Application of a low-cost decision-making tool for sustainable building design of schools

Using a developing region in Indonesia as a case study

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DISSERTATION

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KURZFASSUNG

Das zunehmende Wachstum der Bauindustrie wirkt sich in den Entwicklungsländern auf die Umwelt aus. Nachhaltigkeit ist zur Hauptagenda geworden, um die Auswirkungen des Bauens auf die Umwelt zu minimieren und die Langlebigkeit künftiger Generationen zu gewährleisten. Für ein großes Land wie Indonesien ist es jedoch eine überwältigende Aufgabe, Nachhaltigkeit in einem Gebäude zu erreichen, da seine regionalen Grenzen durch kulturelle Vielfalt, soziale Unterschiede und wirtschaftlichen Wohlstand getrennt sind.

Die meisten Entscheidungen werden im Entwurfsprozess getroffen, der für die Entwicklung eines nachhaltigen Gebäudedesigns von entscheidender Bedeutung ist. Die Bereitstellung von Planungsleistungen wie Zeit- und Kostenschätzung für öffentliche Projekte in Indonesien unterliegt dem nationalen Standard eines Beschaffungssystems. Bei diesem System ist die Flexibilität zur Änderung des zugewiesenen Budgets begrenzt. Die Untersuchung aller möglichen Designalternativen ist daher nicht für Entscheidungsträger von Vorteil. Darüber hinaus wird bei Schulbauprojekten die Verknüpfung der Gestaltung von Schulumschlägen mit den verschiedenen Baumaterialien aufgrund eines standardisierten Schullayouts in Indonesien vom Designer häufig ignoriert. Eine solche Praxis vernachlässigt höchstwahrscheinlich die sozialen, wirtschaftlichen und ökologischen Kriterien für ein nachhaltiges Design, insbesondere den Komfort in Innenräumen, als eines der wesentlichen sozialen Kriterien in den Klassenzimmern. Angesichts der enormen Nachfrage nach neuen Grundschulen und potenziellen Schäden an bestehenden Schulen in diesem von Katastrophen betroffenen Land ist ein praktisches Entscheidungsinstrument für die Auswahl eines nachhaltigen Designs unvermeidlich. Auf der Grundlage der obigen Aussichten wurde ein Rahmen entwickelt, um die sozialen, wirtschaftlichen und ökologischen Kriterien in der frühesten Phase des Entwurfsprozesses voranzutreiben. Im Entwurfsprozess wurde der Schwerpunkt auf die Kombination von Materialien gelegt, die auf vier typischen Schulform- / Designkonfigurationen für die öffentliche Schulentwicklung in Indonesien basieren. Im Mittelpunkt des Frameworks steht eine Entscheidungsmatrix, die eine MCDM-Methode (Multi-Criteria Decision Making) verwendet. Das Gewicht und die Leistung jedes Kriteriums in der Matrix wurden aus der subjektiven und objektiven Bewertung der Kriterien anhand einer Fallstudie von Grundschulgebäuden in Aceh, Indonesien, ermittelt. Beide Bewertungen wurden in Bezug auf die Art der Kriterien für die soziale, wirtschaftliche und ökologische Leistung des Schuldesigns relevant gemacht.

Subjektive Bewertungen wurden durch eine Fragebogenumfrage durchgeführt, um jedes Kriterium und jeden Leistungswert des Materials gemäß den Wahrnehmungen, Erfahrungen und Überzeugungen der Menschen zu gewichten. Zusätzlich wurde der Komfort in Innenräumen subjektiv anhand des von den

Schülern empfundenen Wärmegefühls bewertet. Andererseits konzentrierten sich die objektiven Bewertungen auf die Leistungsbewertung bestimmter Kriterien in einem vollständigen Entwurf. Dazu gehören die Leistung des Kostenkriteriums, die verkörperte Energie (EE), die CO2-Emission der Materialproduktion und insbesondere die Leistung der Innentemperatur für jede Entwurfsalternative, die mithilfe einer Simulationsmethode recht genau bewertet werden kann. Die simulierte Stundentemperatur wurde gegen tatsächliche Messungen getestet, um ihre Gültigkeit zu überprüfen. Es wurde festgestellt, dass das Simulationsmodell von vier typischen Designs zuverlässige Ergebnisse bei der Vorhersage des thermischen diskomfortstunden. Schließlich wurde TOPSIS als eine der MCDM-Methoden verwendet, um alle Entwurfsalternativen zu bewerten. Ein knackiger Wert oder Index von 0 bis 1 wurde als Indikator für eine nachhaltige Leistung abgeleitet, wobei 1 die höchste Leistung bezeichnet. Die Verwendung einer MCDM-Methode im Framework war hauptsächlich darauf zurückzuführen, dass die endgültige Entwurfsauswahl aufgrund von Projektbeschränkungen und Präferenzen des Entscheidungsträgers zusammen mit dem Projektziel beeinträchtigt werden kann. Auf der Suche nach der besten nachhaltigen Leistung des Schuldesigns schienen Kosten und Komfort in Innenräumen die Kriterien für die Auswahl eines Designs für dieses Fallstudienprojekt zu beeinträchtigen.

Die Ergebnisse dieser Forschung zeigen, dass aus 144 Designalternativen der höchste nachhaltige Leistungsindex in einem Design mit zufriedenstellendem Komfort in Innenräumen gefunden wurde, jedoch mit 39% zusätzlichen Kosten im Vergleich zum Baseline-Modell. Die Ergebnisanalyse der Innentemperatur zeigt, dass des thermischen diskomfortstunden dieser Konstruktionsalternative auf 56,5% reduziert werden kann. Die Scheibe. Stunden während der Schulzeit ergeben eine Reduzierung um 68,7%. Für diesen besten Fall ist die Disc. Stunden erscheinen nur von 12.00 bis 13.00 Uhr mit zweieinhalb Monaten zeigt keine Beschwerden. Die Unbehaglichkeitsperiode im Baseline-Modell beträgt meistens von 10.30 bis 13.00 Uhr, wobei insgesamt 728 diskomfortstunden in einem Jahr erzeugt wurden. Wenn die Kosten als Hauptbeschränkung bei der Entscheidungsfindung betrachtet werden, haben sich zwei weitere Entwurfsalternativen als gute Kandidaten erwiesen, da diese beiden Entwürfe eine bessere nachhaltige Leistung aufweisen als das Basismodell. Das erste Design verursacht 4,5% niedrigere Kosten als die Basislinie, während das zweite Design nur 6,3% zusätzliche Kosten verursacht. Beide Designalternativen führen zu einer Reduzierung der gesamten Disc um 12,3% und 68,9%. Stunden im Vergleich zum Baseline-Modell.

Das Ergebnis dieser Forschung stimmt mit der Hypothese überein, dass durch die Verwendung der gleichen Kostendaten aus den retrospektiven Fallstudienschulen eine bessere nachhaltige Leistung erzielt werden kann. Ein Designauswahl-Tool, das auf einer Anwendung des Frameworks in dieser Fallstudie basiert, hat bewiesen, dass ein besseres Design bei gleichzeitiger Kosteneffizienz zur Auswahl steht. Mit dem Vorhandensein eines in dieser Studie entwickelten Tools ist bekannt, dass die Bedeutung von Kriterien und die Leistung der Nachhaltigkeit aus einem bestimmten Entwurf Entscheidungsträgern früh in der Entwurfsphase helfen.

Der vorgeschlagene Rahmen und die vorgeschlagenen Methoden zur Entwicklung des Werkzeugs können auch bei der frühen Planung anderer neuer und bestehender Gebäude in Ländern mit trockenem und gemäßigtem Klima angewendet werden, unabhängig von der Art der Gebäudeformen, der Entwurfskonfiguration und dem Material. Am wichtigsten ist, dass der Entwurfs- und Materialauswahlprozess unter Verwendung des entwickelten Rahmens auch in einem traditionellen Projektabwicklungssystem implementiert werden kann, um das Bewusstsein und die breite Akzeptanz von nachhaltigem Bauen in Entwicklungsländern zu erhöhen. Die Auswirkungen der Umsetzung des entwickelten Rahmens in anderen Regionen Indonesiens werden vorteilhafter sein, da viele öffentliche Schulen und verschiedene Arten von öffentlichen Gebäuden unter Verwendung des Finanzierungsmechanismus für Regierungsprojekte gebaut werden

ABSTRACT

The increasing growth of the construction industry creates negative environmental impact in developing countries. Sustainability in construction has become the main agenda to minimize or eliminate those negative impact and ensure future generations' longevity. However, for a big country like Indonesia, achieving sustainability in a building is an overwhelming task because its regional boundaries are divided by cultural diversity, social differences, and economic prosperity.

Most decisions are taken at the design process, which is crucial for developing sustainable building design. The provision of design services such as time and cost estimation for public projects in Indonesia is governed by the national standard of a procurement system. Under this system, the flexibility to change the allocated budget is limited. Thus, exploring all possible design alternatives is not in favor of decision-makers. Furthermore, for school building projects, the inter-connection of school envelope design with the various selection of building material is often ignored by the designer due to a standardized school layout in Indonesia. Such practice most likely neglects the social, economic, and ecological criteria for achieving sustainable design, especially indoor comfort as one of the essential social criteria in the classrooms. With an enormous demand for new primary schools, and potential damage to existing schools in this disasters' prone country, a practical decision-making tool for selecting a sustainable design is inevitable. Based on the outlook above, a framework was prepared to bring forward the social, economic, and ecological criteria at the preliminary design stage. Focus given during the design process was by combining materials based on four typical school shape/design configurations for public school development in Indonesia. Central to the framework is a decision matrix that employs a multi-criteria decision making (MCDM) method. Criteria weightings and performance of each criterion in the matrix were obtained from the subjective and objective evaluation of criteria using a case study of primary school buildings in Aceh, Indonesia. Both evaluations were made pertinent to the type of criteria across the social, economic, and ecological performance of school design.

Subjective evaluations were performed through a questionnaire survey to weight each criterion and performance value of material according to people's perceptions, experiences, and beliefs. Additionally, indoor comfort was also evaluated subjectively according to the thermal sensation felt by the students. On the other hand, objective evaluations concentrated on performance assessment of specific criteria in one complete design. These include the performance of cost criterion, embodied energy (EE), CO_2 emission of material production, and the performance of indoor temperature for each design alternative, which can be valued quite accurately using a simulation method. The simulated hourly temperature was tested against actual measurements to check its validity. It was found that the simulation model of four typical designs produced reliable results in predicting total Disc. Hours. Finally, TOPSIS, as an MCDM method, was used to rank all design alternatives. A crisp-value or index from 0 to 1 was derived as an

indicator of sustainable performance with 1 denotes the highest performance. The utilization of an MCDM method in the framework mainly because the final design selection can be compromised based on project constraints and the decision-makers preferences alongside the project goal. Hence, while searching for the best sustainable performance of school design, cost and indoor comfort appeared to be compromising criteria for selecting a design on this case study project.

This research shows that from 144 design alternatives, the highest sustainable performance index was found in one design with satisfactorily indoor comfort, but with 39% additional cost compared to the Baseline model. Results analysis from the indoor temperature shows that the total discomfort hours (Disc. Hours) of this design alternative can be reduced to 56.5%. The Disc. Hours during school hours yields a 68.7% reduction. For this best case, the Disc. Hours appear only from 12.00 to 01.00 PM with two and a half months shows no discomfort. Period of discomfort in the Baseline model is mostly from 10.30 AM to 01.00 PM, which makes the total of Disc. Hours of 728 hours all year long. If cost is considered the main constraint during decision-making, another two design alternatives were found to be good candidates because they have better sustainable performances than the Baseline model. The first design produces a 4.5% lower cost than the baseline, while the second design yields only 6.3% additional cost. Both design alternatives produce 12.3% and 68.9% reduction on total Disc. Hours respectively, when compared to the Baseline model.

The result of this research agrees with the hypothesis that by using the same cost data from the retrospective case study schools, better sustainable performance can be achieved. Application of design selection tool based on a framework in the case study confirmed that a better yet cost-efficient design is available for selection. By using such a tool as demonstrated in this research, the importance of criteria and performance of sustainability from a given design are known to assist decision-makers early in the design stage.

The proposed framework and methods used for developing the tool can also be applied during the early design of other new and existing buildings in dry and temperate climate countries regardless of the various type of building shapes, design configuration, and material. Most importantly, the design and material selection process using the developed framework can be implemented even in a traditional project delivery system to increase the awareness and expedite the building sustainability progress in developing countries. The advantage of implementing the developed framework in other Indonesian regions will be significant since many public schools and different types of public buildings will be built using the government projects funding mechanism.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CP	Compromise Programming
DBT	Dry Bulb Temperature
Disc. Hours	Discomfort Hours
DT	Design Type
EE	Embodied Energy
ELECTRE	ELimination and Choice Expressing REality
E+	EnergyPlus
ISO	International Organization for Standardization
LCA	Life-Cycle Analysis
LCI	Life-Cycle Inventory
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
OT	Operative Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSV	Thermal Sensation Vote
WPM	Weighted Product Model
WSM	Weighted Sum Model

CHAPTER 1

INTRODUCTION

1.1 Problem Statement and Research Questions

Construction industry contributes significantly to social development and prosperity in developing countries. In comparison to environmental quality, the construction industry consumes lots of primary energy sources, produce waste and greenhouse gas (GHG) emissions, polluting air, damaging environment, and deplete natural resource (Ortiz *et al.*, 2009). Specifically in the building industry, more than 50% of CO_2 emissions in the world comes from the materials fabrication, construction activities, and operation that leads to climate problems (Meggers *et al.*, 2012). There is a tremendous effort in the building industry to reduce CO_2 emissions. One strategy is by reducing the primary energy usage in developing countries such as limiting the use of fossil fuels in material fabrication. Another effort is to utilize alternative energy source using advanced technology such as wind turbine to catch the wind energy or photovoltaic panel to absorb solar energy. All of these efforts lead to a sustainable development where the building construction industry must achieve for the present and future generations (Asif *et al.*, 2007).

Indonesia has the biggest territory in South East Asia, with numerous construction works across the country. Achieving sustainable development in construction in such a big developing country like Indonesia is not a simple task. According to Ofori (2000), p. 318, "The environmental problems of the developing countries exist side-by-side with a lack of the managerial experience, financial resources, and legal and administrative systems necessary to deal with the issue through public and formal education." In addition, Ali (2013), p. 105 pinpointed that "rapid rates of urbanization, deep poverty, social inequity, low skills levels, institutional incapacity, weak governance, an uncertain economic environment and environmental degradation," are among systemic problems in developing countries. Serious attempt in the development of sustainable building and sustainable construction is so minimum because awareness and interest of sustainability agenda are simply lacking (Samari *et al.*, 2013; Serpell *et al.*, 2013; Abidin and Nazirah, 2010). As these countries are faced with social issue and prosperity problems, their understanding of sustainability in the construction industry is quite different compared to developed countries (Cole, 2005).

Preliminary building design is a crucial step to move towards sustainable building. However, design professionals seem to abandon available green products or sustainable strategy in their design. Such attitude perhaps caused by "lack of awareness and insufficient information, limited availability of green or eco-labeled materials, uncertainty about approvals and regulatory barriers to adopting new green technologies." (Sarvajayakesavalu, 2015). All of these issues provide further challenges in designing sustainable buildings. To enable the adoption of sustainability in building, designers are required to specify specific sustainable criteria for design and building material. Specifically, the standard assessment criterion for comparing and evaluating building materials is not available. Hence, designers and engineers must spend lots of time assessing potentially sustainable or green materials and technology (Secondini *et al.*, 2011). Unlike the road, bridge, or dam construction, the variation of materials is quite many, even in a simple building. Thus, selecting and combining material when designing a building is particularly vital in achieving sustainability in a building.

Construction development for the public building sector in Indonesia shares significant financial burdens, creating greater sustainability problems in building design and construction. As an immense archipelago, Indonesia features a diverse social, cultural, and economic capacity. For building projects financed using the government budget, the Owner must approve the complete design before the bidding process. During the design stage, the awarded design consultant may already be involved in other projects or is looking for other design projects. This creates little attention to propose the design, including the material choice in favor of sustainability. Furthermore, due to staff workload and time constraints, neglecting all aspects of design criteria has become common, especially for building with similar types. As a result, a particular design's decision often depends mainly on the cost as previously allocated by the Owner. It means that cost has always been considered as the primary target for design approval without looking at other criteria. Besides, there is a common belief among building professionals that sustainability will add more cost. To achieve sustainability in a building, the building design needs to consider not only the cost but also other design criteria such as location, weather, social, construction technology, use of material, ecology, and cultural values. Hence, a suitable material and design selection tool is needed to accommodate criteria relevant to a building's sustainability.

In this research, a tool was created based on a framework specifically developed for Indonesia and other developing countries. The functionality of the tool aims at assessing the sustainable performance from a set of design alternatives without having to interfere current project delivery method under government-funded projects in Indonesia. Therefore, the approach used is not contradictory to the current legislation and project delivery system of Indonesia's public projects. A case study project was performed to verify the applicability of the tool in selecting suitable design alternatives during the preliminary design process. Hence, the tool should be able to provide quick information on three main questions. First, if the first cost of original designs has been determined, how sustainable are those designs? Second, what is the most critical design parameter in determining the sustainability of the building? Third, what will be the cost to improve sustainability against the original design?

Since cost is always the primary objective, indoor temperature evaluation during the design process is often neglected. Indoor comfort temperature has been regarded as an essential social criterion because it helps improve concentration and productivity. Hence, thermal comfort study will be included in the framework. As a developing country, Indonesia lies in the hot and humid region, and it has become common beliefs to building designers, the occupant, and community that beside belief in additional cost incurred for sustainability, the use of air conditioning unit is always seen as the only solution to achieve indoor comfort.

Given an enormous need for new school buildings and the potential damage to existing schools as a country vulnerable to natural disasters, it has become the primary motivation of this work to recognize the criteria of sustainable school design in Indonesia. To formalize the tool's functionality in addressing the problems as described above, a case study of primary schools built during the post-disaster reconstruction projects in Aceh Province, Indonesia was selected. These schools were designed according to the 'build back better' principle and in some ways already consider sustainable aspects, such as a cross-ventilation system that allows the breeze and wide clear window glass, which allows natural daylight entering the classroom. The school was also designed to withstand future earthquakes, and they were constructed mostly using local materials and engaging local workers. Hence, these schools can be used as the origin of sustainable strategy or default configuration in assessing overall sustainability performance. By using a retrospective case study of existing schools as described above, only one hypothesis was developed to answer the questions mentioned above:

"Using the same cost data, there will be more improvement to the sustainability''.

Under such cost constraints, the research was designed to address the current design selection process's limitations. As an alternative method for material and design selection during the preliminary design stage, a low-cost decision-making tool will be introduced based on the proposed framework. Such a framework may serve as one solution, because as mentioned by Hayles and Kooloos (2008), "lack of knowledge and information on sustainable construction issues and appropriate, affordable solutions are major obstacles that need to be overcome." ([Hayles and Kooloos, 2008], p. 6). From this standpoint, the research focuses on a case study of completed primary school buildings in Aceh province to identify several sustainability criteria and reviews how better design can be achieved by applying changes to the chosen materials and other design parameters. The pursued goal is to create a holistic decision-making tool for architects and planners in Indonesia to rank design alternatives based on the above parameters to their sustainability performance. This decision tool shall reach a decision that is based not only on economic reasoning but also on ecology and social quality.

In order to develop such a tool, the research was carried out through three major phases. The first phase was dedicated to studying the importance of criteria under the three pillars of sustainability in the local context. The second phase deals with simulation technology and develops an effective and affordable simulation method in producing all possible design alternatives of the school. Finally, the third phase was to implement a Multi-Criteria Decision Method (MCDM) in which all important criteria and performances of each design alternatives can be generated and presented to the decision-makers.

1.2 Scope of Research

The research scope has been designed to meet the research time frame while seeking answers to the main research questions, as stated above. The first and most important scope to be defined is the location of the research area. Banda Aceh and Aceh Besar region were selected for the case-study location since; first, there are no thermal comfort studies in this area which representing part of western Indonesia. Few thermal comfort studies were performed in Bandung and Jakarta, which is located in southern Indonesia. However, the average Dry Bulb Temperature (DBT) is lower in those regions. The second reason was that the use of air conditioning has been increasingly high in Banda Aceh, followed by other parts of Aceh province. The third is that demand for the new schools is still high, and many existing schools are noticeably require upgrading, and lastly, the researcher’s home is in Banda Aceh so that direct monitoring and regular visits can be done for collecting data. Qualitative research was performed to solicit the importance of criteria and performance of locally sourced material from relevant stakeholders in Aceh. Also included in the qualitative study were data collection from the students about the indoor temperature sensation in the classrooms. Eight school buildings were investigated to conclude the students’ temperature and comfort range. This method aims to get an accurate indicator about the students’ sensation on the actual indoor temperature inside the classrooms.

The second research scope is about the design process, construction technology, and cost model typically used in Indonesia. During the design process, the focus was given at the preliminary stage of design concerning the use of local materials for the building envelope because for school buildings, envelope materials have a sizeable portion of construction and these materials also have direct contact with outdoors. For construction technology, attention was given to common structural shape in school design in which most local construction workers are familiar with. This second scope of research is categorized as a design aspect that will be solved quantitatively. Four typical school shapes in Aceh province of Indonesia concerning the selected material were investigated because of the combination of building shapes, ventilation design, ceiling height, type of roof, and materials resulting in the different indoor temperatures in the classroom. As this will result in many possible combinations or design alternatives, simulation technology was used. Finally, the cost model was limited to the initial cost because this cost can be directly calculated during the preliminary design. The standard cost of material, workers, and productivity index was sourced from the Provincial Government Office, which is typically used by a Design and Engineering Consultant to estimate the initial building cost.

The third scope is about making the decision that allows compromised solutions between cost and criteria performances pertinent to the overall sustainable performance. This is consistent with the research goal, which is to obtain feasible sustainable options during preliminary design. Hence, design alternatives were evaluated using the MCDM method. One of the MCDM methods called TOPSIS was selected because it has an algorithm which more than adequate to solve the presented problems.

1.3 Research Objectives

As with any other decision-making method, advising the decision-maker may not change his/her behavior, especially under the conventional project delivery system. As illustrated before that under this type of project delivery, the Owner has full control on cost over the proposed design by a Design and Engineering Consultant. If costs are used as the only criteria to consider, sustainability in buildings will probably difficult to achieve. Hence, subjective and objective assessment of all sustainable criteria during the design process ensures not only transparent results, but also allow the reproduction of results in the future. The inclusion of subjective assessment within this research may influence the result as Sijmons (2009) cited by Allacker (2010), p. 11, stated that “the emotional part of people, like value, belief, and fear to persons cannot be determined quantitatively but will also determine one’s final decision.”

Having recognized common public project practice and the complexity of relationships across the three sustainability pillars in Indonesia, the research's central and specific objectives are specified below.

1) To provide a decision aid tool during the preliminary design stage by taking into account sustainable performances of possible design alternatives based on the combination of all building materials. The primary concern is on the application of the tool under the traditional or conventional project delivery system in Indonesia.
2) To allow quick what-if analysis among sustainable performance, indoor comfort, and cost. The tool is basically the representation of the developed framework featuring transparent results and provides an automatic link to accommodate the selection of design, material, and cost associated with it.

Specific objectives were constructed as follows:

- To obtain the sustainable criteria and level of importance of each criterion.
- To combine all building materials with typical school shape or design configuration.
- To assess the performance of each complete design across three pillars of sustainability.
- To obtain actual indoor temperature during school hours and compare them with the temperature output from simulation software. The sustainable performance of each complete design must not be limited to the selection of material only, but also how each design performed during operational hours and how it can benefit the students. This is part of the social criteria of design

known as a socially acceptable design. Hence, the focus will also be given to analyze and conclude indoor temperature performance since it is correlated to the student's comfort during school hours.

- To estimate the initial cost of each design alternative and compare the resulting cost with the overall performance of sustainable criteria

It should be underlined that the developed tool serves as an aid tool to find the compromise solution among overall sustainable performances of each design where the cost factor was also included. The tool is intended to give an informed decision making earlier to the architect or designer under the traditional project delivery method.

1.4 Outline of the Dissertation

From the objective above, the research used a qualitative and quantitative methods or so-called a multi-method approach. The qualitative method was used when searching the importance of criteria for a sustainable school as well as a subjective assessment on material performance and the student's temperature sensation inside the classroom. The objective evaluation was performed using a quantitative research method to evaluate indoor temperature, cost, and ecological impact. To clearly present the overall view of the topic, this dissertation is divided into five chapters, which are briefly explained below.

Chapter one : This chapter contains statement of the problem, research questions, hypotheses, and the research objectives. Finally, an outline of the overall structure of the dissertation is given.

Chapter two : The criteria selection for sustainable school is presented in this chapter. The process began with discussions on current construction practices in Indonesia. The basic concept of design for sustainability and the current trend of sustainable development in Indonesia was described. The primary focus of this chapter is the selection of criteria for sustainable material and design. These criteria were screened from previous studies and were further evaluated for its fitness using a case study method. Theories on thermal comfort are also presented in this chapter.

Chapter three: In this chapter, the tool development through a framework is presented. Each part of the framework is described, including methods for quantifying subjective and objective criteria as well as methods in making the decision. The selection of sustainable criteria, criteria weighting, the performance of each material, and comfort sensation in the classroom are among the subjective criteria to be quantified. While quantification of objective criteria includes methods for simulation, quantification of ecological performance, and cost calculation method. This chapter also highlights key steps in determining the suitable decision-making method to select sustainable material and school design. A comparison of other MCDM methods was also made and explained why TOPSIS was selected in the framework. Finally, this chapter presents the design selection procedure using the TOPSIS method.

Chapter four : Chapter four presents the results and analysis of qualitative and quantitative methods in the case study project. It began with results from a qualitative study, which includes detailed implementation of methods and evaluation of subjective criteria. For the assessment of thermal comfort, a working method of field survey was explained. The quantitative study analysis comprises: 1) The simulation process to obtain the indoor temperature. Results from this simulated indoor temperature will be compared to the result of the thermal comfort survey and validate the results by comparing prominent studies of thermal comfort in tropical countries, 2) Results and analysis of the ecological performance of material and cost estimation, and 3) Presentation of results and analysis of the TOPSIS method in the case study.

Chapter five : This chapter presents conclusions, including all challenges, strengths, and weaknesses of the developed tool. Recommendations for future works were also presented as well as an outlook of research.

CHAPTER 2

THE MATERIAL SELECTION CRITERIA AND SUSTAINABILITY PERFORMANCE IN BUILDING

2.1 Sustainable Development in Indonesia

Environmental problems in the Indonesian construction industry mainly come from material transportation emission, debris and waste during construction, and excessive timber use. For the use of timber alone, Higgins (2009) and Tacconi *et al.* (2019) reported that most timber for construction comes from deforestation and illegal logging, thus put Indonesia on the third rank of greenhouse gas emitter country in the world.

As a highly populated developing country, Indonesia focuses more on establishing good governance and fighting poverty across the regions. Lack of mass-transportation has forced people to own motor vehicles. The increasing use of motor vehicles contributed to high emission because major energy sources come from the burning process of fossil fuels, such as gasoline and diesel. This may cause "global warming (GWP), acidification (ACP), nutrient enrichment (NEP), photochemical smog formation (PSF)" ([Abeysundara *et al*., 2009], p. 998) to increase up to a worrying level. Energy for industrial and domestic sector is mostly come from electricity supplied by the government owned electrical company. Tarakan (2015) reported that "the source of electrical energy in Indonesia is mainly in a combination of oil (46.08%), coal (30.90%), and gas (18.26%), and renewable energy resources, such as hydropower energy shares only 3.21% in the energy mix, followed by 1.15% from geothermal power, and 0.40% from biofuel." ([Tarakan, 2015], p. 7).

Because most energy in Indonesia is mainly from fossil fuels, domestic energy dominated by electricity demand would increase by about 7% per year, and would be triple in 2030 (MEMR, 2018). Nevertheless, Indonesia expect that the GHG emissions can be reduced in the near future. According to report from The Ministry of Environment, Republic of Indonesia (2010), as cited by Thamrin (2011), p. 4, "Based on the initial estimates, the GHG emission reduction target of 26% by 2020 could be equal to 0.767 Gton CO_2e, and if international financing is available, an addition of 15% (0.477 Gton CO_2e) or reduction up to 41% would be possible." The report highlighted the necessity to use an international accepted methodology, data, and information so that the reduction estimation of GHG emission can be estimated with better accuracy.

In Indonesian practice, recycling and reusing some building materials are popular ways of reducing GHG emissions. The selection of which material to use is subject to the decision maker's choice and the local capacity because the use of most recyclable material is not always the best solution to achieve sustainable performance in the building. There are quite many definitions of recycling and reusing found in the literature. Among others, the European Commission Directorate-General for Environment (2012) emphasized that "The definition of 'recycling' under Article 3(17) WFD is any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" ([European Commission Directorate-General for Environment, 2012], p. 32). Thus, recyclability is the processing of used material, becoming a new resource for other products. Concrete reinforcement steel (rebar) is a popular recycled building material because separation of used rebars from concrete or construction debris is relatively easy. A common way of separating rebar from construction debris is done by hand directly at the project site.

Building demolition and construction waste contribute significantly to the amount of waste filling the undisturbed soil or virgin land. Such activities polluted water, air, and ground and reduce the environmental quality. Waste generation from construction activity can be recycled and can be reduced significantly with proper planning. In Indonesia, at least in Java island and some part of Sumatera island, a popular profession called '*kuli bongkar*' specializes in dismantling buildings. They normally work in a team consisting of many freelancing workmen who work together to dismantle buildings, sort out various building waste and finally dispose the undesirable waste. These people would normally approach homeowners or building Owners who plan to retrofit or major building remodeling and propose a price. The dismantling cost is usually calculated based on the building's floor area, the materials quantity, or the type of materials.

Considering that building waste recycling practice has been done for sometimes, many more building elements can potentially be recycled with the proper equipment and technical knowledge. Common construction waste that can be recycled includes concrete, gypsum board, GRC board, metal, glass, plastic, carpet, asphalt roofing, wood, and aluminum.

In Indonesia, the use of recycled concrete has slowly gained popularity. It is sometimes used for road construction and the airport runway. Apart from building road, used concrete in the form of larger size rubble is also used to fill gabions. In Indonesia, gabion or known as '*kawat bronjong*' is normally filled with river stones. Concrete filled gabions can be used to build, for example retaining walls, erosion prevention walls at areas that are prone to landslides or coastal areas with high abrasion. Another easy way to get building material that can be recycled is gypsum boards. New gypsum boards can be produced using used gypsum board. Up to 30% of the used gypsum board can be processed into gypsum powder and becomes the raw material for the next production (Deloitte, 2017). Even though the utilization of used gypsum is considered small, several cement industries have been using the processed gypsum in their product.

Ceramic tiles and roof tiles are common waste products after building demolition or after the completion of building construction. In developed countries, recycled ceramics can be used as aggregate. Meanwhile, used ceramic and roof tiles in Indonesia are normally used as landfill material. If such waste is not recycled, it will not reduce the demand for natural resources. For instance, emissions from the production of ceramic are high, and some substances are toxic. Thus, by performing recycle or reuse practice, the need for natural resources for new ceramics is decreasing.

Many building designers and contractors in Indonesia have understood the importance of sustainability in building, but the implementation of sustainability in common practice needs time to develop. Lack of support, technical know-how, and resources are the main reasons. Sourcing for recycled building materials is not yet an easy task in Indonesia. Using recycled materials often becomes a novelty for the rich people with green inclination. Recycled materials are often become more expensive than the non-recycled ones due to the special treatment needed for a certain building waste to be ready for use again. Parties involved in the processing of recycled materials often find it difficult to offer attractive rates due to the lack of economy of scale as demands are still scarce. Recycling practice has to be a nationwide movement where everybody from homeowners, designers, builders to building materials manufacturers, and most importantly, local government do their part. In the meantime, engaging local communities is, for now, a workable sustainable solution in Indonesia.

Current practices in Indonesia, particularly in Aceh, show that the recycling of building materials needs more effort or process for the material to be used again, while reusability requires little effort. According to Kim and Rigdon (1998), p.20, “reusability is a function of the age and durability of the material.” This means that if some parts of the building need to be modified or even demolished entirely, materials which have high durability can be used again. Examples of durable materials are: Windows, doors, plumbing fixtures, and even bricks can be reused as well.

Sustainable practices have been practiced by the local communities, such as reusing the broken ceramic tiles by randomly arranging the color and shapes to form a unique pattern. The reuse of ceramic will not only minimize the use of raw materials but can also reduce emissions from the burning process. Another practice commonly held by the community is the reuse of timber from old housing or building, which becomes fashionable as a reclaimed material for new construction.

Bricks have also been used for a long time in the Aceh region since it has good durability. The bricks collected from the debris can still be used without decreasing the performance of the wall-bearing load.

Using the traditional cleaning method by chopping the mortar from the bricks, they can be sold at a lower price, as shown in Figure 2.1.

Figure 2.1: Reuse of bricks and rebar in Banda Aceh, Indonesia
Source: Bjerregaard and Meekings (2008), p. 2.

A similar traditional method is also applied to construction steel. For example, second-hand rebars were laid down on the street and ready for sale. These show that communities are already familiar with sustainable practice in Aceh province and other parts of Indonesia, although performed traditionally.

In Indonesia, where timber is still used mainly as construction materials for ceiling structure, roof structure, doors, and windows frames, and for many other applications, stricter government restriction on timber harvesting has made a specific type of wood challenging to obtain. People can still get some rare woods variety, but the price is normally too high. Hence, recycled wood becomes a more economical option, and it has become a greener option as well. Current practice shows that only certain materials and building fixtures are being resold, such as doors/windows frames, doors/windows panel, glass, metal, roofing materials, sanitary fittings, and natural stone tiles. Building waste that needs to be processed before reusing is not desirable.


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Figure 2.2: Reuse of doors and window’s frame

Figure 2.2 shows the used window and door frame are placed on the street's side and ready for sale. This portrayed that the reuse of wood is also gaining popularity in Banda Aceh compared to other big cities like Jakarta, Bandung, Surabaya, and Medan. Until 15 years ago, the reuse of wood material such as door and window was not popular because of the abundant stock in the market, which makes it affordable. Due to excessive logging, which appears to be illegal in major parts of Aceh and North Sumatera, there have been shortages for wood material. As a result, the wood price was sky-rocketing, which makes the use of second-hand doors and windows a valuable alternative. Nevertheless, it appears that this option is in favor only for people with low purchase power, while others not. This shows that the reuse of wood has not become the first option to act in sustainable construction, but it is more to the financial limit.

2.1.1 Common Building Materials

2.1.1.1 Bricks

Production of bricks in Indonesia is mostly in rural areas. Brick factories are still using conventional methods and traditional tools. The bricks making process starts with mixing soil and sand, and then pressed and trimmed in a flat frame. The next process is the drying process where bricks are placed not to expose with direct sunlight for about one day or up to one week. Then, the dried bricks will be burned using wood in a traditional furnace. The burning process may take 12 to 24 hours for 10,000 to 20,000 bricks.

There are basically two types of building structural frames in Indonesia. 1) Confined masonry brick or concrete block masonry where all walls are built using clay brick or concrete block in confined masonry building to support all loads as one structural element. For a more rigid structure, the walls are tighten using small columns and beams made by reinforced concrete. Confined masonry structures are widely popular in housing sector or single-story buildings in Aceh. 2) Reinforced concrete structural frame which is filled with bricks or concrete hollow block (CHB). For this type of structure, the strength relies on the sizeable columns and beams made from reinforced concrete to support the loads.

The impact of traditional brick production on the environment was studied by Kolodziejek and Tey (2016) in Silih Nara, Aceh. They observed that the exploitation of clay as the main raw material did not comply with the relevant government agency's environmental protection protocol. In addition, timber for the firing process in the kiln is sourced from the nearest forest and also from other places. They suggested that the use of timber for firing in the kiln can be minimized by utilizing suitable forestry and construction waste.

2.1.1.2 Cement

The improvement in the country's economic condition in 2010 has boosted the Indonesian cement industries' development. Cement is still the main product in infrastructure and building projects. "Indonesia's annual installed cement production capacity reached 92 million tons in 2016, hence the country is now the biggest cement producer in East Asia, followed by Vietnam (78 million tons), Japan (60 million tons), and South Korea (55 million tons)." (ASI, 2016). Nonetheless, cement industries lead a bad effect related to environmental and social aspects, such as CO_2 emission, high energy consumption, supplies of raw materials, and bad health condition to humans caused by dust and gas emission exposure.

To reduce such emissions in developing countries, the implementation of new technologies, processes, and cement production methods is currently underway. Schwarzböck *et al.* (2016) reported that since 2011 the use of coal for calciner has been replaced with the rice husk by Lafarge Cement Indonesia operating in Lhoknga, Aceh Besar district of Aceh province. Such a new technology not only produces an environmentally friendly cement product but also trigger local's economic growth by selling rice husk to Lafarge Cement Indonesia. Other alternative fuels are also being observed.

2.1.1.3 Concrete

Concrete is a popular construction material all over the world. The concrete technology is adaptable to various geographical locations and climatic conditions. Concrete also easy to form according to the desired structural shape. According to Okazaki *et al.* (2012), standard concrete is a mixed of 1 cement: 2 sand: 3 aggregate which is common for concrete production in Indonesia. Similar to many developing countries, coarse sand and gravel are usually mixed with ordinary Portland Cement.

Recent development in concrete technology has shifted towards green concrete. Obla (2009), as cited by Suhendro (2014), p. 307, defined "green concrete as the concrete mixed with waste materials." More specifically, Suhendro (2014), p. 306 stated that "major targets to produce green concrete are: (a) the reduction of CO_2 emissions, (b) a reduction in energy consumption or fuel derived from fossils in the cement manufacturing process, (c) reduction of chemicals substances that can endanger the health or the environment, (d) savings the use of cement through substitution with fly ash waste in the higher portion, or the use of other waste, (e) the use of new cement replacement materials, such as inorganic polymers, alkali-activated cement, magnesia cement, and sulfa-aluminate cement, and (f) recycling of concrete and the use of alternative aggregates". Green concrete production is designed to minimize environmental damage, such as using the small amount of ordinary cement and low emission on the manufacturing process. Hence, the use of non-renewable resources such as limestone, sand, and gravel can be minimized.

2.1.1.4 Ceiling Material

Plywood is made of several wood grain layers and it is an ideal ceiling material because of its strength and durability. Plywood also absorbs heat quite well, thus making it good for reducing indoor temperature. In Indonesia, plywood is marketed from 3, 5, 7, or 9 layers. The overall plywood thickness may range from 3 mm up to 18 mm, and the sizes are usually 1.2 x 2.4 meters. Alternatively, the GRC board and PVC are gaining acceptance by construction practitioners and homeowners. GRC board is usually offered with a thickness of 4, 6, and 8 mm. While the PVC board is available with a size of 20 x 400 cm.

In recent years, the gypsum board is also prevalent in Indonesia. Gypsum board has gained broader acceptance in Indonesia as an alternative for plywood. Most of the existing producers of gypsum board offer various thickness, pattern, and functionality for a specific application like for wet area, high level of soundproof, fire-resistant, etc. These producers also offer gypsum compounds, supporting accessories, and skilled-workers.

The Gypsum board is usually made of a mixed synthetic and natural gypsum. However, a recent manufacturing process can produce gypsum boards without using any natural gypsum. The omission of natural gypsum in the manufacturing process contributes to the reduction of environmental problems. For example, most synthetic gypsums used by the industry produce no air pollution. Both natural and synthetic gypsum used for the manufacturing of gypsum boards are considered to be non-toxic and safe (Kubba, 2010). The overall gypsum board thickness ranges from 6 mm up to 18 mm, and the sizes are the same as plywood and GRC board, which is 1.2 x 2.4 meters.

2.1.1.5 Wood

Woods can be found almost in any building type in Indonesia. Wood serves many functions during construction process such as temporary supports for workers, scaffolds and for concrete molding. Woods are easy to find and relatively harmless. Woods are also used as a roof frame, window and door frame. The excessive use of wood may cause global warming effect and location of illegal logging is difficult to trace in Indonesia. Attention to environmental protection is given by certification of wood products confirming the acceptable harvesting locations.

2.1.1.6 Roofing Material

Vijaykumar *et al.* (2007) stated that 70% of the building heat gain comes from roofing material. Hence, the combination of roof covering material will be studied as well. The roof tile sector is characterized by the coexistence of distinct types of firms and production technologies ranging from small industries with traditional hand-driven equipment to medium-sized firms with power-driven presses and mixers. Small firms use clay as the primary raw material, while larger firms rely on cement. There are three roofing materials found in Aceh, which are also common in other Indonesian regions.

Metal roof sheet

The metal roof is very popular in Indonesia, mainly because it is less costly than other roof materials. It is also light and durable. The installation process of the metal roof is fast, and it has better tightness, thus not easily leaking due to heavy rain. The metal roof's top surface comes with glossy, matte, or rough finish with a variety of metal panel profiles. Some panel profiles are ideal on industrial buildings such as manufacturing plants, storage rooms, or big garage, while other profiles may be suitable for housing or fencing.

Metal panels are made from aluminum, stainless steel, galvanized or galvalume. There is also a more affordable metal panel called a corrugated metal panel, which has the U, V, or Ribbed profile. These types of panels normally are less thick and much faster installation time. Despite the cost efficiency, these types of panels require some maintenance, such as retightening the fasteners or repainting.

Clay roof tile

Clay roof tile is made of natural earth or clay, which can be found easily in Indonesia. The factory location normally close to the source of clay. This undoubtedly reduces the energy for transportation to the factory. Clay roof tiles are costly roofing material, but it has good durability, aesthetically appealing, and less noise during heavy rain. Clay roof tile is installed piece by piece, and it has a small gap in between, thus allows better air circulation (airflow) in the attic. Clay roof tile is one of high thermal mass material because of its ability to reduce the indoor temperature in the day-time. At night-time, the absorbed heat is emitted. Thus, the use of air-conditioning unit can be avoided. Furthermore, colored clay roof may also help reduce the indoor temperature. For example, terracotta or light painted color produces a high solar reflectance index (SRI). A high SRI index means that the particular material is able to reduce the heat transfer and it is associated with the reduction of energy consumption when using air conditioning unit. The four characteristics of clay roof, which are thermal mass, solar reflectance, airflow, and thermal emittance may reduce the energy consumption for fans or air-conditioning systems. Clay roof tile is also easy to repair because only the damaged piece of tile needs to be repaired or replaced by the new piece of tile. For Owners looking for little maintenance expenses, such type of roofing material is probably suitable for longtime use.

Cement/mortar roof tile

Mortar roof tiles are traditionally made by mixing sand, cement, and sometimes fly ash with water. The final mixture will be molded and then dried. The strength of this tile is affected by the cleanliness and size of grains of sand used, as well as material cement as a bonding agent. Fly ash is required as a filler between sand grains to get a denser and stronger tile.

Compared with clay roof tile, mortar roof tile has advantages and disadvantages. The advantage is the price is affordable compared with clay roof tile. It is strong as concrete and rustproof, compared with metal tile. Unfortunately, this tile has a disadvantage that burdens the heavyweight of the structure. For comparison, the tile weight is 60 kg/m^2, while the clay roof tile weight is about 45 kg/m^2. Another disadvantage is concrete tile less resistant to leakage because the interlock is not perfect, and small cracks may be detected on the body. To reduce the leak and crack, finishing tile is usually done with paint.

2.1.1.7 Material for Tiling

Ceramic

Ceramic tile uses clay as the main raw material and is considered a durable material for home applications. The ceramic tile industry contributes to a lower environmental impact compared to other tiling materials. Currently, only about 10% is imported from Malaysia and China to fulfill domestic demand of ceramic tile. According to the Indonesian Ceramic Industry Association (ASAKI), as reported in Global Business Guide (2015) that the Indonesian ceramic industry is mainly supported by the strong demand from housing, office buildings, and schools project.

Currently, there is no ceramic recycling process available in the Indonesian ceramic industry. Within Europe, focus is given to the life-cycle assessment of ceramic tile to ensure sustainability of their products. Environmentally friendly tile product can be certified using internationally accepted scheme such as Eco-label and ISO1400. In addition, Ros-Dosdá *et al.* (2018) found that alternatives to ceramic technology are also necessary to reduce greenhouse gas emissions. According to Ros-Dosdá *et al*. (2018), p. 1, “technologic alternatives involved changes in product design (thickness and decoration), changes in the manufacturing process (preparation of raw material by dry or wet route, and simultaneous implementation of thermal energy efficiency techniques), and changes in the energy sources (hybrid or electric driers, and kilns and decarbonization of the power grid mix).”

Granite

Granite tile is made of interlocked crystals from quartz, feldspar, and other minerals (Zhang, 2011). Polished granite tile is typically resistant to scratching, scorching, and staining. In Indonesia, granite tiles are commonly available with a size of 60 x 60 cm and 80 x 80 cm, both polished or unpolished top surface. For commercial housing projects, granite tile is mostly preferred than ceramic due to its better durability, improved aesthetical appearance, and easy to clean, thus increasing the house's value. In public projects such as school building, ceramic tiles are still dominating the market solely because it is cheaper than granite tiles. There is no publicized source of reference regarding the production of granite tile in Indonesia. However, the demand for granite tile in Aceh is increasingly high, which can be observed from a variety of colors and ample stocks available at local building suppliers in Aceh.

2.1.2 Impact of Disaster to the Construction Industry

Natural disasters such as earthquakes, typhoons, or Tsunami strikes more frequently in the recent decade. There will be a bigger task in the reconstruction process because disaster mitigation has become important. Such mitigation measures are normally applied to new infrastructures. Key observations from the Tsunami in Aceh province was found in Mimura (2015). The International Cooperation and Mega Disasters Research Team (2013), as cited by Mimura (2015), p. 170 highlighted that "the disaster-affected region had been suffering from long term conflict and less developed in Indonesia, restoration of Aceh should not just aim to recover damages by the disaster but rebuild the region better than before." The priority setting for Aceh province and Nias (part of the North Sumatera province) recovery process is described as activities sequence shown in Figure 2.3. For example, the Indonesian national recovery agency called The Rehabilitation and Reconstruction Agency for Aceh and Nias (BRR Aceh-Nias), as reported by BRR and International Partners (2005) had given priority on emergency response and basic restoration of daily life in the early stage of the reconstruction process. Subsequently, after most housings were completed in 2006, priority was given to reconstruct infrastructures and livelihood recovery.

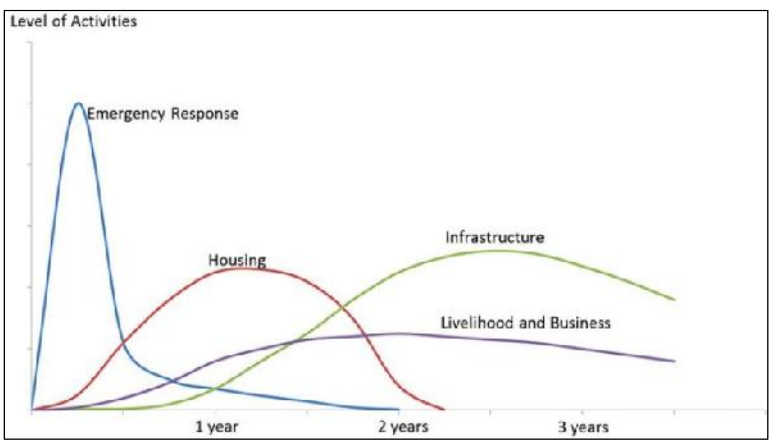

Figure 2.3: Recovery activities sequence in Aceh and Nias
Source: Adopted from BRR and International Partners (2005), p. 172.

The construction of schools commenced two years after the Tsunami. During this period, the construction activities were eventually back to normal, which was detected by the smooth supply of material and workers resulting in timely project completion of most schools. The selection of schools for this case study research was made only to schools built during those normal periods. Therefore, findings from this research may be used as a base model or a reference to other school projects across Indonesian regions.

2.1.3 Construction of Schools in Indonesia

In Indonesia, the provision of basic education is the main concern. According to the World Bank, the size of the Indonesian school system is ranked third in Asia and fourth in the world behind China, India, and the United States. Indonesia has 170,000 primary schools out of 250,000 schools serving over 50 million students and 2.6 million teachers (The World Bank, 2014). Obviously, that in such a highly populated country, there is a tremendous demand for new buildings and other public infrastructures in Indonesia, such as primary schools. Despite the need of new primary schools, existing schools are vulnerable to increasing natural disasters. Due to the proximity from the ring of fire, earthquake undoubtedly occur more frequently and stronger in Indonesia causing greater damage. One of the worse and most publicized disasters was the December 2004 earthquake, followed by a Tsunami that devastated Aceh province in Indonesia. The international community made supports for the recovery, reconstruction, and rehabilitation in Aceh province. Roseberry (2008) highlighted that during Aceh reconstruction process, there are three conflicting priorities to build the new infrastructures in a sustainable way. They are environment, social, and economic issues. Unfortunately, focus was mainly given to the durability of materials and to earthquake resistance building structure development. In contrary, little concern was given to sustainability aspects such as social and environmental that have greater implications in the longer-term. The failure to include environmental assessment are mainly because the people need adequate housing and live in a normal way as soon as possible. Roseberry also pinpointed that, “in the context of a post-disaster situation, time is also a crucial element to quickly settle back people to better houses and schools.” ([Roseberry, 2008], p. 9). A lesson from the post-disaster situation was also highlighted by Fan (2003), mentioning that barriers that limit the adoption of sustainability into the reconstruction process must be translated into another opportunity to encourage more environmentally conscious decisions in the field.

The Indonesian Government has estimated that over 10,000 public primary schools need to be built, and thousands more need immediate repairs or refurbishment. The importance of providing children with adequate space to learn in a productive environment has been set out by the United Nations under the Millennium Development Goals. Hence, to achieve such goals, it is imperative to include sustainability criteria in school design so that the future needs are not compromised. In Indonesia, the construction industry's stakeholders suffer from communication and coordination problems. There is still a massive challenge for effective coordination and good collaboration with their counterparts, although several government bodies, associations, and universities have committed to sustainable development in construction (Alwi *et al.,* 2002).

Most frequently, government-funded school projects are procured through competitive tendering that justifies the Owner's needs. Under such a funding mechanism, the lowest bid remains the first choice before awarding a contract to the contractor. It is not surprising in Indonesia that bidders provide irresponsible prices to win the contracts. Such a low bid price frequently sacrifices quality and project duration.

In preliminary design, especially for a non-complex project such as school, layout and general drawings can be approved by the local authorities. The Owner usually approves the detailed drawing, cost planning, and schedule. Registered architects/civil engineers should initiate architectural/structural drawings and to some extent provide electrical, water distribution, drainage, and sanitation drawings. Typically, approval from local authorities or Owners is required before preparing detailed engineering design. For non-complex buildings, the detailed design had started before acquiring approvals

Before beginning to select criteria for sustainable design, particularly school building, the following sections present some important definitions and highlight basic concepts of sustainability, the design process, and the importance of default configuration. The thermal comfort theory as one of the essential social criteria for school is also presented especially the basic design strategy in hot-humid regions.

2.2 The Project Delivery System

Construction and management of projects consist of multiple players with different academic backgrounds, expertise and experiences. The delivery of projects deals primarily with the design, procurement, construction, and commissioning. After completion, projects are handed over to the respective Owners. The three common project delivery systems are known as Design-Bid-Build, Design-Build, and Construction Management. The methodology and tool developed in this research are designed for the traditional delivery system (Design-Bid-Build) because all public projects which are financed using the Indonesian government budget use the traditional project delivery type. Collaboration between different disciplines is separated under the traditional project delivery system and it has no room for discussions nor brainstorming sustainable design strategies. Unfortunately, the majority of Owners and designers are already familiar with the traditional delivery system because it has been applied in many governments' funded projects, especially in Indonesia. In the traditional project delivery, Owner holds separate contracts with the Design and Engineering Consultant (DEC) company and the construction company or contractor. Since DEC and contractor has no contractual obligations between them, each of them always shows little interest to give their full potential in completing the project to a great success or beyond the Owner's expectation. Hence, the Owner becomes the only focal point of a project and responsible for overall project management functions such as setting the project's goals, determine project requirements, acquisition of project site, monitoring, and financing the project. Owner also has a crucial role in directing the DEC and contractor, and resolving contractual issues and dispute partially because the DEC is responsible for design while contractor implement the design in the field. In certain situations, the DEC also assists the Owner in determining project objective and project's requirement, prepare construction bidding documents and involved in price negotiations. Typical duties of DEC include seeking formal compliance against the national or international building and construction codes.

The design process itself comprises of four stages. The first stage is the Project Start-Up or Pre-design. In this stage, the project brief is developed through consultations with stakeholders regarding design requirements. The second stage is development of building concept called the Preliminary Design stage. In this stage, overall system configurations are defined in schematic drawings. The third stage is the Design Development, where more detailed engineering drawing is prepared to enable accurate cost estimations. The design process of buildings in Indonesia is mainly divided into four main stages, as shown in Table 2.1. Other terms in the design process may also be classified under these main stages.

Table 2.1: Overall design stages in building projects

Stage name	Other typical names
Pre-design	Programming
	Strategic Planning
	Pre-Project
	Basic Investigation
	Design Brief
Preliminary Design	Schematic Design
	Preliminary Studies
	Conceptual Design
Design Development	Preparation of Realization
	Definitive Proposal
	Detailed Engineering Design (DED)
Construction Documents	Building Documents
	Bidding Documents
	Realization

For public school building projects in Indonesia, the design process often starts with preliminary design since most design requirements are already governed by the Ministry of National Education and the Department of Public Works. Most importantly, the floor area for each classroom has also been determined to accommodate forty students at maximum. Therefore, for simple buildings like primary school in Indonesia, cost estimation and time planning can be known earlier during preliminary design stage. Hence, the design produced in this stage contains all costs and schedule information to construct the building. Thus, the developed methodology of this research can be used during the preliminary design stage because all data necessary in assessing the sustainability performance of each design alternative can be collected. The final stage is basically for producing documents such as construction drawings, structural design analysis, technical specifications, and detailed bill of quantities.

2.2.1 The Design Process

In a traditional project delivery system, most of crucial decisions are taken in the design process. The DEC is responsible for meeting many objectives, including designs that consume less energy during a building's operation if the Owner requires it. Consideration of environmental impact during the design process creates more complexities. In this case, Watson (2004) emphasized that the ‘front-loading’ approach should be introduced at the earliest in the design process. Based on several case studies, he suggested that ‘front-loading’ approach shall be done first during the design process because the primary focus is to make decisions regarding the construction impact on environment and the operation of a building (Watson, 2004). The ‘front-loading’ can be defined in what he called the ‘environmental briefing’ process, which finally leads to an Environmental Brief document. Such documents record issues, goals, and objectives, including all decisions taken. The advantage of having an Environmental Brief document is not only for present projects, but also for projects in the future. Environmental Brief document is considered a reliable reference since environmental issues are complex and diverse at any given project location.

On the other hand, environmental performance improvement in the building can be achieved by a ‘feed-forward’ approach, as suggested by Preiser (1994). The concept of ‘feed-forward’ is that all information, experience, knowledge, and solutions from previous projects are considered in the next project. Feed-forward is basically an iterative process because the knowledge gained from previous projects can be used at the earliest time to produce better building design. It may at least prevent drawbacks from previous projects and give knowledge or ideas that can influence designers in solving the design problems. For the Environmental Brief Document becoming useful support for decision-making, it shall contain evidence for making an objective decision during building design development. For instance, the process of outlining goals and project objectives in the brief defines specific issues for the designer or the Owner. Therefore, designers will have greater confidence that the decision taken during the design process are correct.

Simulation technology can be used during design process and is now powerful enough to make early prediction on the impact of design to the environment. The notion of ‘default configuration’ is often used in the simulation process to objectively formulate design goals as part of the ‘front-loading’ mechanism, as described above. For instance, using a simulation software, building geometries and building materials can be inputted and the simulation engine calculates energy consumption, indoor temperature, and air quality performance in one particular building design. More building components can also be inputted and these will be treated as parameters in building design simulation. In searching for an optimal design solution, Diao *et al.* (2011) and Zhang *et al.* (2013) suggested to use parameters in building simulation model as many as possible. Unfortunately, inputting many design parameters for building simulation model is impractical because it will produce so many design variations. To understand performance changes in some design variations, a reference, so-called a baseline building, is usually set and used to evaluate performance improvement. For instance, one particular building design can be improved by optimizing few design variables in the baseline building. In order to understand and distinguish the performance improvement after the design optimization process, determination of proper fixed values before optimization should produce a meaningful information to the decision makers. A proper fixed value can be taken from the former design phase. In case of fixed value is not available or has not been specified, a tentative value can be used. For instance, Hiyama *et al.* (2014) treated default HVAC system data as a default configuration for calculating the heating and cooling load. Hence, if data about wall or window properties are not inputted or have not been decided for the heating or cooling load calculation, default values from the simulation software can be used to perform the heating or cooling load calculations.

2.2.2 The Importance of Default Configuration

The need to objectively assess the sustainability of buildings has been increasing. Research focus on configuring the optimal configuration for use in the simulation process is gaining popularity to meet the ‘front-loading’ task in the building design process (Hiyama *et al.*, 2014; Smith and Tardif, 2009). Besides, demand to understand the environmental and energy performance of buildings using simulation technology is increasingly high. Recent computing power can drastically reduce simulation time so that the simulation process can now be executed during early design phases (Attia and Herde, 2011; Menchaca and Glicksman, 2008). Besides hardware capabilities, quite many software are also capable of processing simulation calculations based on the 3D building model. For example, SketchUp is a 3D modeling software that architects often use for design briefings (Gagne *et al.*, 2011). SketchUp users can transfer some data by using an additional add-on for energy simulation calculation automatically. However, in some cases, the users need to specify some value for the simulations manually. If there are many uncertainties, the users must use default values provided by the simulation software. The quality of the default configuration of a building model is very important to achieve reliable simulation results, particularly in the early design phase.

The default configuration of building simulation model must be specified before optimizing the building design (Hamdy *et al.*, 2013). In any case of optimization, every default value will change for better performance and finally converted to an optimal value. Optimization process is usually time consuming, thus it is recommended that the reoccurrence of default values should be close enough to the optimal values to shorten the optimization time. The 'front-loading' of default values always seek efficiency during design and construction, but it needs to be done in an integrated manner. A project delivery system called Integrated Project Delivery system allows changes in one particular project phase resulting in final cost reduction (AIA, 2007). For instance, when inputting simulation data during early building design under certain assumptions, objective decision becomes mandatory to maintain the validity in the succeeding design phases. Therefore, the closer the default value to the final optimal value, the most efficient project simulation data will be. The problem is that no one knows the default value during the preliminary design stage. Alternatively, default values from codes or engineering standards of specification, such as ASHRAE-55 (2010), can be inputted (Güngör, 2015). However, those values might not relevant to any building designs because the performance target of certain designs are affected by the surrounding environment, different building material properties, or financial constraints. Therefore, setting the default values based on the real-world building project is rational because value in design metrics, typical use of rooms, occupants' activity, and occupants' requirements are taken from actual building data.

2.3 Basic Concept of Sustainability in Building

Brundtland in Chapter 2 of the World Commission on Environment and Development report entitled 'Our Common Future' defined that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" ([Brundtland, 1987], p. 41). Sustainable development is not a new concept in the Indonesian construction industry or in other developing countries. However, the realization of sustainable practice in design and construction in Indonesia is very slow. Even among ASEAN countries, the Indonesian Green Rating System called Greenship in 2010 was established after GreenMark of Singapore in 2005, BERDE of the Philippine in 2007, and GBI of Malaysia in 2009. Slow progress on green development using a rating system is also initiated by a lack of law enforcement for public projects. Moreover, under the traditional project delivery system, the application of rating systems cannot be utilized.

According to some bibliographic study, the sustainable concept can be defined in many ways. Nevertheless, there are numerous documentations stating that environmental, economic, and social aspect are the three dimensions that are always linked with the concept of sustainability (Waage *et al.*, 2005; Nijkamp, 2007). In certain cases, the cultural dimension is also added as the fourth dimension. Despite the importance of all dimensions, the following sub-chapters review the ecological, economic, and social aspects of sustainability which closely related to the research work.

Environmental friendly building projects is widely described as 'green building' or 'sustainable building'. These two terms are often used interchangeably, but sometimes 'green' and 'sustainable' are defined differently. Cole (1999), p. 4, mentioned that: "The emerging debate on building assessment relates to shifting from environmental or 'green' performance to a larger goal of sustainability." This means that the term 'green' and 'sustainable' need to be defined before structuring any assessment methods. One of solutions to define which building categorized as green building or sustainable building was clarified by making a comparison on the main issues, as shown in Table 2.2.

Table 2.2: Main issues in green and sustainable buildings

Major Issues of the Building Performance	Green Building	Sustainable Building
Consumption of non-renewable resources	x	x
Water consumption	x	x
Materials consumption	x	x
Land use	x	x
Impacts on site ecology	x	x
Urban and planning issues	(x)	x
Greenhouse gas emissions	x	x
Solid waste and liquid effluents	x	x
Indoor well-being: air quality, lighting, acoustics	x	x
Longevity, adaptability, flexibility	(x)	x
Operations and maintenance		x
Facilities management		x
Social issues (access, education, inclusion)		x
Economic considerations		x
Cultural perception and inspiration		x

Source: Adopted from Lowe and Ponce (2009), p. 7.

The main difference between green building and sustainable building is that sustainable buildings have more issues, thus require a wide-ranging evaluation and assessment methods than green buildings. As shown in the table, sustainable buildings give further consideration to operation and maintenance, facilities management, economic, social, and cultural issues. In this research, the focus is on sustainable building because the implications of economic and social impacts related to school buildings are considered. As a developing country, Indonesia's population is ranked fourth globally, which makes the adoption of green rating alone may not be the only single solution to achieve sustainability in building. Therefore, it is interesting to recognize how the sustainable development goals in the Indonesian construction industry can be met using resources available in the country (e.g., the capacity of human resources, existing construction technology, and method as well as local building materials).

2.3.1 Sustainable Design

Sustainable design requires innovative solutions to maintain the sustainable principle during construction and until project completion. Applicability of the sustainability feature of building design in the construction process refers to what is known as sustainable construction in many buildings and construction industry's literature. Construction industry alone is complex and involves numerous activities such as material production, site development, planning, designing, constructing, maintenance, retrofitting, and until demolition. Therefore, sustainable design tends to focus on recyclability or reusability of materials, waste minimization, or other sustainable aspects in design and their implications during the construction process.

“The design of a sustainable building that meets all sustainable requirements is often a challenge to the building professionals and building designers.” (WBDG, 2018). To achieve sustainability in building, the design itself must consider all competing sustainable criteria. However, as mentioned earlier, the lack of stakeholders awareness constitute a serious obstacle in developing countries to incorporate sustainability criteria into the design. Bragança *et al.* (2014) pinpointed that “introducing the concept and principle of sustainable development at the early stage of building design may alleviate the existing barriers.” Their research suggests that sustainability in buildings can be achieved by evaluating various building envelope design. Several sustainable development initiatives offer practicability, which can be incorporated into the building envelope because it is directly connected to the surrounding environment. Additionally, McLennan (2004) concluded that sustainability in the building should comprise a philosophy of design that can improve indoor comfort and integrate practical sustainable solutions into the design of building envelopes.

Figure 2.4 shows an overall view of how building envelopes are connected to the sustainability of a building. For instance, the external weather directly influences the building envelope. The function of the building envelope is basically to control such influence for the benefit of the occupants and the operation of a building. Such a controlled mechanism is known as a passive system or active system on designing a sustainable building, which plays prominent roles to maximize a building's performance. The design parameter group is defined as the shape of a building that directly impacts construction costs. The cost of constructing any given shape has a great influence to boost the local economy, which is very important in developing countries. The building's shape can also be determined by environmental quality, existing construction method and technology, and local resources' capacity. Building codes, cultural and social acceptance are also integrated to the shape of building envelope, thus influencing overall environmental quality. The element group is related to the material that makes up the entire design. The properties of the material have different effects on indoor qualities such as temperature through some processes. These processes are grouped under the process group in Figure 2.4. Such complex connections between sustainable design and the envelope can mostly be facilitated by applying simulation technology in recent years.

Simulation software is now capable of solving complex equations despite a lack of integration among them. The recent development of BIM (Building Information and Modeling) is directed to assist architects and engineers in achieving sustainable design. However, it is not easily adapted due to different platforms. Moreover, the cost of implementing BIM is not feasible for small scale building projects. Hence, this research employs simulation technology through a framework that can be adapted in developing countries. From this perspective, the black-thick boxes in Figure 2.4 indicate that only parameters inside those boxes are considered in this research. For example, not all internal influences are studied because the schools used for the case study do not have the equipment, appliances, and HVAC system. The lighting system is not used too often because the existing large windows provide bright classrooms during school hours. Hence, only two factors are considered the internal influence for sustainability in the building; they are occupancy load and indoor comfort requirement. These two factors cannot be separated because if a room is occupied above its intended capacity, indoor temperature will increase as a body heat function.

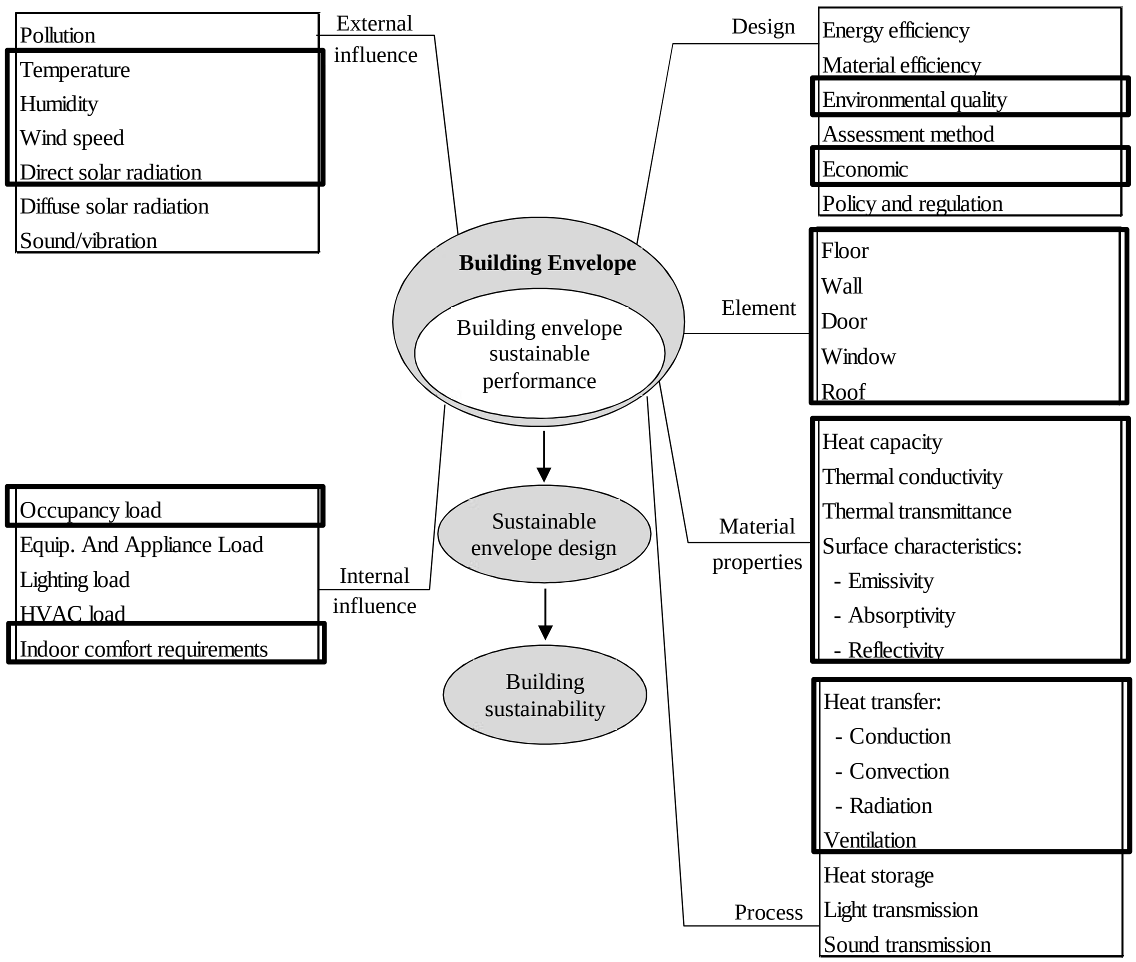

Figure 2.4: Building envelope and building sustainability connectivity
Source: Adopted from (Iwaro and Mwasha, 2013), p. 158.

Häkkinen and Nuutinen (2007) stated that occupants' comfort is part of social perspectives because cooler or warmer indoor temperatures may cause distress or discomfort. On the other hand, a higher comfort level inside a building such as an office room, classroom, library, or other working zone provides better productivity (Seppänen and Fisk, 2006; Singh *et al.*, 2009a). Lützkendorf *et al.* (2012) also confirmed that thermal comfort is an important factor in a sustainable building that cannot be treated separately.

2.3.2 Sustainable Building Material

In view of sustainable building, sustainability of building material has a great influence on the overall sustainable performance in building. Sustainable development in material production is defined as "a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but in the indefinite future." ([Saxena and Khandelwal, 2010], p. 60). The United Nations identified building materials as the primary resource in the construction sector (UNCHS, 1996). Not surprisingly, that all building certification systems include the performance requirement of materials. Construction materials are mostly locally sourced in developing countries, but a proper or an objective selection of materials is vital to achieve sustainability in buildings. Hence, one of rational and effective strategies to support the sustainable development concept needs to begin with the selection of sustainable materials.

The decision of what material to use has already started in the early conceptual design stage because typically, materials for the building structure and envelope need to be determined at this stage. The material quantity for the typical school building envelope has the highest portion among other elements, thus making it significant to assess its sustainability. Environmental problems in building industry has already started with the exploitation of raw material until the finished building products. Each material has different embodied energy as a result of the life cycle process of the material. Each process typically produces emissions to the environment. Specifically, the European Commission[1] defined that "embodied energy is the total energy required for the extraction, processing, manufacturing, and delivery of buildings." For example, the embodied energy for extracting one particular material consist of energy for transportation from the raw material's location to the factory and transportation energy from the factory to the user (Menzies and Muneer, 2000). Thus, embodied energy of each material can be compared to assess the environmental performances. Comparing embodied energy of each material is possible as Abeysundara *et al.* (2006), p. 2 specified that "the inherent energy of the material itself is not included as embodied energy." Therefore, recognizing the sources and types of energy until the material ready for use in the construction of buildings is crucial in assessing the environmental impact.

Construction materials have many functions in a building. Among other functions, materials should withstand external factors such as earthquake, rain, wind, and outdoor temperature. Consideration of these factors is mainly because materials shall be able to provide occupant's comfort. Materials also have aesthetic properties such as texture, color, and shape. Hence, the cost, time, and skill required for construction and installation are mainly dependent on these properties and the functions of materials in a building. Sustainable building material should be seen beyond factors. Environmental factors such as

[1] European Commission, "Embodied energy", Retrieved from: https://ec.europa.eu/energy/content/introduction-3_en Accessed on: 1st September 2020

embodied energy, CO_2 emissions, efficiency, recycled content, reusability, and health add to the complexities of material selection. These environmental factors relate to extraction, manufacture, installation, and reuse or disposal of the materials. Before the analysis is made to the criteria of sustainable materials for a building, sustainable material needs to be defined.

The definitions of 'green' and 'sustainable' related to buildings exist in many pieces of literature. The terms are still in controversy and used interchangeably in various literature because the meaning depends on one's perception (Burnett, 2007). According to Burnett *et al.* (2005) , 'green' implies that a product or activity is environmentally friendly because the environment degradation can be reduced. Thus, a term 'green building' is sometimes loosely interpreted as building that able to reduce the negative environmental impacts only, except a green rating from an environmental assessment method is applied to the building. Because of such confusion, there is no common agreement about the criteria for popular terms such as 'environmentally friendly', or 'green' material. On the other hand, 'sustainable' has a broader interpretation. According to the Merriam-Webster Online Dictionary, "sustainable is capable of being sustained, and 'of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged." Roux and Alexander (2007), as cited by Ihuah and Paulinus (2015), p. 222, gave a definition to sustainable material for building as "materials with overall superior performance in terms of specified criteria of locally produced and sourced materials, transport costs, environmental impact, thermal efficiency, occupant needs and health considerations, financial viability, and recyclability." Understanding what a green or sustainable material is highly dependent on understanding relationships between ecological, social, and economic aspects.

2.3.3 Thermal Comfort

Rakhshan *et al.* (2013) and Retzlaff (2009) concluded that one of critical aspects in determining the sustainable building performance is thermal comfort valuation. During the building design phase, calculation of thermal comfort is typically required in most evaluation methods. A definition of thermal comfort can be found in ASHRAE-55 (2013) as cited by Haddad (2016), p. 16, as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." Hence, thermal comfort is ultimately one of social indicators in sustainable buildings (Hinchliffe, 1996; Chappells and Shove, 2005). The thermal comfort theory was initially developed by Fanger (1970). His research has established the fundamental of indoor comfort temperature in ISO 7730, EN 15251, and ASHRAE Standard 55 (ASHRAE-55) that has been recognized as internationally accepted standards.

Two notions are widely acknowledged for calculating thermal comfort performance. They are the 'Predicted Mean Vote' (PMV) and the 'Predicted Percentage of Dissatisfied' (PPD). PMV and PPD values are typically called an index. ASHRAE-55 (2010), p 3, defined that "PMV is an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale." Fanger (1970), as cited by Charles (2003), p. 4, explained that "PMV is calculated from an equation of thermal balance of the human body, involving the internal heat generation and heat exchange with the surrounding environment." The heat exchange components such as metabolic rate, breathing, and sweating are included in the PMV calculation. In addition, "The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and activity level) into an index that can be used to predict thermal comfort." ([Fanger, 1970], as cited by [Charles, 2003], p. 5). The index would eventually correspond to ASHRAE's thermal sensation scale.

According to Fanger (1970) as cited by Olesen (2003), p. 6;

$$PMV = (0.303e^{-2,100*M} + 0.028) * [(M - W) - H - E_c - C_{res} - E_{res}] \qquad (2.1)$$

Where M is the metabolic rate (W/m^2), W is effective mechanical power (W/m^2), H is sensitive heat losses, E_c is heat exchange by evaporation on the skin, C_{res} is heat exchange by convection in breathing, and E_{res} is evaporative heat exchange in breathing. The human body's thermal parameters symbolized by H, E_c, C_{res}, and E_{res} are used to calculate the heat exchange with the surrounding environment. The equations below are used to calculate these parameters.

$H = 3,96 * 10^{-8} * f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a)$

$E_c = 3,05 * 10^{-3} * [5733 - 6,99 * (M - W) - p_a] - 0,42 * [(M - W) - 58,15]$

$C_{res} = 0,0014 * M * (34 - t_a)$

$E_{res} = 1,7 * 10 - 5 * M * (5867 - p_a)$

Nominators in the equation above represent the following variables:

I_{cl} : clothing insulation (m^{2}K/W);

f_{cl} : clothing surface area factor;

t_a : air temperature (°C);

t_r : mean radiant temperature (°C);

v_{ar} : relative air velocity (m/s);

p_a : water vapor partial pressure (Pa);

t_{cl} : clothing surface temperature (°C).

With the known PMV index, the PPD index can be calculated from the PMV index's value using the following equation ([Fanger, 1970] as cited by [Haddad, 2016], p. 23).

$$PPD = 100 - 95. Exp(- 0.03353 \times PMV^4 - 0.2179 \times PMV^2) \qquad (2.2)$$

The PPD index is derived from occupants' reactions to a certain thermal condition and is often used to interpret the occupants' comfort inside a building. The results typically show the percentage beyond the comfort temperatures range. The PPD index range is between 5% and 75%, and between -2 and +2 of PMV value. Hence, the PMV index value can be plotted as a distribution curve, as shown in Figure 2.5. As shown from the figure, the curve has a minimum of 5% dissatisfied for zero votes (neutral). This 5% dissatisfaction generally exists because of different comfort perceptions, thus considered the optimum comfort condition.

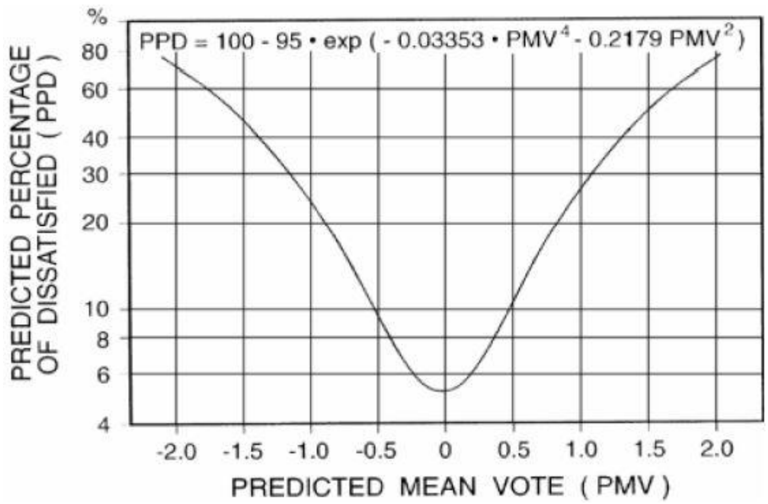

Figure 2.5: PPD as a Function of PMV

Source: Adopted from ASHRAE-55 (2010), p. 7.

Based on the PMV and PPD values, the thermal environment can be divided into three categories (ISO 7730, 2005). Table 2.3 shows each category with the corresponding PPD and PMV values. This means that if the comfort requirements for a particular room is high, then the range of comfort value (PMV) shall be smaller. Categorization of the thermal environment has made comfort parameters, such as air velocity, air temperature, and humidity, less critical. Thus, the validity of such categorization is doubtful in predicting thermal comfort in daily life (Humphreys and Nicol, 2002).

Table 2.3: Thermal environment category

Category	PPD (%)	PMV
A	< 6	-0.2 < PMV < +0.2
B	< 10	-0.5 < PMV < +0.5
C	< 15	-0.7 < PMV < +0.7

Source: ISO 7730 (2005), as cited by Olesen (2011), p. 26.

To determine the satisfaction and acceptability level of the thermal environment to which people are exposed, the three-central scale (-1, 0, +1) of ASHRAE scale can be used (ASHRAE-55, 2010). The ASHRAE's thermal sensation scale is shown in Table 2.4.

Table 2.4: Thermal sensation scale

Index	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Source: Adopted from ASHRAE-55 (2010), p. 5.

The PMV method developed by Fanger (1970) for thermal comfort calculations has been used since ISO 7730 (2005) or ASHRAE-55 (2004). However, the PMV method in these standards are sourced from an experiment using a climate chamber. Such an experiment only suitable for static and consistent thermal conditions. As described by these standards, the indoor design temperatures did not consider the adaptive behavior of people, occupant's clothes and activities, as well as the climatic variations.

Studies have suggested that thermal comfort model in current international standards are not suitable for the real situations because it was developed through experiments in a steady environment (Hanna, 1997; de Dear, 2004). Several thermal comfort studies found that occupants' thermal sensation was subjectively affected by occupants fitness, race, outdoor climate, and habits (Heidari and Sharples, 2002; Khedari *et al.*, 2000). In addition, the thermal sensation is also different from cultural and emotional responses that are impossible to regulate by international standards (Healy, 2008).

2.3.3.1 Relationship of Temperature and Humidity

There are several prominence pieces of research on the relationship between thermal sensation with air relative humidity in the air-conditioned room. McIntyre (1980) reported that 20% or 70% of relative humidity could not be detected within the range of comfort temperature. Tanabe and Kimura (1994) published a similar conclusion that when air relative humidity is increasing, occupants' thermal sensation is not increasing. Additionally, Fountain *et al.* (1999) reported that the impact of air humidity between 60% and 90% on occupants within the temperature range of 20˚C - 26˚C was also undetectable. Previous studies above confirmed that higher relative humidity would not influence the occupant's thermal sensation.

In a tropical country like Indonesia, high humidity may influence comfort temperature in naturally ventilated buildings. This relationship was investigated by Djamila (2012) and Djamila *et al.* (2013) in Malaysia. They predicted the comfort temperature from actual indoor air temperature. The results suggest that air temperature and relative humidity could not be separated to determine the occupant's thermal sensation. This means that indoor thermal comfort prediction using the seven-point ASHRAE scale may be less accurate if using regression analysis because the mean value of air temperature and relative humidity is highly correlated. To understand the effect of occupants' thermal sensation to relative humidity, further prediction on comfort temperature was conducted using the seven-point ASHRAE scale as well. The results showed that the acceptable comfort temperature was recorded from 27.5˚C to 33.5˚C within the range of −1, 0, and 1 of the ASHRAE scale. The mean relative humidity, which corresponds to a neutral temperature of 30˚C, was about 73%. Subsequently, the mean relative humidity values that relate to the indoor thermal comfort range of 27.5˚C and 33.5˚C [33] were about 82% and 63%, respectively. The results clearly show that occupants were more tolerant to higher humidity levels in a tropical country like Malaysia (Djamila *et al.*, 2013).

Therefore, for rooms having a natural ventilation system in the hot-humid tropics like Indonesia and Malaysia, it is not important to consider relative humidity on indoor comfort studies because humidity and indoor air temperature are highly correlated. However, since people in tropical countries are always exposed to higher humidity levels, Djamila *et al.* (2013) suggested further investigations to understand other effect of humidity such as sweating on occupants' thermal sensation.

2.3.3.2 Adaptive Model

In certain climatic conditions, people can adapt to the outdoor temperature or to certain weather conditions. A model for this capability is called the adaptive model. For example, people still feel comfortable in a warmer climate, although comfort parameters yield to a higher PMV. In other words, people has a natural adaptation ability to higher temperatures. Nicol and Humphreys (2002), p. 564, stated that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort." A long-established method that is usually used in adaptive model is the linear regression method. Under this method, the mean comfort temperature from occupants is plotted against outdoor variable, such as the mean value of outdoor temperatures in one month. Since the adaptive model originated from the human's body responses on outside weather conditions, this model is particularly suitable to understand people's comfort in buildings using a natural ventilation system (e.g., wide window openings and louvers). Figure 2.6 shows the concept of naturally ventilated buildings related to indoor conditions (internal parameters) with external parameters.

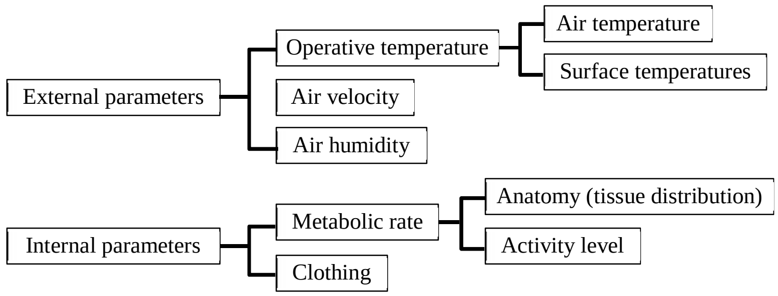

Figure 2.6: Boundary conditions for human thermal sensation
Source: Adopted from Holopainen *et al.* (2014), p. 61.

To create the adaptive model, monthly mean outdoor temperatures (T_{out}) and comfort temperatures (T_c) can be collected from an extensive thermal comfort survey. The surveys normally take place in various type of buildings, different climates as well as different local cultures. A newer version of the ASHRAE standard (ASHRAE-55, 2010) or European Standard (EN 15251, 2007) has included the adaptive model in the standard. According to ASHRAE-55 (2010), p. 3, "the monthly mean outdoor air temperature is defined as the simple running average of the previous thirty daily average outdoor air temperatures." The adaptive comfort model in this standard is limited in two comfort regions. There are 80% acceptability and 90% acceptability limits. Acceptability limits ensure the adaptive model's applicability only when the monthly mean outdoor air temperature is inside those limits.

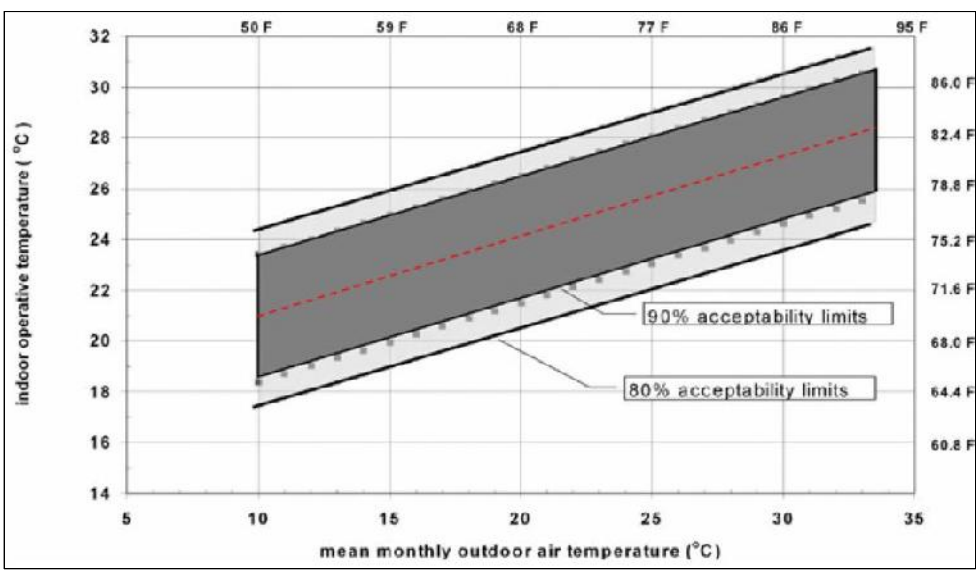

Figure 2.7: Range of operative temperature in naturally conditioned spaces
Source: Adopted from ASHRAE-55 (2010), p. 10.

The red dashed line at the center of the graph is the comfort temperatures, which is plotted using the equation:

$$T_{ot} = 0.31\ T_o + 17.8 \qquad (2.3)$$

Where T_{ot} is the operative temperature (°C). T_{ot} is calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of the zone. T_o is the monthly mean outdoor air dry-bulb temperature (°C).

The 80% and 90% limits are considered as a comfort zone, which is symmetrical about the red centerline.

90% Acceptability Limits: $T_{ot} = 0.31* T_o + 17.8 \pm 2.5$
80% Acceptability Limits: $T_{ot} = 0.31* T_o + 17.8 \pm 3.5$

The model cannot be applied if T_o is less than 10 °C or greater than 33.5 °C.

As mentioned before that the adaptive model is basically a regression that explain correlation between the sensation of indoor temperature with the mean monthly outdoor temperature. There is only one variable to input in the regression equation, which is the average outdoor temperature that has no direct influence on the human heat balance. Hence, the six classical thermal parameters, as shown in Equation 2.1, are not included.

Researchers have studied the adaptability of people to outdoor temperature in different countries or areas. Among others, Tsilingiridis and Sotiropoulos (1998) convinced that local climate should be considered to establish thermal comfort standards. By investigating the local climate's relationship to the occupants' comfort, the comfort temperature range could be adjusted and included in a new design standard or specification of a specific region. Further adaptive comfort study was done by Kwok and Rajkovich (2010), who concluded that people are more tolerant to thermal conditions than the static model. Therefore, the adaptive model has great potential to verify which particular building design is suitable to save energy in buildings.

Several attempts to model adaptive thermal comfort in Indonesia were made by Alfata *et al.* (2012). Occupants in a building located in Medan, Jakarta, Surabaya, and Makassar were selected in the survey. The lowest recorded temperature was 24 °C, and the highest was 34 °C. The average was 28 °C and 28.5 °C. The subject’s comfort was assessed using the seven-point thermal sensation scale. The first observation was done in Medan, Sumatera island involving 111 participants working in a government building. It was found that participants were comfortable at 27.9 °C under an average daily outdoor temperature of 28 °C. The next survey in Jakarta revealed that 169 office workers felt comfortable at

26.6 °C when the outdoor temperature was recorded at a daily average of 28 °C. In Surabaya, located in far eastern Java island, a comfort survey was performed to 110 government staff working in an office building. Occupants were found to be comfortable at 28.9 °C under the average daily outdoor temperature of 28.5 °C. Finally, Makassar located in Sulawesi island was selected in their study involving 109 office workers. The results of their survey revealed that occupants were comfortable at 27.7 °C under an average daily temperature of 28.5 °C. Later following those studies, Karyono (2015) made a regression based on the results from Alfata *et al.* (2012) and combine with his own investigation in other cities to predict the comfort temperature. He concluded that the neutral temperature could be predicted by a regression equation as:

$$T_n = 0.749\ T_d + 5.953 \tag{2.4}$$

Specific for hot and humid climate, several comfort temperature (T_n) equations resulting from adaptive thermal comfort studies are presented in Table 2.5. As shown in the table, with a higher indoor temperature, the occupants' still felt thermally comfortable inside the building. This indicates that people are more adaptive to the outside monthly air temperature (T_o).

Table 2.5: Adaptive comfort equation in naturally ventilated buildings

Climatic zone [*)]	Researcher	Location	Building type	Adaptive model	Indoor Temp at Neutral vote (°C)
Type A (Hot and humid)	(Auliciems and Dear, 1986)	Australia	Office building	$T_n = 0.31\ T_o + 17.6$	25.7
	(Nicol, 2004)	Islamabad, Pakistan	Office building	$T_n = 0.38\ T_o + 17.0$	27.4
	(Karyono, 2015)	Indonesia:		$T_n = 0.749\ T_d + 5.953$	
		Southern Jakarta	Office building		26.9
		Central, North Jakarta	Office building		27.3
		Bandung, Malang	Office building		23.9
Type C (Temperate)	(Ye *et al.*, 2006)	Shanghai	Residential building	$T_n = 15.12 + 0.42\ T_o$	25.9
Type D (Continental)	(Wang *et al.*, 2010)	Harbin	Residential building	$T_n = 11.802 + 0.486\ T_o$	23.7

Remarks: T_o is the outdoor monthly mean temperature; T_n is the neutral or comfort temperature; T_d is the average daily outdoor temperature
[*)] Climatic zone according to Köppen climate classification system

Brager and Dear (1998) also emphasized that in an adaptive approach, the relationship between acceptable temperature range inside a room related to outdoor temperature can be modeled using linear regression. As shown in Table 2.5, based on field survey data, the adaptive model may serve as a standard specification for building design. Such standards could be implemented in the design process for minimizing the use of energy and allows efficient building ventilation system since occupants are adaptive to outside temperature.

The current Indonesian Standard, SNI 6390 (2011) specifies that 25.5 °C is the comfort temperature with a possible range of ± 1.5 °C. In comparison, occupants in Indonesia felt comfortable between 27 °C to 28 °C, as suggested in previous thermal studies above, which is higher than the current standard values. Therefore, Indonesian building industry needs an appropriate thermal comfort standard based on Indonesian climate. The development of more adaptive models may significantly reduce the cooling energy because of various ambient temperatures across the Indonesian region. A field survey to find neutral or comfort temperatures in primary schools is one of the contributions in thermal comfort study in Indonesia, which could be used for sustainable school design.

2.3.3.3 Natural Ventilation

Tropical countries are highly exposed to rain, sunlight, and wind. One strategy to improve a thermally comfort condition in building is by designing a natural ventilation system that allows sunlight and wind to enter the building naturally. In order to save cooling energy for a long period of time, ventilation systems in buildings are designed firmly to maximize the use of natural resources. Such concept is known as "passive design" ([Altan *et al*., 2016], p. 210). The main concept of passive design is to achieve sustainability by utilizing natural resources from the surrounding environment (Altan *et al.*, 2016). This means sunlight, wind, and natural airflow will be considered in the passive design to gain comfort indoor temperature. It is obvious that to achieve comfort temperature and indoor air quality, a mechanical cooling system may not be required in passive design. Furthermore, the building envelope is the most important parameter in passive design as it affects the indoor temperatures (Manioğlu and Yılmaz, 2006). Therefore, analyses of thermal comfort in buildings should consider both building envelope and natural ventilation.

Natural ventilation strategy is very popular in residential housing and schools to gain comfort temperature. Building with large openings can deliver an effective cross air ventilation because the wind direction (windward and leeward sides) enters freely through any openings into the building (Brown and Deekay, 2001). Hence, an effective natural ventilation system is highly dependent on controlling wind forces and wind flow direction.

Brown and Deekay (2001) added that the primary aspects of natural cross ventilation are wind flow and air temperature. Therefore, if a building is designed and orientated to these factors, the openings or ventilation system attached to the building allow fresh air flow crossing through the rooms. Such a cross-ventilation system allows cool natural winds, so-called breezes entering the room. Consequently, a warmer indoor temperature that is generated by the combination of occupants' activity, solar radiation, and radiation from building materials is replaced by cooler wind. As long as occupants felt thermally comfort inside the building, such a natural ventilation system is just the right option to reduce cooling or heating energy. Nishi (1981), p. 33 defined such thermally comfort feeling as “an expression of satisfaction to the thermal environment.”

For a tropical country like Indonesia, natural daylight from the sun always available throughout the year. Especially in Indonesia, which is located on the Equator, the pattern of daytime and nighttime is negligible. Therefore, the window opening and louvers can be built without having to install an active system like modern buildings in Germany. The challenge is now left to maximize the cool winds/breezes in the indoor environment while keeping the air velocity at the safe limit not to disrupt occupants from their activities (e.g., papers are not blowing away). Due to the high uncertainty of airflow and the complex equation it may have, simulation technology is the most accurate way to predict indoor thermal comfort. The cross-ventilation system design used in most public buildings in Indonesia can be modeled to provide a comfortable indoor environment.

2.3.3.4 Thermal Comfort Research in Tropical Climate

For tropical climate, most of the thermal comfort field studies were performed in Singapore. The first study was performed by Ellis (1953) in Singapore. Thermal responses were randomly collected from men and women of 34 European people and 100 Asian people. The study concludes that race, age, and gender do not contribute significantly to thermal comfort. In other words, there is a similarity between the European people and Asian people in assessing their comfort temperature. Apartments in Singapore was observed by Leow (1988). He concluded that the occupants’ neutral operative temperature (OT) was at 28.5 °C. It was found that age and gender do not significantly affect the thermal sensation of the occupants as well.

Further study was performed by Dear *et al.* (1991a) in Singapore again. Occupants in 2 (two) types of buildings were studied. The first building is a high-rise residential building using a natural ventilation system, and the other was an air-conditioned office building. In the air-conditioned building, 24.2 °C (OT) was recorded as the occupants' neutral temperature, while for naturally ventilated building, the neutral temperature was 28.5 °C (OT). Wong *et al.* (2002) and Feriadi *et al.* (2003) also performed another study in Singapore. The naturally ventilated high rise residential buildings occupied by 255 Singaporean was investigated. It was found that the majority of occupants voted outside the ‘neutral comfort’ zone (-1, 0, -1), but occupants still felt comfortable. The reason for this is because 82.6% of occupants accept their thermal environment. Through the statistical analysis, some discrepancies were observed between neutral and preferred temperatures. Under hot and humid tropical climate, people were found to prefer a cooler environment (at 25.1 °C in ET), which is considerably lower than the neutral temperature (29.3 °C in ET).

In Bangkok, Thailand, Busch (1990) investigated occupants' comfort in naturally ventilated buildings and air-conditioned office buildings. In naturally ventilated buildings, the neutral temperature was recorded at 28.5 °C (ET). In air-conditioned buildings the neutral temperature was at 24.5 °C (ET). It is not coincidence that the neutral temperature in buildings using both ventilation systems in Thailand is almost similar to that obtained in de Dear *et al.* (1991a) in Singapore.

A large scale survey was conducted in Malaysia, Indonesia, Singapore and Japan by Damiati *et al.* (2016). They collected 2049 responses from 325 occupants in 13 office buildings operated by centralized mechanical cooling (CL), natural ventilation (FR), and mixed of AC and window (MM). The mean comfort temperatures (TSV = 0) in mechanically cooled buildings was 24.6 °C in Malaysia, 25.8 °C in Indonesia, 24.6 °C in Singapore, and 25.9 °C in Japan. In naturally ventilated buildings, 26.7 °C and 26.6 °C was recorded in Indonesia and Japan respectively. Investigation for mixed-mode ventilation system was performed only in Indonesia, where 27.4 °C was recorded as the mean comfort temperature. Their findings are comparable to results from Leow (1988), Dear *et al.* (1991a), Wong *et al.* (2002) and Feriadi *et al.* (2003) that occupants in naturally ventilated buildings are more tolerant to higher indoor temperature. Although the neutral temperature in naturally ventilated buildings is 2 °C higher than in air-conditioned buildings (Nguyen *et al.*, 2012), occupants prefer cooler temperature (Feriadi and Wong, 2004). Such phenomenon indicates that people in the tropics are more tolerant to higher indoor temperature. At the same time, they still have options to increase their comfort by opening windows, operating fan, or changing their clothing. Findings from some previous thermal comfort studies in the tropics is summarized in Table 2.6.

Table 2.6: Thermal comfort research in tropics

Researcher	Location	Building type	Research findings
Leow	Singapore	NV	T_n at 28.5 °C (OT)
de Dear *et al.*	Singapore	NV	T_n at 28.5 °C (OT)
		AC	T_n at 24.2 °C (OT)
Busch	Bangkok, Thailand	NV	T_n at 27.4 °C (ET)
		AC	T_n at 24.5 °C (ET)
Wong *et al.*	Singapore	NV	T_n at 28.9 °C (OT)

Remarks: OT: Operative temperature; ET: Effective temperature; T_n: Neutral temperature

As shown in the table, the neutral indoor temperature in air-conditioned buildings is lower than in the naturally ventilated building in a tropical climate. Although the neutral temperatures for air-conditioned buildings are close to or within the comfort temperature range in ASHRAE-55 (2010), occupants of naturally ventilated buildings were found to be thermally comfortable even the indoor comfort temperature is higher than in ASHRAE-55 (2010), which is 25 °C. Nicol *et al.* (1999) pinpointed that indoor comfort temperature and outdoor temperature has a strong relationship in building using a natural ventilation system. Such a strong relationship confirms that the adaptive model is highly relevant in the tropical climate and explains the occupant's adaptability in the tropics, which is more tolerant to the warmer thermal environment.

2.4 Criteria Review for Material Selection

A set of comprehensive criteria is required to enable performance assessment of sustainability in building materials. Material performance assessment is a complex issue. Thus, any criterion cannot be separated only to the sustainability in building design but should consider performance during construction and operations as well. The assessment method may comprise point-based or score assigned to each material. Some base values may be applied to meet specific requirements or standards. For instance, a minimum recycled content. Other methods may set some rules about whether a material is recyclable, locally sourced, or made from renewable resources. In designing a building, the criteria that affect the material selection are grouped under various subtitles, which can be followed in Table 2.7.

Table 2.7: Summary of criteria for the materials selection process

Zhou *et al.* (2009)	Sirisalee *et al.* (2004)	(Mangonon, 1999)	(Ashby and Johnson, 2002)	Esin (1980)	(Ashby, 1992)
Mechanical properties	Mechanical properties	Physical factors	General attributes	Production requirement	General properties
Economic properties	Cost	Mechanical factors	Technical attributes	Economic factors	Mechanical properties
Environmental properties		Life of material factors	Eco-attributes	Maintenance factors	Thermal properties
		Cost and availability	Aesthetic attributes		Wear
		Codes, statutory and others			Corrosion

Source: Adopted from Akadiri and Olomolaiye (2012), p. 670.

In most of these sources, the design process is defined as covering both technical and non-technical criteria. However, in reality, they mostly concentrate on the technical side, thereby dominating the architectural-based source. Zhou *et al.* (2009), p. 1211, stated that "when a designer selects a material, he or she must consider fulfilling the three basic properties: mechanical properties, economic properties, and environmental properties." The economic property was considered the most important aspect of material selection because it includes purchase cost, process cost, transportation cost, and recycling/disposal cost. The mechanical property, such as the durability of the material is also important. Zhou *et al.* (2009) put the durability of materials under 'mechanical property'. Finally, they emphasized that a more sustainable lifestyle will become important because the earth has limited resources and is increasingly facing severe environmental pollution. Hence, the 'environmental property' of material is especially important.

Finding from the above studies suggests that decision-making criteria for the material selection have been well documented. The assessment of building materials must integrate all of these factors (i.e., economic, ecological, and social) to provide an overall picture of a material. Experiences and knowledge from relevant project stakeholders would be necessary to set up important criteria under those three main factors, so-called 'the triple bottom line of sustainability'. By doing so, the selection of suitable materials for buildings can be made objectively using any multi-criteria decision-making method. In addition, the potential performance of a building and the use of materials can be captured in a better way and facilitate the sustainable development of the built environment.

A review of relevant studies indicates that economic, environmental, social, and technical aspects are the fundamental aspects to measure sustainability performance. These performance measures become a guideline for determining the selection criteria. The process of material selection involves a large number of criteria which sometimes impractical or ineffective to some extends. To be effective and meaningful, material selection criteria are combined without neglecting the fundamental aspects of sustainability. As a result, these criteria will be classified mainly under ecological, social, and economic criteria.

When the material selection process involves multitude criteria and uncertainty, the use of analytical tools are inevitable. For instance, Sirisalee *et al.* (2004)) and Ashby (2000) used multi-objective optimization. The ranking method was used by Jee and Kang (2000), Chatterjee *et al.* (2009), and Sirisalee *et al.* (2004). Holloway (1998) and Giudice *et al.* (2005) used index-based methods while Farag (2002) used other quantitative methods. However, decision-makers cannot use the existing methods in selecting the appropriate materials because they are not available in current green building literature. The criterion for optimizing sustainability in buildings at least must consider all environmental impacts, economic impacts, and social requirements.

2.5 Development of Criteria for Sustainable Assessment

The selection of criteria for the tool developed in this research depends on many factors. It may include information availability, accessibility, and the analysis complexity (Azapagic and Perdan, 2000). Hence, the criteria selection is a challenging process, but it should at least address economic, environmental, and social aspects as an integral part of sustainability (Singh *et al.*, 2009b). Moreover, Guy and Kibert (1998) pinpointed that the selected criteria must be systematic and straightforward to measure the performance of sustainability in a system. According to them, the use of indicators accommodates the quantitative measurement, which in turn provides a framework to assess sustainability in construction.

They also added that sustainable criteria in construction are not limited to water, energy, and the use of construction material only, but should focus on land issues as well. Wackernagel and Rees (1998) performed a sustainable assessment using an ecological criterion such as food, water, energy, and waste disposal, which reflects the economic and environmental aspects of sustainability. Whilst the sustainability framework developed by Bourdeau (1999) concluded that economic, social, and cultural criteria are the most important criteria for the construction industry. He added that different locations or regions might influence priority in the sustainable assessment. Thus, the selected criteria will not be the same for each region.

Other researchers focus on criteria development for decision-making strategies such as the work conducted by Foxon *et al.* (2002). Using water utilities in the UK construction industry as a case study, two main factors (criteria application and its practicability) were identified to support the sustainability agenda. Singh *et al.* (2009b) argued that indices are an effective tool in making policy or in formulating sustainable strategy in terms of environment, social, economic, and technological improvements. In addition, they emphasized that indicators shall be used with caution. This means that to maintain its contextual effectiveness, indicators should be scrutinized, refined, and verified.

A review of the literature above suggests that the development of criteria and how it is measured cannot be done separately. Discussions among project stakeholders of which criteria need to be considered or prioritized shall also include assessing or measuring any given criteria according to the local capacity. Assessment of sustainability using an index method is used in this research where the selection of criteria is carefully selected, as emphasized by Singh *et al.* (2009b).

A set of criteria can be developed by considering two factors as suggested by Foxon *et al.* (2002). According to them, the two key factors should be able to answer questions of "what use will be made of this set of criteria? and to what extent can any set of criteria encompass the range of issues to be considered under the heading of 'sustainability'?" Other researchers have also given great consideration of these issues, such as studies conducted by Singh *et al.* (2007), Wong, *et al.* (2008), Buchholz *et al.* (2009), and Chen *et al.* (2010a).

The following guideline was developed by Akadiri and Olomolaiye (2012) to help the criteria selection process:

(1) Comprehensiveness: The selected criteria should cover economic, environmental, and social factors to ensure a clear objective toward sustainability.
   Comprehensiveness can be achieved through a questionnaire-based pilot study. In addition, there will be more opportunities to enhance the clarity and the feasibility of the final questionnaire survey. A pilot test was conducted to investigate whether the proposed

sustainability standards were feasible. In addition, several respondents were also requested to put in new standards if required.

(2) Applicability: The selected criteria should be applicable to every alternative to ensure the objective comparison between each alternative.

Applicability refers to the technical, administrative, operational, statutory feasibility, and the local wisdom of implementing an alternative. All criteria should also be applicable to various materials under consideration, including the construction method required during its application.

(3) Transparency: The criteria should be chosen transparently so that stakeholders can easily identify, understand and propose any other important criteria.

Formal consultation is required during the preparation of the plan or program and before its adoption or submission. For example, relevant respondents need to be determined prior to a consultation. Respondents should also be given adequate time frames to participate in the criteria selection process and express their opinions. Hence, through earlier and effective inclusion of the relevant participants, the development of the criteria list can be improved.

(4) Practicability: The set of criteria chosen must form a practicable set for the decision to be assessed, the tools to be used, and the time and resources available for analysis and assessment. The result of the decision will obviously be affected by the chosen standards of the sustainability and the comparison method or the chosen aggregation. The factors mentioned above give directions to decide the standards or criteria.

Practicability refers to the similarity of alternatives in actual situations in the field in addressing real issues and objectives. An alternative will become more relevant and useful if it corresponds with existing issues and objectives. Hence, practical and realistic alternatives might be those that have been filtered from a structured development process.

Another guideline and recommendation can be found in Singh *et al.* (2007) and Chen *et al.* (2010a). They underlined that in order to obtain a meaningful analysis, the transparency and practicability of the selected criteria should be applicable to a broad range of alternatives. Furthermore, comprehensive sustainability criteria that take economic, environmental, social, and technical elements of sustainable construction into account are essential. Blyth and Washington (2001) indicates that developing the performance criteria can be defined as a cycle of converting qualitative statements into quantitative data. The needs of users are first indicated and stated as a set of qualitative statements of functional requirements. These statements are then rewritten into a set of specific data consisting of numerical values, tolerance, and units. This stage includes changing the performance requirements into a set of detailed descriptions which comprise suitable methods of testing, indicators, and target values (Preiser and Vischer, 2005). Examining the design solutions is conducted by means of verification calculations created in the specifications in which normative calculations, simulations, or measurements obtained in the phase of building operation are included. The results of calculation are then combined or aggregated.

Aggregating the data obtained for the analysis results in quantified normalized data called performance indicators. Contrasting the performance indicators with the existing performance targets is a method of validating these performance indicators (Szigeti and Davis, 2005).

Qualitative and quantitative research methods are used in this work. The qualitative research method is used to develop ground knowledge about the selection of building materials. The qualitative method search and analyzed relevant published data from periodicals, journals, conference proceedings, web-based knowledge, and other research reports. A framework for the intended research can then be developed after thorough literature surveys. Based on the secondary data from the previous related research, the criteria for the selection of building material are listed in Table 2.8. These criteria consider mainly the economic, ecological, and social principles of sustainability.

Table 2.8: Sustainable criteria for building and material selection

No.	Criteria	Source
	Ecological	
1	Potential for recycling	(Asokan *et al.*, 2009); (Saghafi *et al.*, 2011)
2	Potential for reuse	(Amponsah *et al.*, 2012)
3	Ozone depletion potential	(Marsono and Balasbaneh, 2015)
4	Ecological Impact during material harvest	(Gustavsson and Sathre, 2006); (Almusaed and Almssad, 2015)
5	Ecological Impact during material production	(Gustavsson and Sathre, 2006)
6	Use of water during construction at minimum	(Solís-Guzmán *et al.*, 2013)
7	Embodied energy within material	(González and García Navarro, 2006)
8	Amount of material waste	(Li *et al.*, 2013); (Lachimpadi *et al.*, 2012)
9	Amount of transportation required	(Mao *et al.*, 2013)
	Social	
1	Ease of construction / constructability	(Chen *et al.*, 2010a)
2	Aesthetics/appearance	(Brimblecombe and Grossi, 2005)
3	Zero or low toxicity for occupant	(Atlee, 2011)
4	Resistance to heat flow	(Samani *et al.*, 2015); (Zhao *et al.*, 2014); (Jeanjean *et al.*, 2013)
5	Locally available workers	(Prayitno *et al.*, 2013)
	Economy	
1	Locally available suppliers	(Bo *et al.*, 2009)
2	Availability in local market	(Shi *et al.*, 2013)
3	Initial cost	(Rahman *et al.*, 2012)
4	Maintainability	(Silva *et al.*, 2004); (Chiu and Lin, 2014)
5	Reparability	(Robery and Shaw, 1997)
6	Upgradability	(Go *et al.*, 2015)
7	Life expectancy of material (strength, durability)	(Borges *et al.*, 2014); (Thomson and Walker, 2014)

For any decision process, the selected criteria must be broadly applicable across all those three principles to ensure an objective evaluation of design alternatives. Therefore, these preliminary criteria will be analyzed further using qualitative and quantitative research methods.

From the extensive literature reviews, lists of criteria as shown in the table can be seen as a representation of measurable criteria in the context of developing countries because one researcher may include more than one criterion in their study. For instance, Abeysundara *et al.* (2007) concluded that cost, thermal comfort, material appearance (aesthetic), quick installation, and strength are criteria that have a big influence on the material selection.

Part of the design selection tool developed in this research is the inclusion of material selected from the list of common building materials in Aceh, Indonesia. The selection process considers specifically on ecological, economic, and social aspects of materials. Materials for the five building elements, which are floor, wall, roof, and ceiling were analyzed. The same strategy was previously adopted by Abeysundara *et al.* (2009) where environmental problems in terms of embodied energy and environmental impacts associated with building elements are analyzed. A broad range of environmental impact analysis includes global warming, acidification, and nutrient enrichment. Analysis of the economic aspect is based on market prices and the affordability of materials. Their analysis also includes thermal comfort, interior (aesthetics), ability to construct quickly, strength, and durability, which were classified as social factors. By compiling the results of analyses, they were able to identify two building types with minimum and maximum impacts. The existing buildings and these two building types were compared in a matrix of environmental, economic, and social scores. Analysis of the results indicates that decision-makers need to give higher consideration on environmental factors over social and economic factors because social and economic scores do not vary significantly between cases. This shows that their decision matrix was able to help decision-makers to select sustainable materials for buildings in a meaningful way. Their matrix would help the construction industry move towards more sustainable buildings and sustainable constructions.

A large number of multi-criteria aggregating methods have been developed. Most of them require appropriate criteria and weights to evaluate sustainable performance. Aggregation is one of the MCDM method procedures, and it may vary according to the way the method is structured. According to Iwaro and Mwasha (2013), the selection of criteria and weighting for the sustainable performance assessment of building envelopes is a tedious process. Especially for building designers, the criteria selection and weighting process are somewhat new to them. Hence, such process needs to be done in a structured manner so that the sustainable performance of the building envelope can be assessed accordingly. In any case, the way toward assessing the performance of criteria and weighting of these criteria for evaluating the material selection for a building is challenging and complex.

A more complex system generally exists in decision making for sustainable energy. This is because sustainable energy has multi-dimension goals and complex socio-economic and biophysical systems. One popular method of multi-criteria decision-making for sustainable energy is known as Multi-Criteria Decision Analysis (MCDA) methods. The use of MCDA in sustainable energy was studied by Wang *et al.* (2009). They reviewed different stages of MCDA, starting from criteria selection, criteria weighting, evaluation, and final aggregation. The selected criteria were categorized under technical, economic, environmental, and social aspects. The weighting methods of criteria are classified into three categories: subjective weighting, objective weighting, and combination weighting methods. For the decision-making task, he then applied several methods based on weighted sum, priority setting, outranking, fuzzy set methodology, and their combinations. The results of their work showed that the investment cost was located in the first place in all evaluation criteria, while CO_2 emission follows closely because of more focused on environment protection. They also concluded that equal criteria weights are still the most popular weighting method. The analytical hierarchy process is the most popular comprehensive MCDA method, and the aggregation methods help get the rational result in sustainable energy decision making. On the other hand, buildings are a complex combination of materials, and the integration of environmental, economic, and social factors will provide an overall sustainable performance of one single material and thus contribute to building sustainability. Therefore, the selection of design alternatives based on a combination of the material may be solved using an MCDM approach.

Materials selection for one particular design or building shape may significantly impact the sustainable performance of a building. Objective factors such as cost constraints, design parameters, and environmental requirements can play a role in selecting materials. However, there may be subjective factors that could also impact the selection and affect sustainability goals. To help decision-makers select appropriate material and other design parameters, this research utilizes an MCDM method that considers both objective and subjective criteria.

In conclusion, this research may provide a more realistic and comprehensive assessment by combining both analytic and subjective evaluation. It is important to highlight that all criteria defined in this research are non-definitive. It can be extended based on the problem, process, and assessment objective. In connection with decision making, the selection of criteria define the problem breakdown. Thus, different criteria may create a different model and may infer different selection results.

2.6 Discussions

The construction industry is reluctant to change the conventional construction methods, especially when it comes to innovative construction methods or the use of sustainable building materials. There always situation that design consultants have a limited freedom to give their ideas because of Owner's constraints. Two constraints are always in the public financed projects. First is budget limitation, and secondly, Owners already have the philosophy of design and a specific requirement for certain function or activities. At certain cases, Owners are willing to use a more advance building technology or materials from the developed countries, but the risks involved and extra costs becomes a barrier. The main reason is that alternative financial and incentive under public financed projects are not available to implement sustainability in buildings. In addition, sustainability in building has not recognized as competitive advantage for developers in the private sector. Another barrier is the existence of outdated building codes or design concepts from the Dutch colonial period in Indonesia. For example, the use of brick and reinforced concrete has been accepted as a safe option while other alternatives to building materials are believed to be costly and difficult to apply. Therefore, there should be a methodological step to bring innovative material or green design that comply with existing building codes and regulation in the developing countries. This would result in a safer project execution and minimize potential conflict between the project stakeholders.

In Indonesia, the government is still the biggest client in the construction industry. Therefore, the government regulation for tendering procedure play a significant role in delivering project to a success. By changing its tender criteria and providing special conditions for the selection of design service or contractors, bidders would eventually start to propose innovative green products or sustainable design leading to faster adoption of sustainability in construction project.

Research on the sustainability of building had led to an abundance of criteria under the economic, environmental, and social aspect of a building. From all of those criteria, only the most suitable and a highly relevant criteria were selected to assess sustainability at the early stages of the school design process. The preliminary selection of criteria has a simple and straightforward characteristic to maximize their application in the sustainability of school designs. The criteria were separated into two categories, objective and subjective criteria. Objective criteria represent criteria that can be represented by a complex mathematical equation. Such an analytical approach provides a tangible performance result. On the other hand, performance measurement of subjective criteria can be solved using qualitative approach which is designed to capture preferences, experiences and knowledge of experts about performance on certain type of criteria.

Sustainable design is one of an increasingly interesting topics especially for countries vulnerable to natural disasters. This chapter has provided a theoretical support and broad knowledge of sustainability in addressing the research’s interest. Furthermore, an overview of sustainable development in Indonesia and how Indonesia may cope with existing problems and limitations has been presented. Through a review of the connection between the sustainability of building design and the environment, the need to have an integrated approach during the design process is not avoidable. Such an integration requires a measurable and objective assessment to achieve sustainability in construction. Therefore, appropriate decision making supported backed with multi-criteria decision making theories can be made available during the design process.

CHAPTER 3

DEVELOPMENT OF A MATERIAL AND DESIGN SELECTION TOOL

3.1 Structure of the Framework

Chapter two has described the Indonesian construction industry, especially on recent sustainability situation of building and construction in Aceh province. The concept of sustainability in the building has been presented as well. Sustainable buildings should at least meet health standard for human occupancy, reduce energy, and maintain the overall quality inside and outside of the building without sacrificing natural resources. Hence, there was a strong indication that the selection of material and design is an area that would bring a positive impact to the society and the building industry. However, the needs for particular public services such as school buildings should consider environmental impact, economic, cultural diversity and social factor in a particular country. For a building itself, one of the design strategies for a building becomes sustainable is that it must maximize the functionality of a building, which among others is to ensure occupants' comfort. Sev (2009) raised the importance of assessing the occupant's comfort and stressing that sustainable building must not only save energy but should also consider the thermally comfort indoor environment to enhance occupants' productivity.

To achieve sustainability in building design, a design selection tool backed by an MCDM method is one rational solution among other tools. Such a tool should be able to process many trade-offs and provide timely valuable information to the decision-makers on various building materials that correspond to several building shape or design. To understand the connection or usability of the tool, an overview of the existing construction industry in Indonesia and current sustainability practice was described in a schematic diagram, as shown in Figure 3.1. As shown in the figure, there is a clear connection between the proposed design selection tool with resource availability, technology, perception of sustainability, and the building industry since the tool was intended to promote the adoption of sustainable design practice in developing countries. Therefore, the tool should be suitable and appropriate for the Indonesian construction industry based on available methods, construction technology, regulation, and resources. Figure 3.1 below illustrates the overall concept.

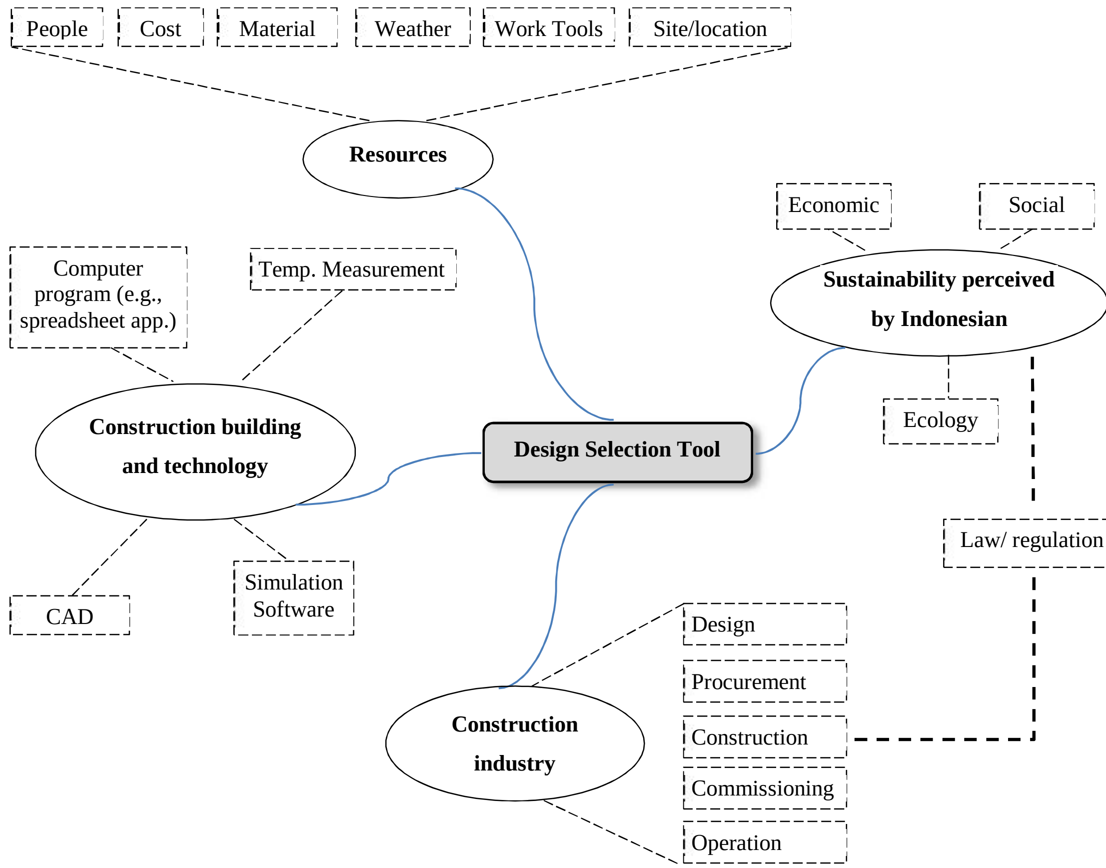

Figure 3.1: Overall concept of research

It can be seen in Figure 3.1 that the concept behind developing such design selection tool is to formalize sustainability in the Indonesian context. A framework was then proposed in which all important criteria can be taken into account early in the design process so that the sustainable performances of any design alternatives are known. The framework was adopted in a case study with the primary objective is to provide a matrix or decision tool for the selection of public primary school design. The tool incorporates all sustainable criteria, which are perceived as important to the community and can provide many alternatives in a timely manner to the decision-maker at the earliest stage of design. Therefore, the integration of the tool was designed not to interfere with the current practice and legislative process in the Indonesian construction industry.

After the scope and objectives are identified, the tool was created following a framework specifically developed for this research. This chapter explained the details of the proposed framework. Three main methods have been chosen to suit the different aspects involves in the framework: 1) Method for subjective evaluation, 2) Method for objective evaluation, and 3) Decision-making method in which all criteria are computed. Employing these methods help to indicate the importance level of sustainable criteria, analyzing the thermal performance inside the classroom, and examining the optimal combination of design parameters. According to Benson and Susan (2009), different methods might have different strengths and weaknesses, thus better conclusions can be achieved using multi-methods. Furthermore, a multi-method approach allows greater flexibility in defining the research problems, and improve validation of results. For instance, evaluation of objective criteria also employed a simulation method which was performed using a software called EnergyPlus (E+) to measure the thermal performance inside the classroom. Furthermore, another method for material combination was applied using a software called JE Plus, which was configured specifically to work alongside with E+. Figure 3.2 below illustrates the overall framework of this research. Illustration of how the three main methods employed in this research can be seen from the framework.

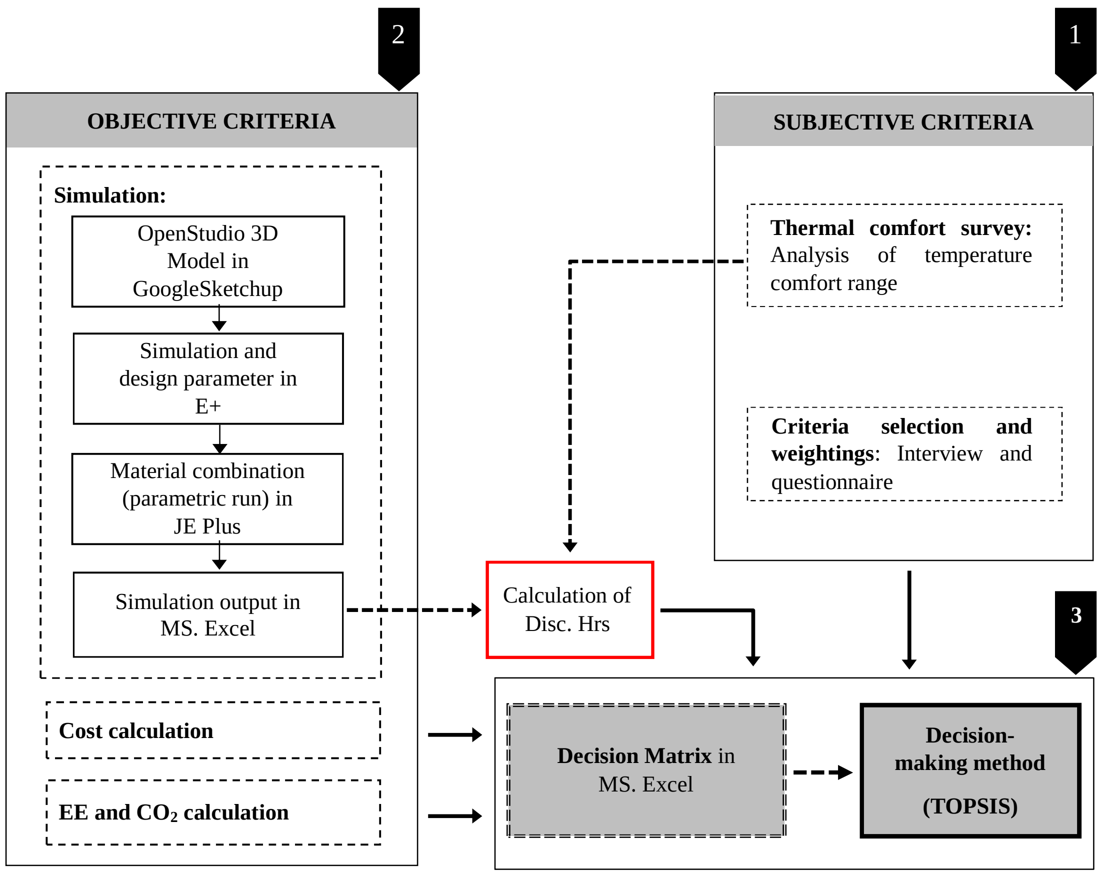

Figure 3.2: Research framework

As shown in Figure 3.2, the framework has three main parts: 1) Subjective criteria, 2) Objective criteria, and 3) Formation of decision matrix and decision-making. The first part contains methods for the evaluation of subjective criteria. These include evaluation on the importance of criteria and material performance using a questionnaire. Another questionnaire was also designed for a thermal comfort survey to evaluate the actual thermal sensation inside the classrooms. The second part was dedicated to evaluate the objective criteria by means of the simulation method, calculation of total initial cost, and calculation of materials' embodied energy (EE) and CO_2. The indoor operative temperature resulting from simulation output was then analyzed based on the results of thermal comfort survey so that the calculation of thermal discomfort period (in hourly basis) felt by students can then be made. The third part is the formation of the decision matrix in which all the elicited data and criteria will be gathered, and finally, the TOPSIS method is applied where the ranking of all design scenarios and evaluation of optimal solutions can be made. Each part of the framework has specific methods which are further elaborated in detail in the following sections.

3.2 Subjective Criteria Evaluation Method

Two models of questionnaire were prepared for evaluating all subjective criteria. The first model serves two things. 1) To identify the most important criteria for building sustainability and 2) To identify criteria for selecting material. The subjective assessment of material performance in the Aceh region was also included in this first questionnaire model. The second questionnaire model was prepared to assess students' thermal sensation inside the classroom of all case study schools. For the first model, the majority of respondents were gathered from the Construction Agency Development Board in Aceh Province. These include Design and Engineering Consultants (DEC) and contractors, which are based in Aceh. Contacts to government officers were gathered from the Regional Planning and Development Agency of Aceh Province and the Regional Construction Works Department of Aceh Province. A pilot survey was performed before the final questionnaire was distributed to ensure a high response rate. For the second model of questionnaire, feedbacks were collected directly at the targeted schools. Explanations on how to fill in the questionnaire were given to the students to ensure a mutual understanding of the questionnaire's objective. The temperature range in which the students vote as comfort was analyzed using descriptive statistic technique. Observation of actual temperature was made hourly, hence using the actual range of voted comfort temperature, the total of Disc. Hours can be calculated as illustrated by a red-colored box in the framework.

3.2.1 Questionnaire Design for Criteria Selection and Material Performance Assessment

3.2.1.1 Questionnaire for Criteria Evaluation

As mentioned in Chapter 2, a list of criteria for sustainable material and design selection was identified from various pieces of literature. From this list of criteria, verification of criteria to be included in the questionnaire survey was done through a semi-structured interview with architects and government. Academia from local Universities was also consulted. The list of criteria was presented to the interviewee and followed by a discussion highlighting the material and design selection process in practice. The results of the interview provided valuable comments and directions for developing the appropriate design selection tool. A list of interview questions can be seen in Appendix 3.1.

Once the final list of criteria is obtained, a close-ended questionnaire will be distributed using the response scale as developed by Likert (1932). A Likert scale (1 to 5) will be used in the questionnaire to identify the importance of criteria for material selection in relation to the sustainability of design.

The interpretation of the Likert scale used is as follows: 1) Low importance, 2) Slightly important, 3) Moderately important, 4) Very important, and 5) Extremely important.

The final form of the questionnaire model is presented in Appendix 3.2. Before distributing the questionnaire, the last review was done together with an experienced architect, government officer, academic staff of Syiah Kuala University in Banda Aceh, and a senior researcher at the Facility Management Institute in KIT, Germany, to ensure the clarity of each question.

Weightings of Criteria

Responses from the questionnaire were evaluated using Equation 3.1. These weightings were basically derived from the subjective judgment of respondents. As like any other decision-making process, the freedom to input user's weightings will enhance the acceptability of the final design to the project parties. Hence the final decision matrix will permit such changes in a spreadsheet format. In other words, by enabling the user to change the weight of criteria in the matrix, the result from his/her decision can be identified instantly. This would also facilitate transparent criteria weightings based on decision-makers' preference under available design alternatives.

From the Likert scale response, the Average Weighted Response (AWR) will be used to rank the relative importance of each criterion (Adams, 1998).

$$\text{AWR} = \frac{\sum f}{N} \tag{3.1}$$

Where f is the number of respondents, x is the numerical rating ranging from 1 to 5 given to the criteria by each respondent, and N is the total number of respondents.

After the average of each weighted criteria was obtained, the last objective is that all weights need to be specified on a 0 – 1 scale. Hence the value of the weights can be used in a numerical formula (Malczewski, 2006). Assuming that r_j is the average weight from the total respondents' responses of the criterion and n is the number of criteria. Hence, normalized weights can be calculated using the equation below.

$$\sum_{j=1}^{n} w_j = 1 \tag{3.2}$$

In many decision-making methods, an accurate assessment of the relevant data is extremely important. Specific for methods that require qualitative information from the decision-maker, such data assessment is crucial. Therefore, the relative importance or weight of each criterion has been used in many decision-making methods as an objective way to solve the decision-making problem.

3.2.1.2 Questionnaire for the Assessment of Material Performance

For assessing the performance of materials, a marking scheme was developed, as shown in Table 3.1.

Table 3.1: Criteria for giving marks on each material

Social aspect	Indicators	Marks	Criteria for giving marks
Aesthetic	Very good	5	Excellent finished look, very attractive
	Good	4	Good looking, attractive
	Fair	3	General appearance
	Poor	2	Not quite attractive
	Very poor	1	Very unattractive, need improvements
Buildability	Very good	5	Very easy, not required much effort or skill
	Good	4	Quite easy to construct/install
	Fair	3	Reasonably easy to construct/install
	Poor	2	Difficult and require much effort
	Very poor	1	Very difficult to construct/install

As can be seen in Table 3.1, the performance assessment of each social aspect was presented in detail to all respondents. Equation 3.3 was then used to calculate the collected data. Hence, if the social aspect has number of respondents ‘‘N’’ and ‘‘x’’ is the numerical score (i.e., very good, good, fair, etc.), then the social performance (SP) for that particular material;

$$\mathrm{SP} = \frac{1}{N} * \sum_{i=1}^{N} x_i \tag{3.3}$$

The total average value of each material across these three sustainable aspects are then inputted for the calculation in the decision matrix. A completed questionnaire form for material performance assessment is given in Appendix 3.2 with an accompanied marking scheme as given in Appendix 3.3.

3.2.2 Questionnaire Design for Thermal Comfort Survey

The study performance and concentration of the students are affected by the thermal condition in classrooms. Thus, student’s comfort must be seriously considered because the negative influences of an unsatisfactory thermal environment may distract the learning process. In tropical Indonesia, people in residential housing and office workers have greater flexibility to cope with warmer indoor temperature by adjusting their clothing and activities. Unfortunately for the students, there is no flexibility to do the same inside the classroom. In Indonesia, the design of school buildings has traditionally relied on a natural cross-ventilation system at all facades. Interestingly, it was found that some classrooms were installed with mechanical ventilation by fans or AC to achieve thermal comfort, which is usually donated by the local communities to meet a higher expectation of the standard of education facilities. The latter use of AC disregards the intended function of the natural ventilation system, which has originally been designed. For example, louvers above the window are closed with a plastic sheet. Since primary school is undisputable an education backbone of developing countries, therefore thermally acceptable school design is one of the social qualities which can be thoroughly evaluated across the entire design parameters.

The specific objectives of this study are:

1) To find out actual thermal conditions in classrooms
2) To investigate students' perception of the level of thermal comfort in classrooms. Particularly, thermal acceptability in classrooms will be analyzed using the ASHRAE scale and Bedford scale.
3) To determine neutral temperature, preferred temperature, and acceptable temperature range in classrooms.

To conclude whether the students are thermally comfortable inside the classroom, a thermal comfort study must be conducted. Assessment of thermal acceptance is known to be subjective because this much depends on personal emotion, metabolic rates, and clothing. Conclusively, thermal comfort is largely a state of mind, separate from equations for heat and mass transfer and energy balances. The thermal assessment inside the classrooms of the selected schools was based on the students' votes on thermal sensation (ASHRAE Thermal Sensation Vote) and comfort perception (Bedford scale).

Table 3.2: Thermal sensation scale used for the field survey

ASHRAE Scale		Bedford Scale	
Value	Sensation	Value	Sensation
+3	Hot	+3	Much too warm
+2	Warm	+2	Too warm
+1	Slightly warm	+1	Comfortably warm
0	Neutral	0	Comfortable
-1	Slightly cool	-1	Comfortably cool
-2	Cool	-2	Too cool
-3	Cold	-3	Much too cool

The Bedford scale was criticized because it consists of a semantic relationship between warmth and comfort, which may not necessarily be constant, whereas the ASHRAE scale contains no explicit reference either to comfort or pleasantness (Schweiker *et al.*, 2017). However, the two scales behave in a very similar way in practice, and the results obtained by them may be compared directly with each other.

Both scales provided the basis for taking surveys regarding how the students feel inside the classroom. The direct measurement of indoor temperature was also conducted at the same time during the data collection from the students. The thermal sensation expressed by the students will be analyzed according to the recorded temperature at the time of filling out the questionnaire. One classroom from eight primary schools will be evaluated. The result of this survey may show the total discomfort hours (Disc. Hours) felt by the students during the school hours.

The thermal comfort assessment in the classrooms was based on the students' responses using a questionnaire, as shown in Table 3.3. These students' responses were collected in parallel with the actual temperature measurements in each class. Each classroom occupies 15 to 20 students, which makes up a total of 128 students who participated in the survey. Additionally, teachers who are assigned to the corresponding classroom were also asked regarding the operation of windows and comments about temperature sensation inside the classroom.

Table 3.3: Scale used in the survey

1. How do you feel about the temperature at this moment? Please put the cross sign inside the empty box.

Cold -3	Cool -2	Rather cool -1	Neutral 0	Rather warm 1	Warm 2	Hot 3

2. Do you feel comfortable? Please put the cross sign inside the box which level of comfort that you feel.

Much too cool	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too warm

3. What is your preferred temperature inside this classroom?

Much cooler	Cooler	A little bit cooler	Just like this	A little bit warmer	Warmer	Much warmer

Since the questionnaire was targeted to the 6th-grade students with an average age of 12 years old, some graphics were inputted in the questionnaire to provide a better understanding in filling out the provided boxes. The actual preview of the distributed questionnaire is provided in Appendix 3.4. In this study, the metabolic rate was set to 1.2, which represents the value of sedentary activities. Taking into consideration that school activities are diverse and might affect the students' metabolic rate, the comfort study was administered only in classes that have settled in for at least 15 minutes. Three measurements were taken for every school at the same interval starting at 08.00 AM, 10.00 AM, and 12.00 PM, respectively. Classes who just had their physical activities in the previous period were avoided. All students wore school uniforms, which consisted of long pants and a collared shirt for boys and a long-length skirt and collared blouse for girls. Almost all girls wore head cover *(hijab/jilbab)* following Islam religion, although it is not mandatory in Public State Primary Schools within and outside the Aceh region.

3.3 Objective Criteria Evaluation Method

A simulation software was employed to run the number of design alternatives and the combination of material. Simulation of a building's thermal performance is necessary to quantify the number of discomfort hours to which students are exposed during school hours and examine alternative enhancements or design strategies to achieve better indoor thermal environments. A simulation program, EnergyPlus (E+) was selected in this study as a main tool for the simulation. E+ can be downloaded at no cost, and it is a very popular simulation software among building simulation community due to its accuracy and flexibility to exchange data between other commercial software. On the other hand, JE Plus was used to conduct a parametric run of various combinations of material for the building envelope. All materials were combined across all possible school design configuration/shapes. The simulation output from JE Plus can also be arranged in a spreadsheet according to the purpose of analysis, which in this case, total hours of discomfort based on actual indoor operative temperature during the school hours.

A major benefit of energy simulation in building design is the ability to compare all design alternatives. Nevertheless, such comparison needs to be validated to ensure the reliability of the simulation result. According to Maile *et al.* (2007), if alternatives to the original building design are validated for both thermal comfort and energy usage, the validity of assumptions in the model is less crucial. Because different design alternatives are based on almost exactly the same assumptions, and the common belief is that relative differences between the simulation results and actual results are reliable. However, if building usage patterns are dependent on the type of design alternative, the comparison of design alternatives may provide less accurate comparison results. Fortunately, the usage pattern or operational activities in school is not as dynamic as activities in family housing. Especially in Indonesia, because all public schools follow the same schedule and activities. Should schedule and activities vary, variations in schedule or student activity can now accurately be predicted by computer-based tools known as whole building simulation (WBS) tools. There are quite many WBS tools available today. E+ was selected because of its compatibility for file exchanges and accuracy despite the complexity of the input and output process.

To calculate the indoor air temperature for different materials and variations of building shape, E+ version 8.1 was used. E+ is a whole building simulation program that predicts indoor thermal conditions by simultaneously solving heat balance equations for the surfaces and room air in each enclosed space. Google SketchUp with OpenStudio add-in was used to create the building geometry. Finally, JE Plus is the chosen manager for the execution of all combinations of material. Figure 3.3 shows the process flow diagram or procedure of the adopted simulation method.

EnergyPlus (E+) has been available since 2001, and the reason for using E+ is because it works on text input and text output. In between, there is an E+ engine. This E+ engine takes an input file, processes it, and then deliver the outputs in a text format. For example, the user can input the building parameters, and E+ will deliver an output, such as the annual energy consumption, energy bills, as well as hundreds of other parameters such as zone temperatures and humidity ranges. Since E+ uses this text-in and text-out approach, practically any computer programmer can easily build applications for interfacing with E+.

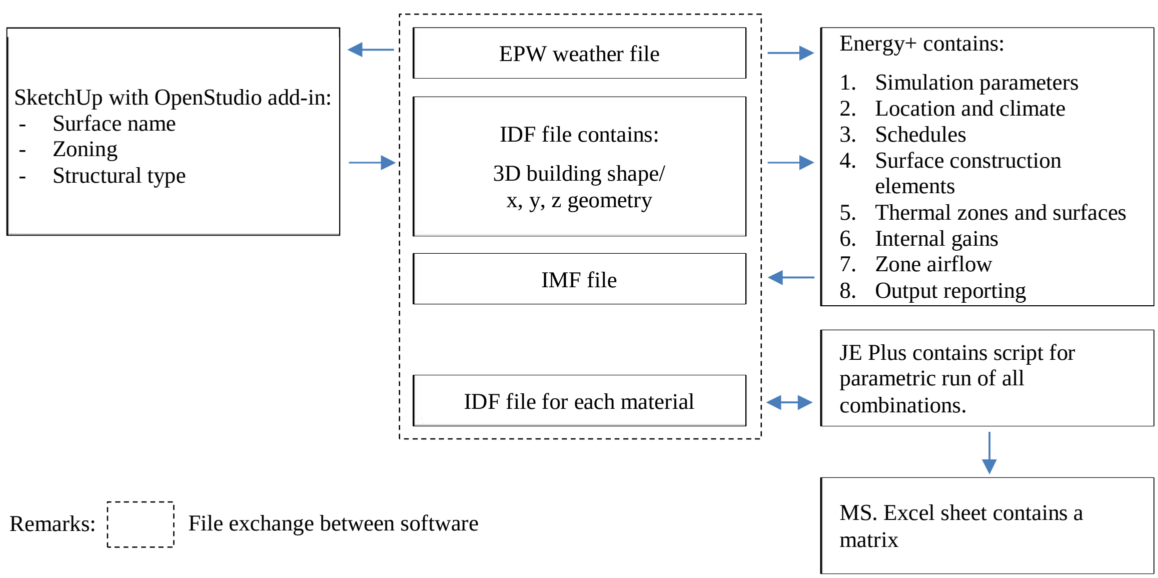

Figure 3.3: Simulation procedure

There are numerous graphic user interfaces (GUI) that can be coupled, which is adequate for this case study. A prevalent user interface is a plug-in to Google Sketchup called OpenStudio, which allows the user to create a building geometry from scratch, add thermal zones and draw heat transfer surfaces, such as the wall, floor, ceiling, roof, windows, and doors. Hence E+ coupled with OpenStudio was used to create the school building models with the necessary level of detail and reliability to complete the analysis earlier in the design. For free-running buildings, different natural ventilation strategies in this school were analyzed to provide adequate comfort. Other comfort indicators, such as direct solar radiation, wind speed, and humidity, were automatically processed by E+. Another variable that is daylighting was not evaluated since the natural daylight is continuously available in the daytime, and no lamps were switched on inside the classroom during the field survey.

Besides using simulation for evaluating indoor temperature, another objective evaluation method was made to the initial cost, EE, and CO_2 emission of each design alternative. Evaluation of cost was made for each design. Each quantity of material was calculated according to each design configuration or shape of the school building. This calculation was also performed in a spreadsheet, following the Indonesian standard for the cost estimating method. Hence, the total cost of each design will not be identical. In terms of the ecological impact of each design, a quantitative analysis can be made on EE and CO_2 emission of material used in each design. Hence, the results of EE and CO_2 calculations were also not identical for each design. In this study, the environmental assessment for material used in the school building is restricted to the 'cradle to gate' material production process. A ‘cradle to gate’ production of material account energy use from the extraction, production, and until ready to transport only. Energy use for transporting material will not be considered, since the transportation distance from material suppliers to the project site is relatively similar. The EE and CO_2 data of each material were obtained from the Inventory of Carbon and Energy (ICE) database. The results of the calculation for one particular school building are presented in Section 4.2.4. Finally, as can be seen in Figure 3.2, results from cost calculation together with the calculation results of EE and CO_2 emission were inputted into a decision matrix.

3.4 Multi-criteria Decision Making in Building Design Process

A building design needs to fulfill a vast range of often contradicting requirements and objectives. Building certification schemes such as DGNB [2], LEED [3], and BREEAM [4] involve the evaluation of many objectives. Some may be estimated quantitatively with simulation software, while others can only be evaluated qualitatively. Another characteristic of the building design process is the complex design parameters connectivity and conflicting objectives (Struck *et al.*, 2009). For example, it is immensely tedious to maximize room acoustics, daylighting, or life cycle performance during conceptual building design, because one particular change in design to meet a specific objective may affect other objectives.

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[2] German Sustainability Building Council, DGNB System, 2015.
Available from: http://www.dgnb-system.de/en/system/gold-silver-bronze/. Accessed on 7 July 2015.

[3] U.S. Green Building Council, LEED Certification, 2015.
Available from: http://www.usgbc.org/certification. Accessed on 7 July 2015.

[4] BRE Global Ltd, BREEAM: The world's leading design and assessment method for sustainable buildings, 2015.
Available from: http://www.breeam.org/. Accessed on 7 July 2015.

Such a complex nature in building design process has challenged designers for a holistic or whole design strategy, especially in the early stage of design process. Cheung *et al.* (2012), p. 68, emphasized that, "there is a clear need for a designer-focused system that can give simultaneous design assessment on various aspects in the conceptual design stage." An important element of holistic or so-called whole building design simulation is to enable simultaneous calculations using simulation technology to satisfy many objectives. A powerful simulation technology can be facilitated by several techniques such as, 1) increasing the interoperability capabilities through standard file exchange, such as IFC or gbXML, 2) integrating algorithms or mathematical equations into one simulation software, or 3) combining the various simulation results and extract relevant information to support decision-making. The latter basically falls into the field of multi-criteria decision-making (MCDM). Reviews on MCDM method that includes variations in MCDM method to deal with conflicting and multiple objectives in making decisions were done by Pohekar and Ramachandran (2004) and Wang *et al.* (2009). Section 3.4.1 presents a comparison of widely used MCDM methods that would eventually assist the researcher to use one of them to meet the research's objective.

The Design and Engineering Consultant (DEC) company is challenged by the increasing demand for green building as part of sustainable development goals. As a result, the design and engineering team need to optimize view or more criteria, such as energy consumption, indoor comfort, materials, cost, etc., which are often conflicting. Supporting decision-making tasks in the early design phase towards sustainable building is of utmost importance since decisions taken at the earliest stage of any type of project delivery have a significant impact on the final performance of a building. To solve such conflicts, the multi-criteria decision making (MCDM) is noticeable as an appropriate method because MCDM typically deals with the evaluation of a set of alternatives in terms of a set of decision criteria.

There are quite many definitions and classifications of MCDM found in the literature. Therefore, based on the specific problems defined in this research, there should be a clear definition and classification about the theory of MCDM. Zimmermann (1991) divided MCDM into Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). MODM deals with decision problems in continuous decision space. A typical example is a mathematical equation or problem using functions for multiple objectives. Kuhn and Tucker (1951) introduced an example of a mathematical equation which they called the 'vector-maximum' problem. On the other hand, MADM solves problems in which the decision space is found to be discrete. This means that the decision-maker needs to determine a set of decision alternatives to solve the problem. There are many variations of MADM methods, but certain aspects are common. They are namely alternatives, attributes, criteria, or goals, as stated by Chen and Hwang (1992). Alternatives represent unique choices. In the case of this research, one alternative represents one type of building design. As mentioned above, a set of alternatives can be predetermined by the decision-makers from quite a few alternatives up to hundreds of alternatives. Subsequently, these alternatives will be screened, prioritized, and finally ranked.

There are basically three steps in a discrete decision problem to determine a set of alternatives ([Triantaphyllou, *et. al*. 1998], p. 4):

1) Formation of the relevant criteria and alternatives.

   The MADM problem is always accompanied by several attributes. Attributes are sometimes referred to as 'criteria' or 'goals' representing the different dimensions of how alternatives can be analyzed. For cases where there are quite many attributes, decision-makers may arrange these attributes into a multi-level or a single-level attribute. For example, each main attribute may be associated with several sub-attributes at the lower level. However, most of the MADM problems assume a single level of attributes. Conflict among attributes somehow may exist. For example, durability may be conflicting with quality. In addition, each attribute probably has a different measurement unit. For example, in selecting a roofing material of a building, the attributes 'endurance' and 'cost' may be measured in terms of usage time (e.g., years) and amount of money in a particular currency (e.g., dollars). Hence, using MADM in the real world is difficult, considering such different units of measurement.

2) Assigning a numerical value to criteria that influence the selection of the alternatives.

   Most of the MADM methods require numerical values to be assigned to each criterion to differentiate each criterion's performance. Such numerical value must be able to express the relative importance of each criterion or the weightings of each criterion. These weightings values are normalized to add up to one. The determination of these weights is described in Chapter 5, Section 5.5.3.

3) Handling the numerical values of each criterion and rank the alternatives.

   Criteria and alternatives can be formatted into a decision matrix. For example, a matrix in Figure 3.4 is an ($M \times N$) matrix (Zimmermann,1991). The performance of alternative A_i was indicated by element a_{ij}, in terms of criterion C_j, (for i = 1, 2, 3,..., M, and j = 1, 2, 3,..., N). It is also assumed that the decision-maker has determined the weights of the criteria' relative importance (denoted as W_j, for j = 1, 2, 3,..., N).

	Criteria				
	C_1	C_2	C_3	…	C_N
Alternative	W_1	W_2	W_3	…	W_N
A_1	a_{11}	a_{12}	a_{13}	…	a_{1N}
A_2	a_{21}	a_{22}	a_{23}	…	a_{2N}
A_3	A_{31}	A_{32}	a_{33}	…	a_{3N}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_M	a_{M1}	a_{M2}	a_{M3}	…	a_{MN}

Figure 3.4: Typical decision matrix

Since alternatives need to be evaluated in terms of those goals and sometimes referred to decision criteria or simply criteria or attributes, the terms MADM and MCDM have been used very often in many publications to denote the same classification of decision-making models. Therefore, the decision-making model used in this research is classified as MADM or MCDM since the concept of both models is the same.

3.4.1 Comparison of some MCDM Methods

Refer to Figure 3.4, a set of M alternatives: A_1, A_2, A_3, ..., A_M, and a set of N decision criteria C_1, C_2, C_3, ..., C_N can be solved using the ten methods classified as MCDM method as described below. These methods can be used to rank the alternatives based on one preference while considering all the decision criteria. The ten MCDM methods presented below are solely to enlighten the researcher about the body of knowledge in decision-making theories and the mathematical equations behind each method.

3.4.1.1 The Weighted Sum Model

The most commonly used model in MCDM is the weighted sum model (WSM). It is particularly used in single-dimensional problems. For instance, in the case of maximizing alternatives where there are M alternatives and N criteria then, the best alternative is the one that meets the following equation (Samouilidis and Mitropoulos, 1982), as cited by Pohekar and Ramachandran (2004).

$$A_W^* \quad = \max \sum_{j=1}^{N} a_i \, w_j, \qquad f \quad i = 1, 2, 3, \ldots, M$$

where: $A*_{WSM}$ is the sum of the weighted score of the best alternative, N is the number of criteria, a_{ij} is the definite value of the *i-th* alternative in terms of the *j-th* criterion, and w_j is the relative importance of the *j-th* criterion by weighting each criterion under consideration.

The assumption applies to this model is the total value of each alternative is equal to the sum of products, so-called additive utility assumption. Summing the total value of each alternative is easy when all units of measurement are the same or so-called single dimensional problem (e.g., kilograms, meters, hours, etc.). However, it would become difficult when it is applied to multi-dimensional decision-making problems such as a combination of different dimensions, different units. For the latter case, the additive utility assumption is no longer applicable.

3.4.1.2 The Weighted Product Model

Quite similar to the WSM, the weighted product model (WPM) uses multiplication in the model instead of addition in the WSM. The difference is that each alternative is compared with other alternatives by multiplication of ratios, one ratio for each criterion. Each ratio is raised to the power equal to the relative weight of the corresponding criterion. In general, a comparison of alternatives can be calculated using the following equations ([Supriyono and Sari, 2018], p. 2).

Calculation of the relative weight of *j-th* criterion to the total weight of all criteria:

$$\overline{w}_j = \frac{w_j}{\sum_{j=1}^{N} w_j}$$

Where *N* is the number of criteria. w_j is the weight of importance of the *j-th* criterion. Thus, the relative weight ($\overline{w}_j$) should be equal to one.

$$\sum_{j=1}^{N} \overline{w}_j = 1$$

The preference value of every i *-th* alternative:

$$S_i = \prod_{j=1}^{N} x_i^{\overline{w}_j}$$

Where the value of $\overline{w}_j$ is positive if the criteria is a benefit otherwise its value is negative.

The relative preference value of each alternative to all alternatives:

$$V_i = \frac{S_i}{\sum_{i=1}^{M} S_i}$$

The higher *V* value means the better the alternative. The analysis involves in WPM is known to be dimensionless because its structure eliminates any measurement units. Hence, the WPM can be applied to single or multi-dimensional decision-making problems. The advantage of the WPM method is that it can use relative values instead of actual ones.

3.4.1.3 The Analytic Hierarchy Process

The analytic hierarchy process (AHP) was firstly introduced by Saaty (1980) including detailed hierarchy in the AHP method. AHP depends on disintegrating a complex MCDM problem into a hierarchy system. The final stage in the AHP deals with an $M \times N$ matrix (where M is the number of alternatives, and N is the number of criteria). The relative importance of the alternatives in terms of each criterion will be calculated in the matrix. The vector (a_{i1}, a_{i2}, a_{i3}, ..., a_{iN}) for each i is the principal eigenvector of an $N \times N$ reciprocal matrix. The matrix is determined by pairwise comparisons of the impact of the M alternatives on the *i-th* criterion.

Proof of the AHP technique was presented by Saaty (1980), which supports the AHP method in eliciting qualitative decisions from experts or decision-makers into the numerical evaluation. Nevertheless, the use of pairwise comparisons and the eigenvector method for determining values for the a_{ij}'s may not be considered because after they have been determined, the a_{ij} values can also be directly processed.

The entry a_{ij}, in the $M \times N$ matrix, represents the relative value of the alternative A_i when it is considered in terms of criterion C_j. In the original AHP,

$$\sum_{i=1}^{N} a_i = 1$$

In the case of maximizing the selection to find the best alternative, the following equation can be used:

$$A_A^* = \max \sum_{j=1}^{N} q_i \, w_j, \qquad f \quad i = 1, 2, 3, \dots, M$$

The AHP also uses relative values instead of actual ones, just like the WPM. Therefore, AHP can also be used in single or multi-dimensional decision-making problems.

3.4.1.4 The Analytic Network Process

The ANP, also developed by Saaty (2004), can be described as the generic form of AHP. It provides a framework that enables the user to handle decision-making, considering dependencies of elements on different levels. The ANP, opposed to the AHP, offers a control network that, instead of a linear hierarchy with a goal on the top down to the alternatives on the bottom (AHP), has a nonlinear structure. This is beneficial if the decision problem does not consist of elements but groups of clusters. Within this control network, different criteria can be dealt with, leading to the analysis of risks, opportunities, etc. (Saaty 2004). A real-world case of the ANP application in BPS is given in Cheng and Li (2007). They propose ANP in process models giving an example of strategic partnering. The problem is divided into partnering information (e.g., communication, team building), partnering application (partnering goals), and partnering reactivation (long-term commitment). The three top-level aspects, information, application, and reactivation, are indirect or directly related to each other. To cover those relations, ANP is a good solution. Hence, AHP is adequate if the relationship between aspects and criteria is unidirectional and the elements of various decision levels along the hierarchy are uncorrelated.

3.4.1.5 Elimination and Choice Translating Reality

Benayoun *et al.* (1966) introduced the Elimination and Choice Translating Reality (ELECTRE) method. The main idea of the ELECTRE method is to deal with the outranking relationship by using pairwise comparisons among alternatives under each criterion independently. The outranking relationship of A_i. A_j defines that even when the ***i***-th alternative does not dominate the ***j***-th alternative quantitatively, the decision-maker may still opt to select alternative A_i which he/she believes to be better than A_j (Roy, 1973). Dominated alternatives are said to be dominant if there is another alternative that exceeds them in one or more criteria and equally the same in the remaining criteria.

An in-depth review of the ELECTRE method can be found in Triantaphyllou *et al.* (1998). Basically, this method begins with pairwise comparisons of alternatives under each criterion. For instance, by using real numbers or monetary values $g_i(A_i)$ and $g_i(A_k)$ of the alternatives A_i and A_k respectively, and introducing threshold levels for the difference $g_i(A_i)$-$g_i(A_k)$, the decision-maker may: 1) State that he/she is not interested in the alternatives under consideration; 2) Has a very low or a stringent preference for one of the two; or 3) Unable to state any of preference in any relations. As a result, the set of binary relations of alternatives, so-called outranking relations, may be complete or incomplete. Subsequently, the decision-maker can be asked to assign weights to each criterion to state their relative importance. Having a calculations process of the outranking relations of the alternatives, ELECTRE elicits the so-called concordance index. This index defines the amount of evidence to support the conclusion that A_i outranks, or dominates, A_k, as well as the discordance index, which is the counter-part of the concordance index. Based on these indices, charts showing the strong and weak relationships can be generated. These charts are used in a repeated way to get the ranking of alternatives by means of a numerical value or index in the range of 0 to 1. The decision-maker can now have evidence supporting his/her decision since each index number provides judgment on the degree of credibility of each outranking relation and signifies a test to verify the performance of each alternative. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that A_i outranks A_k. The organization of the ELECTRE method is illustrated in the following steps ([Triantaphyllou *et al.*, (1998)], pp. 182.

1. Normalization

$$r_i = \frac{x_i}{\sqrt{\sum_i^m = x_i^2}}$$

for i = 1, 2, 3, … m, and j = 1,2,3, … n. Where m is Alternative and n is criteria,

2. Weighted normalized matrix

$$V = R_i \, W_j$$

3. Determination of concordance and discordance index

$$C_k = \{j, v_k \geq v_i\}, f \quad j = 1, 2, 3, \ldots, n$$
$$D_k = \{j, v_k < v_i\}, f \quad j = 1, 2, 3, \ldots, n$$

4. Calculate matrix of concordance and discordance

$$C_k = \sum_{j \in C_k} W_j$$

$$D_k = \frac{m \quad \{|v_k - v_i|\} j \,\square\, D_k}{m \quad \{|v_k - v_i|\} \square_j}$$

5. Determining the dominance matrix of concordance and discordance

Dominance matrix can be built by comparing each element value in the matrix with the threshold value ($\underline{c}$).

$$C_k \geq \underline{c}$$

$$\underline{c} = \frac{\sum_{k=1}^{n} \sum_{i=1}^{n} C_k}{m(m-1)}$$

Each element value in matrix f as dominance concordance matrix is determined by the following condition:

$$f_k = 1, i \; C_k \geq \underline{c}, \text{ and } f_k = 0, i \; C_k < \underline{c}$$

Accordingly, the threshold for the dominance discordance matrix,

$$\underline{d} = \frac{\sum_{k=1}^{n} \sum_{i=1}^{n} D_{ki}}{m(m-1)}$$

$$g_k = 1, i \; D_k \geq \underline{d}, \text{ and } g_k = 0, i \; D_k < \underline{d}$$

6. Determination of aggregate dominance matrix

$$e_k = f_k \times g_k$$

7. Elimination of less favorable alternative

   If $e_k = 1$, then A_k is a better choice than alternative A_i. Therefore, every rows in matrix *e* which has less value can be eliminated.

The ELECTRE method yields an overall binary outranking relation between each alternative. On the other hand, the ELECTRE method allows the incompleteness of the system. Hence, the ELECTRE method is at times, unable to recognize alternatives, which is under the decision maker's preference because it only produces an underlying of leading alternatives. This method has a better view of alternatives by rejecting less preferred ones. Thus, the ELECTRE method is particularly appropriate to encounter a limited or small number of criteria with many possible alternatives in a decision-making problem.

3.4.1.6 PROMETHEE

Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) is one of the outranking methods. Just like the ELECTRE method, several iterations are also involved in the PROMETHEE method. This method uses outranking's rule of thumb to sort or rank the alternatives, featuring the ease of use and reduced complexity. It performs a pair-wise comparison of alternatives before ranking the alternatives according to several criteria. Brans *et al.* (1986) introduced six functions for criteria generalization, namely, usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference indifference area, and Gaussian criterion. The method uses preference function $Pj\ (a, b)$, which is a function of the difference d_j between two alternatives for any criterion *j*, *i. e.* $d_j = f(a, j) - f(b, j)$, where $f(a, j)$ and $f(b, j)$ are values of two alternatives *a* and *b* for criterion *j*. The indifference and preference thresholds *q'* and *p'* are also defined based on the type of criterion function. Two alternatives are indifferent for criterion *j* as long as d_j does not exceed the indifference threshold *q'*. If d_j becomes greater than *p'*, there is a strict preference. Multi-criteria preference index, $\pi\ (a,b)$ a weighted average of the preference functions $P_j\ (a, b)$ for all the criteria can be expressed in the following equation ([Brans and Mareschal, (2005)], p. 171).

Let *a*, *b* □ A, and let:

$$\begin{cases} \pi\ (a, b) = \sum_{j=1}^{k} P_j(a, b) w_j \\ \\ \pi\ (b, a) = \sum_{j=1}^{k} P_j(b, a) w_j \end{cases}$$

π (a, b) is expressing with which degree a is preferred to over all the criteria and π (b, a) how b is preferred to a. In most of the cases there are criteria for which a is better than b and criteria for which b is better than a, consequently π (a, b) and π (b, a) are usually positive. The following properties hold for all $a, b \in A$.

$$\begin{cases} \pi(a, a) = 0 \\ 0 \leq \pi(a, b) \leq 1 \\ 0 \leq \pi(b, a) \leq 1 \\ 0 \leq \pi(a, b) + \pi(b, a) \leq 1 \end{cases}$$

It is clear that:

$$\begin{cases} \pi(a, b) \sim 0 \text{ implies a weak global preference of } a \text{ over } b, \\ \pi(a, b) \sim 1 \text{ implies a strong global preference of } a \text{ over } b, \end{cases}$$

After π (a, b) and π (b, a) are computed for each pair of alternatives of A, a complete valued outranking graph, including two arcs between each pair of nodes, is obtained (Figure 3.5)

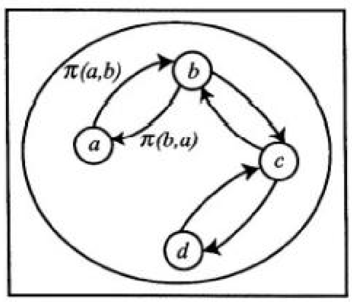


Figure 3.5: Valued outranking graph
Source: Adopted from Brans and Mareschal (2005), p. 172.

Outranking Flows:

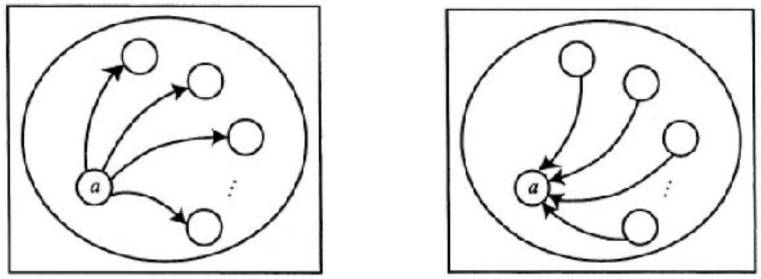
Each alternative a is facing (n – 1) other alternatives in A. The two outranking flows can be defined as follows:

- The positive outranking flow:

$$\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x)$$

- The negative outranking flow:

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a)$$



(a) The $\phi^+(a)$ outranking flow (b) The $\phi^-(a)$ outranking flow

Figure 3.6: The PROMETHEE outranking flows
Source: Adopted from Brans and Mareschal (2005), p. 173.

The positive outranking flow expresses how an alternative *a* is outranking all the others. The higher $\phi^+(a)$ the better the alternative. The negative outranking flow expresses how an alternative *a* is outranked by all the others. The lower $\phi^-(a)$ the better the alternative.

PROMETHEE method basically can be divided into two methods, namely PROMETHEE I for ranking all alternatives in a partial manner and PROMETHEE II for complete alternatives ranking.

The PROMETHEE I partial ranking (P^I, I^I, R^I) is obtained from the positive and the negative outranking flows. It determines the partial preorder (P^I,I^I,R) on the alternatives of *A* that satisfied the following principle:

aP^Ib (a outranks b) if
- $\phi^+(a) > \phi^+(b)$ *a* $\phi^-(a) < \phi^-(b)$, or
- $\phi^+(a) = \phi^+(b)$ *a* $\phi^-(a) < \phi^-(b)$, or
- $\phi^+(a) > \phi^+(b)$ *a* $\phi^-(a) = \phi^-(b)$,

aI^Ib (a is indifferent to b) if
- $\phi^+(a) = \phi^+(b)$ *a* $\phi^-(a) = \phi^-(b)$,

aR^Ib (a and b are incomparable)
- $\phi^+(a) > \phi^+(b)$ *a* $\phi^-(a) > \phi^-(b)$,
- $\phi^+(a) < \phi^+(b)$ *a* $\phi^-(a) < \phi^-(b)$,

Where P^I, I^I, R^I respectively stand for preference, indifference and incomparability.

- When aP^Ib, a higher power of *a* is associated to a lower weakness of *a* with regard to *b*, the information of both outranking flows is consistent and may therefore be considered as sure.
- When aI^Ib both positive and negative flows are equal.
- When aR^Ib, a higher power of one alternative is associated to a lower weakness of the other. This often happens when *a* is good on a set of criteria on which *b* is weak and reversely *b* is good on some other criteria on which *a* is weak. In such a case the information provided by both flows is

not consistent. It seems then reasonable to be careful and to consider both alternatives as incomparable.

In PROMETHEE II, the net flow ϕ is used to rank the alternatives. Alternative with the higher net flow is assumed to be superior. Because PROMETHEE I does not provide a complete ranking, the result of ranking cannot be compared with the ranking resulted from PROMETHEE II. Therefore, PROMETHEE I specialize in the creation of indifferent and incomparable alternatives. In some ranking situations, however, PROMETHEE I can give a complete ranking depending on the evaluation matrix values. The result of the ranking should be the same as the one generated from PROMETHEE II.

PROMETHEE II consists of (P^{II}, I^{II}) the complete ranking. It is often the case that the decision-maker requests a complete ranking. The net outranking flow can then be considered.

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a)$$

It is the balance between the positive and the negative outranking flows. The higher the net flow, the better the alternative, so that:

$$\begin{cases} aP^{II}b \text{ (a outranks b) if} & \phi(a) > \phi(b), \\ aI^{II}b \text{ (a is indifferent to b) if} & \phi(a) = \phi(b), \end{cases}$$

When PROMETHEE II is considered, all the alternatives are comparable. No incomparability remain, but the resulting information can be more disputable because more information gets lost by considering the difference as a result from the net outranking flow calculation above.
Thus, the following properties hold:

$$\begin{cases} -1 \leq \phi(a) \leq 1, \\ \sum_{x \in A} \phi(a) = 0 \end{cases}$$

When $\phi(a) > 0$, a is more outranking all the alternatives on all the criteria, when $\phi(a) < 0$ it is more outranked.

Brans *et al.* (1986) suggested decision makers to consider both PROMETHEE I and PROMETHEE II. Several versions of the PROMETHEE methods such as the PROMETHEE III for ranking based on an interval, the PROMETHEE IV for complete or partial ranking of the alternatives when the set of viable solutions is continuous, the PROMETHEE V for problems with segmentation constraints, the PROMETHEE VI for the human brain representation (Behzadian *et al.*, 2010). The ease of use of the

PROMETHEE method is the main advantage of this method because no assumptions are needed that the criteria are comparable or proportional. The disadvantage of PROMETHEE is that it does not offer a clear method about assigning weights and values. Because of its ease of use and improved iterations processing, PROMETHEE has been utilized for many decades, mainly in water and environmental management, hydrology, management of the business and financial, chemistry, logistics and transportation, product assembly and manufacturing, and energy management.

3.4.1.7 Compromise Programming

Compromise Programming (CP) defines the best solution as the one in the set of efficient solutions whose point is the least distance from an ideal point. Hence, the objective is to find a solution that is as close as possible to ideal. The closeness between a solution and the ideal point is measured by a distance function L_p. The ideal point is not achievable, but is used as a reference point for the identification of the best compromise solution. A family of L_p metrics is given below ([Adeyeye and Allu, (2017)], p. 56).

For any two point in *n* dimensional space a general distance measure is given by

$$L_p = \left(\sum_{j=1}^{n} \left| X_j^1 - X_j^2 \right|^p \right)^{\frac{1}{p}}$$

For each value of the parameter p, a particular distance is determined. If the decision maker considers all distances from the ideal point to be of equal importance, then p = 1. The equation becomes,

$$L_1 = \sum_{j=1}^{n} \left| X_j^1 - X_j^2 \right|$$

If the decision maker weighs each deviation in proportion to its magnitude then p = 2, the equation becomes,

$$L_2 = \left(\sum_{j=1}^{n} \left| X_j^1 - X_j^2 \right|^2 \right)^{\frac{1}{2}}$$

This measures the Euclidean distance. It represents the Pythagorean distance between any two points. If only the largest deviation counts to the decision maker then p = ∞, L_∞ is the largest deviation of $\left| X_j^1 - X_j^2 \right|$

$$L_\infty = \max \left| X_1^1 - X_2^2 \right|, \left| X_2^1 - X_2^2 \right|, \ldots., \left| X_n^1 - X_n^2 \right|$$

In the L_p metrics, L_1 is the longest distance and L_∞ is the shortest distance. Therefore, all possible distances are bounded by L_1 and L_∞. The distance measure is used as a proxy for human preferences (Gan et al., 1996). The degree of closeness is represented by D_j between the j-*th* objective or response and its ideal when the j-*th* objective is optimized. Let $f_j^{*}(x)$ be the anti-ideal or nadir value of the j-*th* objective and $f_j^{**}(x)$ be the ideal or best value of the j-*th* objective. Also, let $f_j(x)$ be the achievement level of the j-*th* objective. If the j-*th* is a desirable performance, then it is maximized. The distance D_j between the achievement level $f_j(x)$ and the ideal value $f_j^{**}(x)$ is given by:

$$D_j = f_j^{**}(x) - f_j(x),\ j = 1, 2, 3, \dots, n$$

And for non-desirable performance, then it is minimized and the distance D_j between the achievement level $f_j(x)$ and the ideal value $f_j^{**}(x)$ is given by:

$$D_j = f_j(x) - f_j^{**}(x),\ j = 1, 2, 3, \dots, n$$

The achievement levels and the units of the objective may be different, therefore, the degree of closeness must be normalized by using relative deviations rather than the absolute one. The normalized degree of closeness is given by:

$$D_j = \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|},\ j = 1, 2, 3, \dots, n$$

By adding the degree of closeness of each objective and its ideal, compromise programming minimizes the following family of L_p metrics.

$$L_p = \left(\sum_{j=1}^{n}\left(W_j D_j\right)^p\right)^{\frac{1}{p}}$$

$$W_j \geq 0, \text{ for every j and } \sum_{j=1}^{n} W_j = 1$$

Where W_j is the weight of the j-*th* objective. This denotes the relative importance of the quality characteristic or responses. Therefore L_p can be written as:

$$L_p = \left(\sum_{j=1}^{n}\left(W_j \frac{\left|f_j^{**}(x) - f_j(x)\right|}{\left|f_j^{**}(x) - f_j^{*}(x)\right|}\right)^p\right)^{\frac{1}{p}}$$

3.4.1.8 Multi-attribute Utility Theory

Multi-attribute Utility Theory (MAUT) considers the preferences of the decision-makers using utility function (Edwards and Newmann, 1982). The utility function can be defined with a set of attributes. The value of the attribute can be determined by single-attribute utility functions. After determining the utility value, the next stage of the method is to verify the preferences, utility independent conditions, and the root of multi-attribute utility functions. The utility functions can be added separately or multiplicatively separable concerning a single-attribute utility. The equation of the multiplicative form for the utility value is defined as follows (Afghan and Carvalho, 2000).

$$1 + k \quad (x_1, x_2, \dots, x_n) = \prod_{j=1}^{n} (1 + k \quad _j u_j \left(x_j\right))$$

Here j is the index of an attribute, k is overall scaling constant, which is greater than or equal to 1, k_j is the scaling constant for attribute j, $u(.)$ is the operator of the overall utility function, and $u_j(.)$ is the utility function operator for each attribute j.

After evaluating the alternatives with respect to each considered criterion and weighting the obtained values according to the relative importance of criteria, the method aggregates these ‘utility’ measures to obtain an overall score for each option. The simplest way to perform this aggregation is by taking the sum of the utility the generic alternative shows according to each criterion.

3.4.1.9 SMART

The simplest form of MAUT is called SMART. The SMART method requires two assumptions, that is ‘utility independence’ and ‘preferential independence’ (Chen *et al.*, 2010b). This method conveniently transforms the weights into an actual numerical value. The main advantages of SMART are its ease of use, and it permits any type of weighting determination method (i.e., relative, absolute, etc.). Compared to MAUT, SMART does not require much effort of decision-makers and is also capable of handling data of each criterion without difficulties. However, a disadvantage is that the determination work process is inconvenient because the framework is complex (Konidari and Mavrakis, 2007). Nevertheless, the application of the SMART method has become common in some sectors such as environmental, construction, transportation and logistics, military, manufacturing, and assembly problems. Its ease of use assists in situations where relevant information is accessible, and access to decision-makers is not difficult to collect. Hence, due to its simplicity, the SMART method has always been widely known by the decision-makers.

3.4.1.10 TOPSIS

Hwang and Yoon (1981) introduced the TOPSIS method, which stands for Technique for Order Preference by Similarity to Ideal Situation. The concept behind this method is that the selected alternative should have the shortest Euclidean distance from an ideal solution, and at the same time, the selected alternative also has the farthest distance from the negative ideal solution. According to Hwang and Yoon (1981) as cited by Hodget (2013), p. 35, "the ideal solution is a hypothetical solution for which all attribute values corresponds to the maximum attribute values in the database comprising the satisfying solutions; the negative ideal solutions the hypothetical solution for which all attribute values corresponds to the minimum attribute values in the database." The mathematical equation in this method gives a solution to the decision-maker that the best alternative is not only closest to the ideal solution hypothetically, but also the farthest from the worst or negative solution.

Previous sub-section presents a well-known MCDM method. All decision-making processes basically involve six steps to be followed. As cited by Caterino *et al.* (2008a), the following step-wise procedure proposed by Caterino *et al.* (2008b), independent from the particular MCDM method used, is adopted herein to solve the fixed decision problem:

1) Evaluation of material and design of the given building, in its original state;
2) Definition and design of the set of alternative solutions to choose among;
3) Definition of the criteria in respect of which each solution should be evaluated;
4) Definition of criteria weights of importance;
5) Evaluation of each alternative solution according to each criterion (decision matrix); and
6) Selection of the best solution through the application of an MCDM method.

Step one is about the determination of what to decide and the objective of the decision-making. For this step, the selection of a method itself is considered an important step. Because different MCDM methods may give different results depending on the problems. Sub-chapter 3.4.2 below presents this process.

In step two, the alternatives must be comparable, real or not ideal, practical, and feasible. Step three is about connecting the concept of criteria to attribute or criteria, as previously discussed when describing MADM and MODM. Eldrandaly *et al.* (2009), p. 4, refer that "an attribute measures the system performance regarding an objective", whereas "the objective is a statement of the desired situation of the system."

Eldrandaly *et al*. (2009), Kornyshova and Camille (2007), and Saaty (1980) agreed that a criterion signifies one of the possible proportions from which the alternatives can be evaluated according to a decision maker's point of view. The criteria can be seen as a stick yard to understand how well a particular action is performing to solve the problem or to meet the goal. Therefore, the criteria must be well understood and fully describe the goals to be achieved in order to recognize the performance of each alternative. The description of criteria can be represented into two data types depending on which decision method to use. They are qualitative or quantitative data type which can be used separately or mixed in one decision-making method. Furthermore, a scale is required, namely, nominal, ordinal, ratio, absolute, and interval scale to measure or judge the alternatives. Determining the proper criteria is crucial because the number of alternatives can be limited to ensure consistent evaluation of alternatives. During the selection of criteria, it is also important to analyze the way criteria interact; otherwise, conflict among criteria may occur. Hence, the performance of an alternative in step three can be fully established based on the well-defined criteria. The score obtained from the scale above is an indicator of how specific criteria are performed on the specific goal, and finally, assist the decision-makers in comparing each alternative objectively.

Step four is about assigning weight to the criteria under consideration. Each criterion in most decision-making is weighted to specify the subjective preferences of the decision-makers. The weight determination methods can be either compensatory or outrank wise. Two examples of Compensatory Method are AHP and Fuzzy Multi-Criteria Decision Making Process (FDM), while ELECTRE and PROMETHEE are examples of outranking method.

The fifth step of the decision process model is the aggregation and the exploitation of all criteria, which is performed inside of the selected method and can be varied according to the particular method. Aggregation and exploitation of all criteria basically use mathematical equations involving every alternative. Finally, the sixth step is the application of the selected MCDM method and presentation of the results to the decision-maker.

3.4.2 Selecting the MCDM Method

Previous section has presented most MCDM methods that are found in the literature. Furthermore, the data used inside these MCDM methods can also be classified based on their characteristics. The method of how these data are treated can be classified as a deterministic, stochastic, or fuzzy method. Additionally, the number of participants or decision-makers involved in the making of the decisions can also be classified as a single decision-maker method and group decision-making method. According to Chen and Hwang (1992), the widely used MCDM methods in practice are the WSM, AHP, revised AHP, WPM, and TOPSIS method. Additionally, PROMETHEE, ELECTRE, CP, and MAUT is also categorized as the MCDM method (Pohekar and Ramachandran, 2004).

Previously, most MCDM method uses in the building design process has been presented. Each method has strengths and limitations. It is necessary, however, before developing a matrix to select which MCDM method is adequate for a given problem. Hence, a comparison of the MCDM method was made to understand the advantages and disadvantages of each method. Table 3.4 presents a comparison among MCDM methods.

Table 3.4: Comparison of MCDM methods

Method	Advantages	Disadvantages
Multi-Attribute Utility Theory (MAUT)	Deal with uncertainty and decision maker's preferences.	Require lots of input. Preferences must be specific and well defined.
Analytic Hierarchy Process (AHP)	Scalable. The structure of the hierarchy can be easily arranged to handle many problems. Deal with a little or reasonable amount of data.	Internal dependency between criteria and alternatives can be conflicting. The criteria ranking and judgment may not be consistent. Rank reversal. Tedious and consume time when dealing with many options and criteria
Simple Multi-Attribute Rating Technique (SMART)	Allows any type of weighting method. Straight forward and less difficult to use.	The procedure may not be convenient considering the framework.
Elimination and Choice Translating Reality (ELECTRE)	Deal with uncertainty and minimize ambiguity.	The process and results are not easy to describe. The strengths and weaknesses of the alternatives cannot be easily recognized.
Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)	Straight forward. No assumptions are needed about the proportion of criteria.	The weights assignment method is unclear.
Weighted Sum Model (WSM)	One of the simplest multi-criteria decision-making methods. Allows compensation among criteria. Straight forward and less difficult to use. Simple calculation and not computing-intensive.	The outcome sometimes does not really solve the actual problem or not logical in reflecting the real situation. Difficulties in making the right decision, especially for multi-dimensional problems which include qualitative and quantitative attributes.
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	Simple and fast. Straight forward and less difficult to use. The calculation steps always the same, even dealing with many criteria.	The inclusion of Euclidean Distance does not reflect the relationship of criteria. Does not include the weighting method.
Weighted Product Model (WPM)	Simple and scalable. Allows open discussion among decision-makers	It can use relative ones instead of the actual values.
Compromised Programming (CP)	Suitable when decision-maker needs to identify the closest distance to an ideal solution. This feature is useful when many objectives concurrently reach their optimum value. CP is superior to the WSM in locating efficient solutions, or so-called Pareto points.	Leave a small room for considering uncertainty.
Analytic Network Process (ANP)	ANP is used when the problem is so complex, thus cannot be modeled as a hierarchy.	Incapable of capturing the uncertainty during value judgment elicitation. Several pairwise comparison questions. Complex survey process for non-expert participants.

Source: Adopted and modified from Velasquez and Hester (2013), p. 63.

As can be seen from Table 3.4, it is quite obvious that no definite superiority of one MCDM approach relative to others and probably never shall be one single best approach to all types of multi-objective mathematical programming problems. The choice of the MCDM method and technique is left to the analyst and depends on several factors, which are the number of attributes or criteria, decision maker's ability to provide information about targets and priorities, and detail of analysis required by the decision-maker. In conclusion, there is no single MCDM method is superior over another, and new or more advanced methods can either be invented in the future or simply by conducting uncertainty analysis and sensitivity analysis based on the existing methods for better accuracy and more proven results validation.

For example, Ugwu and Haupt (2007) proposed an analytical decision model and a structured methodology for sustainability appraisal in infrastructure projects in South Africa. They used the 'weighted sum model' technique in multi-criteria decision analysis (MCDA) and the 'additive utility model' in the analytical hierarchical process (AHP) for multi-criteria decision-making to develop the model for computing the sustainability index. The index was a crisp value for evaluating infrastructure design proposals and construction in developing countries. Fontenelle *et al.* (2014) concluded that the multi-criteria approach is a very effective method to consistently analyze the solutions proposed for a problem and to assist designers in minimizing the conflicts between criteria. It allows performing an integrated approach, enabling a more conscious, accurate, and responsible decision-making. They applied a multi-criteria method called ELECTRE III to define windows for an office building, specifically in Rio de Janeiro, Brazil, under a compromise criterion between landscape view, daylight level on a work plan, and energy efficiency.

Therefore, the selection of the MCDM method itself may be detrimental to the results before one can determine the selection criteria and alternatives. To deal with this issue, Hung *et al.* (2011) recommended 5 (five) steps in using the Multiple Criteria Decision Making (MCDM) method. They are:

1) Problem identification: First, decision-makers should identify the characteristic of the problem realistically. Secondly, he or she should determine the possible criteria to include in the process of decision-making.
2) Problem structuring: Decision-makers should identify the objectives, values, limitations, conflicts, external issues, uncertainties, and possible participants. It is important to gather the relevant data and evidence so that the decision maker's preferences can be recognized and justified with higher accuracy.
3) Model building: In this step, decision-makers need to specify the alternatives, outline all criteria, and produce values for developing a model. This procedure allows decision-makers to assemble a set of possible alternatives to ensure the objective can be met.
4) A model from step three above can now be used as an assessment tool to gather data and synthesize information. Such an assessment tool can also be used to suggest other possible alternatives and analyze the robustness and sensitivity of the model, considering participants' input or thoughts.

5) Action plan development: In this step, the decision-maker may choose a suitable method to evaluate and rank the possible alternatives and finally select the best alternative.

In general, step one and two are essentially understanding the nature of the decision problem or the problems that need to be solved. It starts by identification of possible alternatives, criteria, and constraints, etc. The data or information available to solve the problem can be used as the guideline for selecting the suitable or proper MCDM method, which will be applied by the decision-maker.

In step three, the suitability or appropriateness of the evaluation criteria has the biggest influence because they will assist the decision-maker during the MCDM method selection process. Notwithstanding, considering every criterion in the selection process may become impractical because more information will be needed when many more criteria are added. This will be computationally expensive because the defined evaluation criteria will be used in the MCDM method.

Step four deals with the selection of one of the MCDM methods from the existing methods, as presented in Table 3.4. For multi-faceted problems, decision-makers can select a more complex method or technique. Nevertheless, it is necessary to understand the advantages and disadvantages of particular methods. For this research, the TOPSIS method is selected as the most suitable MCDM method because it is simple to use and is adequate to solve the research problem.

Step five is the execution of all the mathematical equations which every method has. In this work, the computations of TOPSIS is discussed. Although it is important that all the methods be evaluated and compared one each other, it is imperative to observe that TOPSIS seems to be a procedure suitable to the decision problem about the selection of design alternatives since it allows to select only one solution as the 'best' one and it is able to manage each kind of variables and each type of criteria.

MCDM problems comprise of an underlying space of feasible solutions and several objectives that can be evaluated with regard to the feasible solutions. In general, for this kind of problem, there does not exist a generic solution approach and unambiguous concept of optimality, but different approaches depending on the viewpoint of the decision-maker towards the underlying problem.

For this case study, the TOPSIS method which was developed by Hwang and Yoon (1981) was selected among other MCDM methods. TOPSIS has been widely used in the construction industry, and it has an adequate formulation to meet the research objective or goal. Singh *et al*. (2007) concluded that TOPSIS is rational because it will calculate that the chosen alternative should have the shortest distance from the positive-ideal solution and the farthest distance from the negative ideal solution. In other words, TOPSIS take into account the best and worst alternatives and measuring the performance of all alternatives on criteria using simple mathematical forms. These characteristics lead to a quick and reliable selection of the best alternative, and make it intuitive, easy to understand and implement. In recent years, TOPSIS has been successfully applied to different areas, and there exists a large amount of literature involving TOPSIS theory and applications in the sustainability area, e.g. (Wittstruck and Teuteberg, 2012; Zavadskas and Antuchevičiene, 2004; Awasthi *et al.*, 2011).

The procedure of the TOPSIS method is described as follows:

Step 1: Formation of the decision matrix

A decision matrix has the following parts: alternatives (combinations of materials and design options) A_i (i = 1, …, m), which decision-makers have to choose, criteria (sustainability criteria) C_j (j = 1, …, n), relative importance of criteria (or weightings) w_j, and a decision matrix with x_{ij} elements, which is the rating of alternative A_i with respect to criterion j as shown in Table 3.5. Different criteria performance ratings are measured by different functional units in the decision matrix. To allow a valid comparison, all elements must be dimensionless. Therefore, the objective of the normalization of indicators is to avoid scale effects in the aggregation of parameters inside each indicator, and to solve the problem of some of the parameters being of the type ‘higher is better’ and others ‘lower is better’.

Table 3.5: A typical multiple attribute decision-making problem

	Criteria			
Alternatives	w_1	w_2	…	W_n
	C_1	C_2	…	C_n
A_1	x_{11}	x_{12}	…	x_{1n}
A_2	x_{21}	x_{22}	…	x_{2n}
A_3	x_{31}	x_{32}	…	x_{3n}
⋮	⋮	⋮		⋮
A_m	x_{m1}	x_{m2}	…	x_{mn}

Source: Adopted from Jahan and Edwards, (2015), p. 336.

Step 2: Construction of normalized decision matrix

$$x_i = \frac{x_i}{\sqrt{(\sum x_i^2}} \qquad \text{for } i = 1, \dots, m;\ j = 1, \dots, n \qquad (1)$$

where x_i is the actual or original score and r_i is the normalized score

Step 3: Multiplication of the weight and normalized score in the matrix

$$v_i = w_j r_i \qquad \text{where } w_j \text{ is the weight for j criterion} \qquad (2)$$

Step 4: Determining the positive and the negative ideal solutions

Positive ideal solution: A* = {v_1*, …, v_n*} (3)

where v_i* = {max (v_i) if $j \in$ J ; min (v_i) if $j \in$ J’ }

Negative ideal solution: A’ = {v_1', …, v_n’} (4)

where v' = {min (v_i) if j □ J ; max (v_i) if j □ J' }

Step 5: Calculation of the distance or separate measurement for each alternative

The distance from the positive ideal solution is:

$$S_i^* = \sqrt{\sum \left(v_i^{□} - v_i\right)^2} \quad \text{for i = 1, …, m} \quad (5)$$

The distance from the negative ideal solution is:

$$S_i' = \sqrt{\sum \left(v_j' - v_i\right)^2} \quad \text{for i = 1, …, m} \quad (6)$$

Step 6: Calculation of the relative closeness to the ideal solution C_i*

$$C_i^* = \frac{S_i'}{S_i^{□} + S_i'} \quad (7)$$

The value of C_i* which is closest to 1 is the best alternative.

Step 7: Rank or sorting the alternatives in a descending order

In conclusion, the best alternative can be selected according to the descending order of the C_i* value from 1 to 0. Simply put, the best alternative is the one that has the shortest distance to the ideal solution. The relationship between alternatives is explicit that any alternative which has the shortest distance to the ideal solution is guaranteed to have the longest distance to the negative-ideal solution. In other words, the smaller the value of C_i*, the farther distance of the corresponding alternative (alternative A_i) to the ideal solution. Right after the final ranking of all alternatives is available, the decision-maker has the freedom to select the best alternative or alternatives, which has the optimal performance according to a particular situation.

3.5 Integration of Simulation Tool with MCDM

The previous chapter has discussed the limitations facing by developing regions to implement the sustainable practice of a given project. It should be noted again that the most barrier is the lack of green experts or professionals in this area. BIM software offers a more intuitive and interactive interface with greater capabilities to the conventional 3D CAD software. The main feature of BIM is for 3D modeling, interactive visualizations, and 4D modeling, where material cost can also be integrated into the model. The recent development of BIM also included capabilities of energy modeling like Revit, ArchiCAD, and DesignBuilder and are able to produce alternatives for energy reduction. Although BIM offers great capabilities, the number of big or mega construction projects in the developing countries is limited. Consequently, the application of BIM is considered too expensive to be used by construction companies or the Design and Engineering Company in the developing countries. Capabilities of energy modeling in BIMs software are basically a simulation engine to solve the complex equation of energy modeling. In recent years, assessment of a building's thermal and daylighting performance can be estimated using quite many simulation software available today. For example, Ecotect which is a powerful simulation tool for comparing different designs pretty quickly and easily. Ecotect has a graphical user interface that visually shows the comfort performance, daylighting, and resource consumption by changing building geometry and materials. Limitation of Ecotect is that the process of varying design parameters is very time consuming. Energy Plus (E+) is a simulation software written in C language. Users can give input through a user interface in E+, but inputting the building geometry is difficult. Hence, other drawing software such as GoogleSketchup provides an add-in application to transfer building geometry to E+. Such simulation software can calculate and predict the performances of numerous building designs pretty quickly with higher accuracy. As a result, a designer design can select which design alternative consumes less energy based on several designs and major architectural features of a building.

For more specific purpose, researchers use the capabilities of simulation software combined with the capabilities of MCDM to identify the best scenario or strategy, such as research done by (Anastaselos *et al.*, 2009), who assessed the energy consumption, environmental impact, and cost using a simplified rating tool. TRNSYS was then used to perform a simulation based on the extended database in Greek construction practice. Emissions data such as CO_2, SO2, C_2H_4, and PO_4 from production, transportation, and installation procedures were used for analysis. Furthermore, thermal and physical properties data of building materials were also included in the simulation, and finally, data on the material's embodied energy and cost of material were also integrated into the simulative calculations. The simulations results were collected and a ranking was presented for environmental, energy, and economic parameters. Their tool supports the decision maker's preferences or priorities about energy efficiency, total cost, or environmental performance from various building materials.

Assad *et al.* (2015) proposed a decision tool for the designer to view his/her selection from available construction material in the Egyptian market. The tool is able to compare life cycle cost and energy that suits in the early design stage. An excel spreadsheet was adapted and use as a simulation interface where a simple algorithm of thermal calculation was used in the model. Since the model was built on Microsoft the trade-off analysis between cost and energy can be easily performed. Their research has demonstrated that more considerations and sustainable parameters are possible to include in the analysis. Hence, Assad *et al.* (2015) suggested that to add the value of the tool, other parameters can be easily included, such as carbon footprint, embodied energy, and recycle content.

An index based method was used by Chung and Lee (2009) to evaluate and determine the priorities from a range of alternatives for minimum instream flow maintenance and enhance water quality. Their model used FORTRAN to simulate hydrological parameters and MCDM methods, called HSPF. AHP was used to determine criteria weightings, while the HSPF simulation tool was used to measure the effects of quantity and the quality of the water. Their study used a combination of ELECTRE II, Evamix method, and Regime method to accommodate the measurement scale, uncertainty in weightings, discrete ranking, and priority ranking.

Another tool is targeted at building Owners, such as the one developed by Burton and Shaxted (2012). They developed a web-based application tool that allows users or Owners to investigate retrofitting strategies for energy efficiency in commercial buildings. Their tool utilizes large databases resulting from a parametric simulation. The user interface was designed quite intuitively but requires technical expertise to ‘pick’ and ‘choose’ from several options available to the user regarding envelope parameters, including options for reducing heating and cooling energy, and lighting energy. The targeted output of the tool was to gain energy use intensity, lighting, equipment, cooling, and heating load. MATLAB was used to compile and post-process the simulation results conducted in JE Plus. The post-processing in JE Plus produced 300 thousand models run and transferred the results in a spreadsheet containing more than hundreds of million Excel’s cells. Such a big data requires more post-processing effort so that only important results, such as total energy consumption and end-use consumption are presented to the users.

Petersen and Svendsen (2010) used MATLAB to develop a tool called iDbuild to fulfill energy consumption reduction targets and maximize occupants’ comfort inside the building. More specifically, their tool gives a prediction on the energy use, indoor temperature, daylight level, and indoor air quality of a given building model. Two simulation tools, namely BuildingCalc (Nielsen, 2005) and LightCalc (Hviid *et al.*, 2008) called BC/LC were used as the backbone of the program. The current limitation iDbuild is basically rooted from BC/LC tool which uses a rectangular single-sided room with one window. As a result, the tool only generates design advice for this type of room only. The users can give input and see the simulation results through a MATLAB interface. Another limitation of the proposed tool is that it requires designers who have sufficient knowledge of changing the input parameter. Although the tool offers a well-informed design decision to the user, the designer was expected to understand the workflow in the user interface. Additionally, this tool does not have an option to input costs in the process.

Jalaei *et al.* (2015) developed Entropy-TOPSIS method. The method integrates TOPSIS with BIM. The objective was to assist designers in selecting the optimal sustainability of building components during conceptual design process. To achieve such objective, a Decision Support System (DSS) was developed using MCDM method. The impact of various designs on the building sustainability was analyzed against environmental, social, and cost efficiency. The tool was able to present the effect of design changes to its costs. However, costs estimation cannot be made accurately because the tool was designed for conceptual design stage of design.

Some evaluation tools are a stand-alone software programs, like ArchiCAD, Revit and DesignBuilder while other tools are designed by integrating the capabilities of MCDM method and simulation tool or equation. There is also simulation tool that is designed purely for engineers and programmers so that the presentation of the simulation results can be organized to serve certain audiences (Jönsson, 2000).

There are quiet view researches which use simulation in combination with MCDM during the early design stage of sustainable building, especially if costs are included in the design problems. Furthermore, although many tools are available to perform various simulation of building design, but the decision of which to use is subject to different needs. To achieve the objective of this research, a simulation software called EnergyPlus (E+) was selected. E+ is basically a simulation engine that is capable to define each component such as building material, weather, or ventilation in details. Such a capability becomes the ultimate advantage when using E+ because the user may intercept the simulation model. Therefore, the input for simulation model and the simulation results are in the form of text files. Another strength of E+ is that simulation for comfort parameters such as indoor temperature can be done with a higher accuracy.

Central in any decision matrix is the creation of a matrix. The basic format (Table 3.5), as presented by Jahan and Edwards (2015), was extended to fit the problems under consideration. Table 3.6 is the presentation of the decision matrix for TOPSIS calculation. The matrix was designed in Excel. As such, it has some advantages and disadvantages. Based on the underlying problems and the specific objective of the study, such presentation of the table provides transparent and objective results to the decision-makers. Additionally, each cell contains links to the cost of material and manpower, coefficient of works as well as EE and CO_2 database. The weight of each criterion and the performance of material are also linked. The disadvantage of the developed matrix is the variation in the design parameter of school models were pre-configured. These parameters are the height of the ceiling, the width and length of the floor, the opening area (window, door, and ventilation), and the type of roof, including its height. However, these variations have become a standard of practice for most school designs in Indonesia. Therefore, four typical school designs were created, resulting in up to 144 unique designs based on the combination of floor, wall, ceiling, and roofing materials. Another drawback of using such matrix is the number of columns and cells it contains. For example, it has become impractical to change the input for cost and weight in another sheet and then switch back again to see the overall change of ranking.

Table 3.6: A short form of decision matrix

Design Type	#	Floor	Walls	Ceil.	Roof	Total Cost (IDR)	EE	CO_2	Ecol.	Soc.	Econ.	#Disc. Hours	Index	Rank
Type 4	16	ceramic	CHB	ply	clay	167,201,599	147,778	19,607	3.37	4.09	3.95	1,773	0.726	1
Type 2	16	ceramic	CHB	ply	clay	168,817,133	154,710	20,754	3.37	4.09	3.95	1,879	0.704	2
Type 4	7	ceramic	bricks	ply	clay	163,258,756	177,877	21,129	3.33	4.15	4.09	2,139	0.694	3
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

For the matrix to be more informative, the results can be visually presented using a chart to show the performance of every alternative, as presented in Chapter 4, Section 4.3. From this point onwards, the final decision can be taken to determine which alternative is suitable given the actual and real situation in the field.

All selected sustainable criteria, together with the corresponding weight, simulation results, performances of all materials, and costs, were organized in MS. Excel as one matrix for decision-making. TOPSIS, as one of the MCDM methods, was finally used to rank design alternatives. This may serve as the front layer of the tool. If the user wishes, a what-if scenario can be made possible to the decision-maker.

3.6 Discussions

A framework has been structured to accommodate stakeholders or public participation in terms of criteria selection, weighting assignments, and subjective material performance assessment through questionnaires. Stakeholders of the project may participate in reviewing the results and identifying the best sustainable performance against the initial cost. In addition, the framework delivers a tool that facilitates the decision-making process. Trade-offs analysis can be made between criteria so that decision makers have an opportunity to see the impact to overall sustainability performance.

TOPSIS method used in the framework was simply to rank design alternatives. Key consideration shall be given to the weights because weightings determination is relative to stakeholders' priorities that for certain situation may not satisfy the building users or overall community. Besides, with numerous criteria and large amount of data generated in the framework, there is a likelihood that truthful stakeholders preference may not be fully realized. Such a drawback may lead to uncertainty and inconsistencies when selecting design alternatives. The uncertainty problems may be solved by applying several MCDM methods to a single predefined problem to verify the results. However, testing the outcome using another MCDM method is out of the research scope. Nevertheless, uncertainty in the decision-making model for this particular school design selection process can be minimized because all criteria included for the selection of material and design must undergo a comprehensive evaluation, which is presented in Chapter 4.

Although uncertainty cannot be fully eliminated, important sustainable development problems has been considered into the building material and design selection process through a framework developed in this research. The index derived from an implementation of the framework in a case study enable decision-makers to consider sustainability performance from several design alternatives. Such an index-based method is considered adequate because both subjective and objective criteria on social, economic, technical, and environmental issues of materials and the building's shape have been included. Therefore, the criteria for material selection process have undergone a rigorous evaluation process, and attached to each configuration of design alternative, thus allows objective comparison of each design. Such index approach was supported by Uher (1999) stressing that absolute criteria is more effective to measure and justify the impact of materials and building design on the environment. For example, the advantage of obtaining absolute data is that calculation for assessing the environmental impact such as EE and CO_2 for a whole building design can be made and compared.

A simple school models created for this research was just ideal to accommodate multiple criteria of building materials, and design so that economic, social, and ecological impacts can be quantified thoroughly. A framework developed in this research has given a positive contribution to the decision-making process during the preliminary design stage of building projects. The applicability of such a framework in measuring the sustainability performance in the Indonesian building industry may deliver piece of evidence that sustainability in buildings is attainable. Chapter 4 was devoted to demonstrate how the framework may facilitate the design selection problem, including to what extent that the tool can provide an informed decision-making to building designers.

CHAPTER 4

RESULTS AND ANALYSIS OF THE FRAMEWORK APPLICATION IN A CASE STUDY

4.1 Evaluation of Subjective Criteria

4.1.1 Survey on Sustainable Criteria and Performance of Material

The determination of subjective criteria employs a qualitative research method. A thorough survey of relevant literature has listed some criteria, as presented in Chapter 2, Section 2.5, which helps in identifying the most sustainable material criteria for designing sustainable buildings. These preliminary criteria need to be analyzed thoroughly using a semi-structured interview followed by a pilot questionnaire survey. The pilot survey and semi-structured interviews were performed with some experienced construction practitioners to enhance or improve the contents of the questionnaire before the final questionnaire is distributed. The preliminary listed criteria or any other new relevant criteria for the selection of material from the interviews were studied and confirmed with the participants. A total number of 7 (seven) construction project professionals were contacted for face to face interviews following the pilot study questionnaire survey. Feedbacks from interviews and pilot surveys did not show any potential conflicts or any particular interests from the participants during interview process and the pilot survey. Any clarification from participant suggestions, comments, or opinions were conducted through individual interview. It was decided that the material selection criteria for sustainable school design need to be revised. A revision includes criteria modifications and elimination from the preliminary criteria listing assessment, as shown in Table 4.1.

The results of the pilot surveys and interviews deliver convincing input or information regarding three things. 1) Relevant criteria to be included in the final questionnaire. 2) The scales used for determining each criteria performance value, and 3) The clarity of marking scheme for the material performance assessment. Finally, the verification and determination of the relevant criteria to be included in the final questionnaire encompass 14 (fourteen) criteria. These criteria are undisputedly classified under ecological, social, and economic main criteria representing the notion of the ‘three pillars of sustainability’ as shown in Table 4.3.

Table 4.1: Selection of criteria

No.	Criteria	Reason of changes to the criteria list	Selected criteria
	<u>Ecological</u>		
1	Potential for recycling		√
2	Potential for reuse		√
3	Ozone depletion potential *)	No data are available. Not sure how this criterion can be assessed	
4	Ecological impact during harvest	Criteria 4, 5 was changed to CO_2 emission for both processes	√
5	Ecological impact during production		
6	Use of water during construction		√
7	Embodied energy within material		√
8	Amount of waste in use of material *)	Difficult to quantify the amount of wastage for each material	
9	Amount of transportation required *)	Most materials transported from Medan except bricks and cement	
	<u>Social</u>		
1	Ease of construction / constructability		√
2	Aesthetics/appearance		√
3	Zero or low toxicity for occupant *)	No data. Cannot be determined by just subjective assessment	
4	Resistance to heat flow		√
5	Locally available workers	Changed to “Employ local workers at maximum”	√
	<u>Economy</u>		
1	Locally available suppliers *)	All materials are supplied and available from the local suppliers	
2	Availability in local market *)	All materials are easily procured locally	
3	Initial cost		√
4	Maintainability		√
5	Reparability		√
6	Upgradability		√
7	Strength or durability		√

Remarks: *) These criteria were eliminated

The final questionnaire can be completed roughly in 15 to 20 minutes. The questionnaire was sent to 105 participants comprises of 35 design consultants, 35 contractors/developers, and 35 people from local government and university lecturers. Some of the questionnaires were directly delivered, and the remaining were sent by e-mail. A final look of the distributed questionnaire is presented in Appendix 3.2. The first part of questionnaire was prepared for collecting information about the demographic status of respondents and their experiences. The second part of the questionnaire allows respondents to rate using a five-points scale in determining the importance level of each criterion. After one to two months, 74 questionnaires were returned, which gives a 70% response rate. Such a high feedbacks is more than adequate to provide the reliable results because the returned questionnaire in the construction industry is normally between 20% to 30% (Akintoye, 2000; Dulaimi *et al.*, 2003).

Information about demographic status such as academic background, experience, etc. obtained from the respondents was considered important because the aim of the research focused on the design process. Hence it was an advantage that the survey was able to involve respondents having a long experience in building design, management, and construction of projects. Table 4.2 shows the respondents' demographic status from the returned questionnaire.

Table 4.2: Respondent's demographic information

Variables	Frequency	Percentage (%)
Experience		
2 - 4 years	6	12.0
5 - 7 years	20	40.0
8 - 10 years	18	36.0
> 10 years	6	12.0
Education level		
Bachelor	50	67.6
Master	21	28.4
Doctor	3	4.1
Type of organization		
Architect & Design	20	27.0
Contractor	19	25.7
Consultant Engineering	3	4.1
Developer	2	2.7
Education	2	2.7
Government	28	37.8
Project experience		
Commercial	5	11.4
Residential	10	22.7
Public building	29	65.9
Regular client type		
Public	42	95.5
Private	2	4.5
Knowledge in sustainability		
Do not know	1	1.4
Insufficient	8	10.8
Sufficient	51	68.9
Good	14	18.9
Knowledge on sustainable material selection		
Do not know	1	1.4
Insufficient	3	4.1
Sufficient	59	79.7
Good	11	14.9

The results of demographic status show that the majority of respondents are a highly experience individual from the public sector. In this sector, respondents with 5 to 7 years of experiences accounted about 40%, while 48% of respondents have project experiences above eight years. Around 67.6% of the respondents hold a bachelor's degree, while 28.4% of the respondents hold a Master's degree. The participation of design and engineering consultants, developers or contractors in different building projects can also be seen in the demographic status. As shown in the table, respondents have different project experiences but most of them are experienced in public building and residential construction projects. Demographic status of respondents concludes that the outcome of the questionnaire survey was credible because respondents are mostly educated and knowledgeable in providing useful data, information and suggestion for developing a complete decision-making model in this research.

4.1.1.1 Weight of Criteria

From the returned questionnaire, the weight of each criterion was calculated using the weighting method, as described in Chapter 3, Section 3.2.1.1. Cronbach's alpha coefficient value was used to verify the scale's reliability and to determine the internal consistency of the scale ([Gliem and Gliem, (2003)], p. 87). In this case, the consistency of Likert's scale used in ecology, social, and economic criteria was checked. If the alpha value is more than 0.7, then the internal consistency of criteria can be considered adequate and reliable. The alpha values of ecology, social and economic criteria are 0.842, 0.708, and 0.706, respectively. Thus, all of the three main criteria are considered reliable.

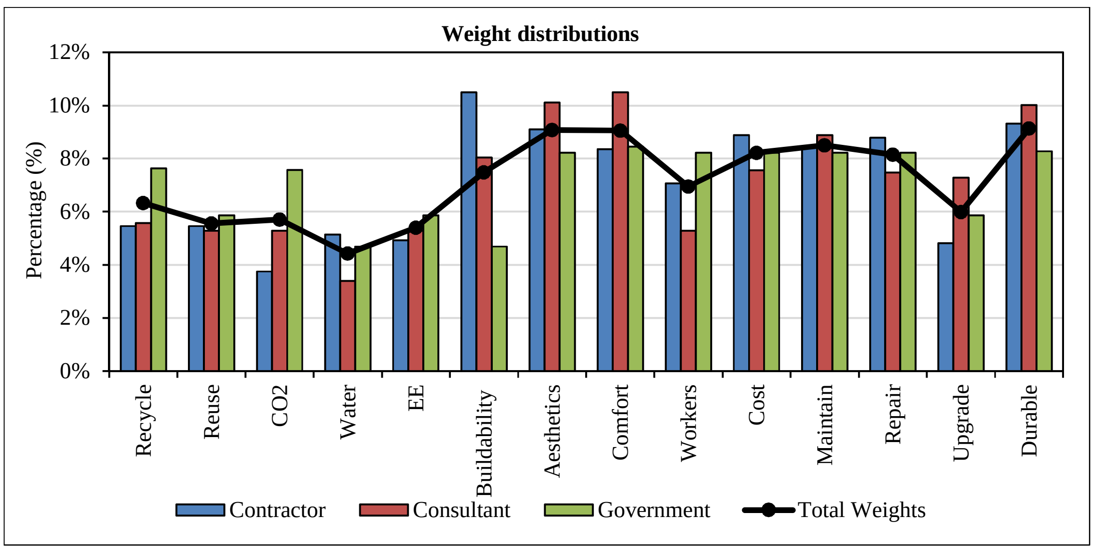


Figure 4.1: Distribution of final weights

Figure 4.1 shows the result of the questionnaire survey. As shown in the figure, that respondents having working experience as contractors, consultants, and the government agreed that aesthetics, comfort, and durability are most important for school design. Interestingly, the response from the government gave high scores across the six criteria almost equivalently. They are cost criteria, aesthetic, comfort, workers, maintainability, repair, and durability. This clarifies the nature of an MCDM problem of the school design. For instance, cost criterion is most important according to government and contractor, but design consultants voted aesthetic, comfort, and durability as the most important. Hence, the selection of design may lead to incorrect decisions if the decision is taken by one particular project party, which may not satisfy other parties. Additionally, it worth mentioning that, by obtaining weights of each criterion from all project parties, the goal or objective of the design selection process would become clearer, attainable, and reduce conflicts of interest among project parties. Details on each weight are grouped according to the main criteria, as outlined in Table 4.3.

Table 4.3: Weight of each criterion

Final criteria	Weight (%)
Ecological criteria	
Potential for recycling	6.33%
Potential for reuse	5.57%
CO_2 emission from material harvest and production	5.70%
Use of water during construction at minimum	4.43%
Embodied energy of material	5.40%
Social criteria	
Constructability/buildability	7.49%
Aesthetics / appearance	9.08%
Indoor comfort	9.06%
Employ local workers at maximum	6.96%
Economic criteria	
Initial cost	8.21%
Maintainability	8.50%
Reparability	8.15%
Upgradability	5.99%
Durability	9.13%
Total	100%

The decision matrix requires more objective input, so-called Relative Important Index (RII) values, as described in the following section. Furthermore, the performances of each material were also inputted. These performances were obtained from 4 (four) sources. The CO_2 emission and EE of each material were taken from the LCI database. The initial cost was calculated using the Indonesian Standard (SNI). Indoor comfort which is presented by the total number of Disc. Hours were obtained from the thermal study survey and output of the simulation. Other than the four sources above, the performance of the material was obtained using subjective assessment, which was also included in the last section of the questionnaire (Appendix 3.2).

4.1.1.2 Ranking Analysis of Criteria

The responses from all respondents on the criteria ranking were measured using an ordinal type of scale called a five-point Likert scale (1–5). The scale from 1 to 5 means that the criteria are not important at all, low important, neutral, very important, and extremely important, respectively. Such respondents' preference assessment using the scale from 1 to 5 is quite subjective. Siegel and Castellan (1988) mentioned that such technique is considered a parametric technique, thus they are not adequate for preference assessment. Therefore, a non-parametric technique, namely the Relative Importance Index

(RII) method, was used. Johnson and LeBreton (2004) highlighted that the RII assists the researcher in evaluating the input of a predictor or independent variable to the prediction of a criterion or dependent variable, both by itself and in relation to other independent variables.. According to Kometa *et al.* (1994), the RII method was found to be useful in construction projects and facilities management research, especially for data analysis which involve ordinal measurement of attitudes from a structured questionnaire. To determine the degree of importance of each criterion, RII values were calculated manually using Equation 4.1 ([Badu *et al.*, (2013) as cited by Somiah *et al.*, (2015)], p. 120).

$$R = \frac{\sum w}{A \times N} \qquad (4.1)$$

According to the above equations, *w* is the weighting or score from one to five, which has been received from respondents. A score of 1 means the lowest, while the highest preference is scored as 5. The highest score is represented by *A*, and the total number of respondents is represented by *N*. The result of RII will be in the range from 0 to 1 (index). A low index value means that the criteria are less important than criteria having a higher index value. Thus, the importance levels of RII can be classified as follows:

High (H)	0.8 < RII < 1.0
High-Medium (H-M)	0.6 < RII < 0.8
Medium (M)	0.4 < RII < 0.6
Medium-Low (M-L)	0.2 < RII < 0.4
Low (L)	0.0 < RII < 0.2

Table 4.4 shows the RII value of each criterion, including criteria ranking and the degree of importance (importance level). As shown in the table, the importance levels of six criteria are in the range of 0.814 – 0.903, thus they are classified as ‘High’. These ‘High’ ranking criteria are part of social and economic criteria. These 6 (six) criteria are Soc2: Aesthetic/appearance, Soc3: Indoor comfort, Econ1: Initial cost, Econ2: Maintainability, Econ3: Reparability and Econ5: Durability. This means that these six criteria have the biggest influence on the sustainability of the material selection process. For example, ‘Durability’ has the highest RII value (0.903) among all the criteria. Therefore, the durability of building material is the most important criterion to achieve sustainability of a building. The second highest criterion is ‘Indoor comfort’ with an RII value of 0.900. This shows that respondents were also highly concerned about the material, which has the capability to minimize the heat transfer from outdoor. In other words, occupants’ comfort inside the building has received serious attention from the respondents due to excessive heat in a natural ventilated building such as primary schools in Indonesia. The third highest criterion of a material is the ‘aesthetic/appearance’ which has the RII value of 0.897. The fourth highest criterion is ‘maintainability’ with an RII of 0.846. Maintainability is defined as the minimum

effort required to clean or preserve the material. The fifth and sixth criteria are ‘initial cost’ and ‘reparability’ with RII value of 0.819 and 0.814, respectively.

Table 4.4: Criteria ranking based on the Relative Importance Index

List of criteria from the questionnaire survey		RII	Ranking under main criteria	Overall ranking	Importance level
	Ecological criteria				
Eco1	Potential for recycling	0.649	1	9	H-M
2	Potential for reuse	0.559	3	12	M
3	CO2 emission from material harvest and production	0.595	2	11	M
4	Use of water during construction at minimum	0.443	5	14	M
5	Embodied energy of material	0.546	4	13	M
	Social criteria				
Soc1	Ease of construction / buildability	0.711	3	7	H-M
2	Aesthetics / appearance	0.897	2	3	H
3	Resistance to heat thus improving indoor comfort	0.900	1	2	H
4	Employ local workers at maximum	0.708	4	8	H-M
	Economic criteria				
Econ1	Initial cost	0.819	3	5	H
2	Maintainability	0.846	2	4	H
3	Reparability	0.814	4	6	H
4	Upgradability	0.600	5	10	H-M
5	Life expectancy of material (e.g. strength, durability)	0.903	1	1	H

The result of the ranking has shown that amid the top six criteria which have been classified as ‘High’, two criteria are under social criteria, and four are under economic criteria. Apart from ‘High’ importance of criteria, the eight remaining criteria were categorized as ‘High-Medium’ (4 criteria) and ‘Medium’ importance (4 criteria). For ‘High-Medium’ includes one criterion under ecology criteria, two criteria are under social criteria, and one criterion is under economic criteria. The last four criteria are considered as ‘Medium’ and are ranked under the ecological aspect.

4.1.1.3 Analysis of Material Performance

Subjective assessment mostly occurred during the selection of materials. In the case of Aceh, almost too often that the selection of material is determined by the subjective judgment of a single architect or one architect with one or two representatives of the Owner. To enable a comparable analysis, the selected criteria for assessing the material performance was determined using the scale from 1 to 5. Therefore, the performance of each material needs to be quantified based on the criteria marking scheme, as shown in Table 3.1. This performance assessment was grouped under ecological, economic, and social aspects as well. Experienced respondents were required to determine how each material was performed under each group. The results of the subjective assessment of each material are presented in Table 4.5.

Table 4.5: Results of subjective assessment of material performances

	Floor		Wall		Ceiling			Roof		
	ceramic	granite	Brick, plastered	CHB, plastered	gypsum	ply	GRC	clay	alu	mortar
<u>Ecological:</u>										
Potential for recycling	2.49	2.86	2.73	2.86	2.81	4.31	2.97	2.70	4.09	2.96
Potential for reuse	2.53	2.86	1.86	1.90	2.79	4.20	2.89	4.74	4.17	4.71
Use less water	2.83	3.00	1.91	2.19	4.74	4.83	4.67	4.89	4.79	4.84
<u>Social:</u>										
Buildability	4.17	3.80	4.31	3.80	3.96	4.21	3.71	3.73	4.14	3.56
Aesthetics/appearance	3.89	4.80	3.24	3.00	3.43	3.00	3.06	4.29	3.00	4.06
Employ local workers	4.74	4.63	4.81	4.83	3.94	4.80	4.06	4.59	4.61	4.51
<u>Economy:</u>										
Maintainability	4.14	4.73	4.87	4.81	3.90	4.11	2.99	4.86	4.09	4.70
Reparability	4.06	3.01	4.31	3.83	3.67	2.94	2.96	4.19	4.73	4.06
Upgradability	2.27	2.09	3.66	2.70	2.00	4.06	2.11	4.06	3.47	4.11
Life exp. (durability)	4.01	4.96	4.86	4.09	2.94	4.20	3.04	4.87	3.87	4.66
Average	3.51	3.67	3.66	3.40	3.42	4.07	3.25	4.29	4.10	4.22

Performance data of each material in Table 4.5 above were collected from 21 local construction companies and 23 design and engineering consultants in Aceh province. To ensure the reliability of results, only skilled persons from each company who have experiences for more than two years in building design and construction are eligible to fill out the questionnaire.

Flooring

The ecological performances of flooring materials are assessed from their recyclability, reusability, and use of less water during construction. The questionnaire survey revealed that granite tile is better than ceramic under these three criteria. For social criteria, it was also voted as a better flooring material for its aesthetic or appearance. Ceramic is better in terms of buildability and is easier to install, thereby increasing the employment opportunity for the locals. For economic criteria, granite tile was voted better than ceramic under maintainability and durability except for reparability and upgradability. Ceramic tiles are commonly marketed with a size of 40 x 40 cm with less color or texture variation than granite. Hence, the reparability or upgrade process becomes easier than granite, which is normally sold by 60 x 60 cm in size. In addition, variation in color and texturing of granite is always changing following the current trend, which makes it difficult to match the old granite with the new ones should reparation works are needed. Similarly, when an upgrade work is perhaps unavoidable, it then becomes impractical when granite tile in a particular room needs to be replaced with more superior qualities.

Wall

Clay bricks and CHB shared relatively equal performance in terms of recyclability and reusability except for the use of less water, which is CHB performed better than clay brick. In social criteria, clay brick is buildable than CHB. This is because clay brick is smaller in size and lighter than CHB, which makes it easier to construct. Aesthetic and employability of local workers criteria are scored relatively equal because the wall is plastered and painted. For economic criteria, the wall made of clay brick is much easier to repair and upgrade. Past experiences on the earthquake disaster in Aceh have shown that the brick wall is easier to repair or upgrade than CHB because the large part of the brick wall was still left intact with the main structural frame. It is also common in Indonesia that the building Owner modifies the room, which sometimes requires changes to the wall, hence this makes brick received better performance than CHB on those criteria.

Ceiling

For ceiling material, plywood received a better score in ecology, social and economic criteria compared to the other two materials except for aesthetic and reparability criteria. The typical plywood board comes with 1.2 by 2.4 m in size. Low scores on aesthetical criteria of wood are usually coming from cracks alongside the edge of one board to another. This is also normally identified on the GRC board. For aesthetic criteria, gypsum performed better because it can provide a smooth finish. Gypsum is also easy to repair because the damaged part can be repaired using its special compound.

Roofing

The ecological performance of aluminum roof is better than clay and mortar roof tile. The recycle and reusability of the aluminum roof was voted to perform better than those two material options. While clay and mortar roof tile were given almost equal performance on all three criteria. In terms of social performance, the aluminum roof received low scores on the aesthetic criteria. This is because of the long and plain look of aluminum sheeting from the factory. For other criteria, the three material options share almost identical performance. In social criteria, aluminum roof performs low in terms of its upgradability due to its large dimension compared to clay and mortar roof tile. Hence, the upgrade process requires more effort, and the initial form may be easily deformed during the dismantling process. Aluminum roofing also scores low in terms of durability. All three materials options for roofing shared almost equal performance scores in maintainability and reparability.

The performance of each material under the three main criteria can be seen from Figure 4.2. As shown in the figure, that especially for ecological criteria, the majority of respondents voted that flooring and wall materials are not easy to reuse nor to recycle. This is because these materials form the main structure of the school building itself. Non-structural materials such as ceiling and roof received a higher score under ecology criteria.

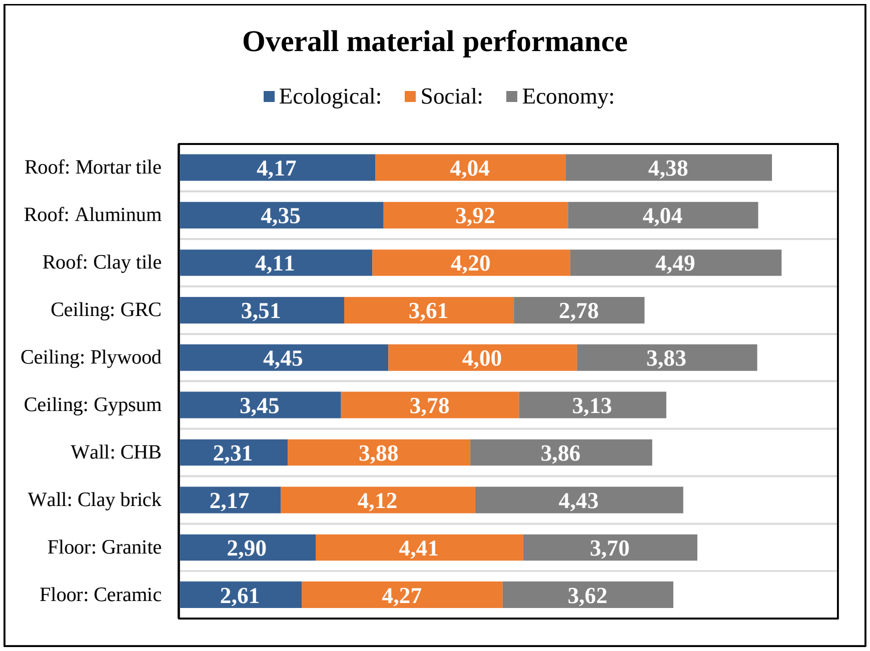


Figure 4.2: Material performances under ecological, social and economic criteria

For the social criteria, material that has good buildability and able to construct by the locals received better scores. This includes material such as granite tile, ceramic tile, clay brick, all roofing materials, and plywood for the ceiling. In addition, in terms of providing jobs for local workers, material availability and proficiency in installing building materials are considered an important social aspect to reduce the unemployment rate in developing countries.

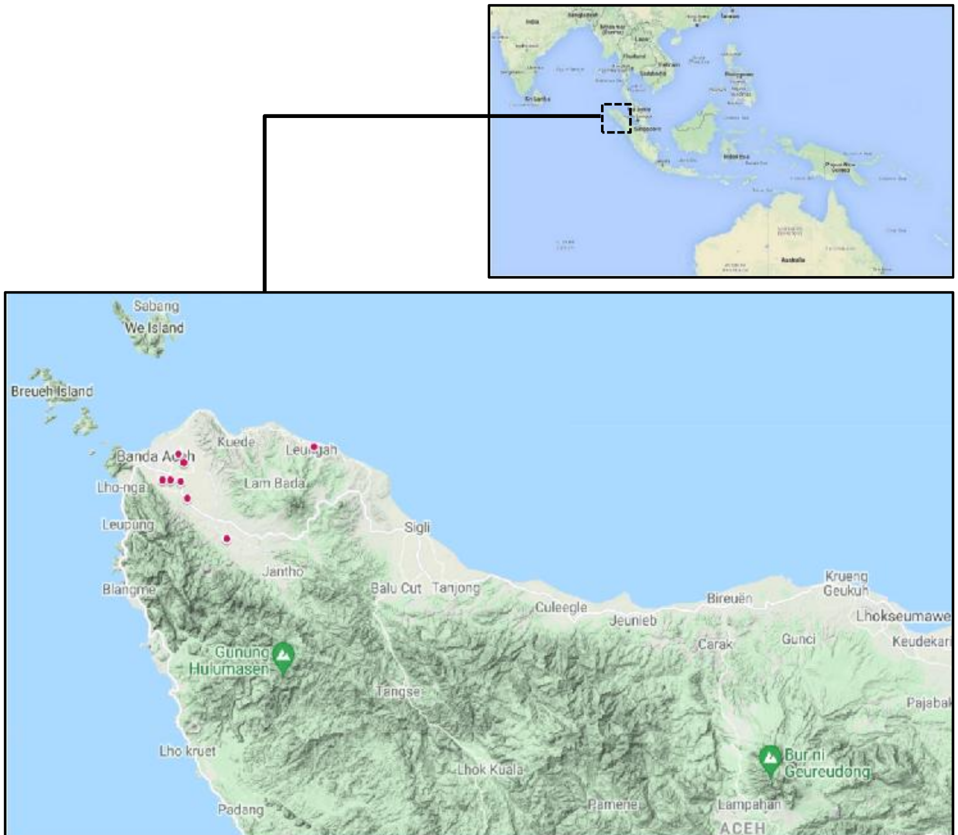
The economic performance of the material was mainly influenced by reparability, upgradability, and durability of the material. For example, materials with longer service life need not be replaced more often. Hence, the purchasing of new material for the replacement, the cost for installation, and manpower cost would eventually be avoided. Furthermore, durable materials require fewer maintenance and reparation costs over the building's lifetime. Roofing material such as clay tile and mortar tile received high scores, followed by clay brick. These materials may have a longer service life even though the building is decommissioned or upgraded because clay and mortar roofing tile can be easily dismantled and reinstalled. Other materials have average performances except for GRC and gypsum ceiling, which have lower performance than the others.

4.1.2 Thermal Comfort Field Survey

Evaluation of thermal comfort is considered an important subjective criterion for school design, which needs detailed analysis. In this section, the method for finding the range of comfort temperature of the case study schools in Aceh is presented. This comfort temperature range is part of subjective criteria evaluation, as previously explained in Chapter 3. Thus, it will be analyzed with the result from simulation output to find out the total Disc. Hours.

All schools selected for this thermal comfort study are located in Aceh province, Indonesia (Figure 4.3). The province of Aceh has 57,365 km^2 of land area. Aceh province is the most western province of Indonesia surrounded by the Indian Ocean to the West and the Malacca Strait to the East. The climate in Aceh is tropical having an average temperature at 28 °C at the coastal area. Inland and mountain areas have an average temperature at 26 °C and average temperature in the higher mountain regions is 23 °C. Sea waters cover 81% of Indonesia's territory and the warm temperature of sea waters makes the temperatures variation on land relatively small. The relative humidity in Aceh is between 70% and 90%. Aceh province only experienced with dry season from June to September and starting from December until March is raining most of the time. Winds are moderate and generally predictable. The South to East Monsoons is usually blowing in June until September. Monsoons from the North-West typically appear in December until March. A large-scale storm like Typhoons is extremely rare in the Aceh ocean (ISC-Audubon, 2013).

The field survey was conducted at eight public primary schools. These schools were built between 2005 and 2007, occupying a land area of 1800 - 2000 m^2 for each school. All schools were not shaded by other buildings nor by tall trees on its north, south, and east. The classrooms are arranged into two or three blocks and are oriented differently to meet the available land. In tropical countries, the classroom's orientation is detrimental to thermal comfort assessment. However, the roof of the case study schools spanned up to 1.1 meters from the outer wall, hence blocking the penetration of direct sunlight into the classrooms.



No.	School name	Coordinate
1	SDN Kuta Malaka	5.4527898503218815, 95.397722325991
2	SDN Siron	5.35863049900202, 95.49404424335279
3	SDN Abulyatama	5.534467968691416, 95.38970164687913
4	SDN Kayee Lhee	5.494197228991726, 95.35623804135524
5	SDN Neusok Teubalui	5.493900109162212, 95.33767109876291
6	SDN Leungah	5.57010828135046, 95.70433348382696
7	SDN Rumpet	5.554465487364162, 95.37415438231619
8	MIN Bukloh/MIN 39	5.4897529172128, 95.38019153033723

Figure 4.3: Location of the selected schools in the case study

Verandah (corridor) also gives maximum protection from direct sunlight into the classroom. These two design considerations help to reduce the temperature inside the classrooms. Moreover, all classrooms are naturally ventilated by large clear glass windows and louvers (Figure 4.4).

Figure 4.4: Verandah (corridor) and long roof span to minimize solar heat gain

Most primary schools in Indonesia have 6 (six) classrooms, which comply with the minimum of six years' enrollment following the Indonesian national primary education system. After completion of the 6^{th}-grade study, a student shall enter a junior high school, which is usually located in another place. There is also a case for one school to have more than six classrooms, especially if the school is located in a highly-populated area. Thus, for school with a large number of students, one grade may have more than one classroom. Another common practice is to build two-story schools. Being classified as an earthquake-risk territory, two-story primary schools are very limited, and there has been no school built up to three stories high in Aceh. The layout arrangement for one school is normally in the combination of 2+4 and 3+3 classrooms, which depend on the availability of land (Figure 4.5).

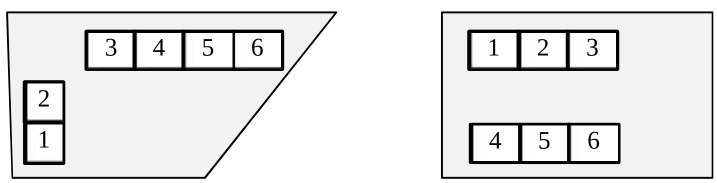


Figure 4.5: Typical layout arrangement of school blocks

Figure 4.6 shows a simplified layout plan of one school. For this particular model, the school comprises of three building blocks. Two blocks are used for the classroom, with one block attached to the toilet for boys and girls. The third block is used for teachers, school principals, and a small library. The floor area of one classroom is a rectangular shape of 8 meters by 7 meters, with a 3 meters of ceiling height from the top finished floor. The floor area was designed following the regulation of the Indonesian Ministry of National Education, which stated that the number of students in one classroom ideally should not more than 24 students. Other design parameters such as layout, orientations, ceiling height, roof type, or building materials may vary throughout the country.

Using the actual layout and geometry of one school (Figure 4.6), a building 3D model was developed. In any simulation technique, this 3D model is called a Baseline model, which served as a basis of comparison to other models generated during the simulation processes. The creation of a Baseline model by using the actual school as a reference in the case study is highly related to the accuracy of simulation output rather than designing a Baseline which involves many assumptions and guessing works. Having the actual project data at hand is beneficial because they serve as an excellent comparison basis for testing the sustainable performance of other possible design alternatives.

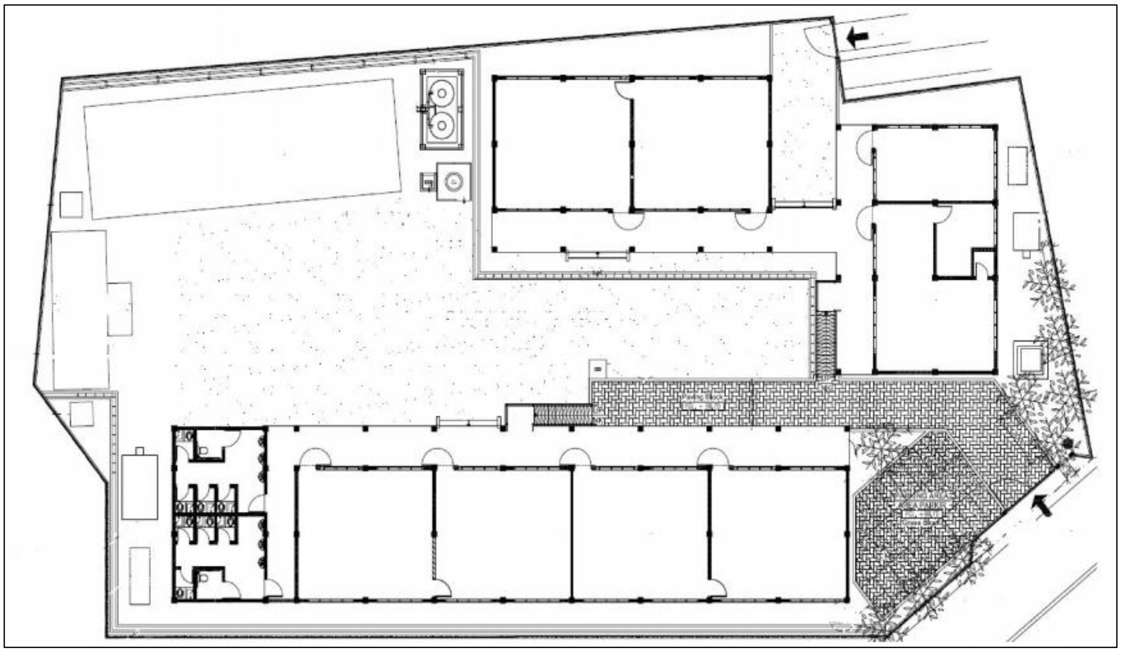


Figure 4.6: Layout plan of the building blocks of SDN Kayee Lhee

(a) Back view

(b). Front view

Figure 4.7: SDN Kayee Lhee primary school

Figure 4.7 shows one sample of schools in the case study, namely SDN Kayee Lhee. SDN stands for '*Sekolah Dasar Negeri'* and is translated as public primary school. All 8 (eight) schools have exactly similar geometry and roof shapes except for one school, namely MIN Bukloh, which has 4 m ceiling height. For all eight schools, the internal and external walls are made of 100 mm burnt clay bricks and

20 mm cement-plastered at both sides. The roof cover was built using a corrugated metal sheet supported by light steel truss and rafters. A radiant barrier or heat insulation is installed right below the metal sheet. The pitch of the roof is at 30 degrees above horizontal. The floor is covered by anti-slippery white ceramic tiles, while the ceiling is made of Fibred-Glass Reinforced Cement (GRC) panel. All schools also adopt a wide clear glass window with louvers on top of each window. Each window can be operated manually except for the louvers. For the structure, all schools were built using reinforced concrete. The abundant source for concrete materials and the durability of reinforced concrete has made it a common building structure in most Indonesian regions. Furthermore, many workers are familiar with the construction method of concrete structure. Therefore, the cost for reinforced concrete structure is known to be reasonably low and adequate for public primary school building. Layout and the cross-section of the school are supplemented in Appendix 4.1 and 4.2, respectively.

4.1.2.1 Data Collections

To verify the accuracy of OT from the output of the simulation, two temperature data loggers were installed at SDN Kayee Lhee and MIN Bukloh, respectively. The locations of these schools are marked as * (asterisk) in Figure 4.6. The actual indoor temperature inside one classroom of both schools was recorded hourly from 19th July through 15th September 2015. Subsequently, data collection on thermal sensation vote was conducted between 2nd and 8th September 2015 to record the students' thermal sensation while also recording the indoor temperature. Table 4.6 shows details on visits to every school.

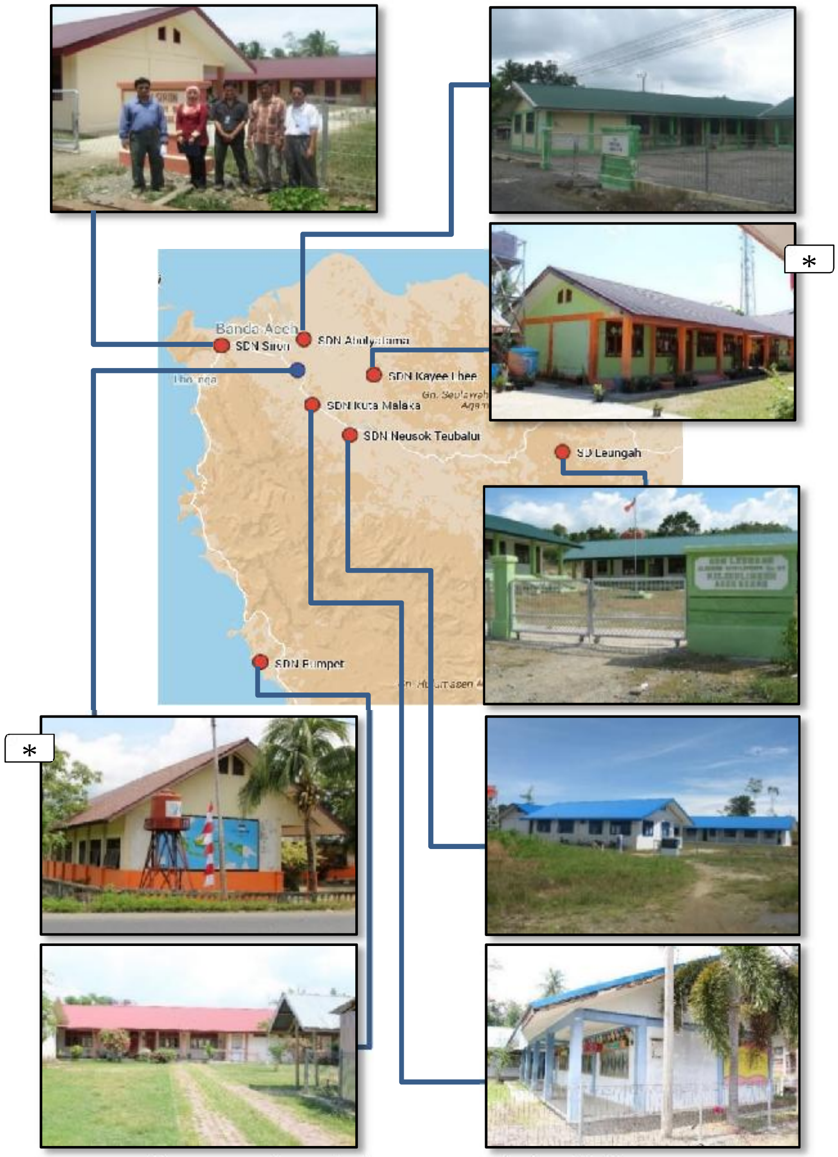


Figure 4.8: Actual photos taken during field survey

Table 4.6: Situation of schools during field survey

No.	School name	Orientation *)	Number of students	Ceiling height (m)	Date of visit	Observed weather
1	SDN Kayee Lhee	West – East	15	3	2 Sep. 2015	Clear
2	SDN Leungah	North – South	15	3	2 Sep. 2015	Clear
3	SDN Rumpet	West – East	15	3	3 Sep. 2015	Light rain
6	SDN Abulyatama	North – South	20	3	3 Sep. 2015	Cloudy
4	MIN Bukloh 2)	North – South	16	4	19 Jul. 2015	Clear
5	SDN Kuta Malaka	North – South	15	3	7 Sep. 2015	Clear
7	SDN Neusok Teubalui	North – South	17	3	8 Sep. 2015	Clear
8	SDN Siron	West – East	15	3	8 Sep. 2015	Clear

Remarks: West-East orientation means that the longer façade faces the North and the South.

Two schools were visited for each day, resulting in total of 4 days of the site visit. The observation was made right at the student's lesson hours, which is from 08.00 AM to 01.00 PM. Figure 4.9 shows the hourly values of the outdoor dry bulb temperature (DBT). Based on the observation, the outdoor DBT at 08.00 AM was around 24 °C on all four observation days and was raised to 31 °C. The outdoor hourly temperature from 08.00 AM to 01.00 PM averaged at 27.6 °C for all days of observation.

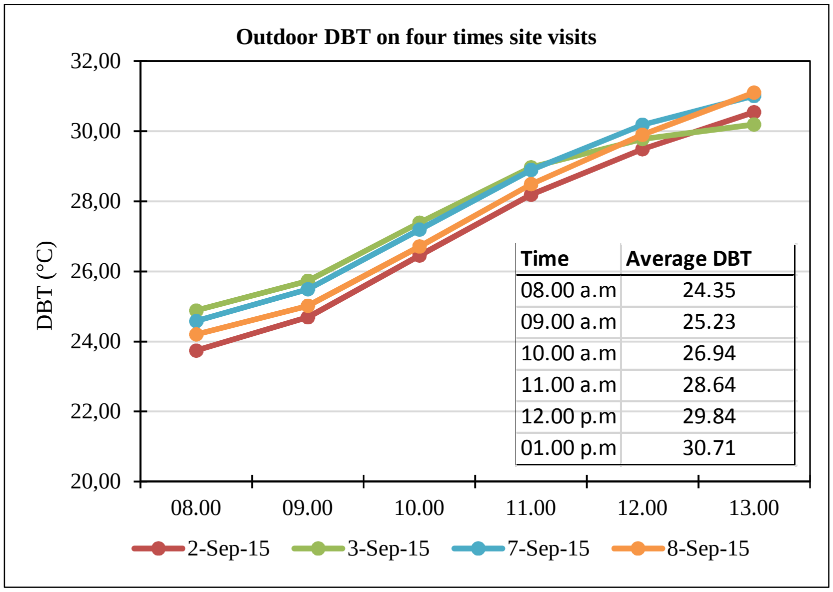


Figure 4.9: Outdoor DBT from normalized Blang Bintang weather station

The four days site visit with relatively little variations on weather conditions will be advantageous, because the impact of building design parameters on indoor temperature can be realized for a conclusive analysis. Furthermore, a wide range of DBT, which is from 24.35 to 30.71 °C may be useful to understand the neutral or comfort temperatures or indoor temperatures preferred by the occupants. The DBT shown in Figure 4.9 above, was obtained after a normalization process from the nearest weather station, which is Penang, Malaysia. This procedure is presented in detail in Section 4.2.1.1. Nevertheless, it should be noted here that due to the unavailability of an outdoor temperature measuring device, the application of DBT from Normalized weather data is not as accurate as results from prominent studies in this field. A more accurate device for measuring DBT was demonstrated in Wong and Khoo (2003). Notwithstanding, one of the main objectives of this study can still be fulfilled because the neutral or comfort temperature can be determined by conducting a comparative analysis between measured indoor temperature and TSV, as described in the next sections.

In conclusion, both objective and subjective measurements were adopted in this thermal comfort study. Objective measurement was performed by means of actual readings using data loggers while subjective measurements was conducted by recording indoor temperature at the same time when students completing a thermal comfort questionnaire. The collection of TSV were made in 7 classrooms occupied by the 6th grade of students to maintain the reliability of the results.

4.1.2.2 Results and Analysis of Comfort Indoor Temperature

The students' votes, so-called Thermal Sensation Vote (TSV), were collected using ASHRAE scale in the questionnaire as depicted in Table 3.3, Section 3.2.2. The measurement of students' comfort temperature was conducted for eight schools at various indoor temperatures. Figure 4.10 presents the frequency of votes at a certain observation time.

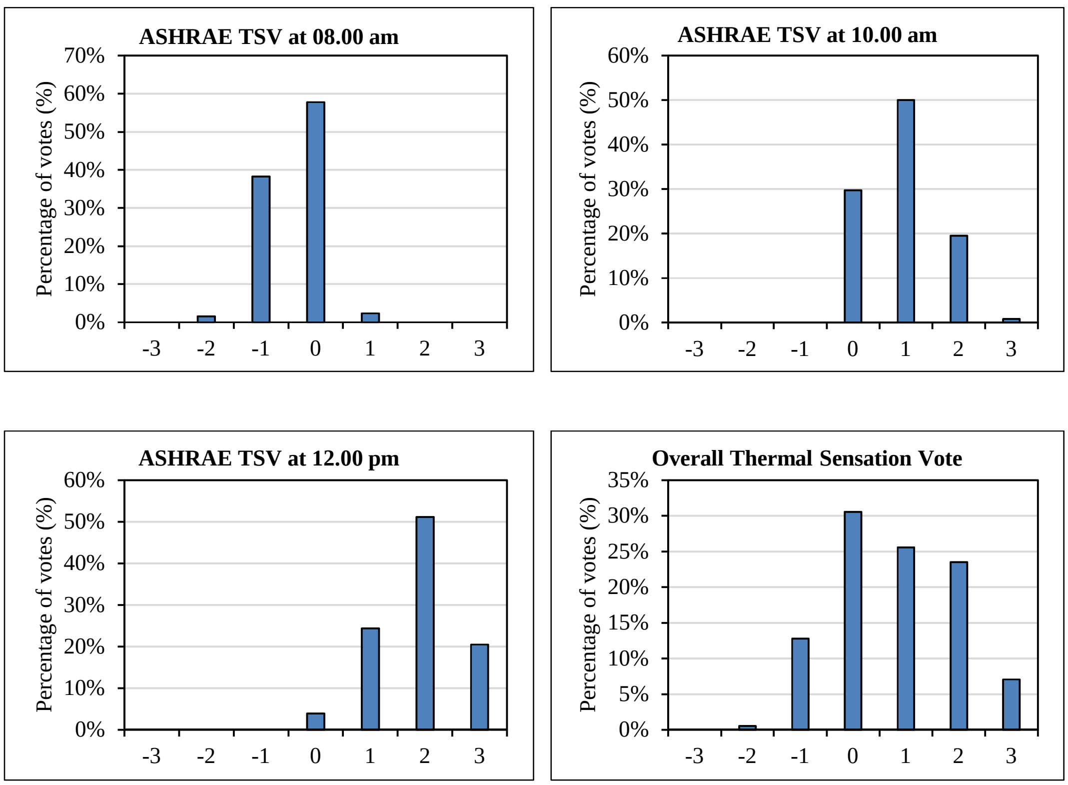


Figure 4.10: Frequency of votes using ASHRAE scale on all days

From the figure, the TSVs on four days of observation centered around -1 (slightly cool) and 0 (neutral category at 08.00 AM, around 0 (neutral) and +1 (slightly warm) at 10.00 AM and continue to increase at 12.00 PM where TSV centered around +1 (slightly warm) and +2 (warm). Accordingly, the Overall TSVs are mostly between 0 (neutral) and +2 (warm) category on four days of observation.

Neutral temperature is simply air temperature inside the classroom, that most students vote within the 'neutral' category of the seven-point ASHRAE scale. Therefore, for students who voted within 0 (neutral) is an optimal comfort condition. However, it does not mean that students who voted below or above 0 (neutral) did not feel comfortable. For this reason, Figure 4.12 was constructed to show the level of acceptability of comfort sensation in the classrooms.

According to the adaptive theory, the neutral temperature can be analyzed using the linear regression method. The observed TSV is considered as dependent variable that is plotted on the '*y*' axis, while OT is an independent variable, plotted in the '*x*' axis. Figure 4.9 shows the regression model of TSV and OT. As shown in the figure, the neutral temperature (T_n) based on TSV regression is 27.99 °C. The T_n of 27.99 °C which was derived from the actual TSVs, is slightly lower with the result from Wong *et al.* (2002) who reported a higher T_n of 28.6 °C and from both studies (de Dear *et al.*, 1991a; Busch, 1990) which is 28.5 °C (OT) and 28.5 °C (ET) respectively. According to de Dear *et al.* (1991b), the result from Busch (1990) is close to his result even when the effective temperature is converted into operative temperatures. The neutral temperature (T_n) from this study was a little bit higher than the T_n obtained by Kwok (1998) at the naturally ventilated classrooms in Hawaii, which is 26.8 °C (T_n). A lower neutral temperature in Hawaii is not surprising because the outdoor temperature during sunny days does not appear to be similar to tropical countries. Therefore, the people in Hawaii are likely less tolerant under high temperatures when compared to people in Aceh province. The findings from the research above confirm that people in a warmer climate still feel comfortable or adapt to higher indoor temperatures. Therefore, according to the adaptive theory, it is logical that T_n could be higher.

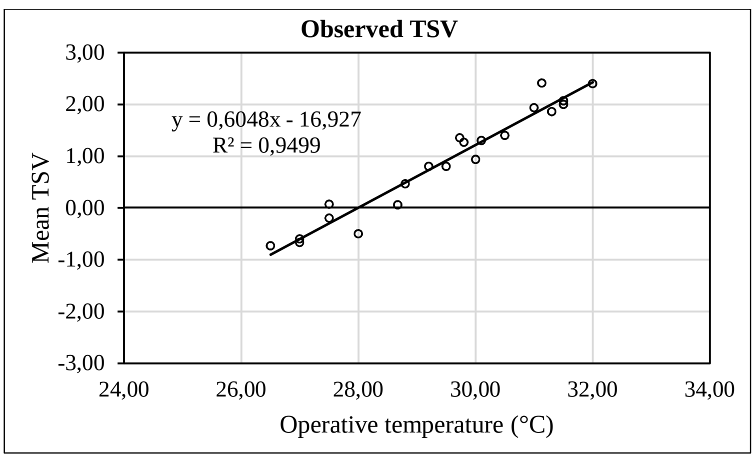


Figure 4.11: Regression model between TSV and OT

Thus, the correlation between TSV and operative temperature (OT) at naturally ventilated schools in Aceh province can be written as:

$$TSV = 0.6048\ T_{op} - 16.927 \qquad (4.2)$$

The standard deviation is 1.05, the correlation coefficient r is 0.91, and the correlation is statistically significant ($P < 0.0001$). The gradient line or slope coefficient is 0.6048 indicating that occupants will be experiencing one-unit change in their thermal state (based on TSV) for every 1.65 °C change in OT

(Brager and Dear, 1998). For a comparison, regression models from other studies are presented in Table 4.7.

Table 4.7: Regression model between mean TSV and OT in naturally ventilated buildings

Researcher	Location	Regression equation	R^2
Mallick (1996)	Dhaka, India	$TSV = 0.18\ T_{op} - 5.11$	0.25
Karyono (2000)	Jakarta, Indonesia	$TSV = 0.31\ T_{op} - 8.33$	0.40
Fato *et al.* (2004)	Bari, Italy	$TSV = 0.28\ T_{op} - 5.82$	0.87
Brager *et al.* (2004)	San Fransisco, USA	$TSV = 0.19\ T_{op} - 4.20$	0.69
Ye *et al.* (2006)	Shanghai	$TSV = 0.13\ T_{op} - 2.92$	0.48

Remarks: T_{op} = operative temperature (OT)

Source: Adopted and modified from Ye *et al.* (2006), p. 323.

Using Equation 4.2, the accepted temperature range in Aceh province is between 26.33 and 29.64 °C (OT). The neutral temperature at 0 (neutral) vote is 27.99 °C (OT). As shown in Table 4.7, The gradient in the regression equation from other studies are higher than gradient resulted from this study. The gradient of the regression model is related to the sensitivity of mean thermal sensation to the operative temperature (de Dear and Brager, 1998). Ye *et al.* (2006), p. 323 mentioned that “weighted linear regression model of the relationship between mean thermal sensation and mean indoor operative temperature was used to judge how quickly people felt too warm or too cool as temperatures deviated from the optimum”. The slope of the regression line of observed students’ comfort temperature in this study is high. Thus, it suggests that students in the observed schools are quite intolerant of a wider range of temperatures than occupants in other studies. According to Ye *et al.* (2006), the reason for the lower gradient is because the occupants in residential or office buildings can change their clothes whenever needed, while students in this study are prohibited to change their school uniform.

Acceptable temperature was assessed using two methods, as shown in Figure 4.12. As can be seen, the central three categories (-1, 0, +1) of ASHRAE’s method concluded that 64.8% of the students accepted the indoor temperature in their classrooms.

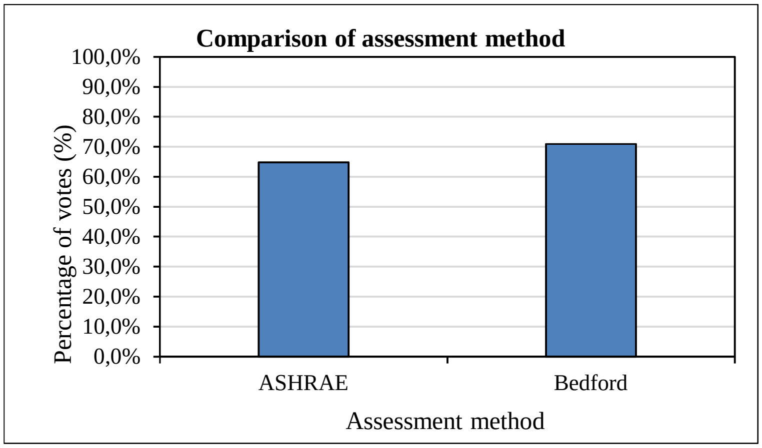


Figure 4.12: Method comparison for thermal acceptability assessment

When using the Bedford scale, 71% of the students accepted the indoor temperature and became the highest satisfaction level among the other two methods. Both methods indicate that not all students have accepted the indoor temperature in their classrooms.

4.2 Evaluation of Objective/Quantitative Criteria

The following sections present results and analysis from part 2 of the framework. It mainly presents detailed quantitative methods and evaluation of hourly simulation of indoor operative temperature, initial cost, evaluation of material's embodied energy (EE), and CO_2. The selection of building material by comparing the EE and CO_2 emission data using the typical building is essentially accurate. The reason is that buildings which have typical shape or model do not have many variables and usually encompass only a one-floor plan. Hence, primary school buildings were selected because they represent typical single-story buildings in Indonesia. The materials used in primary school buildings in Aceh province are mostly similar to other buildings in Indonesia. Hence, the evaluation method of EE and CO_2 in this research is applicable to other buildings in the country.

4.2.1 Baseline Model for Simulation

The baseline model is basically a 3D presentation of a real building. It will be used as a reference to compare the result of different parameters inputted in the simulation. Performing simulation in E+ is a tedious task because E+ read all necessary input data, including the geometry of the model as text files. An effective technique to create building geometry as text file in E+ was by using the standard drawing tools available in Google Sketchup, except the louvers above the window. Louvers are an array of plain wood installed horizontally with an interval of 5 cm above the window. This enables fresh air to enter the classroom at any time. To model this, manual input was done in E+ under 'Ventilation object'. The opening area of louvers was calculated manually from the construction drawing documents, and the value was entered in E+ except for one school, namely MIN Bukloh which its opening louver area was measured directly in the field due to the unavailability of the drawing document. Four 3D models were developed in Google Sketchup. The geometry and material object of these four models can be read and saved as four E+ input data file (IDF). Figure 4.13 presents the four 3D models, namely Design Type 1, Design Type 2, Design Type 3, and Design Type 4.

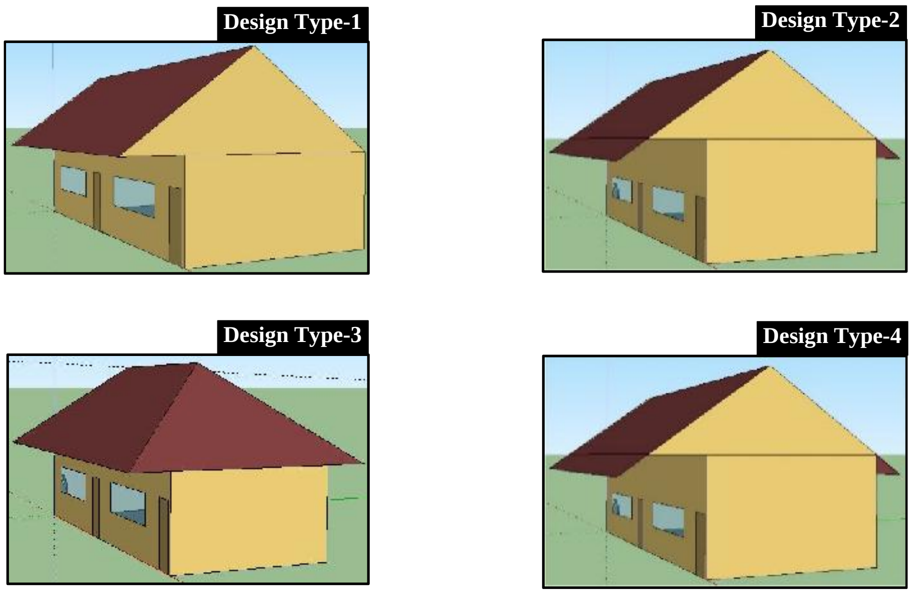


Figure 4.13: 3D model of typical schools

The parameter inputs for simulation were organized into fixed and varied parameters. Fixed parameters include geometry, weather data, and occupancy schedule within the IDF file hence it will not be varied by JE Plus. These fixed parameters are called default configurations for these four building models. Details of the default configuration are supplied in Appendix 4.4. On the other hand, varied parameters include all materials which will be executed from JE Plus environment. Detail of execution of various material is further explained in details in Section 4.2.1.3.

4.2.1.1 Weather Files

To run a simulation in E+, a weather file with the file extension of *.epw (or simply EPW file) is needed. EPW weather files are available for download from the Environmental and Protection Agency (EPA) website. These EPW files contain detailed weather information and are commonly used in energy analysis software such as E+. Unfortunately, there is no currently EPW file for the Aceh region. The nearest location found was Penang, Malaysia. An EPW file containing Penang weather data is not suitable for the Aceh climate. Although Penang is located at 800 km from Aceh with the same climate classification, and share the same latitude, however using a Baseline model, the results of indoor temperature were quite different from the measured indoor temperature. This was probably due to Penang EPW file was created based on weather data from 1993. Comparison of simulation results using the Penang weather file and the observed indoor temperature from 19 July and 15 September 2015 is presented in Figure 4.14. The annual average deviation between the measured and simulated Baseline model is 0.6 °C. Due to such differences, the new EPW file representing the actual Aceh climate might give better accuracy. The minimum and maximum daily temperature for Aceh was obtained from climate reports published in a website[5]. The best climate reports for Aceh were found from the year 2013 and up to the present.

The local weather data becomes a crucial variable for the simulation input. However, creating an executable EPW file for E+ is not a straightforward process. To have a proper and complete set of weather data is, unfortunately beyond the research's scope. Alternatively, a complete weather data for Aceh province can be created based on the Penang weather file by using a weather file editor. Not only the relative humidity and local temperature were successfully obtained, E+ also read and calculate other variables such as wind speed and solar radiation.

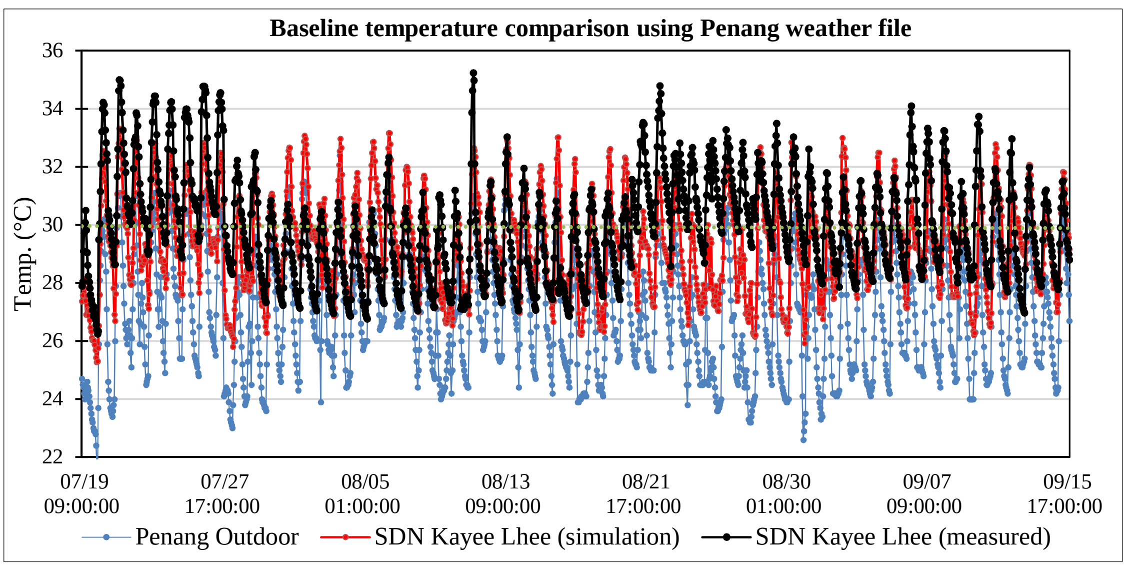


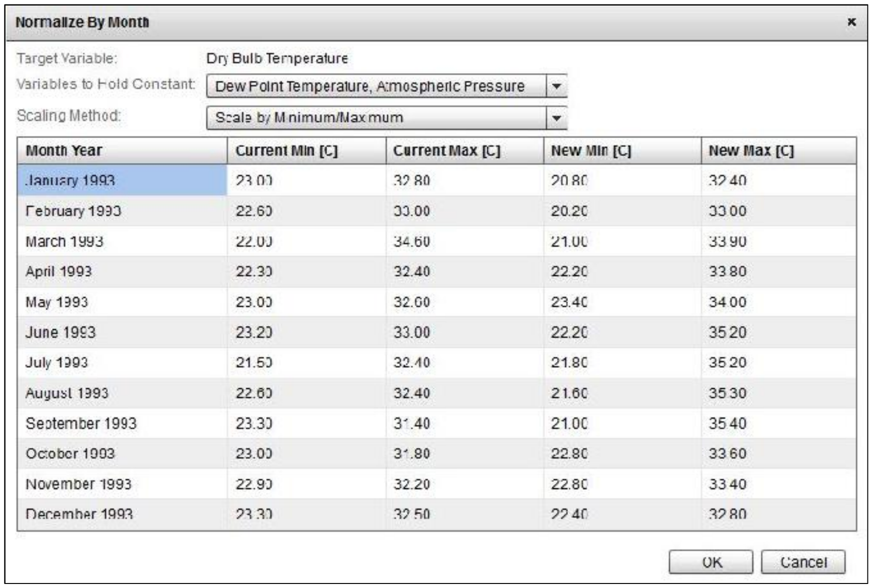
Figure 4.14: Baseline simulation result using Penang weather file

A weather file editor software called Elements is available at no cost[6]. Elements was used to create an EPW file in which the hourly temperature can be changed according to measured outdoor temperature in Aceh. Unfortunately, the period of observation was performed for only 2 months. Therefore, to study the total of Disc. Hours in one year, annual data from a weather station located in Blang Bintang, Aceh

[5] http://www.wetter.com/wetter_aktuell/rueckblick/?id=IDXXX0095

[6] http://bigladdersoftware.com/projects/elements/

Besar district was used. The database consists of minimum and maximum of daily temperature from 1st January 2013.



Normalize By Month

Target Variable: Dry Bulb Temperature

Variables to Hold Constant: Dew Point Temperature, Atmospheric Pressure

Scaling Method: Scale by Minimum/Maximum

Month Year	Current Min [C]	Current Max [C]	New Min [C]	New Max [C]
January 1993	23.00	32.80	20.80	32.40
February 1993	22.60	33.00	20.20	33.00
March 1993	22.00	34.60	21.00	33.90
April 1993	22.30	32.40	22.20	33.80
May 1993	23.00	32.60	23.40	34.00
June 1993	23.20	33.00	22.20	35.20
July 1993	21.50	32.40	21.80	35.20
August 1993	22.60	32.40	21.60	35.30
September 1993	23.30	31.40	21.00	35.40
October 1993	23.00	31.80	22.80	33.60
November 1993	22.90	32.20	22.80	33.40
December 1993	23.30	32.50	22.40	32.80

OK Cancel

Figure 4.15: Screenshot of ‘Normalize by Month’ window in Elements

The average monthly maximum and minimum recorded from 2013 until present in the database were then inputted into Elements. Other variables, such as wind speed, solar radiation, and relative humidity were automatically altered by the software using a function called Normalization. Once the annual weather data was normalized, the newly reproduced EPW file can be used by E+. Normalization is a process in which a monthly Min and Max Temperature from Blang Bintang weather station was inputted in the New Min and New Max column, as shown in Figure 4.15.

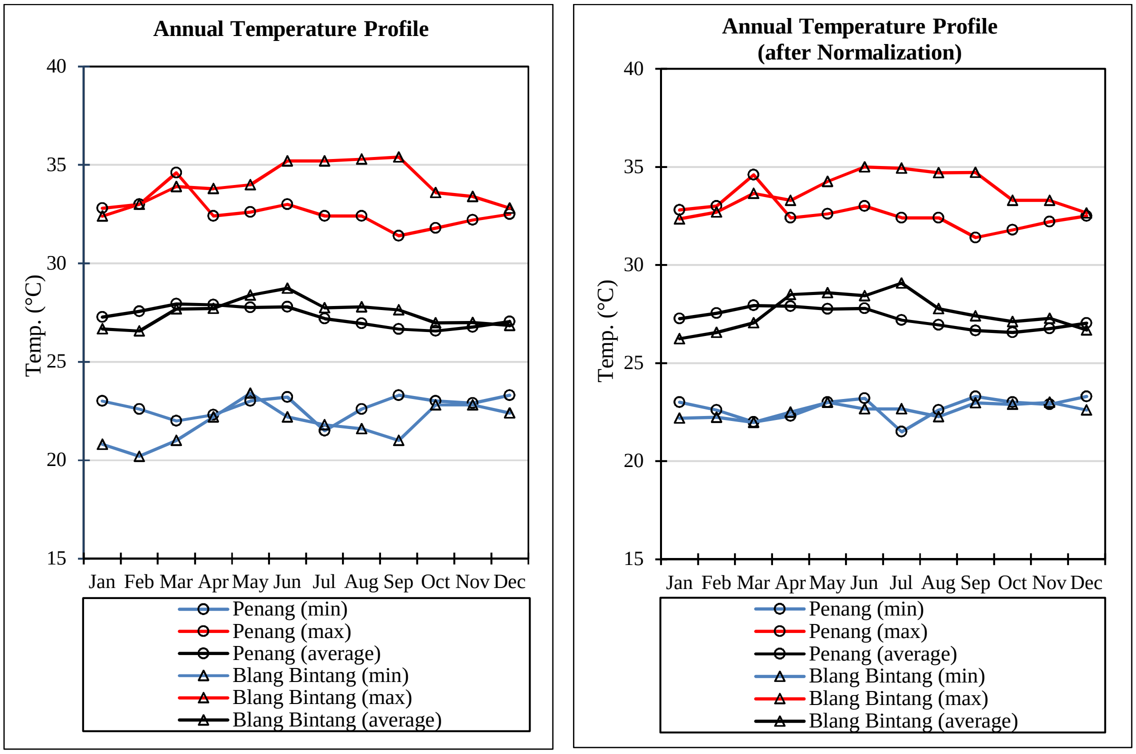


Figure 4.16: Comparison of annual temperature between Penang and Blang Bintang weather station.

The results of the normalized weather file are presented in Figure 4.16 and Table 4.8. The Min, Max, and Average value of Penang weather data can be obtained directly from the EPW file. For Aceh weather file, the hourly temperature data for one year can only be obtained after conducting the normalization process in Elements software. Elements was able to produce a normalized hourly temperature based on the inputted Minimum and Maximum at each month. After the new hourly temperature was obtained, a new EPW file was created and ready for use by E+.

Table 4.8: Comparison of Penang and Blang Bintang temperature

Month	Penang			Blang Bintang			Blang Bintang *)		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Jan	23.00	32.80	27.27	20.80	32.40	26.68	22.20	32.35	26.24
Feb	22.60	33.00	27.55	20.20	33.00	26.56	22.24	32.70	26.56
Mar	22.00	34.60	27.94	21.00	33.90	27.68	21.98	33.65	27.05
Apr	22.30	32.40	27.90	22.20	33.80	27.71	22.50	33.30	28.49
May	23.00	32.60	27.76	23.40	34.00	28.39	23.00	34.27	28.59
Jun	23.20	33.00	27.78	22.20	35.20	28.74	22.67	35.00	28.44
Jul	21.50	32.40	27.20	21.80	35.20	27.74	22.67	34.93	29.08
Aug	22.60	32.40	26.94	21.60	35.30	27.78	22.27	34.70	27.78
Sep	23.30	31.40	26.66	21.00	35.40	27.64	22.97	34.73	27.41
Oct	23.00	31.80	26.56	22.80	33.60	26.98	22.90	33.30	27.11
Nov	22.90	32.20	26.77	22.80	33.40	27.00	23.00	33.30	27.28
Dec	23.30	32.50	27.04	22.40	32.80	26.84	22.60	32.65	26.69
Yearly average	22.73	32.59	27.28	21.85	34.00	27.48	22.58	33.74	27.56

Remarks: *) After normalization

The overall differences are shown in Figure 4.17. Those include the 5%, 50%, and 95% quantiles of the temperature distribution for Penang and Aceh Besar climate. This graph emphasizes the increase in the temperature range between 50% and 95% quantiles for Aceh Besar climate.

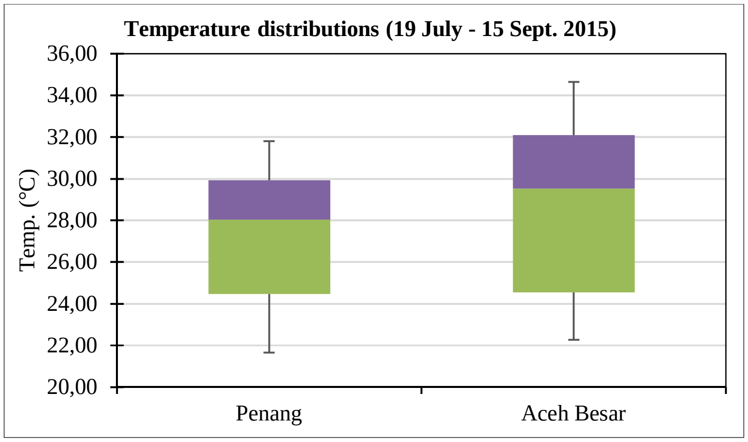


Figure 4.17: The 5%, 50% and 95% quantile plot of DBT distribution for each location

Table 4.9: Minimum, maximum, 5%, 50% (Median) and 95% quantiles of DBT from two locations

Weather data	Minimum	5% Quantile	Median	95% Quantile	Maximum
Penang	21.65	24.48	26.5	30.07	31.95
Aceh Besar *)	22.27	24.55	27.16	32.15	34.70

Remarks: Aceh Besar is the name of the region where the Blang Bintang weather station is located

The whiskers in Figure 4.17 shows the maximums and minimums in comparison to the quantile ranges for each climate. From this graph, it is evident that the maximum temperature is higher than Penang EPW file. Therefore, by using Blang Bintang EPW file for the whole simulation, better accuracy is expected because the inputs for the normalization process in Elements were taken from published data from Blang Bintang weather station.

4.2.1.2 Construction Elements

To perform building thermal simulation, data about the building geometry, weather data, orientation of building, and thermal properties of building materials must be available at hand (Crawley *et al.*, 2001). Building model in E+ comprises of type of building materials and the composition of materials, so called constructions of material. Furthermore, building surfaces are specified using geometrical coordinates as well as referenced constructions (Lawrence Berkeley National Laboratory, 2005). Essentially, a building model for simulation using E+ is broken down following a hierarchical pattern as depicted in Figure 4.18.

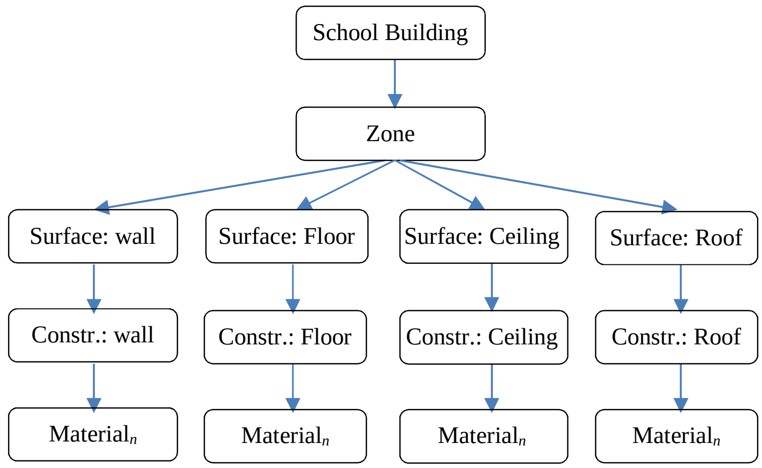


Figure 4.18: Hierarchy of school building element in E+

The case study school building was modeled following the hierarchy in Figure 4.18. The bottom of the hierarchy is Material$_n$, meaning that more than one material can be assigned to the construction element. The material assignment shall be in the order of 'outside' to 'inside'. The term 'outside' means that the layer is furthest away from the zone. 'Inside' means that the layer is next to the zone. For example, the walls contain three layers (plaster-brick-plaster) on its construction. The floor has two layers, which are tiles and mortar beneath the tiles. Other construction only has one layer, such as the ceiling and roof. Each material has thermal, physical, and optical properties based on the laboratory's test. Using the database of material properties in E+ combined with sources from ASHRAE-55 (2005), a database of materials for this specific case study building was created complete with all physical and thermal properties of materials required by the simulation. Table 4.10 shows the list of all materials and their properties.

Table 4.10: List of material input in the simulation

Construction Elements	Material name	Roughness	Thickness (m)	Conductivity (W/m-K)	Density (kg/m^3)	Specific Heat J/kg-K
Floor	Ceramic tile_7 mm*	Smooth	0.007	0.84	1900	800
	Granite tile_10 mm	Smooth	0.01	2.9	2650	900
	Mortar for tiles_20 mm*	Medium Rough	0.02	3.4	2080	840
Wall	Brick_100 mm*	Medium Rough	0.1	0.27	950	840
	Concrete Hollow Block_10 mm	Medium Rough	0.1	0.812	1618	837
	Plaster_25 mm*	Medium Smooth	0.025	0.721	1858	837
Ceiling	Gypsum_9.5 mm	Medium Smooth	0.0095	0.58	800	1090
	Cement Board_6 mm*	Medium Smooth	0.006	0.388	1276	897
	Plywood_6.4 mm	Medium Smooth	0.0064	0.12	540	1210
Roof sheeting	Aluminum sheeting*	Smooth	0.0008	45.28	7824	500
	Clay tile	Medium Rough	0.02	0.84	1900	800
	Cement tile	Medium Rough	0.02	0.36	1050	700

*) Asterisks denotes the material used in the Baseline model

The material properties data, as shown in the table above, are common in the field of building simulation. Therefore, those material property data were also used by E+ in this research. For better simulation accuracy, the database of material must be sourced from factual material data or from laboratory studies. Unfortunately, data or information concerning the thermal properties of materials produced in Indonesia is not yet available.

4.2.1.3 Combination of Material

JE Plus software was used to combine all materials used in the model. By utilizing JE Plus, the result of the combination of materials was easier to collect. This is because all building materials were organized in the form of a parameter tree. The parameter tree in JE Plus is presented in Figure 4.19 below.

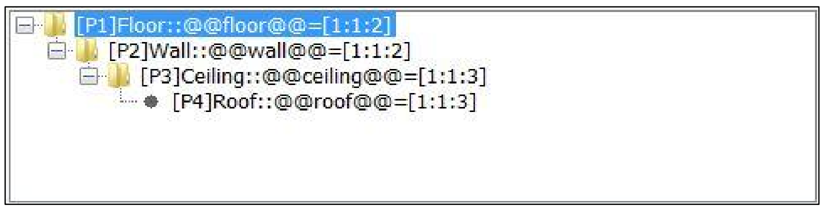


Figure 4.19: Screenshot of the parameter tree for the combination of material

The parametric run was done using a discrete parameter, which means that JE Plus directly call E+ material database, which was previously prepared. For example, the roof has three combinations of material. This was written in JE Plus as [1:1:3], which means that in the case of a school building, the first material (whatever it is) is tagged as one (1), with the increment value of one (1) until maximum three (3) materials.

As mentioned, the properties of materials as listed in Table 4.10 was taken from E+ material object database. In order to meet the research objective, it is not imperative to alter each property, because the construction elements and material used in the Baseline models are the same for all three types of designs. The simulation run has been successful and reveals important results. As discussed briefly in Section 3.3, the combination of all materials was executed by JE Plus software. A pre-prepared IDF file had to be converted to *.imf (IMF file) so that JE Plus can read this file. On the top row of the script of IMF file which basically contains code from the IDF file of E+, the following instruction or macro command was written in JE Plus interface.

```
##fileprefix C:\Users\Hamdi\Documents\SIMULATION_BASELINE\JE_Plus_Baseline\PCM
material_Final
##include floor@@floor@@.idf
##include wall@@wall@@.idf
##include ceiling@@ceiling@@.idf
##include roof@@roof@@.idf
```

Figure 4.20: Typical macro command

Such techniques were originally introduced by Zhang (2010). He mentioned that by writing a macro command inside the IMF file, a better performance running multiple inputs using the same IMF file could be achieved. These macros will read the routine, which is written in the new IDF file. This new IDF file is basically also part of a routine in the IMF file. Therefore, to mitigate the errors, the used routine in the IMF file must be deleted. An alternate approach is introduced so that the combination of material becoming simple. Each construction element with its corresponding material object was grouped into one IDF file. The creation of one IDF file for each construction element and material is more informative if current material properties need to be altered or modified in the future. This means that each layer of materials can be easily identified to which construction element they belong. Figure 4.21 shows in detail the construction of the ceiling was grouped together with the property of the cement board ceiling as one IDF file.

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========

Material,
    cement board_ceiling,     !- Name
    MediumRough,              !- Roughness
    0.006,                    !- Thickness {m}
    0.388,                    !- Conductivity {W/m-K}
    1276,                     !- Density {kg/m3}
    897,                      !- Specific Heat {J/kg-K}
    0.9,                      !- Thermal Absorptance
    0.7,                      !- Solar Absorptance
    0.7;                      !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========

Construction,
    Interior Ceiling,         !- Name
    cement board_ceiling;     !- Outside Layer
```

Figure 4.21: Preview of material type and properties in Notepad as a single IDF file

As can be seen in Figure 4.21, the property of material and the construction type were written as a single IDF file. This IDF file can be opened by using Notepad software. This means that current material property can be modified or other new material can also be created and saved using Notepad, thus providing greater flexibility for future use in the model. Therefore, the total IDF files for materials to be executed by the macro in JE Plus were ten files. Table 4.11 shows the name of the material used except Mortar for tiles_20 mm and Plaster_25 mm, which was grouped under Floor and Wall construction elements, respectively. For example, the Floor consists of ceramic tile 7 mm, and mortar_20 mm is grouped as one construction element, and these are counted as one IDF file. Another type of construction element is Floor, which consists of granite, as well as mortar underneath, is accounted as one IDF file. The coding system was then introduced to differentiate each material for the purpose of the parametric simulation executed by JE Plus.

Table 4.11: Material code numbering in JE Plus

Construction elements	Material name	Code number
Floor	Ceramic tile_7 mm*	1
	Granite tile_10 mm	2
	Mortar for tiles_20 mm*	-
Wall	Brick_100 mm*	1
	Concrete Hollow Block_10 mm	2
	Plaster_25 mm*	-
Ceiling	Gypsum_9.5 mm	2
	Cement Board_6 mm*	1
	Plywood_6.4 mm	3
Roof sheeting	Aluminum sheeting*	3
	Clay tile	2
	Cement tile	1

*) Asterisks denotes the material used in the Baseline model

The simulation was executed from JE Plus and the result of all material combinations for one design type (Baseline model) was exported into one Excel file. Table 4.12 shows part of the matrix exported by JE Plus in MS. Excel.

Table 4.12: Material combination of the Baseline model

#	Job_ID	@@floor@@	@@wall@@	@@ceiling@@	@@roof@@
0	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_0	1	1	1	1
1	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_1	1	1	1	2
2	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_2	1	1	1	3
3	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_0	1	1	2	1
4	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_1	1	1	2	2
5	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_2	1	1	2	3
6	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_0	1	1	3	1
7	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_1	1	1	3	2
8	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_2	1	1	3	3
…					
35					

As can be seen from Table 4.12, that one typical design with one orientation produced 36 design alternatives with a unique combination of material. The time spent on the simulation of one typical design was approximately 24 seconds. At the end of the simulation process, E+ sometimes reported one or more errors. The simulation process can still run and produce results with reported errors. Therefore, the simulations were performed repeatedly until no errors were reported by E+. Hence, the method developed by organizing each material relative to its construction in a single IDF file was successful. The effect of various orientation was also investigated, which further explained in Section 4.2.2.1 (a).

4.2.2 Results and Validation of Simulated Indoor Temperature

To verify the accuracy of indoor temperature from the output of simulation, actual temperature collected from data logger device was compared. Direct measurement was carried out by placing one temperature data logger at the wall in each classroom. Figure 4.22 shows the position of the data logger device.

This measurement of actual temperature aims to answer the second questions of this research. The simulation modeling schema enables a direct comparison between simulated and measured indoor temperature. A data logger device (Onset HOBO UX100-011) was used to get an hourly indoor temperature. The size of this device is quite small, measuring at 3.66 × 8.48 × 2.29 cm. It will record hourly temperature and relative humidity inside the classrooms. The measurement results will be compared to the simulation output. The indoor temperature measurement data from the actual school building will be used to verify the accuracy of simulated indoor temperature value.

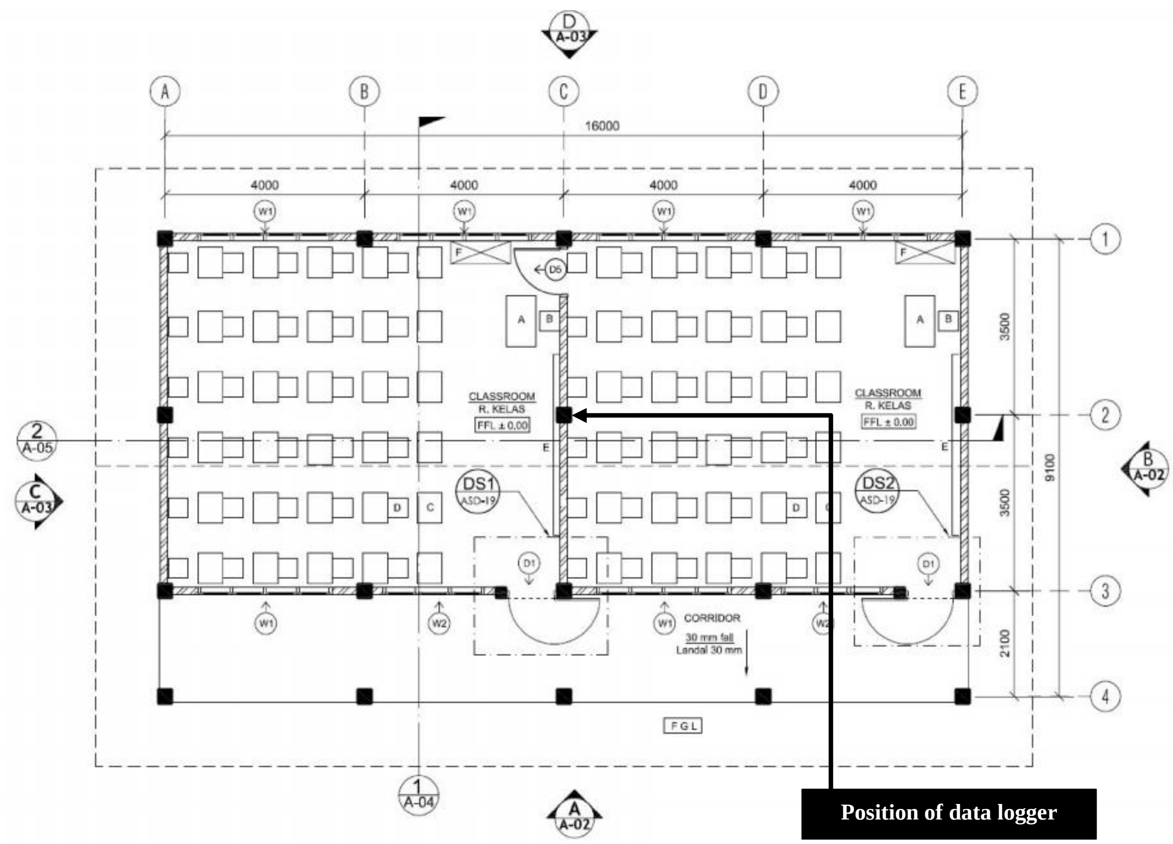


Figure 4.22: Placement of temperature data logger

The temperature data logger should ideally be placed at the height of 1 (one) meter from the finished floor. Such height basically represents the height of the students while sitting in the classrooms. However, to prevent obstruction from the children, the device was attached to the wall at a height of 1.5 meters above the floor. The ideal and safe location for installation will be on the partition wall between the two classrooms. As mentioned, two temperature data loggers were placed at SDN Kayee Lhee and MIN Bukloh. These two schools have the different ceiling height, as shown in Table 4.1. Regarding the students' personal conditions, metabolic rate and clothing value based on ASHRAE-55 (2010) were considered as two important parameters to use for estimating the students' comfort.

The actual hourly temperature obtained from MIN Bukloh and SDN Kayee Lhee was compared to the simulated indoor temperature, which is presented in Figure 4.23 and Figure 4.24, respectively. Comparative analysis of MIN Bukloh (Figure 4.22) shows that the temperature from the simulation was mostly hotter during the daytime, but it is slightly cooler during nighttime compared to the measured temperature. The average maximum temperature from the simulation of MIN Bukloh is 31.34 °C, while the average maximum temperature from the measurement was recorded at 30.28 °C. The average minimum is 25.24 °C (simulation) and 25.86 °C (measured). This variation was caused by many variables involved in both the result of simulation and actual measurement. For example, the normalized EPW weather file use for simulation consist of variables such as wind speed, humidity, solar radiation etc., which are not exactly the same from the local climate during the period of observation. When comparing the result of simulation and measured temperature to the outdoor temperature, it is found that the indoor temperature from the simulated school tends to follow the pattern of outdoor temperature throughout the day. This means that the simulation produced a sensitive temperature output based on the inputted weather file. However, the presence of a brick-wall, which has a high thermal capacity, is able to minimize the variation or diurnal outdoor temperature. In the daytime, the simulated indoor temperature was found to be cooler than the outdoor temperature. At nighttime, simulated indoor temperature was hotter than the outdoor temperature. This phenomenon explains the influence of thermal mass used in the school, in which it absorbs the heat during the daytime and then releases the heat again during nighttime. The use of brick-wall having a high thermal capacity is more noticeable from the result of actual measurement. As shown in Figure 4.23, the measured temperature inside the classrooms does not vary significantly to the outdoor temperature.

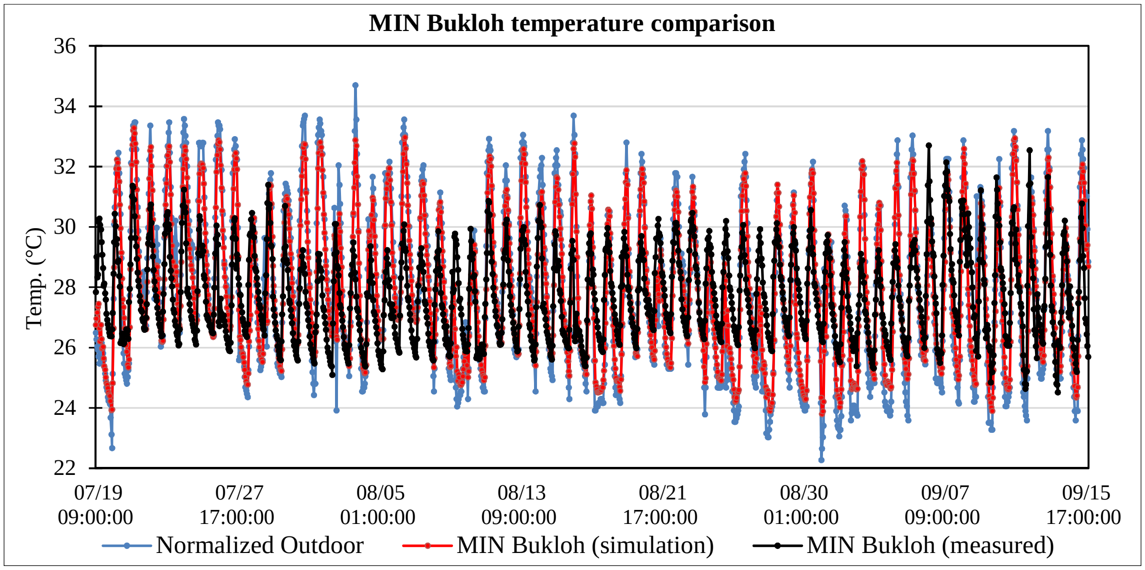


Figure 4.23: Comparison of measured and simulation result of MIN Bukloh

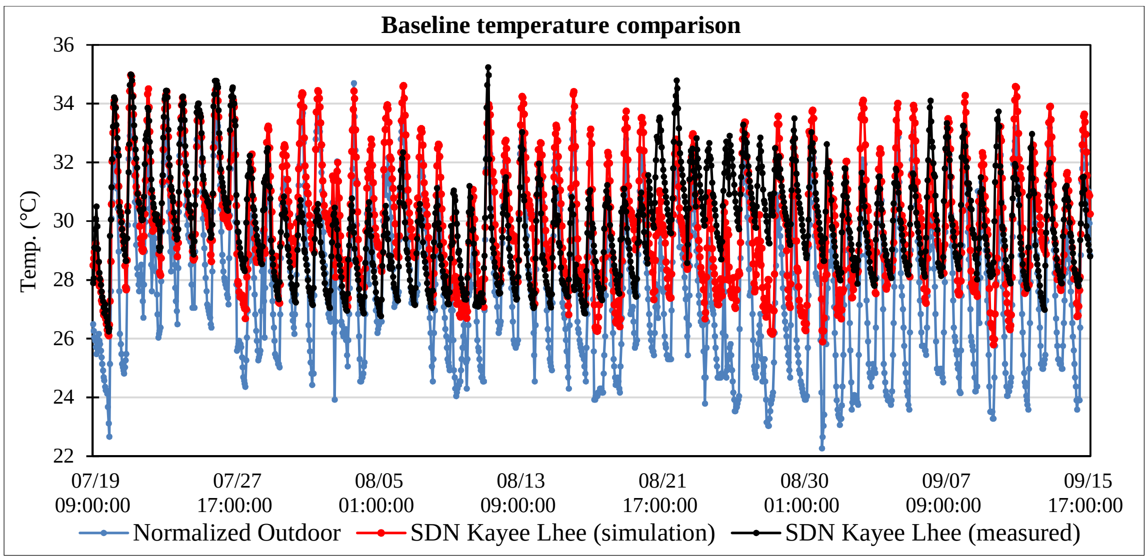


Figure 4.24: Comparison of measured and simulation result of the Baseline model

A different result was detected from the simulation of SDN Kayee Lhee (Figure 4.24). The simulation result shows that indoor temperature is not sensitive to the outdoor temperature changes. The indoor temperature is hotter from DBT during the daytime and nighttime. In this case, the ceiling of SDN Kayee Lhee is only 3 meters high compared to MIN Bukloh of 4 meters. Lower ceiling placement forces the louvers positioning even lower. This is because the ceiling was installed at the top edge of the concrete beam or lintel beam. Hence, the ventilation process in and out of the classroom was not optimum because the prevailing wind normally flows at a higher altitude. Furthermore, the small gap between each wood slate at the louver also contributes to hotter indoor temperature, which makes it difficult for air circulation inside the classroom to dissipate the heat. Observation from actual measurement also shows that SDN Kayee Lhee experiencing hotter indoor temperature during the daytime, but with an irregular pattern compared to the simulated case. Again, this happened due to the variability of the local climate. Comparison of both actual temperature measurements from these two schools is presented in Figure 4.25. It is clearly shown from the figure that a higher indoor temperature was recorded from the measurement SDN Kayee Lhee compare to measured temperature in MIN Bukloh. It is also observed that SDN Kayee Lhee experiencing higher irregularities compare to the MIN Bukloh. This explains that with the small room volume that SDN Kayee Lhee has, there is little buffer inside the classroom to anticipate or minimize the variation of DBT at the location of this school.

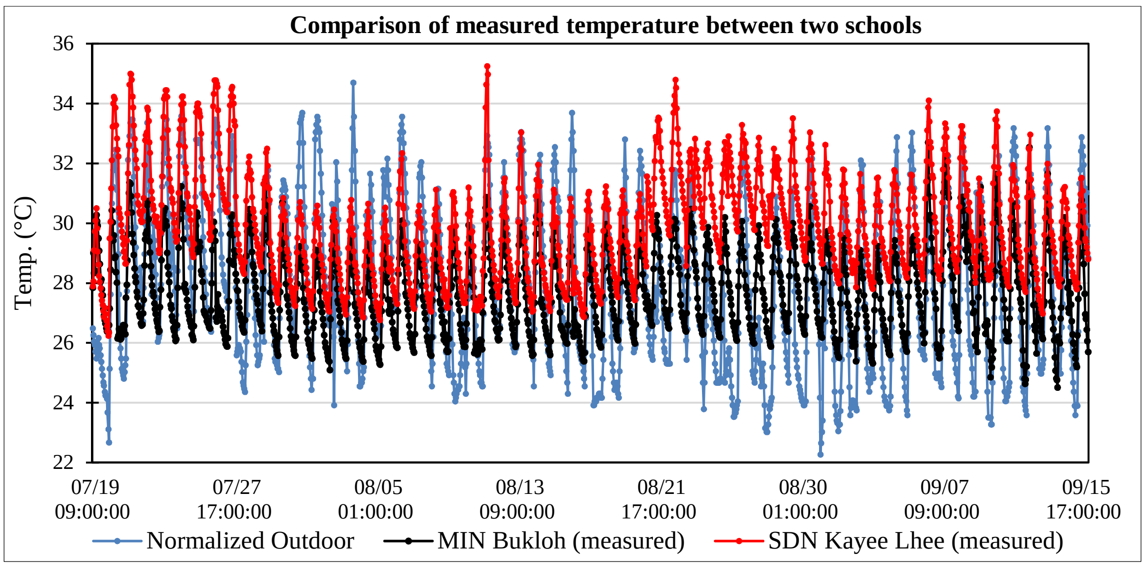


Figure 4.25: Comparison of measured temperature between MIN Bukloh and Baseline model

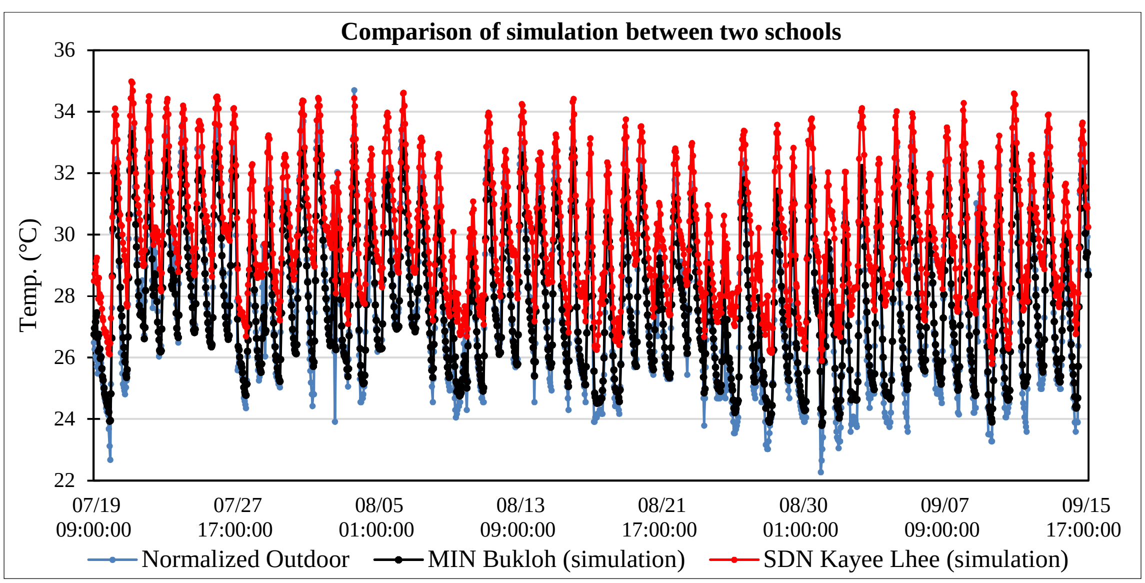


Figure 4.26: Comparison of simulated temperature between MIN and Baseline model

For the simulation case, SDN Kayee Lhee also produced a higher temperature compared to MIN Bukloh (Figure 4.26). The figure shows that both cases (measured and simulated) also yield higher indoor temperature at SDN Kayee Lhee. For the case of actual measurement, the average indoor temperature of SDN Kayee Lhee and MIN Bukloh is 29.93 °C and 27.73 °C, respectively. For the case of simulation, the average temperature of SDN Kayee Lhee and MIN Bukloh was 30.02 °C and 27.93 °C respectively. The deviation between the measured and simulated temperature of SDN Kayee Lhee is 0.09 °C during the period of observation, while for MIN Bukloh, the deviation between the simulation results and actual measurement was 0.2 °C. The results of simulations from both schools provide quite accurate indoor temperature. Therefore, the procedure of simulation presented in the research is reliable enough to study the impact of design alternatives, because the primary focus is only during the school hours (from 08.00 AM until 01.00 PM), which has a minor variation on the outdoor temperature.

4.2.2.1 Comparison of Various Models

a. Effect of orientation to indoor temperature

A simulation was performed to evaluate the effect of orientation using the Baseline model. It was found that the orientation of West - East (the long façade facing North) was higher, especially from 09.00 AM - 10.30 AM compared to the North-East orientation during the same hours. The difference is however, negligible as the yearly average for the West - East orientation is 29.77 °C compare to the North - East orientation of 29.75 °C.

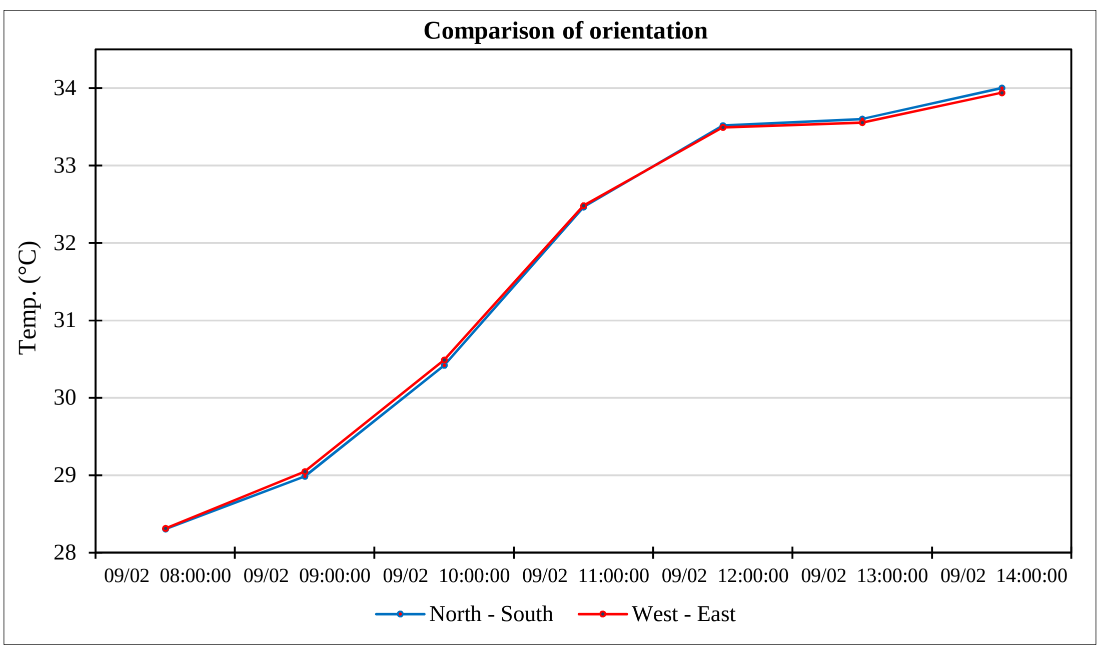


Figure 4.27: Simulated indoor temperature according to the Baseline model's orientation

Although the direct sunlight hit the wall, as it can be seen in Figure 4.7, the wall which made of clay bricks and plastered at both sides, has a high thermal capacity, thus does not affect the increase of heat significantly inside the classroom.

b. Effect of material combination to indoor temperature

The baseline model was used as a reference point to understand and evaluate the impact of the material combination on indoor temperature. A variety of roof material is compared for this Baseline model because walls are shaded almost entirely by roof.

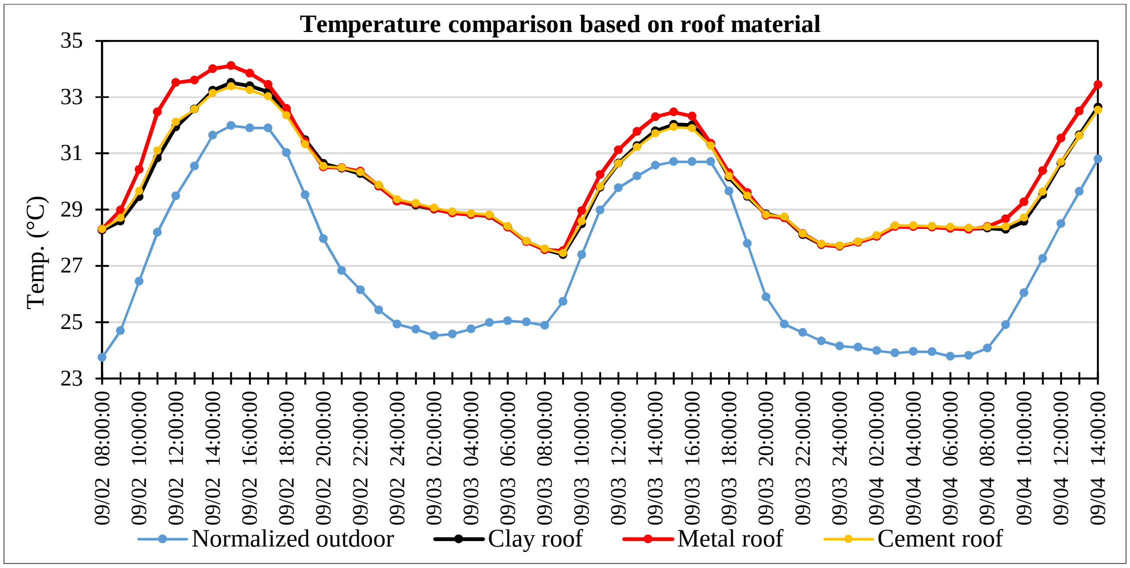


Figure 4.28: Temperature profile based on roof material combination of the Baseline model

As shown in Figure 4.28, the temperature does not change significantly after varying roof material. This showed that the wall is mostly shaded by the large overhang. In addition, the presence of ventilation at both edges of the gable are able to dissipate the heat more quickly. Thus, the temperature in the roof space does not affect too much by different roof material. Liping and Hien (2007) used a thermal analysis software to investigate the ventilation effect during nighttime, daytime, full-day, and without ventilation with different materials in the building envelope. Their research was performed in buildings located in Singapore and classified as a hot and humid region. They also concluded that the combination of materials did not significantly affect the indoor temperature. Research on natural ventilation has confirmed that to some extends, fixed ventilation openings can maintain a comfortable temperature in hot and humid climates. Another comparison of school design was made to Design Type 3. With the same ceiling height of 3 meters, this type of school uses a hip type roof model where all walls are fully shaded. Unlike the gable roof, which has ventilation at both edges, the hip roof model does not.

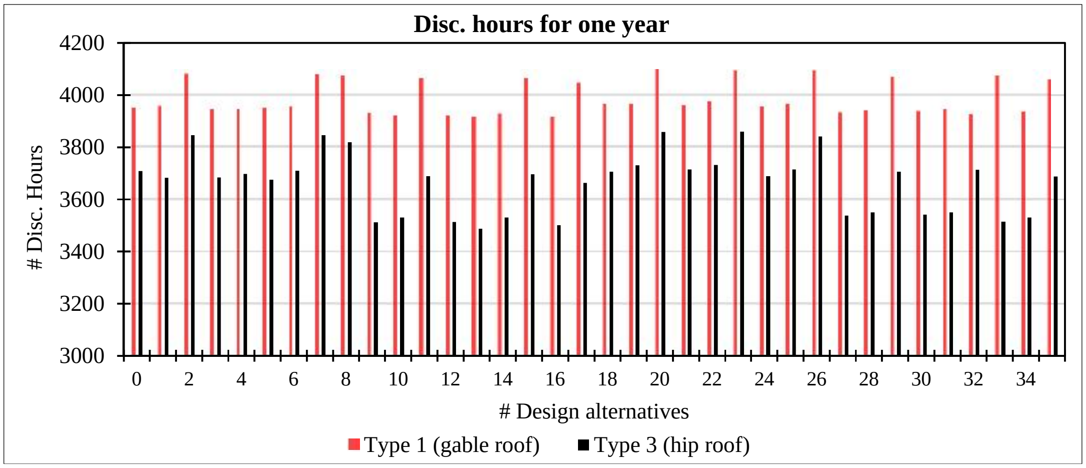


Figure 4.29: Total Disc. Hours for one year (Type 1 and Type 3)

Therefore, based on the results of the two simulated models, it is suggested to place louvers directly on building facades at the highest position as possible for thermal comfort improvement.

4.2.2.2 Discomfort Hours from Simulation Output

All simulations performed in this research focused on studying the operative temperature (OT) inside the classroom because students' comfort temperature is critically important in the classroom. Each zone in the school model was loaded with relevant properties to simulate the actual classroom's space. Several design values were inputted to E+, such as the number of students, total clothing values, activity levels, and the learning schedule. The hourly temperature values from E+ simulation output was exported to MS. Excel. Using MS. Excel as a platform, calculation of discomfort hours during the occupied time can be done using Equation 4.3, as suggested by Hwang and Tsai (2007).

$$\text{Overheated hours} = \sum_{i=1}^{N} \Delta t_i \quad f \quad P \quad \geq 0.5 \qquad (4.3)$$

However, Equation 4.3 only calculates the Disc. Hours beyond the upper limit of the sensation scale, which is more and equal to 0.5. For this research, the definition of Disc. Hours is "the number of hours within the three central sensation scales", thus the equation below was used:

$$\text{Discomfort hours} = \sum_{i=1}^{N} \Delta t_i \quad , whe \quad \leq -1\, T \quad \leq +1 \qquad (4.4)$$

The temperature range (Δ_t) for the particular TSV value was obtained based on the findings from the thermal comfort survey, as presented in Section 4.1.2.2.

The total of Disc. Hours were calculated using Equation 4.4. The recorded actual temperature outside -1 (comfortably cool) and +1 (comfortably warm) at a given time was counted as one. This involved a tedious filtering process in MS. Excel where each temperature value from a yearly simulation output that falls below 26.33 °C and above 29.64 °C was counted for every design alternative.

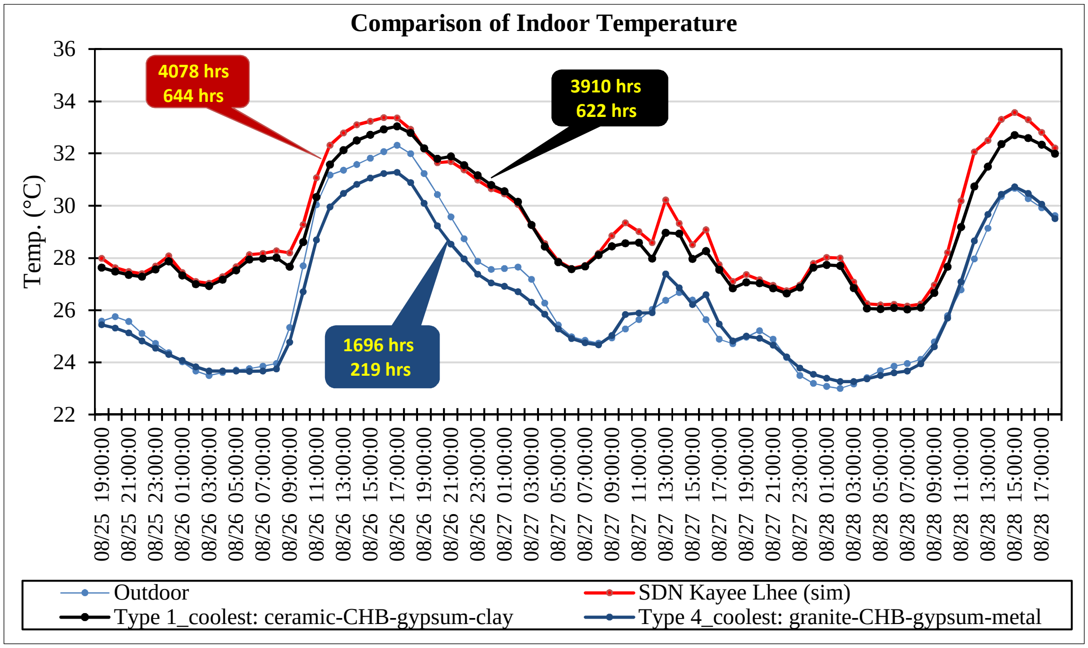


Figure 4.30: Comparison of total discomfort hours between Type 1, Type 4 and Baseline model

Figure 4.31 shows the total of Disc. Hours extracted from an hourly simulation result. It can be seen that Design Type 1, which has a type of gable roof, produce a slightly higher temperature than Design Type 3, which has a hip type of roof. This explains that during the school hours, the direct solar path which comes from an angle, is blocked by the large overhang provided by the type of hip roof. However, analysis for the whole year shows that this type of hip roof provides significant cooler indoor temperature (Figure 4.29). This is reasonably understandable because the actual Baseline model, which is a member of Design Type 1 is facing the North thereby walls at both sides are mostly exposed to the sun radiation before and after 12.00 AM. Analysis has been made to compare the effect of orientation of this Baseline model, as described in Figure 4.27. There was no significant temperature reduction if the Baseline model is simulated to face the West. This is also not unpredictable because the location of this school is not exactly on the equator. Thus at least one side of the building is exposed to the sun. That is why Design Type 3 provides a cooler temperature compared to Design Type 1.

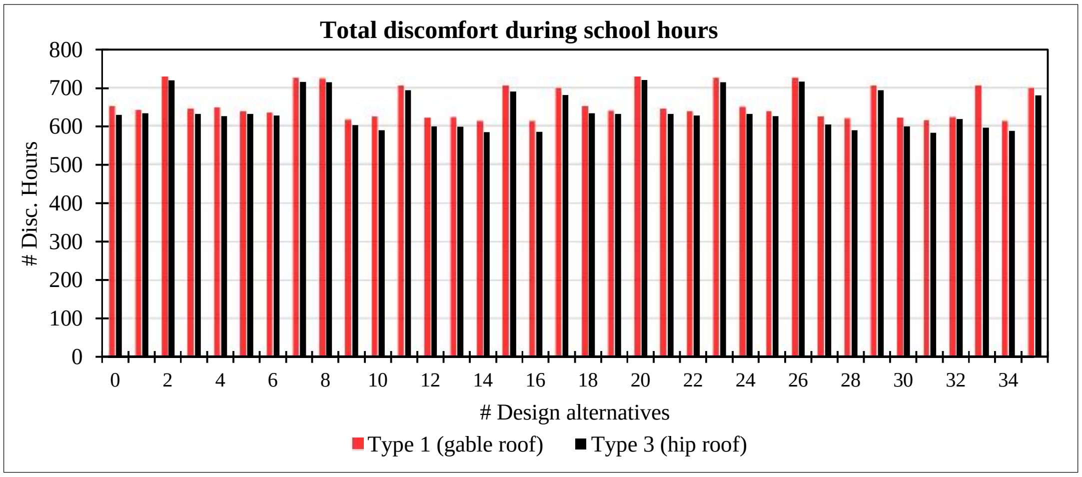


Figure 4.31: Total discomfort hours during lesson's hours (Type 1 and Type 3)

Figure 4.32 shows that a much lower Disc. Hours was produced by Design Type 2 and Design Type 4. Being modeled as the same shape of Design Type 2 (MIN Bukloh), all material combinations from Design Type 4 provides cooler indoor temperature all the year. On this type, the louver was positioned higher than Type 2, providing a stack effect inside the classroom. Detail construction of this type of louver for Design Type 4 is given in Appendix 4.5.

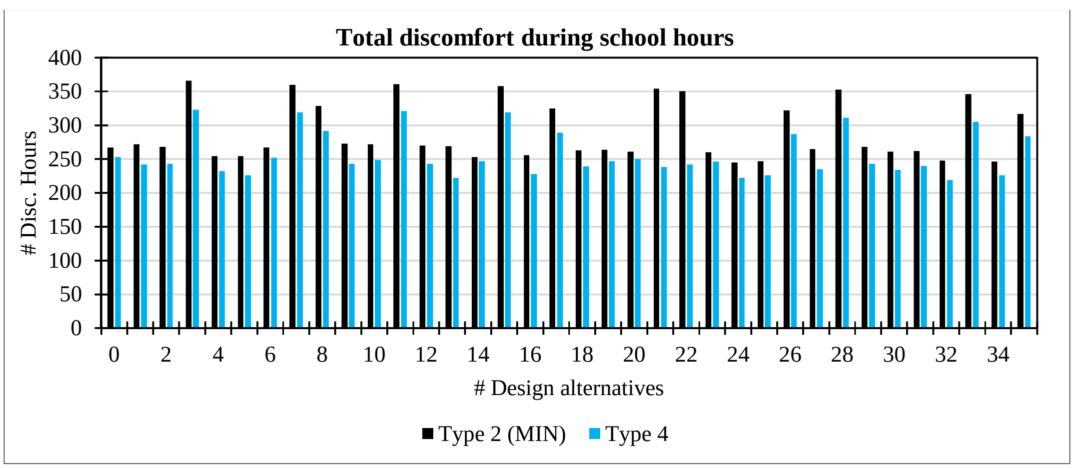


Figure 4.32: Total discomfort hours during lesson's hours (Type 2 and Type 4)

4.2.3 Building Cost Analysis

Evaluation of cost was made only to the initial cost. Initial cost is the cost of the direct purchase of material from material suppliers. It already includes the transportation cost and installation cost at the project site. This method of cost calculation is in accordance with the cost estimation procedure under the Indonesian Standard of Cost Planning (SNI) issued by The Indonesian National Standardization Agency during the preliminary design stage[7]. According to this standard;

$$\text{Initial cost (IDR)} = \text{unit rate analysis per-m}^2 \text{ (IDR)} \times \text{total area (m}^2\text{)} \quad (4.5)$$

The total area of a particular building element was taken from the Bill of Quantity data of the original project documents. The cost of each material and manpower was obtained from the project document as well. Therefore, the same unit rate of work was used to calculate the total cost of each design alternative. Table 4.13 presents an example of the unit rate analysis for 1 m^2 ceramic tiles.

Table 4.13: Unit rate analysis

SNI 7395:2008	1 m^2 ceramic floor tile 30 x 30 cm	Unit	Quantity *)	Price (IDR)	Total (IDR)
	Materials				
	Ceramic	piece	11.870	3,836	45,538
	Portland cement (40 kg)	kg	10.000	2,240	22,400
	Sand	m^3	0.045	114,500	5,153
	Coloured cement	kg	1.500	4,428	6,642
	Manpower				-
	Labour	man-day	0.700	50,000	35,000
	Skilled labour	man-day	0.350	80,000	28,000
	Leader	man-day	0.035	95,500	3,343
	Foreman	man-day	0.035	71,500	2,503
			Cost for 1 m^2 ceramic tile (IDR)		146,075

Remarks: Quantity in the project document equals to the quantity in the Indonesian National Standard (SNI 7395:2008)

[7] *Badan Standardisasi Nasional (BSN)*. The Indonesian National Standardization Agency. Retrieved from : https://pesta.bsn.go.id/produk/by_ics?ics_no=91&key=

Table 4.14: Initial cost of the Baseline model

Works Items	Quantity		SNI code *)	Unit rate (IDR)	Total (IDR)
<u>Brick Masonry Work</u>					
Brick wall 1:2 (1/2 brick)	15.288	m2	SNI 6897:2008	114,056	1,743,680
Brick wall 1:4 (1/2 brick)	104.6598	m2	SNI 6897:2008	97,711	10,226,414
Internal & External plaster 1:2	30.576	m2	SNI 2837:2008	54,697	1,672,408
Internal & External plaster 1:4	200.2196	m2	SNI 2837:2008	46,231	9,256,272
<u>Roof covering</u>					-
Metal roof sheeting	224.28	m2	SNI 3434:2008	203,528	45,647,260
<u>Ceiling Work</u>					-
GRC board exterior-6 mm	103	m2	SNI 2839:2008	130,487	13,440,136
GRC board interior -6 mm	112	m2	SNI 2839:2008	130,487	14,614,517
<u>Floor</u>					-
Ceramic Tile-30 x 30 cm	109	m2	SNI 7395:2008	146,075	15,922,135
<u>Architectural Work</u>					-
Window	23.5248	m2	LS	175,000	4,116,840
Ventilation	14.896	m2	LS	75,000	1,117,200
Door	8.2314	m2	LS	300,000	2,469,420
Grand Total					120,226,283

Remarks: *) SNI stands for *Standar Nasional Indonesia* (The National Indonesian Standard)

The calculation of initial cost follows the procedure as normally applied in government-financed projects in Indonesia. Table 4.14 shows an analysis of the initial cost from the Baseline model.

The unit rate per-$m^{2,}$ which was obtained using Equation 4.5, was multiplied by the quantity of each building element to yield the total cost. Hence, the provision of a decision matrix in the framework will not change the current cost estimation method as normally adopted by Design and Engineering Consultant in Indonesia.

4.2.4 Ecological Performance of Material

The EE and CO_2 emission data of building materials used in the case study schools were taken from the Inventory of Carbon and Energy (ICE) database (Hammond and Jones, 2008). It is a freely available Life Cycle Inventory (LCI) data based on the cradle to gate process. LCI as defined by Verbeeck and Hens (2010) is the calculation of energy from raw materials of the particular manufacturing process of the product on a per-unit basis with a predefined system boundaries. Table 4.15 shows the quantity of CO_2 and EE of each material for all building elements.

As shown in the table that transportation distance from the materials' factory to the construction site was estimated. Almost all materials are transported about 600 km from North Sumatera Province, while cement, sand, clay, and concrete hollow brick (CHB) are produced locally.

Table 4.15: Ecological performance data of common building materials

		Floor				Wall			Ceiling			Roof		
		Ceramic	Granite	Bare Mortar Finish	Local brick+Plaster	Exposed Brick	GRC double sided	CHB+Plaster	Gypsum	Plywood	GRC Board	Ceramic tiles	Aluminum sheet	Mortar tiles
1	CO_2 emission from material harvest and production ($Kg.CO_2/Kg$) *)	0.7	0.8	0.1	1.1	0.2	2.1	0.9	0.4	0.8	2.1	0.2	12	2.1
2	Embodied energy of material (MJ/Kg)	10	14	0.8	7.7	3	11	5.4	6.8	15	11	3	218	1.6
3	Transportation /distance (km)	600	600	50	50	600	600	50	600	600	600	600	600	600

Remarks: *) Sometimes called embodied carbon which refers to CO_2 emitted during material harvest and production

The data in the ICE database is mostly from the literature of different countries, thus there the real EE and CO_2 data in Indonesia should be different. The differences may come from the type of fuels used in Indonesia. For instance, the type of fuel used for types of machinery or the percentage of lead in petrol. The condition of the road, transportation system, type or capacity of the engine, and vehicle productivity are also other determining factors for different EE and CO_2 data compared to other countries. Hence, the EE and CO_2 data, as shown in Table 4.15 will not be the same when using data from Indonesia. However, data in the above table can be used because the purpose is to compare all materials. Table 4.16 shows the calculation result of EE and CO_2 for each material in one design alternative.

The ecological performance of each material is presented by comparing the LCI value across all combinations of building envelope materials aimed at identifying the lowest CO_2 emission and the lowest EE. The total amount of CO_2 and EE of each material were inputted into the decision matrix, as previously described in Figure 3.2. To evaluate the environmental impact of the whole building, a functional unit had to be determined. According to ISO 14040 (2006), "a functional unit is a reference unit used to quantify the system performance in LCA techniques." There are several functional units in a life-cycle analysis of a building because the selection of functional unit is dependent on the study's objective. In this study, meter-square (m^2) of floor, wall, ceiling, and roof area was chosen as the functional unit since the goal was to compare EE and CO_2 output using LCI data of common materials.

Table 4.16: Amount of EE and CO_2 for one design alternative

Works Items	Area (m2)	Volume (m3)	Total Vol. (m3)	Density (kg/m3)	Weight (kg)	MJ/Kg	Total EE (MJ)	CO_2 eq (kg)	Total CO_2 (kg)
<u>Brick Masonry Work</u>									
Brick wall 1:2	8.60	0.1	0.86	950	817.00	3	2,451.00	0.22	179.74
Brick wall 1:4	71.70	0.1	7.17	950	6,811.50	3	20,434.50	0.22	1,498.53
Internal & ext. plaster 1:2	17.20	0.025	0.43	2,080	894.40	4.7	4,203.68	0.835	746.82
Internal & ext. plaster 1:4	143.40	0.025	3.59	2,080	7,456.80	4.7	35,046.96	0.835	6,226.43
<u>Roof covering</u>									
Metal roof sheeting	238.10	0.0003	0.07	7,824	558.87	218	121,833.29	12	6,706.42
<u>Ceiling Work</u>									
GRC board ext. -6 mm	66.96	0.006	0.40	1,276	512.65	11	5,639.10	2.1	1,076.56
GRC board int. -6 mm	131.84	0.006	0.79	1,276	1,009.37	11	11,103.04	2.1	2,119.67
<u>Floor</u>									
Ceramic Tile 30 x 30 cm	109.00	0.007	0.76	1,900	1,449.70	10	14,497.00	0.7	1,014.79
Grand Total							215,208.57		19,568.96

Remarks: Volume = Thickness * 1 m^2 of material; and Weight = Density * Total Volume

Several sources have presented EE from various building materials (Dixit *et al.*, 2010). However, the definition of EE is quite unclear that resulting in variability problems and incompatibility of the EE value (Calkins, 2009). Variables in EE consists is regional specific involving multi-faceted production processes. Thus, variables for common building materials in Indonesia should be calculated accurately by the manufacturers or independent institutions based on existing technologies in Indonesia. For the purpose of this research, the EE from international databases can be used, but the results must be comparable to others' findings. A common comparison method is by dividing the total EE value with the total building floor area. Based on the calculation results, the smallest EE value is 0.93/m^2, and the highest is 2.91 GJ/m^2 for Design Type 1-15 (DT 1-15) comprises of ceramic, CHB, plywood, cement roof, and DT 2-20 (granite, bricks, GRC, and metal roof), respectively. The Baseline model has an EE of 2.18 GJ/m^2. Suzuki *et al.* (1995) and CSIRO[8], as cited in Balderstone (2004) found that EE of single-story house is 3 GJ/m^2 for wooden family houses and 4.5 GJ/m^2 for housing with steel structures. A 4.5 - 5.5 GJ/m^2 was found from buildings with different types of elements in Australia (Balderstone, 2004). Although the type of buildings in those studies are different from the school buildings used for this research, the results of EE value from 2.9 to 4.6 GJ/m^2 for buildings is generally acceptable. Besides,

[8] Commonwealth Scientific and Industrial Research Organization. MIT Brochures. Available from: http://www.cmit.csiro.au/brochures/tech/embodied/. Accessed on June 2016.

the EE calculation in this research is used to compare the environmental aspect or ecological performance between design alternatives of school buildings.

A case study revealed that decision-makers may neglect the amount of EE and CO_2 emitted from the production of material for school design. Though some efforts noteworthy to highlight in reducing the environmental impact was the use of certified timber for windows and doors panels and frames. Overall, the EE and CO_2 value portrays the importance of ecological parameters besides social and economic factors. Therefore, the selection of design was made for all three factors using one of the decision-making methods.

4.3 Results and Analysis of TOPSIS Method

Results from the evaluation of subjective and objective criteria, as previously presented, were arranged in the form of a decision matrix. Table 4.17 shows a cut version of the matrix from a total of 144 design alternatives. In this analysis, consideration was given to cost, sustainable performance, and Disc. Hours. Despite the relationship between cost and overall sustainable performance, comfort criterion as part of social criteria was discussed in detail, which is explained by the number of Disc. Hours. The first analysis began by looking at the number of Disc. Hours for a period of one year. It can be seen from the table that DT 4-16, 2-16, and 4-7 were ranked as the top three design alternatives but with a 35% to 40% increase of costs compared to the Baseline model (DT 1-2). The Disc. Hours of these three top rankings scored at 1,773, 1,879, and 2,139 hours compared to 4,078 hours in the Baseline model. This means that the top three designs produce 48% to 57% lower Disc. Hours compare to the Baseline model. The downside of these three design alternatives is that they have a high initial cost. Other design alternatives gave lower costs if compared to the top three designs except for DT 3-16 and DT 4-34, which scored more than 40% expensive than the Baseline model. DT 3-16 scored the highest-ranking among the Design Type 3. The inflated costs for this type were because Design Type 3 adopts the hip roof model, which consumes a larger quantity of roofing material compared to other types. The cheapest design of this type is DT 3-5, but still, the cost is 7% higher than the Baseline model. Although the performance of Disc. Hours and sustainable index are better than the Baseline model however, DT 4-5 scored lower cost compared to all Design Type 3 with much lower Disc. Hours and better sustainable index. From the above analysis, it can be concluded that Design Type 3 is not a feasible solution.

Table 4.17: Ranking of design alternatives

Design Type	#	Floor	Walls	Ceil.	Roof	Total Cost (IDR)	EE	CO_2	Ecol.	Soc.	Econ.	#Disc. Hours	Index	Rank
Type 4	16	ceramic	CHB	ply	clay	167,201,599	147,778	19,607	3.37	4.09	3.95	1,773	0.726	1
Type 2	16	ceramic	CHB	ply	clay	168,817,133	154,710	20,754	3.37	4.09	3.95	1,879	0.704	2
Type 4	7	ceramic	bricks	ply	clay	163,258,756	177,877	21,129	3.33	4.15	4.09	2,139	0.694	3
Type 4	34	granite	CHB	ply	clay	175,335,724	173,720	20,903	3.44	4.12	3.97	1,746	0.690	4
Type 4 [1)]	5	ceramic	bricks	gyps	alu	127,820,851	274,774	26,045	3.14	4.02	3.80	1,733	0.568	43
Type 3	16	ceramic	CHB	Ply	clay	172,888,313	124,574	15,246	3.37	4.09	3.95	3,500	0.552	54
Type 1 [2)]	5	ceramic	bricks	gyps	alu	114,825,793	230,377	20,448	3.14	4.02	3.80	3,946	0.412	119
Type 1	14	ceramic	CHB	gyps	alu	117,555,719	209,195	19,377	3.18	3.96	3.66	3,925	0.409	121
Type 3	5	ceramic	bricks	gyps	alu	129,113,925	266,514	22,437	3.14	4.02	3.80	3,675	0.372	133
Type 1 [3)]	2	ceramic	bricks	GRC	alu	120,226,283	237,957	23,317	3.16	3.98	3.72	4,078	0.352	136
Type 3	20	granite	bricks	GRC	alu	142,623,422	300,001	26,589	3.23	4.02	3.73	3,859	0.262	144

Remarks: [1)] Lowest Disc. Hours; [2)] Lowest initial cost; [3)] Baseline model

Subject to cost consideration, a decision-maker may opt to select DT 1-5 or DT 1-14. This type of design produces 4% and 2.3% lower cost compared to the Baseline model. Additionally, both designs also provide lower Disc. Hours and better sustainable index. It can be recognized earlier using the matrix above that there is an option to be more cost-efficient, even the reduction of Disc. Hours, EE, and CO_2 emission was small.

Further consideration may be directed towards the overall performance of sustainability at a reasonable cost. With just a 6.3% increase in cost compare to the Baseline model, DT 4-5 is the best candidate. Although this type scores a higher EE and CO_2 emission, the performance of indoor temperature, which scores only 1733 of Disc. Hours may outweigh the priority for cost-saving as it was previously thought to be the better option.

The analysis was then continued to see the impact of the ranking if the input of annual Disc. Hours are changed to Disc. Hours during school hours only. Table 4.18 presents the result of the TOPSIS method in which Disc. Hours' column shows the number of Disc. Hours during school hours.

Table 4.18: Change of design alternatives' ranking

Design Type	#	Floor	Walls	Ceil.	Roof	Total Cost (IDR)	EE	CO_2	Ecol.	Soc.	Econ.	#Disc. Hours [1)]	Index	Rank
Type 4	16	ceramic	CHB	ply	clay	167,201,599	147,778	19,607	3.37	4.09	3.95	228	0.755	1
Type 2	16	ceramic	CHB	ply	clay	168,817,133	154,710	20,754	3.37	4.09	3.95	256	0.732	2
Type 4 [2)]	34	granite	CHB	ply	clay	175,335,724	173,720	20,903	3.44	4.12	3.97	226	0.723	3
Type 4 [3)]	7	ceramic	bricks	ply	clay	163,258,756	177,877	21,129	3.33	4.15	4.09	319	0.708	7
Type 4	5	ceramic	bricks	gyps	alu	127,820,851	274,774	26,045	3.14	4.02	3.80	226	0.615	39
Type 3	16	ceramic	CHB	Ply	clay	172,888,313	124,574	15,246	3.37	4.09	3.95	586	0.552	72
Type 1	14	ceramic	CHB	gyps	alu	117,555,719	209,195	19,377	3.18	3.96	3.66	613	0.409	113
Type 1	5	ceramic	bricks	gyps	alu	114,825,793	230,377	20,448	3.14	4.02	3.80	638	0.401	116
Type 3	5	ceramic	bricks	gyps	alu	129,113,925	266,514	22,437	3.14	4.02	3.80	633	0.372	129
Type 1	2	ceramic	bricks	GRC	alu	120,226,283	237,957	23,317	3.16	3.98	3.72	728	0.314	136
Type 3	20	granite	bricks	GRC	alu	142,623,422	300,001	26,589	3.23	4.02	3.73	721	0.225	144

Remarks: [1)] Disc. Hours during school hours, [2)] Previously was ranked 4th; [3)] Previously was ranked 3rd

It can be seen from Table 4.18, DT 4-16 and DT 2-16 remain as the first and second-best solution. However, DT 4-7 which was previously ranked third now becomes seventh, while DT 4-34 which was ranked fourth, becomes third. This means the shortest distance to the ideal solution, as calculated by the TOPSIS method did not change. The change of rankings among other design alternatives is because the relative distance to the ideal solution, which is DT 4-7 has changed due to different input of Disc. Hours. Nevertheless, if cost is the primary consideration for the decision-maker, then DT 1-5, DT 1-14 and DT 4-5 remain the feasible options with an index of 0.401, 0.409, and 0.615, respectively. Besides the ranking diversity, it is possible to identify the compromise solution for these three options. For instance, one may argue that DT 1-5 is the best option because it performs better in terms of cost, EE, and CO_2 emission compared to DT 4-5, however with 638 hours of discomfort during school hours on DT 1-5, the increase of CO_2 may come from the usage of electricity by an additional cooling device such as fan or AC during the school operational hours. As shown in the table that these two types shared the same material. The higher level of EE and CO_2 in DT 4-5 is basically derived from the use of a higher quantity of bricks and plastering since the wall is up to 4 meters high. From this analysis, the development of sustainable material in Aceh may focus on alternative energy for clay bricks and cement production.

In general, the change of Disc. Hours input in the matrix did not significantly alter the ranking of each design alternative. It means the Disc. Hours resulting from annual simulation happened mostly during the school hours. It can also be seen from Table 4.17 and 4.18 that in general, Design Type 4 produces higher cost and lower Disc. Hours. This means that while changing the ceiling height to 4 meters with a split ventilation system, Design Type 4 provides more cooling environment inside the classroom, but with a higher quantity of wall material.

The data used for the creation of the decision matrix were classified as subjective and objective data. The subjective data inputted into the model was to make sure any subjective criteria can also be assessed objectively. Because according to the additive utility theory, it is necessary to assess the performance of an alternative using the weights and performance of criteria objectively. As such, all performances of the criteria in Table 4.18 were normalized by converting performance value using the TOPSIS method. The performance scores in Table 4.18 were arranged with their respective weights from Table 4.4. The results of the arrangement were similar to the typical form of MCDM problem as presented in Table 3.5. The overall sustainable performance value for each design alternative was represented by the performance index after calculating the relative closeness to the ideal sustainable performance values for all the criteria under each design alternative. Thus, the higher the index, the better the sustainability performance of that particular design alternative. Therefore, the applicability of the developed model to assist decision-makers in making better selection has been demonstrated.

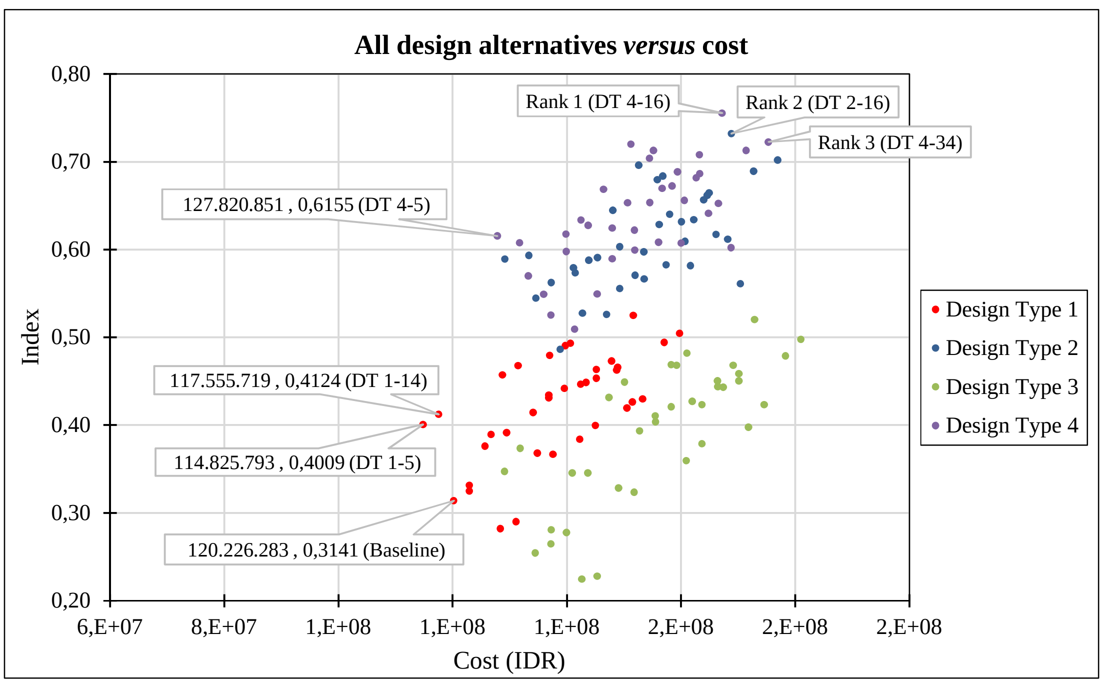


Figure 4.33: Relationship between sustainability index and initial cost

The complete ranks for all design alternatives are presented in Appendix 4.6. For more informative and better visualization of the entire ranking, Figure 4.33 shows a scatter plot between cost and sustainable index. All 144 design alternatives were plotted with four distinct colors. The color of dots indicates the four types of the model used, while each dot represents one design alternative. Therefore, the decision-makers can spot a design alternative of his/her choice quite quickly without having to go through all the ranks in the matrix.

Should there some modifications are needed, the ranking will also change instantly. Modifications usually arise when cost is the priority, which has been allocated prior to the design stage. Common changes during preliminary design are usually made to the choice of material, cost variation of material, number of workers, or productivity /coefficient of work. All those processes normally taking place in Excel's spreadsheets and can be operated by a person without high proficiency in MS. Excel. It is noticeable from Figure 4.33 that the combination of material and design under Design Type 2 and Design Type 4 are mostly more sustainable than Design Type 1 and Design Type 3. Thus, the decision-makers can draw his or her attention to searching the most economical solution by looking at the initial cost of each design alternative along the *x*-axis.

Referring to Figure 4.33, decision-makers can quickly spot two design alternatives with better sustainable performance and lower initial cost compared to the Baseline model. Therefore, if cost is considered the main constraint as it always the case in public project delivery, then DT 1-5 and DT 1-14 become the best alternatives. These two designs use the same material, such as ceramic tiles, gypsum board for the ceiling, and aluminum roof except for the wall. DT 1-14 use Concrete Hollow Block (CHB) while DT 1-5 uses clay brick. Hence the wall made of bricks is cheaper because there are quite many clay bricks factory operated in Aceh. Hence, DT 1-5 is the most feasible option because it not only produces lower indoor temperature, but it also has the lowest initial cost and higher sustainable index than the Baseline model. The considerable savings in cost comes from the use of the gypsum board for the ceiling in DT 1-5 compared to the GRC board in the Baseline model. Gypsum is not only cheaper than the GRC board, but it is able to retain the heat from the ceiling better. In addition to its price and the thermal performance of the gypsum board, the frame and installation cost for these two materials is the same.

Subject to the availability of budget, the selection of design may continue to other alternatives scoring higher sustainable index with a reasonable amount of additional cost. Represented by green dots, DT 4-5 has 6.3% of additional cost than the Baseline model but scores relatively high in terms of indoor comfort, which makes the overall sustainable index of 0.615. The difference between DT 1-5, DT 1-14, Baseline model, and DT 4-5 is that for DT 4-5, the height of the ceiling was positioned up to 4 meters from the finished floor, and the louver was placed separately above the windows. The use of material for this design is identical with DT 1-5 which proved to be the most economical. They are ceramic tile, clay bricks, and aluminum roof, while gypsum is also used as the ceiling material to retain the heat. The strategy concludes that DT 4-5 produced a much lower Disc. Hours and a much higher sustainable index than those three alternatives.

Access to the cost of material is considered very helpful since the change of cost during the preliminary design stage always occur quite frequently. In principle, all changes can be made in one spreadsheet except for the quantity of material which is bound to the shape or design configuration of the school building. Nevertheless, the four typical school models developed in this research are adequate to demonstrate the selection process of each variation in design configuration towards better sustainability in Indonesia.

4.4 Discussions

This chapter has presented the application of a framework in a case study. The most difficult part of the framework was the preparation of the energy simulation model. In this case, the case study schools were modeled according to their present shape and actual condition in the field. To create such an accurate model, one should have adequate 3D building modeling skills and knowledge in energy modeling to enable E+ run the simulation. Such a 3D model was basically a basic energy model or baseline with fixed geometry in a 3D space. Before varying design parameters and combining materials, the validity of the baseline was verified. The results of verification showed that the indoor temperatures generated by E+ were very close to the measured indoor temperature. This means that baseline models pose a high accuracy to represent the actual school models and further simulation can be executed to see the impact of material changes and other variation of design parameters on indoor temperature. As a fundamental aspect of indoor comfort criteria, the resulting indoor temperature were analyzed using a thermal adaptive model. The results of analysis showed that each school design produces different comfort level which is indicated by the period of students feels discomfort (discomfort hours).

Other sustainability criteria have also undergone different method of assessments. The results were unique for each design alternative. Therefore, a decision making tool was needed to find the best sustainable performance. Implementation of the TOPSIS method as a multi criteria decision making method for the selection of design alternatives in a case study has been demonstrated. The results showed that in general, the existing schools in the case study, which is represented by Design Type 1 has a lower performance of overall sustainability or smaller sustainable index compared to Design Type 2 and Design Type 4, while Design Type 3 scores the lowest. The high indoor temperature in almost all types of design in Design Type 1, Design Type 2, and Design Type 3 constitute significantly to the overall sustainable performance. The use of aluminum roof also contributes to low performance because of its high EE and CO_2 emission during the production of aluminum. It can be seen in Figure 4.33, a Baseline model developed based on one existing school in the case study was ranked 136 with an index of 0.314 (colored in red). This Baseline model, which is a member of Design Type 1 should not have been selected because the results showed that Design Type 1 generally performs low in almost all criteria. Despite the downside, the cost performance given by Design Type 1 was mostly better compared to other types of models. The cost of the Baseline model was higher than DT 1-5 and DT 1-

14, although these both alternatives have a higher sustainable index. Nevertheless, the decision taken during the design of the case study schools subjects to other criteria pertaining to existing conditions and situation at that time.

The method to achieve sustainability in building through the selection of materials and designs has been demonstrated in this research. According to the results of the TOPSIS method as depicted in Table 4.18, the performance of sustainability for DT 4-16 is 0.755, DT 2-16 scored a performance value of 0.732 while DT 4-34 had a performance of sustainability of 0.723. This means DT 4-16 is the best or the ideal sustainable option as it has the highest performance score in sustainability. In addition, in view of criteria performance and contribution to sustainable performance, EE and CO_2 criteria under DT 4-16 appeared to be the most sustainable option, which gave the lowest value of 147,778 and 19,607 respectively when compared with DT 2-16 and DT 4-34. In other words, DT 4-16 has the lowest EE, lowest CO_2 emission, and possesses better energy consumption. It also means that DT 4-16 had a better combination between subjective and objective performance from EE and energy consumption during school hours. The potential of reducing energy during operational hours was verified by indoor comfort performance as DT 4-16 became the most sustainable design giving the lowest Disc. Hours of 228 hours when compared to DT 2-16, while DT 4-34 scored slightly lower Disc. Hours with 226 hours. Therefore, according to the results as presented in Table 4.18, the matrix indicated that EE, $CO_{2,}$ and Indoor Comfort have the biggest influence in school design to achieve sustainability. This means DT 4-16 has the lowest life cycle cost in relation to operating cost and maintenance cost. This can also be interpreted that in the long term, DT 4-16 is the most cost-efficient alternative, although it has a higher initial cost than the Baseline model.

In relation to the thermally comfort environment by the shape or envelope of school design to students inside the classroom, DT 4-34 and DT 4-5 recorded the lowest Disc. Hours of 226 hours. This means those two design alternatives have great influence in maximizing indoor comfort, but since DT 4-5 uses aluminum roof, which poses high EE and CO_2 value, it was ranked 39. Similarly, DT 4-34 was ranked third because it uses a combination of granite tile and clay roofing tile, which makes the cost of this option became the most expensive one.

Besides the performance value of EE, $CO_{2,}$ and indoor comfort, other criteria were grouped under the main criteria, namely ecology, social, and economy. As presented in Table 4.18, two alternatives have the highest performance score. These values were obtained from a subjective assessment using a questionnaire. The use of granite, CHB, Plywood, and clay roof tile in DT 4-34 has the best ecological performance because these materials can be recycled, reuse and use minimum water during construction better than other combinations of material in other design types.

In terms of social and economic performance, DT 4-7 performed very well with a social performance score of 4.15 and an economic performance score of 4.09. Hence, these both designs were ranked pretty high (rank 3 and 7 in the matrix) out of 144 alternatives. The high-performance score of social criteria was derived from the combination of clay roof, plywood, ceramic, and brick in DT 4-7, because these materials were assessed as the most constructible, accommodate the aesthetic, and can be installed by local workers. The highest economic performance of DT 4-7 is derived from the maintainability, reparability, upgradability, and durability of those materials.

Overall, DT 4-7 is better in terms of overall performance. The evaluation made on Disc. Hours for one year was ranked third, and it was ranked seventh when the evaluation was made to only during school hours. It was superior in social and economic performance with just slightly lower in ecological criteria. The constraint is left to the availability of the budget. Because DT 4-7 costs 26.36% higher than the Baseline model. When compared to the Baseline, the CO_2 is also lower, resulting in 2.188 Kg CO_2eq reduction. The high cost of DT 4-7 comes from the use of clay roof and plywood for the ceiling. Therefore, cost production for these two materials is an area which can significantly help the vast adoption of sustainable building in Indonesia.

It is a rare situation that more than 20% increase in initial cost is granted using public project funding mechanism. From the analysis, the possible choice is finally left to DT 4-5 because it has higher performance in social and economic criteria, but the ecological performance is lower compared to the Baseline model. This was shown by higher EE and CO_2 performance compared to the Baseline model. However, the result of the TOPSIS method shows that it has a better sustainability index. This means the number of Disc. Hours is a significant measure of sustainability in this particular school building because it scored only 226 hours of discomfort during school hours in one year compared to the Baseline model of 728 hours.

Decision-makers in the developing countries need a tool to find a set of alternatives according to the specific objectives (i.e., cost and overall sustainability of a building) in an objective way because budget and options for affordable green material are generally limited. The presentation of sustainable index presented here is more than adequate in giving a well-informed decision-making during the preliminary design because it allows decision-makers to select a design based on the rankings of design alternatives, budget availability, and the capacity of local resources. A better decision-making tool may include indicators of the material selection criteria. Indicators allow access to product information or data between the producer and the decision-makers, thus may become a crucial guideline for decision-making.

CHAPTER 5

SUMMARY AND OUTLOOK OF RESEARCH

5.1 Conclusions

The assessments performed in the case study project confirmed that the sustainability performance of school design was portrayed mainly by EE, CO_2, and indoor temperature performance. The results showed that the lower the EE, CO_2, and the number of discomfort hours (Disc. Hours) of one particular school design, the higher is the sustainability performance of that design. However, the selection by considering only at these criteria produced an inflated cost, while cost is usually the primary constraint in developing countries. A better sustainable option is available through a design selection tool developed in this research based on the same cost data from the case study schools. It means that the tool could generate alternatives having as low or equal to the cost of the case study schools with better ecological, social, and economic performance. This supports the hypothesis of the research that there are improvements in terms of sustainability by using the same cost data. Improvement in sustainability can be realized by selecting DT 1-5 and 1-14, which has a lower cost than the Baseline model. Specifically, DT 1-5 and DT 1-14 performed well in EE, CO_2 emission, and indoor temperature than the Baseline model. However, the reduction of Disc. Hours were only 90 hours and 115 hours than the Baseline model may not be significant to provide comfort for students during school hours. As a result, additional energy will be required to cool the classrooms. A simple cooling strategy can be done by opening all windows, but it is impractical because of external disturbances such as noise and wind. Alternatively, better performance can be reached by selecting DT 4-5 with an additional cost of 6.3%. However, the high EE and CO_2 impact of this design alternative are the highest, among other alternatives. From this analysis, incentive or alternative renewable technology is best to be focused on the reduction of EE and CO_2 on the production of material used in DT 4-5. They are ceramic tiles, clay bricks for walls, gypsum board for the ceiling, and the aluminum roof. The most significant impact on EE and CO_2 came from gypsum and aluminum production because the roofing and ceiling component is the most influential part of a free-flow building to reduce the indoor temperature in a hot and humid climate of tropical countries.

Based on the analysis results from the school shape or design envelope, it is concluded that out of four typical school designs in Indonesia, the Design Type 2 and Design Type 4 has better performance in most of the sustainability criteria. Design Type 2 and Design Type 4 also have a better cost performance than the existing schools in the case study, which was modeled as Design Type 1. On the other hand, Design Type 3 generally produced higher costs than those three typical designs. The results confirmed that sustainability in buildings could be achieved affordably by designing the building envelope or the school's shape and selecting sustainable material. Therefore, to capitalize on building sustainability in developing countries, it is necessary to explore sustainable initiatives such as using alternative energy in mass production of building materials and include them in the selection of design alternatives. In addition, a comprehensive method for building sustainable performance assessment must include all sustainable criteria and values such as ecological and social impact, economic efficiency, including regulation and legislation process. The framework applied in a case study produce a tool that capable to rank, and select the best sustainable design alternative under the triple bottom line of sustainability. Therefore, the selection of design using a tool introduced in this research will eventually serve as a vehicle to promote sustainable practice, especially in the Indonesian building industry.

The decision-making tool which has been developed for the selection of design in this study has close the gap between existing design selection process in the developing countries and an advanced assessment method for gaining sustainability recognition in the preliminary design process. The tool was specifically developed for designing school buildings, which allows a comprehensive assessment method towards the sustainability of school buildings in Aceh and other parts of Indonesia as well as the South East Asia region with the same climate classification. After all, the framework provided a structured methodology for sustainable performance assessment during preliminary design or assessment of the existing school building. Such methodology can also be used to predict the overall sustainable performance of the whole school building through the envelope design. Since the tool required only a few data, any relevant sustainable performance criteria such as economic efficiency, energy efficiency, environmental and social impact can be assessed to achieve sustainability in building envelope design.

Sustainable development in developing countries highlights the importance of minimizing environmental resources through recycling and reusing local building materials. Hence, the community and local building practitioners' early involvement is critical to ensure credible sustainable design decision-making, as demonstrated in this study. The framework has also been validated to ensure that such a framework is adequate in designing building envelopes to achieve sustainability in building in tropical countries. For other climatic conditions, another building model can also be created by following the procedures in the framework, as developed in this research.

This research concludes that the development of sustainable school building is a sector worth of attention by the Indonesian government. A case study in Aceh Province showed that using a developed framework, alternative designs with costs as lower or equal to the case study schools is available for selection. Furthermore, the current framework is applicable for selecting designs for new school construction and can also be used to assess the sustainability of existing schools. Thus, objective assessment for design improvement (e.g., retrofitting) can also be provided. The default configuration of objects in the IDF file such as schedule object, ventilation, materials properties, orientation, and people object can be modified for another design decision-making process using four typical models created in this study. Unfortunately, the usability of school models in this research is restricted to Indonesia or in countries with similar weather classification. Nevertheless, the methods and procedures demonstrated in this research may be adopted in other countries with various weather classification other than Indonesia.

It is also necessary to conclude some survey findings on thermal comfort as an essential social criterion. The results indicated that: 1) Actual temperature measurement inside occupied classrooms showed that the acceptable temperatures are between 26.33 to 29.64 °C. It confirms that students are more tolerant to higher indoor temperature compare to colder climate zone. Such temperature range was recorded mostly below 11.00 AM during almost two months of observation at eight schools. After 11.00 AM, the indoor temperature recorded as high as 29.59 to 32 °C resulting in discomfort during the school hours; and 2) The neutral temperature of 27.99 °C is pretty close to other studies' result in Indonesia. The neutral temperature was obtained by performing a regression analysis of TSVs on operative temperature. The regression equation for the comfort temperature range in classrooms is:

$$TSV = 0.6048\ T_{op} - 16.927 \qquad , whe \quad \leq -1\ T \quad \leq +1$$

.

As a result, the usage of fans and air-conditioning (AC) units in the school's classrooms located in Aceh has been increasing with nearly similar geometry as Design Type 1 and Design Type 2, indicating that these schools need colder room temperature. However, the use of additional cooling energy should have been avoided because there are currently 3,286 public primary schools[9] operating in Aceh province alone. The estimated electricity cost for AC system in one classroom may reach about 2.7 million US Dollars per year excluding the purchase cost of the AC unit, cost for installation, and maintenance cost. Although the use of one or two AC unit is seemed affordable for one school, the total energy use of such practice overburden the Indonesian electricity supply. Additionally, the usage of air-conditioning units may have a positive or negative implication on students' health.

Evaluation of indoor temperature had brought to four important design parameters to be considered for school project development in the future. They are the type of ventilation, the height of the ceiling, ceiling material, and roofing material. Whereas the effect of orientation to minimize direct angle sunlight for a single-story school building is negligible if the building has at least 1.1 meters' roof span from the outer wall, which gives adequate shading.

Results of the TOPSIS method shows that actual schools of Design Type 1 provide low sustainable performance. In fact, Design Type 2 and Design Type 4 generally has better performance on Disc.

[9] Statistical Bureau of Aceh Province. Available from: http://aceh.bps.go.id/linkTabelStatis/view/id/52

Hours, lower EE, lower CO_2 emission, and with a higher score on social and economic criteria. However, ecology performance was generally lower than the Baseline model because gypsum for the ceiling in these two models received low marks compared to GRC use in the Baseline model. According to the returned questionnaire responses, gypsum is more difficult to reuse and recycle compared to GRC.

This research serves as a critical first step to convince the Indonesia people, specifically in the Aceh region, that more thermally comfort schools, yet ecologically friendly and economically efficient schools can be designed and constructed using the government funding mechanism. In the long-term, the selected design alternative can greatly achieve a significant saving in operational cost and reduce energy use as well.

5.2 Benefits and Limitations

The output of this research has opened up the early adoption of sustainable design concepts during the design process by making the selection of material and design easier to perform through an assessment framework developed during the research time frame. The case study revealed that by using the presented method and procedures, the sustainable performance of each school design could be assessed objectively without technological, economic, social, and regional restriction. By doing so, the realization of sustainable practice can be easily understood because it is supported by relevant data resulting in the improvement of the existing process about delivering school projects in a sustainable way.

Specifically, the application of the developed framework and tool using a case study approach yield several benefits which are given as follows:

1) The execution of material combination from JE Plus is more intuitive because materials were organized according to the specific construction element in one IDF file. Hence, should any alteration, such as adding more layers to its construction element, can be done without having to modify the main IMF file. Moreover, properties such as thermal conductivity and density of building material can be modified at any time.
2) The four IDF files which were created from the typical school models have been tested in a case study. These IDF files can be used in the future as they can be used as a basis of comparison with other simulation input or design parameters.
3) As for the selection of design by considering the material selection criteria and indoor comfort, the developed matrix for this research can be used as a decision aid tool for other similar types of schools in Indonesia. The materials used for school buildings are mostly similar to other school buildings in Indonesia. Hence, the four typical school models which were inputted as a basis of design in the matrix have accommodated all information necessary to provide a well-informed decision-making early during the preliminary design stage. Results from the TOPSIS

method shows that all information and data pertaining to the sustainability criteria in the matrix are adequate to identify better design.

Despite some benefits mentioned above, the tool developed in this research has some limitations at the current stage of its development.

1) The current tool cannot directly be used for other design and material selection tasks at a location other than Aceh because all values in the decision matrix apply only to the Aceh region, which is the location of the case study. Values such as criteria weight and material performance may not necessarily be modified. The selected criteria for design and material selection were used during the preliminary design stage, hence the weight and performance of material included in this research are generally complies with existing construction method and material in Indonesia. In addition, the results' accuracy of Disc. Hours may be lower if the tool is used directly for the analysis of design alternatives. To maintain the same level of accuracy, the simulation process in part 1 of the framework must be repeated by using a local weather file based on the intended are of construction. Nevertheless, for regions having similar temperature profiles like Aceh, the variations of Disc. Hours may not be significantly different. For regions with different temperature profiles such as Jakarta, Bandung, and highlands area, the new weather file must be created. EPW weather files for big cities in Indonesia are now available, hence the development of new weather files using the normalization process can be done. The thermal comfort study should also be conducted to conclude the range of comfort temperature inside the building (part 2 of the framework). Lastly, the total number of Disc. Hours can be determined after the completion of both parts.
2) The current tool lacks the practical ability to interact with the decision-maker because a user interface is currently not available at this stage. As a result, the users need to interact directly with the provided decision matrix. A more intuitive user interface can be designed as a front-end of the developed matrix. The development of scenario templates can also be designed that can be adapted to specific situations, thus enhancing the user-friendliness of the tool for better-informed decision-making.
3) Presently, the calculation of Disc. Hours were done manually (e.g., automatic sorting, filtering, etc. in MS Excel). Due to a sizeable hourly temperature output from the combination of materials, a macro should have been created in the matrix to automatically collect the output of hourly temperature after it is exported to MS. Excel by JE Plus.
4) The non-availability of Life Cycle Inventory (LCI) data of materials and products for the building sector in Indonesia has made the analysis of environmental impact such as EE and CO_2 emission relies only on the international database, which subjects to uncertainty.

5.3 Recommendations

The research is multi-disciplinary in a way that several established methods are used in the framework. Therefore, findings from this research lead to several recommendations, as outlined below.

1) The presented framework allows objective material comparison during the design process. However, it would be better to include overall building life cycle phases, such as maintenance, operation, and end of life. The inclusion of life cycle analysis is necessary to fully understand the impact of material choice to the sustainability of building. Such strategy will give a clear direction to the development of life cycle cost data of each material used in a building. It is also deemed necessary to create local or regional construction materials databases that are publicly accessible. Thus, there would be a credible environmental impact data of building materials that relevant to the building location. Without regional life cycle cost data, the environmental impact can only be assess using existing inventories from other countries.
2) The validation of results is limited only to a single case study using existing school models in the Aceh region. Although most school buildings in other regions in Indonesia are closely similar to the four school models built for this research, a different construction type (e.g., steel construction, timber construction) needs further evaluations. Future studies may also consider other school types such as two stories schools that are needed in a highly-populated area.
3) The framework developed in this research provides a transparent and well-informed sustainable performance of each design alternative. Thus, the application of this framework in other building projects can positively contribute to meeting the government's emission target. To operationalize this target, the academic institution in Indonesia can play a crucial role in introducing and formalize the same concept and method, especially in using the simulation tools which are available at no cost.
4) It is also recommended that thermal comfort study in public schools shall be conducted in other regions in Indonesia because the result of such study may prevent the use of fans or air-conditioning systems. Prominent research in this field was currently limited only to the office building in four big cities in Indonesia, which are Jakarta, Medan, Surabaya, and Makassar.
5) To speed up the implementation of sustainable building design in developing countries, the IDF file shall be created containing default configuration for other common building types such as low-cost mass-housing projects. The reason is that the housing project is one of the major construction programs in Indonesia.

5.4 Outlook of Research

Like many other developing countries, Indonesia has serious problems in its construction sector. Major problems come from poor government data and information system, unforeseen project cost, delays, lack of professional certification system, irregular supply of material, and material cost uncertainty. The nonexistence of construction data is a severe problem because it would expedite the sustainable development in the Indonesian construction industry. Establishing a comprehensive information system for construction activities is one of the basic requirements for developing the sector of construction. This will provide relevant data that are needed to assess industry potentials and determine the needs accurately. In general, the data pertinent to construction activities can be obtained from professional institutions. However, the corresponding institutions in Indonesia have not fulfilled their main objectives. For example, there is no the official or published information that can be obtained from engineering council, engineers' associations, contractors' unions, or architects. As previously mentioned, the fact that there is lack of effective communication and coordination between industry's stakeholders like professional's institutions, unions, and association has made the situation worse. This has been a further impediment to the development of industry. The inadequacies in design and project management techniques aggravates the situations. Moreover, another problem is ineffective and inefficient building code and outdated regulations to keep up with technological breakthrough or trends in the construction industry.

Milford *et al.* (2002) highlight that industry organizations such as professional's institutions, engineer's association, etc has a limited ability to solve the majority of problems faced by developing countries. Many problems are strongly connected to multiple factors. Hence, the sustainable construction industry needs to step forward through available technology in developing countries to implement sustainable development successfully.

The framework developed for this research allows an objective and transparent Indonesian GHG emissions' reduction target of 26% by 2020 or equals to 0.767 giga-ton CO_2e. Specifically, the approach used in this research may be used in the policy level using a similar decision-making technique from the project level. This is because MADM/MODM allows the type of alternative to change from discrete or definite alternatives to a broader alternative definition. Even though the type and number of alternatives available in the project level are different from the policy context, the same approach can also be used.

The impact of sustainable design can be assessed if several alternatives are available during the sustainable design process. However, in actual practice, the project participants only focus on completing the projects without too much concern about possible design alternatives. Consequently, the decisions made at lower levels cannot be used for making decisions at a higher level. On the other hand, alternatives development at the higher levels should consider conflicts, compromises, and trade-offs normally experienced at the lower level without leaving the three pillars of sustainability (social, economic, and ecology) during the decision-making process.

The selection of sustainable alternatives has been one of the main tasks for reducing Indonesian GHG at the strategic level. Since the reduction target was set for the longer-term, it allows alternate ways to achieve certain goals or issues. Therefore, if looking at the Indonesian National objective and evidence-based approaches to the reduction target, alternatives should be able to counter the current problems and be able to fulfill the program or project objectives.

5.4.1 Technical Need

The case study of existing primary schools in Aceh provides some evidence that the sustainable performance of school can be measured, hence providing opportunities for improvement of other school designs in Indonesia. For common building shapes like schools, design documents as a preliminary design product are used as a basis for the detailed design stage. Design changes are very rare, although the Owner has the right to initiate changes. Design changes normally occur due to the availability of budget. Should changes are avoidable, this normally affecting the use of material type. Changes to structural members are strict, and it is bound to strict regulation for earthquake code Zone. Therefore, most changes are usually applied to material selection, resulting in a lower grade of quality. Modification on the type of material used is not considered a severe technical problem to some extent. However, suppose sustainability is included in the design goal. In that case, a what-if scenario is necessary to open up the possibility of a transparent and objective selection of material, cost, and other sustainable criteria under consideration. Specific to Indonesia or probably most developing countries using the traditional project delivery system, a what-if scenario based on an MCDM method is incredibly supportive. Especially for a situation where first, the time available during preliminary and detailed design is short, second, there are no experienced project members or green experts, and third, change of budget in the middle of the detailed design stage.

The Indonesian construction materials market is enormous compared to other countries in the region. Consequently, foreign companies may initiate a joint-ventured with local companies for a long-term growth opportunity on environmentally friendly materials and green building technology. Indonesian companies should be receptive to such cooperation, particularly about sustainable building materials.

5.4.2 Public Procurement

Any government project, such as public school buildings, is bound to the public procurement act. A more transparent procurement system has been implemented and regularly updated since 2003. Moreover, the utilization of a web-based procurement system (e-procurement) has speeded up the process of completing public works projects and allowed many bidders from other regions to participate in the bidding process creating fairer competition. However, there is still a need legislation that regulates a precise mechanism for handling disputes, clear sanction for those who violate the procurement procedure, and provision authorizing civil society to monitor the procurement. Lewis and Faupel (2014) mentioned that although government staff and bidders are required to sign an integrity pact, it only denotes as a vow. Therefore, a more detailed law regulating the procurement that is integrated with presidential decree on sustainable initiatives is required.

Delivering sustainable initiatives and regulations in the procurement process may help boost the GHG emission reductions' target since infrastructure construction projects are essential to Indonesia's development. The sector of construction Industry in Indonesia is ranked third in terms of prosperity improvement through human recourses engagement after food and textile industries (Royat, 1994). The project Owner is in the position to establish sustainable initiatives in the procurement process. For example, bidders may be requested to submit environmentally friendly alternative materials. The project Owner may also specify other criteria for the construction process, such as using recycled water, minimizing construction waste and debris, or reducing noise and air pollution.

5.4.3 Policy and Legislation on Green Initiatives

During the last term (2009 - 2014), Indonesia’s government did not make any notable progress to reduce carbon emission produced by the built environment. There are no regulation and policies that support environmental friendly development, such as allocated budget and supports for institutions to carry out research and develop reasonably priced renewable energy. Only provincial government of Jakarta who provide support for the Indonesian rating tool called Greenship. The form of support is by issuing the Jakarta Governor’s decree No. 38/2012[10], that regulate green building criteria for acquiring building permits for new buildings or new facilities. Nevertheless, Greenship has not yet been an effective tool for reducing energy and sustainable development because it only concentrates on developments of new and retrofitting of multi-story buildings. Established in 2010, Greenship has shown positive progress as in Jakarta, but large constructions and building projects are mostly at the outskirt of Jakarta, such as Bogor, Tangerang, Depok, and Bekasi, where projects are executed using the traditional project delivery system. Major barrier for implementing green building development is the cost premium which based on previous green building projects accounted for more than 8% of the cost initially needed in conventional project development[11]. Therefore, to promote green building practice, specific guidelines should be developed at other regions and supported with the Governor’s regulation at every provincial level.

The current planning and design practice for construction building projects relies mostly on various standards and specification originated from the material producers with little or no information about the green feature of the products. The expedite green building initiative and sustainable development,

[10] *Peraturan Gubernur Provinsi Daerah Khusus Ibukota Jakarta Nomor 38 Tahun 2012 Tentang Bangunan Gedung Hijau.* The Government of Jakarta decree No. 38 Year 2012 about Green Buildings. Retrieved from: https://greenbuilding.jakarta.go.id/

[11] The Jakarta Post, “Jakarta set to see high-rise ‘green’ buildings.” April 13, 2013. Retrieved from: http://www.thejakartapost.com/news/2013/04/13/jakarta-set-see-highrise-green-buildings.html

directive policy should be available to support environmentally friendly production, material supply change, and construction including reusing, reducing or recycling materials. Professional institutions and engineer's association should have been proactive to encourages or enforces the use of sustainable building materials, and sustainable design. On the other hand, academic institutions are in the right position to show cases of successful sustainable design and construction and support the government in making green building policy and regulations.

5.4.4 Project Financing

There is a huge opportunity for achieving sustainability using government budget because government is the major clients of Design and Engineering Consultants (DEC) and construction companies in the public sector. Although demand for sustainable design and sustainable construction practices is increasingly high in the private sector, existing government budgetary system limit the financing mechanism for achieving sustainability in building. One of possible way to promote sustainable building projects is by the use of government subsidies as incentives for adopting sustainable design and sustainable construction if the estimated costs go beyond the current budget.

In terms of advanced technologies such as photovoltaic system, wind energy, geothermal, and biomass or traditional materials such as earth and bamboo, funds are also difficult to acquire because the existing financial system was not prepared for their utilization. A major challenge would be to develop alternative financing mechanisms because renewable technologies required additional cost. Available financing may come mainly from government funding or non-government institutions in the form of small grants and technical assistance. For modern sustainable technology, government funding is only available for renewable technology at the demonstration stage. Most of the government-funded projects only cover the up-front capital costs but does not extend to the operational and maintenance of the facility. In the commercial or private sector, there has been little interest in financing green building projects. This limitation could jeopardize sustainability development progress in Indonesia. Without economic and regulatory measures, it would be difficult to implement sustainability in buildings in developing countries.

At present, common institutional problems in Indonesia include inadequate skills, poor monitoring system, gratification, bribery, lack of coordination, and inadequate legislative frameworks about the sustainability concept. To cope with such problems, the local governments may position themselves as the Owners or as clients in determining the form and function of their community buildings. For instance, the local government may specify sustainable building criteria at the preliminary design stage. In addition, local government can also determine the orientation of a building, the functionality, shape of the building, and the materials used, and the targeted community. Moreover, local governments can encourage the DEC to propose an efficient design, while contractors can be accredited for cost savings during the construction process.

5.4.5 Challenge of Material Selection and Indoor Comfort

The material selection process introduced in this research may contribute to the application of the Greenship in Indonesia because the minimization of construction waste and CO_2 emissions reduction received a high score in the Greenship rating system. However, the reduction of construction waste is not easy because it is related to habit and the thinking process about protecting the environment. Hence, the construction process needs an affordable waste reduction process. Such process can be started by selecting building materials that are easy to recycle and to reuse. In addition, law concerning the construction standards in Indonesia has not clearly specified the criteria of green building, such as the Indonesian National Standard (SNI) for building materials and construction methods that is not linked to sustainable performance. For instance, the SNI still does not include sustainable building waste management in which the users are not obliged to sort their waste into organic and non-organic waste. The waste problem in Indonesia has never been managed so well because of poor community awareness. Even though the technology for the waste management of building materials exist, the community should be environmentally minded and care about public health. For the new building material, the third-party declaration of material performance is becoming more important. The construction industry in Indonesia shall be prepared to create the assessment standard and make it transparent to the public. This will help a more objective selection of material available to the decision-maker rather than using the subjective measure as introduced in this research.

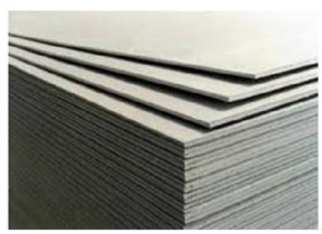
In terms of indoor thermal comfort of the building, indoor air quality is also important so that not only occupants stay productive but healthy as well. Indoor air quality assessment in Greenship is strongly connected to the type of building ventilation systems. For example, for building with natural cross-ventilation system the highly polluted air may enter the building and distract occupants. Occupants comfort can be more challenging as well if the building is located in a density area. In this case, the option to use natural ventilation system becomes unrealistic. Hence, to achieve quality indoor air in a dense built environment, the air conditioning systems are likely the best option because it can handle air purification. Especially in the tropical climate of Indonesia, building design must at least able to regulate indoor temperature, air quality, and humidity levels based on continuous air circulation. For this reason, Greenship includes the assessment of mechanical ventilation systems to maintain indoor air quality for apartments, public, commercial, public buildings. Although the installation and operation procedure of the mechanical ventilation system is done properly, the maintenance of such system is rarely executed well in Indonesia. Activities for building maintenance in Indonesia has been widely misunderstood that it is only about cleaning and repairing parts of the building and not include the maintenance of the mechanical ventilation system. Hence, most buildings fail to meet the Greenship's indoor air quality requirement.

For an air-conditioned building, ASHRAE's recommended temperature is 24 °C while in Indonesia, air conditioning unit in most office buildings are set around 26.5 °C with 60 – 70% humidity. This implies that comfort temperature of Indonesian people is higher than those specified in international standard. Thus, the use of air-conditioning system can basically be avoided if occupants are not affected by polluted air. The result of this research confirmed that comfort temperature inside the classrooms in most public schools in Indonesia could be achieved without having to use fans or air conditioning systems. In addition, the schoolyard is mostly large, so there is still enough space to implement another strategy, such as planting trees to shade the building, constructing a water pool, and arranging the building blocks or classrooms to allow the breeze to come from any direction as possible. Such strategy would be adequate to maintain indoor air quality to an acceptable level in the naturally ventilated classrooms.

APPENDIXES

LIST OF APPENDIXES

Appendix 2 – 1: Common Building Materials in Indonesia

Building components	Building material		
Wall	 Traditional Clay brick	 Concrete hollow block (CHB)	 Exposed clay brick [1)]
Floor	 Ceramic	 Granite	 Bare cement finish [2)]
Ceiling	 Plywood	 Glass Reinforced Cement (GRC)	 Gypsum
Roof	 Aluminum-zinc roof sheet	 Cement/mortar roof tile	 Clay roof tile

Remarks: [1)] Not common for primary school building
[2)] Bare cement floor was excluded in the analysis, because does not meet regular standard of public schools

Appendix 3 – 1: Interview Questions and Answers

Question 1
Are architects and designers aware of the environmental implication of their design decision?

Answers:

Architect & Design consultant

They are national regulation governing the environmental impact of design and construction but current practice shows very little awareness on impact of design to environment. Design considerations typically considers only on location/space availability and waste water management.

Government

Yes, but the implication of design has not fully considered. Budget is still the main factor to consider following any design proposal. The environmental factor is more considered and get more attention after the Tsunami, due to demand from the international aid organization, such as NGOs operated in Aceh. For example, structural codes for building were revised to achieve an earthquake resistance building. Environmental consideration such as re-using grey water for plantation to save clean water or implementing a rain water harvesting system. In short, design decision are more flexible and can be changed during the reconstruction process. For instance, due to the shortages of timber, many roof structures were changed to galvanized roof frame.

Question 2
How important is environmental consideration at the conceptual stage of building projects?

Answers:

Architect & Design consultant

Important.

Government

Not quite important since there is no mandatory regulation from government for this stage of design. However, credits can be given to proposed design which includes environmental criteria.

Question 3
To what extent are environmental issues considered in building projects?

Answers:

Architect & Design consultant

Mainly considered how the design can fit to the available site. There are no decisions made to the selection of sustainable use of material and form of façade or building envelope.

Government

Mostly considered only during the period of AMDAL *(Analisis Mengenai Dampak Lingkungan)* / environmental impact analysis.

Question 4
Should environmental consideration be included in building material assessment?

Answers:

Architect & Design consultant

Yes. Building codes are available but often neglected.

Government

Yes, but again cost is the main consideration. If the design and the selected material are within the budget then it can be considered.

Question 5
Is sustainability assessment of building materials an important issue for building development?

Answers:
Yes.

Question 6
Is there a correlation between awareness and implementation of sustainable practice in building projects?

Answers:
Yes.

Question 7
To what extent are sustainable practices implemented in practice?

Answers:
It is hardly possible to find implementation of sustainable practices in Aceh even if it is executed by the government owned construction companies. Clearly, one could not expect sustainable practice if the project is executed by the local companies.

Question 8
How important is material selection in achieving sustainable building?

Answers:
Very important.

Question 9
Who are the principal stakeholders in building design and what influence do they have in material selection?

Answers:
Architect & Design consultant
Design consultant i.e., an architect who normally decide the type of material, room size and color. However, the size of doors, windows and louvres are directly drafted by the draftsmen.
Government
Owner, because all the decision regarding administration, and budget for public building must comply with the government budget

Question 10
What are the criteria considered in the selection of sustainable materials for building projects?

Answers:
Architect & Design consultant
Mainly cost, durability, availability in local market and fast installation. However, if a discussion with prospective occupant main criteria are aesthetic and comfort.
Government
First cost then durability. For the selection of material normally recommended to use material which comply with the SNI.

Question 11
How can the criteria be assessed for evaluating building materials?

Answers:
Assessment of criteria is subjective since the designer relies only on her/his past experiences. Should new materials exist in the market, designers are reluctant to use them.

Question 12

What are the obstacles in the use of sustainable materials?

Answers:

Architect & Design consultant

First is because of limited knowledge and experiences of the designers and the perception that sustainable use of material is not that important. Second is because not enough promotion or socialization to the building community. For example, the health risk from asbestos material for ceiling was publicized by NGO just after Tsunami in 2003.

Government

Cost is normally obstacles during early design as well as skills of local workers. Material supply chain is also important to recognize because most of materials for building delivered from Medan, North Sumatera.

Question 13

Does cost consideration affect sustainable material usage?

Answers:

Yes.

Question 14

What are the existing design assessment techniques used by building professionals?

Answers:

Architect & Design consultant

Use national regulation for building design. Mostly used is requirement for minimum floor area and minimum build-up area.

Government

Nothing special. Drawing or sketches are often use to evaluate the design. It is hard to find the design assessment techniques in objective way. Another way to understand the proposed design is by visiting the similar building.

Question 15

What are the perceived obstacles to the usage in practice?

Answers:

National building codes are made too general hence to some extent not suitable to local situations.

Question 16

Why are there problems in their use in practice?

Answers:

As mentioned, national building codes are not details. Problems arise when other factors must be decided such as limited space, shortages of material, local climate and skill of local workers.

Question 17

How can the assessment techniques be improved for effective usage?

Answers:

Building codes need to be updated. Currently the codes are not fully effective. Especially for the selection of material, decisions are made usually based on the available budget. Structural integrity and comfort are always sacrificed due to the limited budget of a given building project.

Appendix 3 – 2: Final Form of Questionnaire

SECTION A. BACKGROUND OF RESPONDENT

Name of organization: ……………………………………………………………

Position in organization: ……………………………………………………….

Work experience in the construction industry:.………(Years) ……...... (Months)

Education level :

- High School ☐
- Bachelor ☐
- Master ☐
- Doctor ☐

Address: …………………………………………………………………………..

Telephone: ………………………. E-mail:………………..………….. (optional)

SECTION B. GENERAL INFORMATION

- *Please tick in the box where applicable*
- *You may tick more than one or leave it blank*

1 What type of organization do you work for?

- Architecture & design office ☐
- Contractor ☐
- Engineering ☐
- Developer ☐
- Education ☐
- Real Estate ☐
- Government Agency ☐

Others (Please specify)……………………………………………………………

2 What type of building project do you specialize in?

- Commercial ☐
- Residential ☐
- Public or Government Building ☐
- Educational ☐
- Industrial ☐

Others (Please specify)……………………………………………………………..

3 Your regular client type?

- Public ☐
- Private ☐

SECTION C. APPLICATION OF SUSTAINABILITY PRINCIPLES IN BUILLDING DESIGN AND MATERIAL SELECTION

- *Please tick in the box where applicable*

4 How will you rate your knowledge in sustainable and or green building design?

a. Excellent ☐
b. Good ☐
c. Sufficient ☐
d. Insufficient ☐
e. Do not know ☐

5 How will you rate your knowledge in sustainable use of material selection?

a. Excellent ☐
b. Good ☐
c. Sufficient ☐
d. Insufficient ☐
e. Do not know ☐

6 Do you consider sustainability assessment of building material an important issue for building development?

a. Yes ☐
b. No ☐

If No, Please give reason(s)…………………………………………………………..

7 Below is a list of sources of information on building products. Kindly indicate on a scale of 1-5 how often you consult the sources.

1 = Never
2 = Sometimes
3 = Average
4 = Often
5 = Very often

List of sources	Responses				
a. Newspaper	1	2	3	4	5
b. Trade journals & Magazines	1	2	3	4	5
c. Brochures	1	2	3	4	5
d. Trade representatives	1	2	3	4	5
e. Colleagues	1	2	3	4	5
f. Exhibitions	1	2	3	4	5
g. Web-site / internet	1	2	3	4	5

Others (Please specify)……………………………………………………………

SECTION D. DEVELOPMENT OF MATERIAL SELECTION DECISION CRITERIA

- *Please tick options where applicable*

8 Rate on a scale of 1 to 5 the following criteria in term of their importance in the selection of building material and in relation to the sustainability categories under which they are listed.

1 = Least important ---------> 5 = Extremely important

		Responses				
Environmental criteria						
1	Potential for recycling	1	2	3	4	5
2	Potential for reuse	1	2	3	4	5
3	CO2 emission from material harvest and production	1	2	3	4	5
4	Use of water during construction at minimum	1	2	3	4	5
5	Embodied energy of material	1	2	3	4	5
Social criteria						
1	Ease of construction / buildability	1	2	3	4	5
2	Aesthetics / appearance	1	2	3	4	5
3	Resistance to heat thus improving indoor comfort	1	2	3	4	5
4	Employ local workers at maximum	1	2	3	4	5
Economy criteria						
1	Initial cost	1	2	3	4	5
2	Maintainability	1	2	3	4	5
3	Reparability	1	2	3	4	5
4	Upgradability	1	2	3	4	5
5	Life expectancy of material (e.g. strength, durability)	1	2	3	4	5

9. According to your judgement, please rate the performance of following materials under listed criteria

1 = Very poor; 2 = Poor; 3 = Fair; 4 = Good; 5 = Very good

Responses

		Floor		Wall		Ceiling			Roof		
		Ceramic	Granite	Local brick+Plaster	CHB+Plaster	Gypsum	Plywood	GRC Board	Ceramic tiles	Metal/aluminium	Mortar/cement tiles
Ecology criteria											
1	Potential for recycling										
2	Potential for reuse										
3	Use of water during construction at minimum										
Social criteria											
1	Ease of construction / buildability										
2	Aesthetics										
3	Employ local workers at maximum										
Economy criteria											
1	Maintainability										
2	Repairability										
3	Upgradability										
4	Life expectancy of material (e.g. strength, durability)										

SECTION E. MATERIAL SELECTION TOOL or SOFTWARE

10 Have you ever use material selection tool or software during design?

1 Yes ☐

2 No ☐

If Yes, please specify the name of the software:

....

SECTION F. FEEDBACK

11 Are you available to provide further clarifications with regard to some of your replies?

1 Yes ☐

2 No ☐

Appendix 3 – 3: Subjective Assessment for Valuing Material Performance

Criteria	Indicators	Marks	Criteria for giving marks
Ecology criteria:			
Potential for recycling	Very poor	1	Very difficult to recycle or to sell at local recycle
	Poor	2	Difficult to recycle or to sell at local recycle facility
	Fair	3	Nor difficult or easy
	Good	4	Easy to recycle or to sell
	Very good	5	Very easy to recycle or to sell with high second hand
Potential for reuse	Very poor	1	< 20% can be re-used. Many defects thus give little
	Poor	2	20 – 40% can be re-used
	Fair	3	40 – 60% can be re-used
	Good	4	60 – 80% can be re-used
	Very good	5	> 80% of material can be re-used after dismantling
Use less water	Very poor	1	Very large quantity of water needed for installation
	Poor	2	Large quantity of water is needed
	Fair	3	Not so much
	Good	4	Very little water is needed
	Very good	5	No water is needed for installation
Social criteria:			
Buildability	Very poor	1	Very difficult to construct/install
	Poor	2	Difficult and require much effort
	Fair	3	Reasonably easy to construct/install
	Good	4	Quite easy to construct/install
	Very good	5	Very easy, not required much effort or skill
Aesthetic	Very poor	1	Very unattractive, need improvements
	Poor	2	Not quite attractive
	Fair	3	General appearance
	Good	4	Good looking, attractive
	Very good	5	Excellent finished look, very attractive
Employ local workers	Very poor	1	Highly skilled workers. Use special tools or equipment
	Poor	2	Relatively difficult to construct by local workers
	Fair	3	Fair quality if constructed by locals
	Good	4	Can be done mostly by locals
	Very good	5	Local workers are easy to find with very good quality

Appendix 3 – 3: Subjective Assessment for Valuing Material Performance *(continued)*

Criteria	Indicators	Marks	Criteria for giving marks
Economic criteria:			
Maintainability	Very poor	1	Very difficult to maintain. Require lots of effort / special tool
	Poor	2	Difficult to maintain
	Fair	3	Moderately easy to maintain
	Good	4	Easy to maintain.
	Very good	5	Very easy to maintain. No special tool required
Reparability	Very poor	1	Very difficult to repair. Require much effort and special tool
	Poor	2	Difficult to repair
	Fair	3	Nor difficult or easy
	Good	4	Easy to repair
	Very good	5	Very easy. Little effort. Can be returned to the original shape
Upgradability	Very poor	1	Very difficult to repair. Require much effort and special tool
	Poor	2	Difficult to repair
	Fair	3	Nor difficult or easy
	Good	4	Easy to repair
	Very good	5	Very easy. Little effort. Can be returned to the original shape
Durability	Very poor	1	Very weak material. Easy to break or damage
	Poor	2	Not too strong material
	Fair	3	Relatively strong
	Good	4	Strong material
	Very good	5	Very strong and can stand for many years

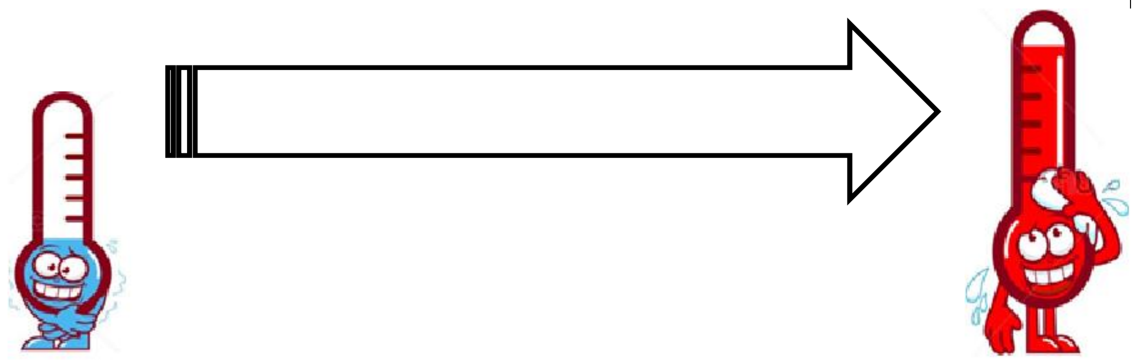
Appendix 3 – 4: Thermal Comfort Questionnaire

Date : ....
Time : ....

---

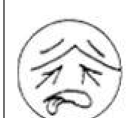
1. How do you feel about the temperature at this moment?. Please put the cross sign inside the empty box.

[12]



Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2. Do you feel comfortable? Please put the cross sign inside the box which level of comfort that you feel.

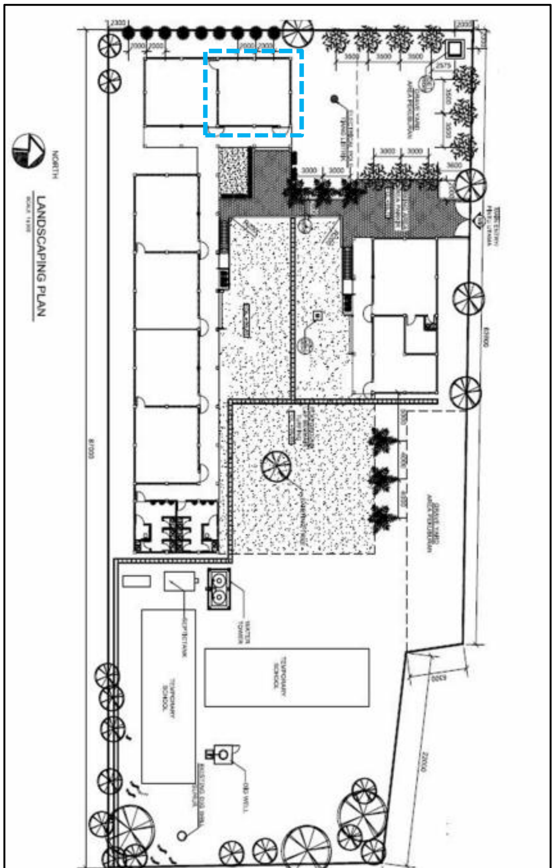
Much too cool	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too warm
						

3. What is your preferred temperature inside this classroom?

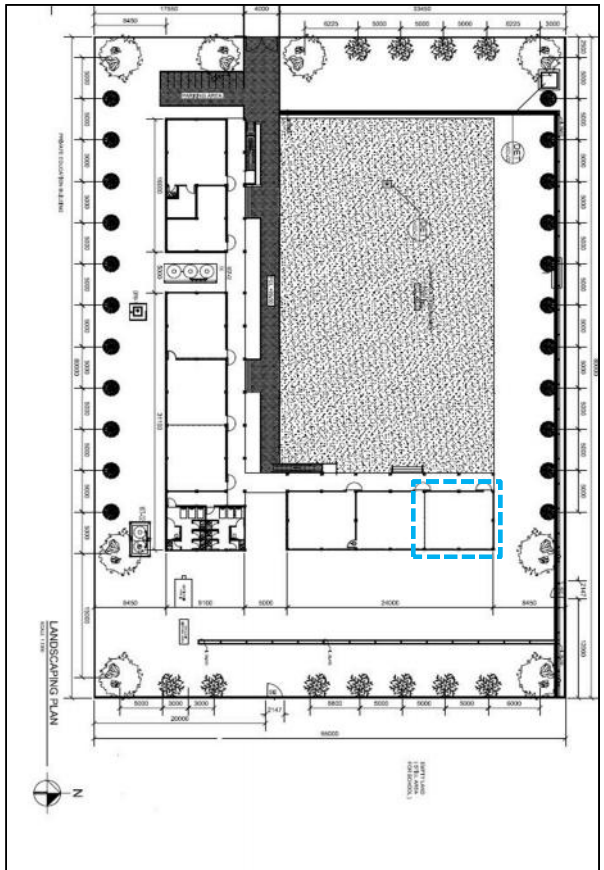
Much cooler	Cooler	A little bit cooler	Just like this	A little bit warmer	Warmer	Much warmer

[12] Image provided by "stockakia".
Available from: https://depositphotos.com/210600516/stock-illustration-shivering-hot-sweating-thermometer-funny.html

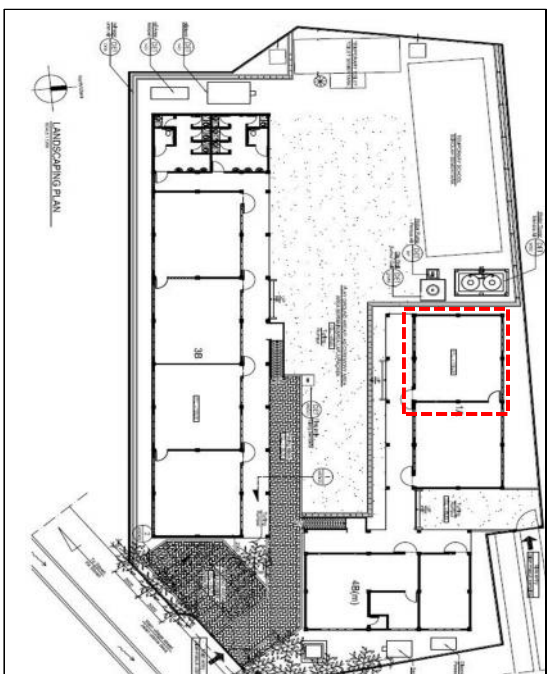
Appendix 4 – 1: Layout of School and Observed Classroom



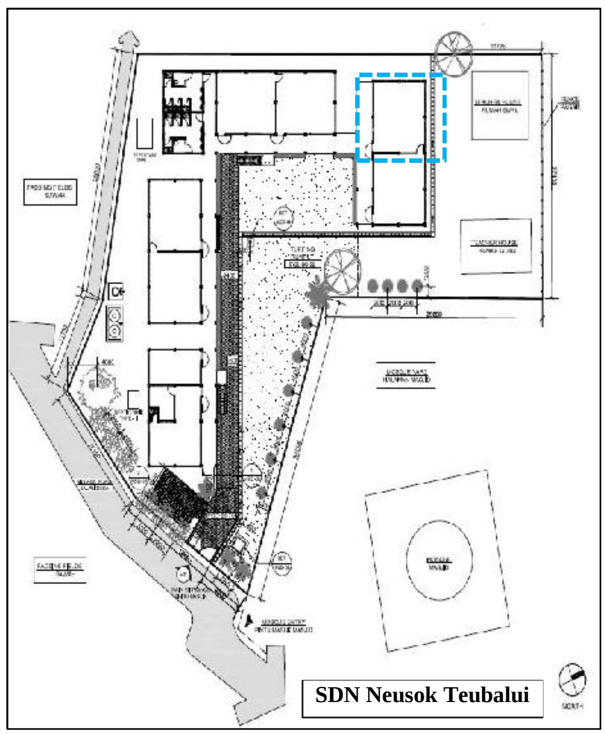
SDN Siron



SDN Abulyatama

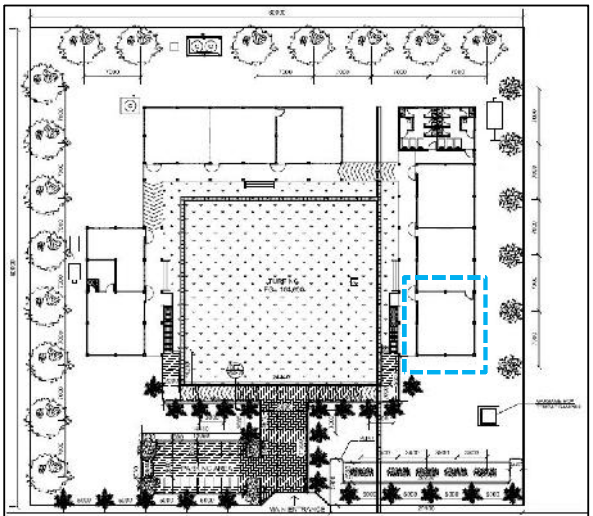


SDN Kayee Lhee

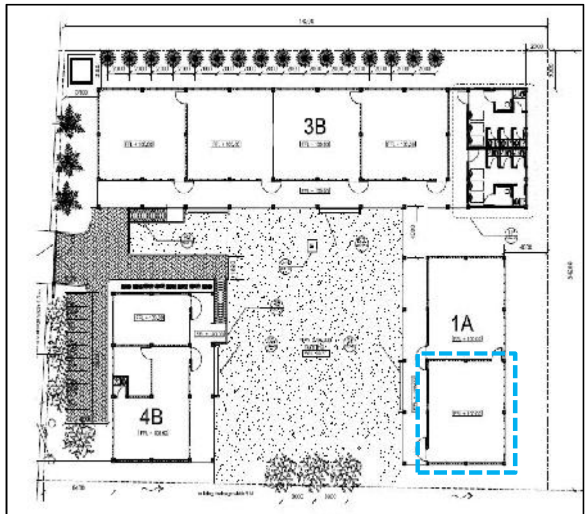


SDN Neusok Teubalui

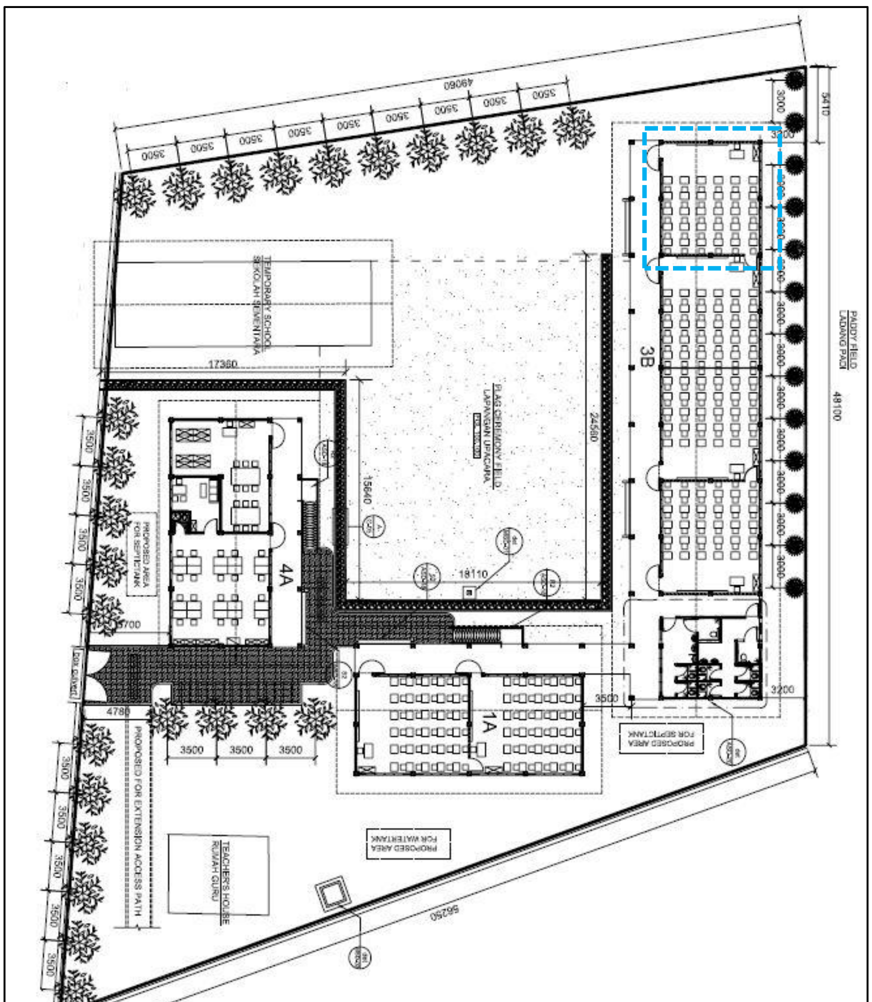
Appendix 4 – 1: Layout of School and Observed Classroom *(continued)*



SDN Leungah



SDN Rumpet



SDN Kuta Malaka

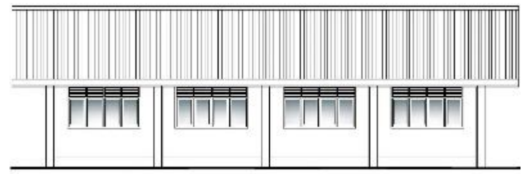
Legend:

(blue dashed box) Observation: One day from 08.00 – 13.00 using simple Temp. Record. Device

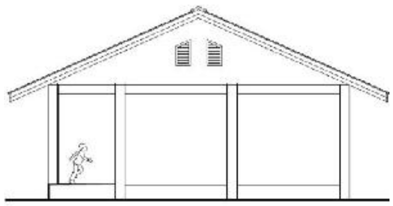
(red dashed box) Observation: From 19 July – 15 Sep. 2015 using Temp. Data Logger

Appendix 4 – 2: Construction Drawing (Baseline)

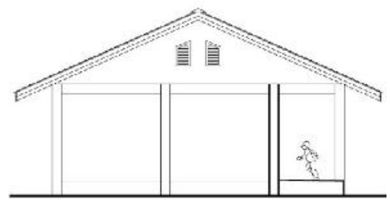
Front view



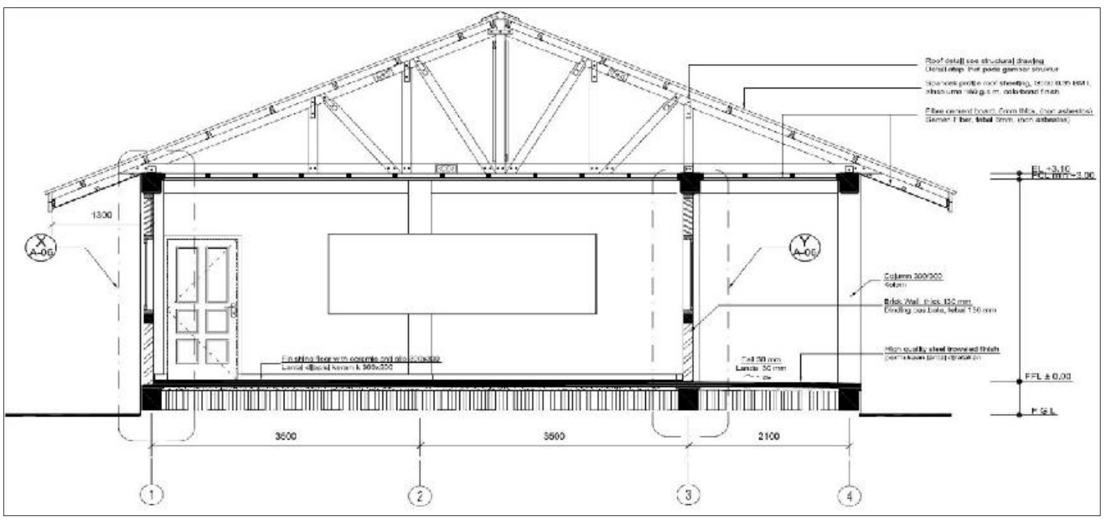
Back view



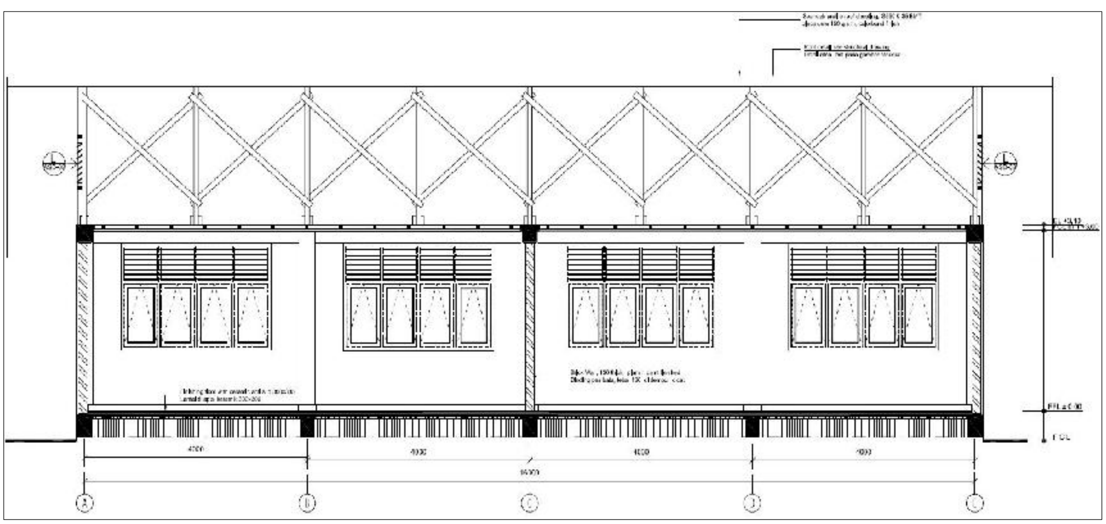
Right side view



Left side view



Section 1/A-04



Section 2/A-05

Appendix 4 - 3: IDF Text File for Material Assembly

Floor material assembly:

(1) Ceramic

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    ceramic_7mm,             !- Name
    Smooth,                  !- Roughness
    0.007,                   !- Thickness {m}
    0.84,                    !- Conductivity {W/m-K}
    1900,                    !- Density {kg/m3}
    800;                     !- Specific Heat {J/kg-K}
Material,
    mortar for ceramic_20mm, !- Name
    MediumRough,             !- Roughness
    0.02,                    !- Thickness {m}
    3.4,                     !- Conductivity {W/m-K}
    2080,                    !- Density {kg/m3}
    840;                     !- Specific Heat {J/kg-K}

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Interior Floor,          !- Name
    ceramic_7mm,             !- Outside Layer
    mortar for ceramic_20mm; !- Layer 2
```

(2) Granite

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    granite_tile,            !- Name
    Smooth,                  !- Roughness
    0.01,                    !- Thickness {m}
    2.9,                     !- Conductivity {W/m-K}
    2650,                    !- Density {kg/m3}
    900,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    mortar for ceramic_20mm, !- Name
    MediumRough,             !- Roughness
    0.02,                    !- Thickness {m}
    3.4,                     !- Conductivity {W/m-K}
    2080,                    !- Density {kg/m3}
    840;                     !- Specific Heat {J/kg-K}

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Interior Floor,          !- Name
    granite_tile,            !- Outside Layer
    mortar for ceramic_20mm; !- Layer 2
```

Wall material assembly:

(1) Brick

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    brick_100mm,             !- Name
    MediumRough,             !- Roughness
    0.1,                     !- Thickness {m}
    0.27,                    !- Conductivity {W/m-K}
    950,                     !- Density {kg/m3}
    840,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    plaster_25mm,            !- Name
    MediumSmooth,            !- Roughness
    0.025,                   !- Thickness {m}
    0.721,                   !- Conductivity {W/m-K}
    1858,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Exterior Wall,           !- Name
    plaster_25mm,            !- Outside Layer
    brick_100mm,             !- Layer 2
    plaster_25mm;            !- Layer 3
```

(2) CHB

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    con_hollow_block_100mm,  !- Name
    MediumRough,             !- Roughness
    0.1,                     !- Thickness {m}
    0.812,                   !- Conductivity {W/m-K}
    1618,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance
Material,
    plaster_25mm,            !- Name
    MediumSmooth,            !- Roughness
    0.025,                   !- Thickness {m}
    0.721,                   !- Conductivity {W/m-K}
    1858,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance


!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Exterior Wall,           !- Name
    plaster_25mm,            !- Outside Layer
    con_hollow_block_100mm,  !- Layer 2
    plaster_25mm;            !- Layer 3
```

Ceiling material assembly:

(1) Cement board (GRC)

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    cement board_ceiling,    !- Name
    MediumRough,             !- Roughness
    0.006,                   !- Thickness {m}
    0.388,                   !- Conductivity {W/m-K}
    1276,                    !- Density {kg/m3}
    897,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Interior Ceiling,        !- Name
    cement board_ceiling;    !- Outside Layer
```

(2) Gypsum

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    gypsum_95mm,             !- Name
    MediumSmooth,            !- Roughness
    0.0095,                  !- Thickness {m}
    0.58,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    1090,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Interior Ceiling,        !- Name
    gypsum_95mm;             !- Outside Layer
```

(3) Plywood

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    Plywood (Douglas Fir) - 6.4mm,  !- Name
    MediumSmooth,            !- Roughness
    0.0064,                  !- Thickness {m}
    0.12,                    !- Conductivity {W/m-K}
    540,                     !- Density {kg/m3}
    1210;                    !- Specific Heat {J/kg-K}

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Interior Ceiling,        !- Name
    Plywood (Douglas Fir) - 6.4mm;  !- Outside Layer
```

Roof material assembly:

(1) Cement

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    F08 Metal surface,       !- Name
    Smooth,                  !- Roughness
    0.0008,                  !- Thickness {m}
    45.28,                   !- Conductivity {W/m-K}
    7824,                    !- Density {kg/m3}
    500;                     !- Specific Heat {J/kg-K}

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Exterior Roof,           !- Name
    F08 Metal surface;       !- Outside Layer
```

(2) Clay

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    Clay_tile_Roof,          !- Name
    Rough,                   !- Roughness
    0.02,                    !- Thickness {m}
    0.84,                    !- Conductivity {W/m-K}
    1900,                    !- Density {kg/m3}
    800,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Exterior Roof,           !- Name
    Clay_tile_Roof;          !- Outside Layer
```

(3) Metal

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========
Material,
    F08 Metal surface,       !- Name
    Smooth,                  !- Roughness
    0.0008,                  !- Thickness {m}
    45.28,                   !- Conductivity {W/m-K}
    7824,                    !- Density {kg/m3}
    500;                     !- Specific Heat {J/kg-K}

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
Construction,
    Exterior Roof,           !- Name
    F08 Metal surface;       !- Outside Layer
```

Appendix 4 - 4: Default Configuration in E+

Simulation Parameters Class

Building object

Field	Object	Field description
Name	Primary_School	Building name is specified for output convenience.
North Axis	0	The Building North Axis is specified **relative to true North**. Buildings frequently do not line up with true north. For convenience, one may enter surfaces in a "regular" coordinate system and then shift them via the use of the North Axis. The value is specified in degrees from "true north" (clockwise is positive).
Terrain	Suburbs	The site's terrain affects how the wind hits the building
Solar Distribution	FullExterior	In this case, shadow patterns on exterior surfaces caused by detached shading, wings, overhangs, and exterior surfaces of all zones are computed.

Note: By, default North Axis is specified as 0 in EnergyPlus. This orientation will refer to West – East (WE orientation). The North – South (NS orientation) will be specified as 90 in North Axis field.

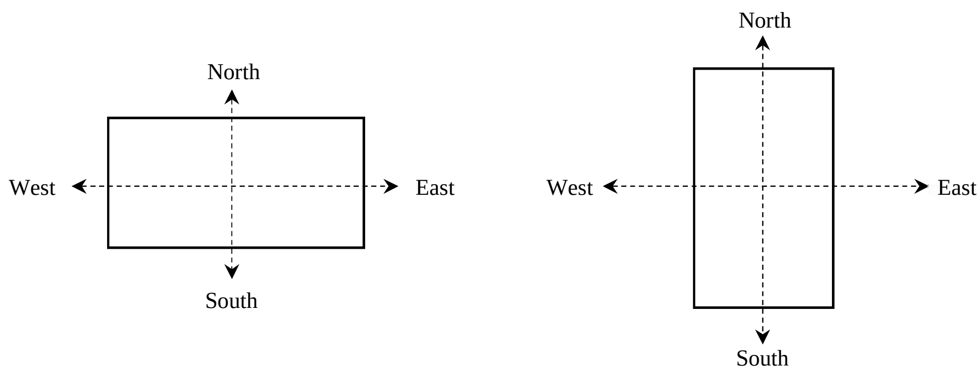


Figure F.1 Orientation setting in EnergyPlus

Surface Convection Algorithm object: Inside

Field	Object1
Algorithm	TARP

Surface Convection Algorithm object: Outside

Field	Object1
Algorithm	SimpleCombined

Heat Balance Algorithm object

Field	Object1
Algorithm	ConductionTransferFunction
Surface Temperature Upper Limit	200
Minimum Surface Convection Heat Transfer Coefficient Value	0.1
Maximum Surface Convection Heat Transfer Coefficient Value	1000

Schedules Class

Schedule:Compact object

Field	Object1	Object2	Object3	Object4	Object5
Name	Opening area baseline	Opening area stack	School Hours	Student clothing	Student activity
Schedule Type Limits	Fraction	Fraction	Fraction	AnyNumber	AnyNumber
Field 1	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31
Field 2	For: Monday	For: Monday	For: Monday	For: AllDays	For: AllDays
Field 3	Until: 07:00	Until: 07:00	Until: 07:00	Until: 24:00	Until: 24:00
Field 4	0.37	0.55	0	0.5 1)	108 2)
Field 5	Until: 13:00	Until: 13:00	Until: 13:00		
Field 6	1	1	1		
Field 7	Until: 24:00	Until: 24:00	Until: 24:00		
Field 8	0.37	0.55	0		
Field 9	For: Tuesday	For: Tuesday	For: Tuesday		
Field 10	Until: 07:00	Until: 07:00	Until: 07:00		
Field 11	0.37	0.55	0		
Field 12	Until: 13:00	Until: 13:00	Until: 13:00		
Field 13	1	1	1		
Field 14	Until: 24:00	Until: 24:00	Until: 24:00		
Field 15	0.37	0.55	0		
Field 16	For: Wednesday	For: Wednesday	For: Wednesday		
Field 17	Until: 07:00	Until: 07:00	Until: 07:00		
Field 18	0.37	0.55	0		
Field 19	Until: 13:00	Until: 13:00	Until: 13:00		
Field 20	1	1	1		
Field 21	Until: 24:00	Until: 24:00	Until: 24:00		
Field 22	0.37	0.55	0		
Field 23	For: Thursday	For: Thursday	For: Thursday		
Field 24	Until: 07:00	Until: 07:00	Until: 07:00		
Field 25	0.37	0.55	0		
Field 26	Until: 13:00	Until: 13:00	Until: 13:00		
Field 27	1	1	1		
Field 28	Until: 24:00	Until: 24:00	Until: 24:00		
Field 29	0.37	0.55	0		
Field 30	For: Friday	For: Friday	For: Friday		
Field 31	Until: 07:00	Until: 07:00	Until: 07:00		
Field 32	0.37	0.55	0		
Field 33	Until: 12:00	Until: 12:00	Until: 12:00		
Field 34	1	1	1		
Field 35	Until: 24:00	Until: 24:00	Until: 24:00		
Field 36	0.37	0.55	0		
Field 37	For:	For:	For:		
Field 38	Until: 24:00	Until: 24:00	Until: 24:00		
Field 39	0.37	0.55	0		

Remarks:
1) This value was sum of total clothing factor in Table T.1
2) This value was typical metabolic rate taken from Table T.2
3) Value of 1 means a fraction of student from 0 to 1. Here, 1 means fully occupied and 0 means empty room. The actual number of student is entered in the People Object under Internal Gains Class.

Garment description	Icl (Clo) *)
Briefs	0.04
Ankle-length athletic socks	0.02
Shoes	0.02
Short-sleeve dress shirt	0.19
Straight trousers (thin)	0.24

Remarks: Source: ASHRAE (2005), Thermal Comfort, ASHRAE Handbook of Fundamentals, Atlanta, GA, USA.

Figure F.2: Typical primary school uniform and the relevant clothing index

Table T.2: Metabolic Rates for Various Activities

Activity	Activity Level W/Person EnergyPlus Schedule Value	Activity Level W/m²	met*
Resting			
Sleeping	72	40	0.7
Reclining	81	45	0.8
Seated, quiet	108	60	1
Standing, relaxed	126	70	1.2
Walking (on level surface)			
3.2 km/h (0.9 m/s)	207	115	2
4.3 km/h (1.2 m/s)	270	150	2.6
6.4 km/h (1.8 m/s)	396	220	3.8
Office Activities			
Reading, seated	99	55	1
Writing	108	60	1
Typing	117	65	1.1
Filing, seated	126	70	1.2
Filing, standing	144	80	1.4
Walking about	180	100	1.7
Lifting/packing	216	120	2.1
Miscellaneous Occupational Activities			
Cooking	171 to 207	95 to 115	1.6 to 2.0
Housecleaning	207 to 360	115 to 200	2.0 to 3.4
Seated, heavy limb movement	234	130	2.2
Machine work			
sawing (table saw)	189	105	1.8
light (electrical industry)	207 to 252	115 to 140	2.0 to 2.4
heavy	423	235	4
Handling 50 kg bags	423	235	4
Pick and shovel work	423 to 504	235 to 280	4.0 to 4.8
Miscellaneous Leisure Activities			
Dancing, social	252 to 459	140 to 255	2.4 to 4.4
Calisthenics/exercise	315 to 423	175 to 235	3.0 to 4.0
Tennis, singles	378 to 486	210 to 270	3.6 to 4.0
Basketball	522 to 792	290 to 440	5.0 to 7.6
Wrestling, competitive	738 to 909	410 to 505	7.0 to 8.7

*Note that one met = 58.1 W/m2

Surface Construction Elements Class

Material object

Field	Units	Object1	Object2	Object3
Name		plaster_25mm	brick_100mm	con_hollow_block_100mm
Roughness		MediumSmooth	MediumRough	MediumRough
Thickness	m	0.025	0.1	0.1
Conductivity	W/m-K	0.721	0.27	0.812
Density	kg/m3	1858	950	1618
Specific Heat	J/kg-K	837	840	837
Thermal Absorptance		0.9	0.9	0.9
Solar Absorptance		0.7	0.7	0.7
Visible Absorptance		0.7	0.7	0.7

WindowMaterial:Glazing object

Field	Units	Object1
Name		Clear 3mm
Thickness	m	0.003

Construction object

Field	Object1	Object2	Object3	Object4	Object5	Object6
Name	Interior Floor	Exterior Wall	Exterior Roof	Interior Ceiling	Exterior Window	Exterior Door
Outside	ceramic_7mm	plaster_25mm	metal	gypsum_9mm	Clear 3mm	G05 25mm
Layer 2	mortar_20mm	brick_100mm				
Layer 3		plaster_25mm				

Thermal Zones and Surfaces Class

GlobalGeometryRules object

Field	Object
Starting Vertex Position	UpperLeftCorner
Vertex Entry Direction	Counterclockwise
Coordinate System	Relative

Zone object

The actual school building is modeled into two zones. First is ceiling zone which “roof_space” is assigned as name for it. The two classrooms were modeled into one zone and it is named as “room”.

BuildingSurface:Detailed object

Field	Object1	Object2	Object3
Name	floor	w_front	ceil
Surface Type	Floor	Wall	Ceiling
Construction Name	Interior Floor	Exterior Wall	Interior Ceiling
Zone Name	room	room	room
Outside Boundary Condition	Adiabatic	Outdoors	Zone
Outside Boundary Condition Object			roof_space
Sun Exposure	NoSun	NoSun	NoSun
Wind Exposure	NoWind	WindExposed	NoWind

Internal Gain Class

People object

Field	Object1	Field description
Name	student	User defined name
Zone or ZoneList Name	room	Zone name which is occupied
Number of People Schedule Name	Number of student	This field take values specified in the Schedule:Compact object
Number of People Calculation Method	People	This method uses number of occupants
Number of People	15	Total number of students
Activity Level Schedule Name	Student activity	This field take values specified in the

Zone Airflow Class

Zone Ventilation: Wind and Stack Open Area object

Field	Units	Object1	Object2
Name		Louvre	Gable Louvre
Zone Name		room	roof_space
Opening Area	m2	16	1.4
Opening Area Fraction Schedule Name		Opening area baseline	Always On
Opening Effectiveness	dimensionless	autocalculate	autocalculate
Effective Angle	deg	0	0
Height Difference	m	0	0
Discharge Coefficient for Opening		autocalculate	autocalculate

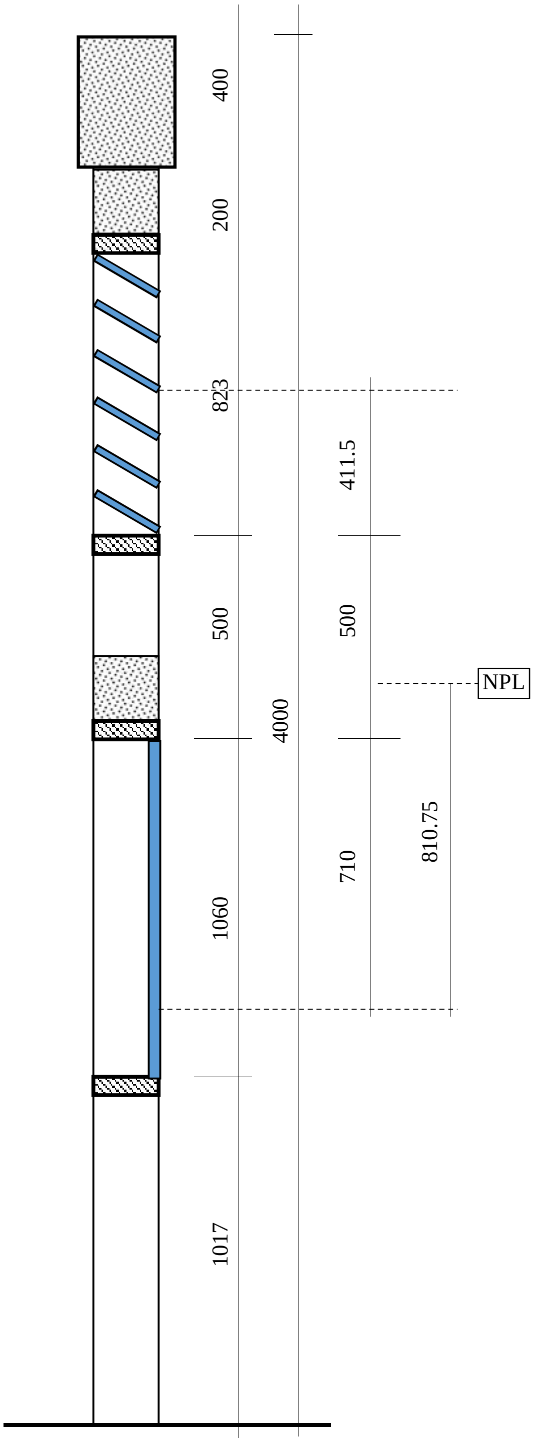
Output Reporting Class

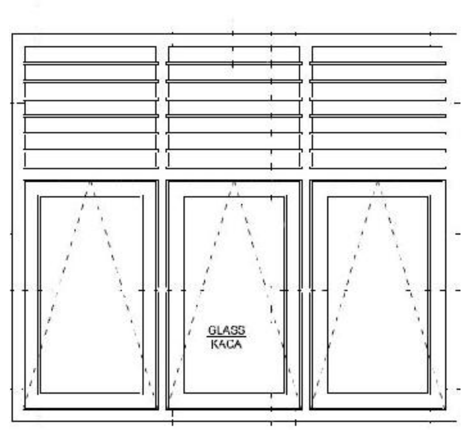
Output:Variable object

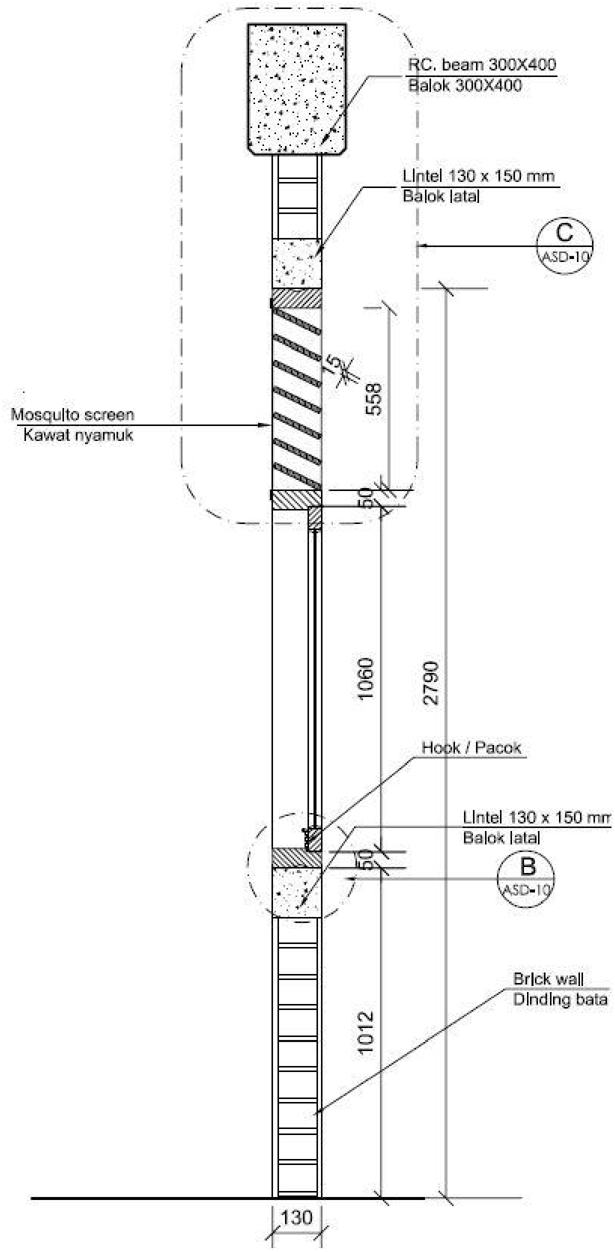
Field	Object1	Object2	Object3
Variable Name	Site Outdoor Air Drybulb Temperature	Zone Operative Temperature	Zone Operative Temperature
Reporting Frequency	Hourly	Hourly	Annual
Schedule Name		School Hours	

For the purpose of parametric simulation, an .rvi file should be created. This is required for executing simulation in JE Plus. An .rvi file was created by running .idf file in EnergyPlus.

Appendix 4 - 5: Ventilation model







Appendix 4 - 6: Decision Matrix

Appendix 4 – 6: Decision Matrix

#	Job_ID	ModelFile	Floor	Walls	Ceiling	Roof	Total Cost (IDR)	EE	CO2	Ecology	Social	Economic	#Disc Hours	Index	Rank
16	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_1	Type 4.imf	ceramic	CHB	plywood	clay	167,201,599	147,778	19,607	3.37	4.09	3.95	228	0.755	1
16	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_1	Type 2.imf	ceramic	CHB	plywood	clay	168,817,133	154,710	20,754	3.37	4.09	3.95	256	0.732	2
34	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_1	Type 4.imf	granite	CHB	plywood	clay	175,335,724	173,720	20,903	3.44	4.12	3.97	226	0.723	3
4	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_1	Type 4.imf	ceramic	bricks	gypsum	clay	151,243,075	177,955	21,160	3.08	4.09	3.92	232	0.720	4
25	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_1	Type 4.imf	granite	bricks	plywood	clay	171,392,881	203,819	22,425	3.41	4.18	4.11	226	0.713	5
13	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_1	Type 4.imf	ceramic	CHB	gypsum	clay	155,185,918	147,856	19,638	3.12	4.03	3.78	222	0.713	6
7	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_1	Type 4.imf	ceramic	bricks	plywood	clay	163,258,756	177,877	21,129	3.33	4.15	4.09	319	0.708	7
6	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_0	Type 4.imf	ceramic	bricks	plywood	cement	154,513,799	161,547	29,785	3.35	4.11	4.06	252	0.704	8
34	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_1	Type 2.imf	granite	CHB	plywood	clay	176,951,258	180,652	22,050	3.44	4.12	3.97	246	0.702	9
4	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_1	Type 2.imf	ceramic	bricks	gypsum	clay	152,579,810	186,936	22,410	3.08	4.09	3.92	254	0.696	10
25	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_1	Type 2.imf	granite	bricks	plywood	clay	172,729,615	212,800	23,675	3.41	4.18	4.11	247	0.689	11
22	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_1	Type 4.imf	granite	bricks	gypsum	clay	159,377,200	203,897	22,456	3.16	4.13	3.94	242	0.689	12
31	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_1	Type 4.imf	granite	CHB	gypsum	clay	163,320,043	173,798	20,934	3.19	4.07	3.79	240	0.687	13
13	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_1	Type 2.imf	ceramic	CHB	gypsum	clay	156,801,453	154,788	20,785	3.12	4.03	3.78	269	0.684	14
24	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_0	Type 4.imf	granite	bricks	plywood	cement	162,647,924	187,489	31,081	3.42	4.15	4.08	222	0.682	15
6	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_0	Type 2.imf	ceramic	bricks	plywood	cement	155,850,534	170,528	31,036	3.35	4.11	4.06	267	0.680	16
15	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_0	Type 4.imf	ceramic	CHB	plywood	cement	158,456,643	131,448	28,264	3.39	4.05	3.92	319	0.673	17
1	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_1	Type 4.imf	ceramic	bricks	GRC	clay	156,693,802	185,606	24,055	3.10	4.05	3.83	242	0.670	18
12	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_0	Type 4.imf	ceramic	CHB	gypsum	cement	146,440,962	131,526	28,295	3.14	3.99	3.75	243	0.669	19
31	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_1	Type 2.imf	granite	CHB	gypsum	clay	164,935,578	180,730	22,081	3.19	4.07	3.79	262	0.665	20
7	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_1	Type 2.imf	ceramic	bricks	plywood	clay	164,595,490	186,858	22,379	3.33	4.15	4.09	360	0.662	21
24	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_0	Type 2.imf	granite	bricks	plywood	cement	163,984,659	196,470	32,332	3.42	4.15	4.08	245	0.657	22
10	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_1	Type 4.imf	ceramic	CHB	GRC	clay	160,636,646	155,507	22,534	3.14	3.99	3.69	249	0.656	23
30	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_0	Type 4.imf	granite	CHB	gypsum	cement	154,575,087	157,468	29,591	3.21	4.03	3.77	234	0.653	24
21	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_0	Type 4.imf	granite	bricks	gypsum	cement	150,632,243	187,567	31,112	3.17	4.09	3.91	238	0.653	25
33	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_0	Type 4.imf	granite	CHB	plywood	cement	166,590,768	157,390	29,560	3.46	4.08	3.94	305	0.652	26
12	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_0	Type 2.imf	ceramic	CHB	gypsum	cement	148,056,496	138,457	29,442	3.14	3.99	3.75	270	0.645	27
19	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_1	Type 4.imf	granite	bricks	GRC	clay	164,827,927	211,548	25,351	3.17	4.09	3.85	247	0.641	28
1	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_1	Type 2.imf	ceramic	bricks	GRC	clay	158,030,537	194,587	25,305	3.10	4.05	3.83	272	0.640	29
10	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_1	Type 2.imf	ceramic	CHB	GRC	clay	162,252,180	162,438	23,680	3.14	3.99	3.69	272	0.634	30
3	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_0	Type 4.imf	ceramic	bricks	gypsum	cement	142,498,118	161,625	29,816	3.10	4.05	3.89	323	0.634	31
15	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_0	Type 2.imf	ceramic	CHB	plywood	cement	160,072,177	138,379	29,410	3.39	4.05	3.92	358	0.632	32
30	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_0	Type 2.imf	granite	CHB	gypsum	cement	156,190,621	164,399	30,738	3.21	4.03	3.77	261	0.629	33

Appendix 4 – 6: Decision Matrix *(continued)*

#	Job_ID	ModelFile	Floor	Walls	Ceiling	Roof	Total Cost (IDR)	EE	CO2	Ecology	Social	Economic	#Disc Hours	Index	Rank
17	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_2	Type 4.imf	ceramic	CHB	plywood	metal	143,779,375	244,597	24,493	3.43	4.02	3.84	289	0.628	34
0	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_0	Type 4.imf	ceramic	bricks	GRC	cement	147,948,846	169,275	32,711	3.12	4.01	3.80	253	0.625	35
9	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_0	Type 4.imf	ceramic	CHB	GRC	cement	151,891,689	139,177	31,190	3.15	3.95	3.66	243	0.622	36
8	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_2	Type 4.imf	ceramic	bricks	plywood	metal	139,836,531	274,696	26,014	3.39	4.08	3.98	292	0.618	37
19	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_1	Type 2.imf	granite	bricks	GRC	clay	166,164,662	220,529	26,601	3.17	4.09	3.85	264	0.617	38
5	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_2	Type 4.imf	ceramic	bricks	gypsum	metal	127,820,851	274,774	26,045	3.14	4.02	3.80	226	0.615	39
33	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_0	Type 2.imf	granite	CHB	plywood	cement	168,206,302	164,321	30,706	3.46	4.08	3.94	346	0.612	40
22	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_1	Type 2.imf	granite	bricks	gypsum	clay	160,713,935	212,878	23,706	3.16	4.13	3.94	350	0.609	41
18	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_0	Type 4.imf	granite	bricks	GRC	cement	156,082,971	195,217	34,007	3.19	4.05	3.82	239	0.609	42
14	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_2	Type 4.imf	ceramic	CHB	gypsum	metal	131,763,694	244,675	24,524	3.18	3.96	3.66	247	0.608	43
27	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_0	Type 4.imf	granite	CHB	GRC	cement	160,025,814	165,119	32,486	3.23	3.98	3.68	235	0.607	44
0	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_0	Type 2.imf	ceramic	bricks	GRC	cement	149,285,581	178,257	33,962	3.12	4.01	3.80	267	0.603	45
28	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_1	Type 4.imf	granite	CHB	GRC	clay	168,770,771	181,449	23,830	3.21	4.02	3.71	311	0.602	46
35	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_2	Type 4.imf	granite	CHB	plywood	metal	151,913,500	270,539	25,789	3.50	4.05	3.86	284	0.600	47
32	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_2	Type 4.imf	granite	CHB	gypsum	metal	139,897,819	270,617	25,820	3.25	4.00	3.68	219	0.598	48
9	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_0	Type 2.imf	ceramic	CHB	GRC	cement	153,507,224	146,108	32,337	3.15	3.95	3.66	273	0.597	49
14	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_2	Type 2.imf	ceramic	CHB	gypsum	metal	133,379,229	251,607	25,671	3.18	3.96	3.66	253	0.593	50
17	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_2	Type 2.imf	ceramic	CHB	plywood	metal	145,394,909	251,529	25,639	3.43	4.02	3.84	325	0.591	51
26	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_2	Type 4.imf	granite	bricks	plywood	metal	147,970,656	300,638	27,310	3.47	4.11	4.00	287	0.590	52
5	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_2	Type 2.imf	ceramic	bricks	gypsum	metal	129,157,585	283,755	27,296	3.14	4.02	3.80	254	0.589	53
3	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_0	Type 2.imf	ceramic	bricks	gypsum	cement	143,834,853	170,606	31,067	3.10	4.05	3.89	366	0.588	54
18	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_0	Type 2.imf	granite	bricks	GRC	cement	157,419,706	204,199	35,258	3.19	4.05	3.82	263	0.583	55
27	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_0	Type 2.imf	granite	CHB	GRC	cement	161,641,349	172,050	33,633	3.23	3.98	3.68	265	0.582	56
8	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_2	Type 2.imf	ceramic	bricks	plywood	metal	141,173,266	283,677	27,265	3.39	4.08	3.98	329	0.579	57
32	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_2	Type 2.imf	granite	CHB	gypsum	metal	141,513,354	277,549	26,967	3.25	4.00	3.68	248	0.573	58
21	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_0	Type 2.imf	granite	bricks	gypsum	cement	151,968,978	196,548	32,363	3.17	4.09	3.91	354	0.571	59
2	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_2	Type 4.imf	ceramic	bricks	GRC	metal	133,271,578	282,425	28,940	3.16	3.98	3.72	243	0.570	60
35	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_2	Type 2.imf	granite	CHB	plywood	metal	153,529,034	277,471	26,935	3.50	4.05	3.86	317	0.567	61
23	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_2	Type 2.imf	granite	bricks	gypsum	metal	137,291,710	309,697	28,592	3.22	4.06	3.82	260	0.563	62
28	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_1	Type 2.imf	granite	CHB	GRC	clay	170,386,305	188,380	24,976	3.21	4.02	3.71	353	0.561	63
26	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_2	Type 2.imf	granite	bricks	plywood	metal	149,307,391	309,619	28,561	3.47	4.11	4.00	322	0.555	64
29	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_2	Type 4.imf	granite	CHB	GRC	metal	145,348,547	278,268	28,715	3.27	3.95	3.59	243	0.549	65
23	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_2	Type 4.imf	granite	bricks	gypsum	metal	135,954,976	300,716	27,341	3.22	4.06	3.82	308	0.549	66
2	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_2	Type 2.imf	ceramic	bricks	GRC	metal	134,608,313	291,406	30,191	3.16	3.98	3.72	268	0.545	67

Appendix 4 – 6: Decision Matrix *(continued)*

#	Job_ID	ModelFile	Floor	Walls	Ceiling	Roof	Total Cost (IDR)	EE	CO2	Ecology	Social	Economic	#Disc Hours	Index	Rank
20	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_2	Type 2.imf	granite	bricks	GRC	metal	142,742,438	317,348	31,487	3.23	4.02	3.73	261	0.528	68
29	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_2	Type 2.imf	granite	CHB	GRC	metal	146,964,081	285,199	29,862	3.27	3.95	3.59	268	0.526	69
11	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_2	Type 4.imf	ceramic	CHB	GRC	metal	137,214,422	252,326	27,419	3.20	3.92	3.57	321	0.526	70
16	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_1	Type 1.imf	ceramic	CHB	plywood	clay	151,656,695	117,367	14,717	3.37	4.09	3.95	613	0.525	71
16	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_1	Type 3.imf	ceramic	CHB	plywood	clay	172,888,313	124,574	15,246	3.37	4.09	3.95	586	0.520	72
20	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_2	Type 4.imf	granite	bricks	GRC	metal	141,405,703	308,367	30,236	3.23	4.02	3.73	312	0.509	73
34	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_1	Type 1.imf	granite	CHB	plywood	clay	159,790,820	143,309	16,013	3.44	4.12	3.97	613	0.505	74
34	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_1	Type 3.imf	granite	CHB	plywood	clay	181,022,438	150,516	16,542	3.44	4.12	3.97	588	0.498	75
25	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_1	Type 1.imf	granite	bricks	plywood	clay	157,060,893	164,491	17,084	3.41	4.18	4.11	638	0.494	76
6	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_0	Type 1.imf	ceramic	bricks	plywood	cement	140,639,622	123,073	23,991	3.35	4.11	4.06	635	0.493	77
13	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_1	Type 1.imf	ceramic	CHB	gypsum	clay	139,751,758	117,444	14,748	3.12	4.03	3.78	622	0.491	78
11	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_2	Type 2.imf	ceramic	CHB	GRC	metal	138,829,956	259,257	28,566	3.20	3.92	3.57	361	0.486	79
13	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_1	Type 3.imf	ceramic	CHB	gypsum	clay	161,038,748	124,651	15,277	3.12	4.03	3.78	599	0.482	80
4	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_1	Type 1.imf	ceramic	bricks	gypsum	clay	137,021,831	138,626	15,819	3.08	4.09	3.92	648	0.480	81
25	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_1	Type 3.imf	granite	bricks	plywood	clay	178,292,511	171,698	17,613	3.41	4.18	4.11	627	0.479	82
31	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_1	Type 1.imf	granite	CHB	gypsum	clay	147,885,883	143,386	16,044	3.19	4.07	3.79	614	0.473	83
4	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_1	Type 3.imf	ceramic	bricks	gypsum	clay	158,308,821	145,833	16,348	3.08	4.09	3.92	627	0.469	84
31	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_1	Type 3.imf	granite	CHB	gypsum	clay	169,172,873	150,593	16,573	3.19	4.07	3.79	584	0.468	85
6	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_0	Type 3.imf	ceramic	bricks	plywood	cement	159,258,136	125,401	27,107	3.35	4.11	4.06	628	0.468	86
12	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_0	Type 1.imf	ceramic	CHB	gypsum	cement	131,464,612	101,969	22,951	3.14	3.99	3.75	620	0.468	87
7	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_1	Type 1.imf	ceramic	bricks	plywood	clay	148,926,768	138,549	15,788	3.33	4.15	4.09	724	0.466	88
22	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_1	Type 1.imf	granite	bricks	gypsum	clay	145,155,956	164,568	17,115	3.16	4.13	3.94	637	0.464	89
24	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_0	Type 1.imf	granite	bricks	plywood	cement	148,773,747	149,015	25,287	3.42	4.15	4.08	649	0.463	90
33	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_0	Type 3.imf	granite	CHB	plywood	cement	170,122,188	130,161	27,332	3.46	4.08	3.94	597	0.459	91
3	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_0	Type 1.imf	ceramic	bricks	gypsum	cement	128,734,685	123,151	24,022	3.10	4.05	3.89	644	0.457	92
10	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_1	Type 1.imf	ceramic	CHB	GRC	clay	145,152,248	125,024	17,616	3.14	3.99	3.69	624	0.454	93
7	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_1	Type 3.imf	ceramic	bricks	plywood	clay	170,158,386	145,756	16,317	3.33	4.15	4.09	716	0.451	94
10	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_1	Type 3.imf	ceramic	CHB	GRC	clay	166,414,119	132,196	18,132	3.14	3.99	3.69	590	0.450	95
12	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_0	Type 3.imf	ceramic	CHB	gypsum	cement	150,138,498	104,296	26,067	3.14	3.99	3.75	600	0.449	96
15	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_0	Type 1.imf	ceramic	CHB	plywood	cement	143,369,549	101,891	22,920	3.39	4.05	3.92	703	0.449	97
1	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_1	Type 1.imf	ceramic	bricks	GRC	clay	142,422,322	146,206	18,687	3.10	4.05	3.83	640	0.447	98
22	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_1	Type 3.imf	granite	bricks	gypsum	clay	166,442,946	171,775	17,644	3.16	4.13	3.94	628	0.444	99
24	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_0	Type 3.imf	granite	bricks	plywood	cement	167,392,261	151,343	28,403	3.42	4.15	4.08	633	0.443	100

#	Job_ID	ModelFile	Floor	Walls	Ceiling	Roof	Total Cost (IDR)	EE	CO2	Ecology	Social	Economic	#Disc Hours	Index	Rank
30	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_0	Type 1.imf	granite	CHB	gypsum	cement	139,598,737	127,911	24,247	3.21	4.03	3.77	620	0.442	101
9	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_0	Type 1.imf	ceramic	CHB	GRC	cement	136,865,102	109,549	25,820	3.15	3.95	3.66	616	0.434	102
3	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_0	Type 3.imf	ceramic	bricks	gypsum	cement	147,408,571	125,478	27,138	3.10	4.05	3.89	633	0.432	103
21	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_0	Type 1.imf	granite	bricks	gypsum	cement	136,868,810	149,093	25,318	3.17	4.09	3.91	644	0.431	104
28	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_1	Type 1.imf	granite	CHB	GRC	clay	153,286,373	150,966	18,912	3.21	4.02	3.71	619	0.430	105
15	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_0	Type 3.imf	ceramic	CHB	plywood	cement	161,988,063	104,219	26,036	3.39	4.05	3.92	691	0.427	106
33	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_0	Type 1.imf	granite	CHB	plywood	cement	151,503,674	127,833	24,216	3.46	4.08	3.94	703	0.426	107
1	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_1	Type 3.imf	ceramic	bricks	GRC	clay	163,684,193	153,378	19,203	3.10	4.05	3.83	635	0.424	108
28	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_1	Type 3.imf	granite	CHB	GRC	clay	174,548,244	158,138	19,428	3.21	4.02	3.71	590	0.423	109
30	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_0	Type 3.imf	granite	CHB	gypsum	cement	158,272,623	130,238	27,363	3.21	4.03	3.77	600	0.421	110
19	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_1	Type 1.imf	granite	bricks	GRC	clay	150,556,447	172,148	19,983	3.17	4.09	3.85	639	0.420	111
0	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_0	Type 1.imf	ceramic	bricks	GRC	cement	134,135,176	130,731	26,890	3.12	4.01	3.80	651	0.415	112
14	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_2	Type 1.imf	ceramic	CHB	gypsum	metal	117,555,719	209,195	19,377	3.18	3.96	3.66	613	0.412	113
9	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_0	Type 3.imf	ceramic	CHB	GRC	cement	155,513,869	111,841	28,922	3.15	3.95	3.66	603	0.411	114
21	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_0	Type 3.imf	granite	bricks	gypsum	cement	155,542,696	151,420	28,434	3.17	4.09	3.91	633	0.404	115
5	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_2	Type 1.imf	ceramic	bricks	gypsum	metal	114,825,793	230,377	20,448	3.14	4.02	3.80	638	0.401	116
27	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_0	Type 1.imf	granite	CHB	GRC	cement	144,999,227	135,491	27,116	3.23	3.98	3.68	624	0.400	117
19	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_1	Type 3.imf	granite	bricks	GRC	clay	171,818,318	179,320	20,499	3.17	4.09	3.85	632	0.398	118
0	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_0	Type 3.imf	ceramic	bricks	GRC	cement	152,783,943	133,023	29,993	3.12	4.01	3.80	630	0.394	119
17	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_2	Type 1.imf	ceramic	CHB	plywood	metal	129,460,656	209,117	19,347	3.43	4.02	3.84	698	0.392	120
8	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_2	Type 1.imf	ceramic	bricks	plywood	metal	126,730,730	230,299	20,417	3.39	4.08	3.98	722	0.390	121
18	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_0	Type 1.imf	granite	bricks	GRC	cement	142,269,301	156,673	28,186	3.19	4.05	3.82	651	0.384	122
27	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_0	Type 3.imf	granite	CHB	GRC	cement	163,647,994	137,783	30,218	3.23	3.98	3.68	605	0.379	123
32	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_2	Type 1.imf	granite	CHB	gypsum	metal	125,689,844	235,137	20,674	3.25	4.00	3.68	622	0.376	124
14	EP_G-T_0-W_0-P1_0-P2_1-P3_1-P4_2	Type 3.imf	ceramic	CHB	gypsum	metal	131,843,851	245,332	21,367	3.18	3.96	3.66	585	0.374	125
26	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_2	Type 1.imf	granite	bricks	plywood	metal	134,864,855	256,241	21,713	3.47	4.11	4.00	724	0.368	126
35	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_2	Type 1.imf	granite	CHB	plywood	metal	137,594,781	235,059	20,643	3.50	4.05	3.86	698	0.367	127
18	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_0	Type 3.imf	granite	bricks	GRC	cement	160,918,068	158,965	31,289	3.19	4.05	3.82	635	0.360	128
5	EP_G-T_0-W_0-P1_0-P2_0-P3_1-P4_2	Type 3.imf	ceramic	bricks	gypsum	metal	129,113,925	266,514	22,437	3.14	4.02	3.80	633	0.347	129
17	EP_G-T_0-W_0-P1_0-P2_1-P3_2-P4_2	Type 3.imf	ceramic	CHB	plywood	metal	143,693,417	245,255	21,336	3.43	4.02	3.84	682	0.345	130
8	EP_G-T_0-W_0-P1_0-P2_0-P3_2-P4_2	Type 3.imf	ceramic	bricks	plywood	metal	140,963,490	266,437	22,407	3.39	4.08	3.98	715	0.345	131
23	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_2	Type 1.imf	granite	bricks	gypsum	metal	122,959,918	256,319	21,744	3.22	4.06	3.82	724	0.332	132
26	EP_G-T_0-W_0-P1_1-P2_0-P3_2-P4_2	Type 3.imf	granite	bricks	plywood	metal	149,097,615	292,379	23,703	3.47	4.11	4.00	717	0.328	133

#	Job_ID	ModelFile	Floor	Walls	Ceiling	Roof	Total Cost (IDR)	EE	CO2	Ecology	Social	Economic	#Disc Hours	Index	Rank
11	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_2	Type 1.imf	ceramic	CHB	GRC	metal	122,956,210	216,775	22,246	3.20	3.92	3.57	705	0.325	134
35	EP_G-T_0-W_0-P1_1-P2_1-P3_2-P4_2	Type 3.imf	granite	CHB	plywood	metal	151,827,542	271,197	22,632	3.50	4.05	3.86	681	0.324	135
2	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_2	Type 1.imf	ceramic	bricks	GRC	metal	120,226,283	237,957	23,317	3.16	3.98	3.72	728	0.314	136
29	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_2	Type 1.imf	granite	CHB	GRC	metal	131,090,335	242,717	23,542	3.27	3.95	3.59	704	0.290	137
20	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_2	Type 1.imf	granite	bricks	GRC	metal	128,360,408	263,899	24,613	3.23	4.02	3.73	728	0.282	138
23	EP_G-T_0-W_0-P1_1-P2_0-P3_1-P4_2	Type 3.imf	granite	bricks	gypsum	metal	137,248,050	292,456	23,733	3.22	4.06	3.82	715	0.281	139
32	EP_G-T_0-W_0-P1_1-P2_1-P3_1-P4_2	Type 3.imf	granite	CHB	gypsum	metal	139,977,976	271,274	22,663	3.25	4.00	3.68	691	0.278	140
11	EP_G-T_0-W_0-P1_0-P2_1-P3_0-P4_2	Type 3.imf	ceramic	CHB	GRC	metal	137,219,223	252,877	24,222	3.20	3.92	3.57	694	0.265	141
2	EP_G-T_0-W_0-P1_0-P2_0-P3_0-P4_2	Type 3.imf	ceramic	bricks	GRC	metal	134,489,297	274,059	25,293	3.16	3.98	3.72	720	0.254	142
29	EP_G-T_0-W_0-P1_1-P2_1-P3_0-P4_2	Type 3.imf	granite	CHB	GRC	metal	145,353,348	278,819	25,518	3.27	3.95	3.59	694	0.228	143
20	EP_G-T_0-W_0-P1_1-P2_0-P3_0-P4_2	Type 3.imf	granite	bricks	GRC	metal	142,623,422	300,001	26,589	3.23	4.02	3.73	721	0.225	144

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