Architecture. Several researches in the past focused on daylighting in buildings. One of the prominent research on daylighting centered on perception of daylight as a function that increases human activities performance and comfort within indoor spaces (Omer, 2008; Baker and Steemers, 2002). Thus, using daylight in a building seems to be an excellent strategy to offset artificial illumination and to make a space more comfortable and enjoyable for any human activities.

In office building, daylight quantity and quality are essential, therefore it is very reasonable to ensure that daylighting has important role in the design and construction of building for any purpose, especially office building. Previous researches have proved that the amount of daylight needed in an office is lesser than artificial light in the same task (Ander, 2003; Robbins, 1986). Moreover, daylight has influence on the productivity as the better illuminated office encourages proper attendance by the users and reduced absenteeism of office users (Galasiu and Veitch, 2006). On the other hand, it is prerogative to know that daylight in office building has positive impact on the users and provide peaceful and aesthetic environment compared to electric light that can fail over time.

In the tropics, there is abundance of daylight because of high intensity of the sun and longer period of its illumination in the tropical climate. The global illuminance in clear sky can reach around 120,000 lx. On the other hand, studies carried out by researchers show that the high daylight in a tropical area has not been utilised to the maximum (Yeh *et al*., 2011; Ahmad, 1996). The solar radiation, intensity and hours of radiation is high and uniform throughout the year in the tropical climate, which suppose to be an advantage for daylighting. However, there may be a variation in global illuminance for tropical sky within a few minutes due to cloud formation, though this may cause unpredictable indoor daylight availability. On the contrary, Malaysian tropical sky is mostly intermediate, in other words, it is neither overcast nor clear (Lim *et al*., 2008; Ossen, 2005).

In buildings design for any purpose, windows are on the vertical facades that provide the aperture for daylight penetration into the building. However, daylight can only penetrate a limited depth through the window, even if there is no obstruction to the sky (Tregenza, 1980). Using taller and larger windows with higher transmittance glazing can improve the daylight area within an office or room as the case might be. However, adopting this method to achieve small gains in daylighting at the back of a room may lead to introducing disproportionate amount of solar radiation into the front part of a room, which increases cooling load and glare. Also, this gives rise to large non-uniformity of illuminance and luminance gradient within the space, resulting in visual discomfort and/ or unfavourable psychological effects on habitation of such room by the users.

In order to solve the above-mentioned problems, the use of some form of daylight and sunlight redirection system to transfer light to a greater distance inwards from the facade is encouraged. The following are some of the daylighting systems that could be used to transfer and redirect the intensity and illumination ability of daylight in a building: light pipes, Anidolic daylight, minor louvers, holographic grating, laser cut panels and prismatic glazing (Littlefair, 1990).

This research focused on Anidolic Daylighting System (ADS). It is a highly effective daylighting system that provides opportunity for ray of light to be transferred to back of the room (Scartezzini and Courret, 2002). Anidolic was designed according to the non-imaging optics principles (Linhart and Scartezzini, 2010; Wilson *et al*., 2002). Moreover, it has the advantage of collecting external daylight ray and redistributes it into the deeper part of the plan building with a minimum reflection number. This has been carried out in various climatic regions and different sky conditions (Linhart and Scartezzini, 2010; Wittkopf *et al*., 2006). Experiments performed by researchers on the Anidolic in various sky conditions; climatic regions and system configurations have proved that this system can considerably decrease the electric lighting in buildings (Linhart and Scartezzini, 2010; Wittkopf *et al*., 2006).

Therefore, it is an attempt to understand the varying condition that affect the interior daylight in deeper area of building. Further research on the use of Anidolic is very important to improve daylight in rear area of building and provide a potential to energy-efficiency as well as improvement of occupant's health and well-being. This research focus on improving the quantity and quality of daylight performance by Anidolic in open plan office in tropical climate. The next part of this research looked at the problems of Anidolic system in tropical climate.

2.2 Problem Statement

Due to the need for energy conservation and raising demand in utilization of daylight has become a crucial issue in the design and construction of buildings. Providing natural light in the rear area of the open plan buildings has always been a challenge for architects and building designers. As daylight can penetrate only a limited depth from the window, the question is: how natural light can be transferred into the deeper area in open plan office to improve visual comfort in workplace conditions for office workers and energy efficiency?

Innovative daylighting systems may be the answer to this question. ADS can bring natural light to the deeper area of the building. Previous researches have shown that the this system has enormous potential to transfer daylight into deeper area of building. Despite this potential, there is a lack of adequate data about the Anidolic performance in open plan office buildings in the tropical climate. there is insufficient research in configuration of duct shape, duct width, duct length and distributor of ADS. Furthermore, there is inadequate data on design methodology for innovative daylighting systems in tropical climate. Majority of existing ADS systems were designed in temperate or subtropical climate under clear sky and there were insufficient research in ADS under tropical climate. Therefore, this study investigates the performance of ADS and develop this device for transferring light horizontally in building.

There are problems in open plan office about daylighting. As open plan office has deep area and windows only provide limited daylight, artificial lighting is employed to provide light in interior of office. Using larger and taller window will increase non-uniformity of lighting and glare problem. Furthermore, due to inconstant cloud formation and glare problem in tropical climate, workers usually close their windows and use artificial lighting.

2.3 Research Question

For the purpose of this research the following research questions were formulated to achieve the aim of the study. This include the following:

i. What is the best orientation for an office with installed ADS for optimum daylight performance?
ii. Which design variables (various duct shape and duct width of ADS) indicate the optimum daylight performance in ADS?
iii. How deep is the optimum depth of office and appropriate duct length to provide sufficient illuminance with ADS?
iv. How is the daylight quality and quantity of indoor office determined by the ADS distributor variables (location and number)?

2.4 Aim and Objectives

The aim of this research is to provide sufficient daylight illuminance in the deeper area of open plan office in tropical climate. In order to achieve the stated aim, the following specific objectives are formulated.

i. To investigate the influence of different office facade orientation with installed ADS for optimum daylight performance.

ii. To evaluate the design variables (different duct shape and duct width of ADS) on determining daylight performance in ADS.

iii. To assess the appropriate duct length of ADS that provide sufficient illuminance.

iv. To determine the daylight quality and quantity of indoor office by introducing the ADS distributor variables (location and number).

2.5 Research Gap

Many research in ADS were carried out under subtropical and temperate climates in clear sky condition (Kwok, 2011; Lau and Baharuddin, 2009; Hien and chiraratananon, 2009; Singal *et al.*, 2009; Tsikaloudaki *et al.*, 2008; Wilson *et al.*, 2005; Scartezzini & Courret, 2002), while the configurations of Anidolic system in tropical climate are different from Anidolic configuration under other climates. Although, some researches were carried out using ADS under tropical climate (Wittkopf *et al.*, 2010; Linhart & Scartezzini, 2010; Linhart *et al.*, 2010; Wittkopf *et al.*, 2006). These researches are not sufficient in configuration of duct shape, duct width, duct length and distributor of ADS. Thus, it is necessary to investigate the design variables in duct shape, duct width, duct length and distributor of ADS in tropical climate. Thus, the investigation into the design variables and Anidolic performance that can be applied in a tropical climate under overcast and intermittent sky conditions is required.

Although there are some researchers who have investigated the Daylighting Systems, most of them studied on the simulation tools that were done CIE sky (International commission of Illumination) (Hu *et al.*, 2013; Linhart *at el.*, 2010; Wittkopf *et al*., 2006; Canziani *et al.*, 2004). CIE sky is remarkably different from tropical sky condition. For this reason, real model or scaled model to measure daylighting at real climate can improve the accuracy of results and also simulation tool. Hence, it is necessary to employ physical scale model with simulation software for this research.

Moreover, majority of previous researchers investigated daylight quality or quantity separately (Linhart *at el*., 2010; Wittkopf *et al.,* 2010; Lau and Baharuddin, 2009; Wilson *et al*., 2005). For having an optimum daylight in space, an appropriate situation regarding the daylight quantity and quality of daylight is important too. Thus current research determine optimum cases of ADS for tropical daylighting on quantitative and qualitative daylight performance.

Therefore, in current research is an attempt to study previous research gaps on Anidolic in tropical climate and also use two method of physical scale and simulation tool for ADS. Furthermore, this research focuses on determining the daylight quality and quantity base on uniformity of indoor office simultaneously.

2.6 Scope and Limitation

This research focuses on the daylight efficiency in the rear of the office building by installed ADS. This research studies Anidolic Daylighting System under tropical climate where the sky is not clear (intermediate and overcast sky conditions) and. Other aspect of Anidolic Daylighting System such as thermal comfort, solar heat gain and energy consumption are not considered in this research.

There are various types of spaces in office buildings such as meeting room, cubical office room, open plan office and so forth. The area of current study is limited to open plan offices. In open plan offices, there are many users that perform various tasks simultaneously. Therefore, users adjust their workplace and lighting condition to obtain comfortable setting according to task performance. Open plan offices are more critical for achieving visual comfort. These kinds of offices need more consideration for daylighting efficiently.

Two methods are employ in this research which are physical scale model and simulation model. The scale model approximates the characteristics of full-scale office and furniture of that is ignored in this research. Four cardinal orientations were selected to experiment.

2.7 Importance of Research

Innovative daylighting systems have been an extremely popular topic in recent area of research. Anidolic is a promising system that distributes daylight in the rear of building which is deeper than what ordinary window can provide especially in open plan office. ADS is essential in a building with one side façade due to vertical wall as a barrier to daylighting. This has always been an impediment for designer to introduce ADS in the tropical climate. This research is essential to identify the critical variables to improve ADS for open plan office in tropical region of the world with particular reference to Malaysia as a choice location in the tropics.

The process of designing the Anidolic Daylighting System with tropical climate under intermittent and overcast sky conditions will allow for utilization of ADS in this region. The research will establish the criteria needed to enable ADS to function properly and effectively in the tropical climate. The recommendations can provide visual comfort for the occupant's health and effective productivity. Moreover, optimum ADS can reduce energy consumption in electric lighting.

2.8 Thesis Organization

This thesis is arranged in five chapters and are summarized as the following in a chronological order:

Chapter one is the introduction which reviews the main research issue. It contains the following sub sections such as background to the study, the problem statement, aim and objectives, hypothesis of study and research questions of the study. Moreover, the research gap, research objectives, scope and limitations of the study, importance of research and the overall thesis structure are also explained in this chapter.

Chapter two focuses on literature review of the daylight, office building, tropical climate and daylight devices. Theory of light is discussed in this chapter to give an understanding of the characteristics of light and human vision. Moreover, benefits of daylight in architecture is discussed. The daylight availability and issues in tropical daylighting is explained to understand the sky condition. Besides, standards in the building are mentioned. In the next section, daylight systems are discussed on issues such as in properties, advantages and disadvantages in various climate condition. Elaborate literature from the previous researchers on ADS provide the opportunity for proposing the improved ADS for tropical climate.

Chapter three explains the methodology used in this research to achieve the stated objectives and daylight analysis. This chapter first reviews the research methodology used in daylight analysis. Secondly, it discusses the methodology used in this thesis that includes: physical scaled model measurement and daylight simulation model. Next, designed variables are explained in detail in this chapter. The assumptions and criteria used for the experiments and simulations are explained.

Chapter 4 include the process of validations physical scale model and simulation model. In this part base simulation model office room base simulation office room with the ADS was designed and compared with the base physical scaled model. The four objectives were also discussed. Firstly, physical scale model and simulation model were tested to analyse first objective. In this case, quantitative performance analysis of absolute WPI under real sky condition and simulated model was examined to evaluate the effective test case for the four cardinal orientations. Secondly, the simulation results of Daylight Factor (DF), Work Plane Illuminance (WPI) and Daylight Ratio (DR) were evaluated to analyse quantitative and qualitative performance in order to determine the effective variable design in objective two, three and four. In this section, quantitative and qualitative performances analysis of selected variable were studied. Finally, the optimum cases for tropical daylight efficiency were selected.

Finally, chapter five presents the overall review of the research questions and research objectives. Moreover, this chapter concludes on the findings of principle and design recommendations for ADS in the open plan office. This chapter summarizes contribution of research and recommendations for the future research to complement with findings of this thesis. The research process flow and thesis organization are summarized in Figure 1.1 and Figure 1.2.

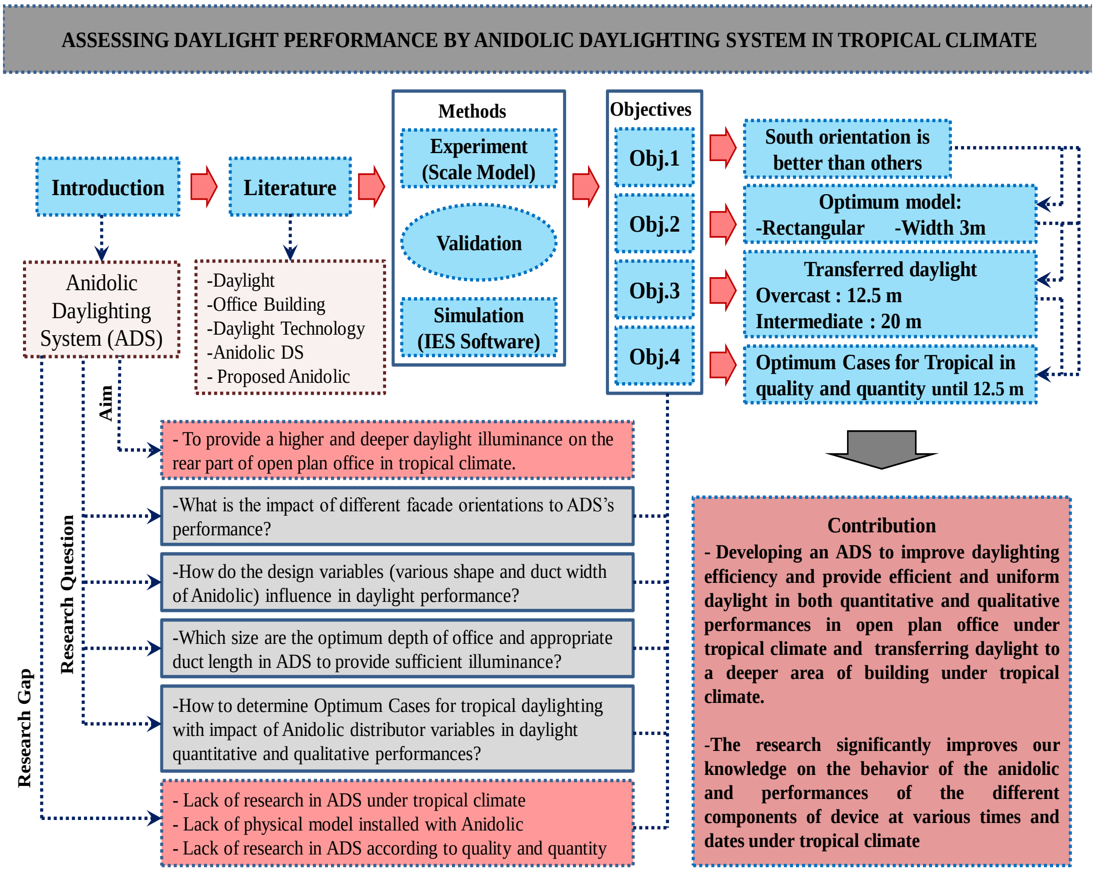

Figure 1.1 The research process flow and thesis organization

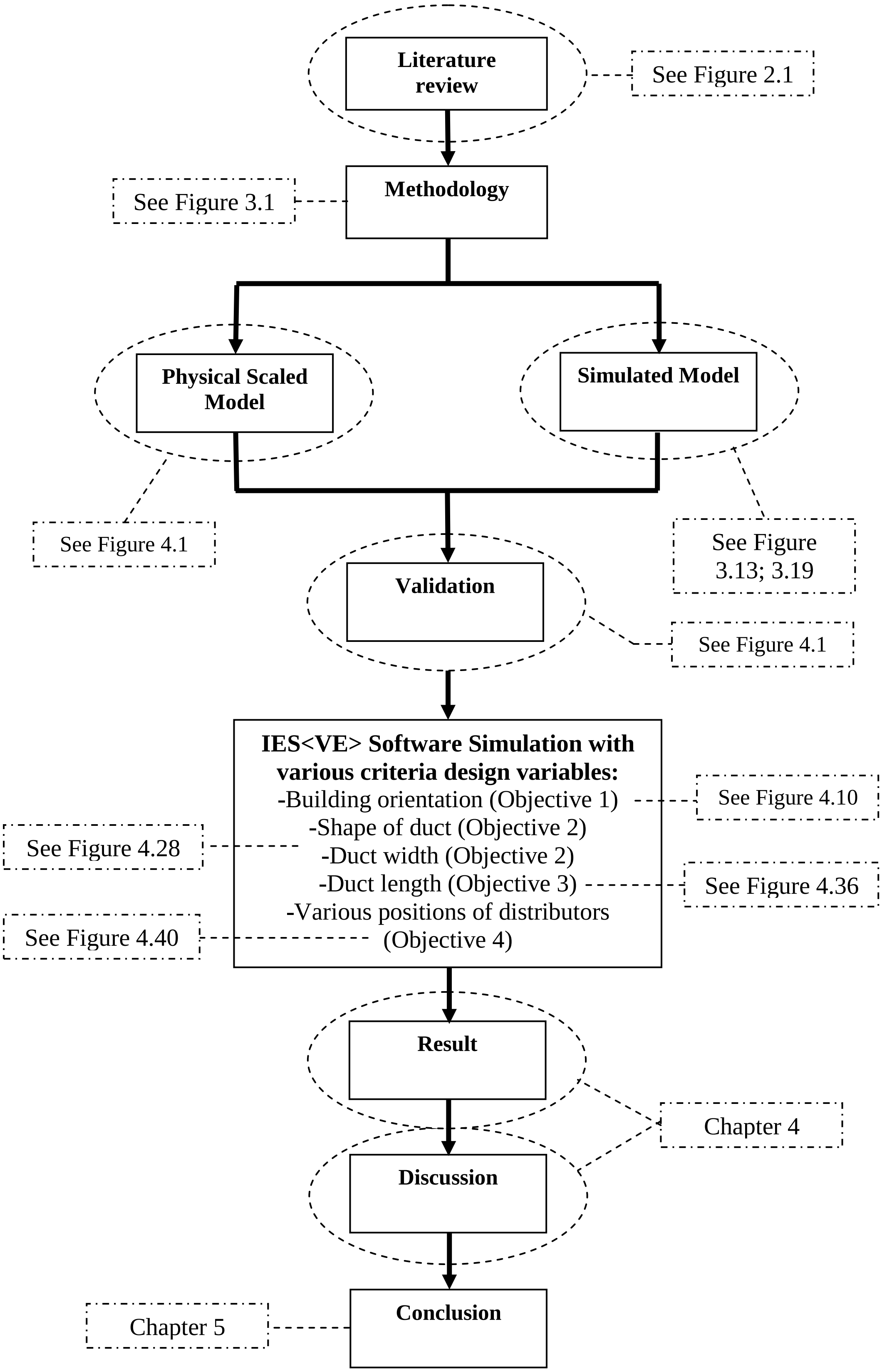

Figure 1.2 The research process flow chart

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