Commercial Building Façade Design:

Improving the Consistency of Early Design Tool Predictions and Detailed Design Tool Calculations

By

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A thesis
submitted to the School of Architecture, Victoria University of Wellington,
in fulfilment of the requirements for the degree of
Master of Building Science.

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ACKNOWLEDGEMENTS

Firstly, I would like to dedicate this research thesis to one of my best friends, the late Geoffrey Payne. Rest in peace brother, love you and miss you always. To the Payne family, thanks for all the great memories throughout the years; Geoffrey will be forever in our hearts.

I would like to mention a special acknowledgement to my family and friends, their support and encouragement made this all possible. I love you Mum & Dad, thanks for always reminding me to "provide for a rainy day". It has been a year to remember, thank you all for believing in me and being there for me when it mattered the most.

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PREFACE

This research thesis was submitted in fulfilment of the requirements for the degree of Master of Building Science at the School of Architecture, Victoria University of Wellington, New Zealand.

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ABSTRACT

The focus of this research is the concept of the 'Performance Sketch' tool. This is to use detailed simulation software to calculate (plausible) energy performance of designs quickly. Analogous to the Architectural Sketch the Performance Sketch uses high quality tools (detailed simulation) to create an accurate, but simple representation of the essential properties of a building, as opposed to a detailed representation.

The aim of this research is to assess the consistency between the predictions produced by performance sketch design tools and the calculations produced by detailed design tools.

The Lawrence Berkeley National Laboratory's (LBNL) computer software COMFEN (COMmercial FENestration) is a performance sketch tool. It makes the power of the complex detailed design simulation package EnergyPlus available in the very early stages of the design process. It uses a single zone, single external façade EnergyPlus model to explore the costs and benefits of alternate façade designs.

The hypothesis tested is that the COMFEN (single-zone) energy performance calculation method is plausible for early design analyses. It evaluates the performance sketch approach from three different points of view: first, COMFEN was introduced to various practitioners in the building industry to gather use-case feedback on the performance sketch approach. A list of specifications for performance sketch design tools was developed based on these use-cases. Second, it examines whether the optimum façade identified by COMFEN creates the optimum performance complex building when this optimum façade is incorporated into detailed building models. Finally, refinements of the nature of the performance sketch based on this use-case feedback were tested in EnergyPlus.

The thesis concludes by drawing together these three threads into an outline of a practitioner-based definition of an ideal performance sketch which has been tested in practical application.

Key Definitions & Abbreviations

Definitions

COMFEN: An example of a Performance Sketch early design tool used for this research (single-zone simulations); it uses EnergyPlus (a detailed design simulation tool) to quickly calculate energy performance of building façade designs.

Consistency: COMFEN/single-zone and EnergyPlus/multi-zone predictions of energy performance will produce the same design advice/feedback (i.e. the ranking of the façade ideas will be the same, as well as similarity in distribution of energy end-uses).

Detailed design lessons: The lessons learnt from the detailed design tool.

Detailed Design Tool (DDT): A DDT is a complex building energy simulation tool (e.g. EnergyPlus) used during the detailed design process, where all the details are included in the computer model.

Early design lessons: The lessons learnt from the early design tool.

Early Design Tool (EDT): An EDT is a building energy simulation tool used during the early design process, where a small amount of detail is available.

EnergyPlus (EP): An example of a detailed design tool used for this research (multi-zone simulations).

Multi-zone: Complex computer simulations in EnergyPlus (time consuming calculations); modelling of associated spaces within a building design.

Performance Sketch Tool: It uses a detailed design tool on a sketch of the building design. For example, COMFEN allows the user to sketch building designs with the power of a detailed simulation tool (e.g. EnergyPlus).

Single-zone: Simple 1 zone computer simulations in COMFEN (quick calculations).

Use-cases: Feedback based on the introduction of COMFEN program to practitioners.

Abbreviations

ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers

COMFEN: COMmercial FENestration

DoE: Department of Energy (USA)

EUI: Energy Use Index

HVAC: Heating, Ventilation, and Air-Conditioning

IWEC: The International Weather for Energy Calculation

LBNL: Lawrence Berkeley National Laboratory (Berkeley, CA, USA)

NREL: National Renewable Energy Laboratory (USA)

TMY: Typical Meteorological Year

1 INTRODUCTION

This is a usability study focusing on the ‘Performance Sketch’. The concept of the performance sketch is to use a detailed simulation tool that calculates energy performance of designs quickly because it: uses a sketch model that is simple and easy to understand; is an accurate ‘sketch’ of the important environmental features; and avoids the complexity of interoperability with CAD software in order to gain speed and efficiency.

Early design tools play a crucial role in a building project. To design an energy efficient building, the design team must simulate the mechanical system from day one of the project (i.e. determine the size of equipment); and carefully assess comfort and performance issues. Like the architect’s sketch, if it is as flexible in application as the ideal performance sketch, then the early design tool can be returned to at any stage in the design process. Should it become necessary to explore a new idea for a façade during developed design, the sketch tool may allow a rapid analysis of new design options that can be returned to the comprehensive model once resolved.

The research uses a three-method approach to evaluate the performance sketch concept:

Method 1: An example of a performance sketch early design tool was introduced to various practitioners for usability feedback. The feedback gathered from interviews around the world was used to analyse the consistency of performance sketch tools’ energy predictions with the calculations of detailed design tools. In this research the interview feedback are ‘Use-cases’. “A use-case defines a sequence of actions a system performs that yields an observable result of value to a particular actor. A use-case describes primarily functional but also non-functional requirements from the perspective of an actor achieving particular goals.” (Haumer 2004). The goal was to work alongside practitioners (architects & engineers) to obtain the opinions of professionals who would use tools similar to a performance sketch tool on a day-to-day basis. The significance of this research is that the outcome should help improve the usability and capability of future performance sketch tools.

Method 2: A performance sketch tool and a detailed design tool were used to examine the energy performance of various façade designs. The research tests high performance heavily glazed façades for commercial buildings to examine the relationship/consistency between early design lessons (single-zone simulations) and detailed design lessons (multi-zone simulations).

Method 3: The feasibility of adding complexity to the performance sketch tool was explored in order to address some of the concerns of the use-case interviewees (i.e. use-case suggestions: desired design features). A detailed design tool was used with various levels of model complexity to explore the balance between simplicity and speed on the one hand and complexity and lack of response on the other.

This unique three-method approach offers the potential to critique the performance sketch concept in accuracy and usability terms.

1.1 Focus: Performance Sketch Concept

The performance sketch concept is to use a detailed design tool on a sketch of the building design. It allows the user to sketch building designs with the power of a comprehensive simulation tool.

COMFEN was used as an example tool for this research because it has characteristics and properties which match the performance sketch concept:

- It uses a sophisticated and flexible energy modelling tool (e.g. EnergyPlus) but reduces the complexity of what it is modelling, which provides gains in speed and efficiency during simulations
- It therefore calculates energy performance of building façade designs quickly
- It is simple and easy to understand
- It is not an exact copy of the appearance of the final building but it is a 'sketch' of the important environmental features of the fenestration system.

COMFEN is a simplified interface to a sophisticated and flexible simulation tool EnergyPlus (LBNL 2010). It is intended to make it easy to assess fenestration designs for commercial buildings. This interface has a very different set of input parameters and appearance to stand alone EnergyPlus. Each interface is intended for a different stage of design (i.e. early or detailed). With a detailed simulation engine like EnergyPlus the user can examine all essential design variables (hour by hour). With a Performance Sketch interface like COMFEN, there is less flexibility, but the calculation has the same rigour.

The inspiration for the research was to explore a series of use-cases and determine practitioners' simulation needs from an early design perspective. Essentially, these use-cases are professionals' evaluations of the performance sketch concept. Any performance sketch tool is a simplified model of reality and thus restricts some designs from being simulated (limitations/parameters). The use-case studies were designed to establish what practitioners need in a performance sketch interface; so it is reliable and comprehensive enough to kick-start their project on a solid foundation. The long term goal is to have an early design simulation package that examines all essential design variables (environmental factors) during the early stages of design.

Decisions made during the early design stage of a building affect ones made in the detailed design stage, which ultimately determines project success or failure (Hari 2001).

The hypothesis tested is that by testing the use-cases performance sketch based decisions will be more relevant (consistent) to multi-zone simulations. In other words, the performance sketch concept is plausible for early design analyses. Examples of the issues examined are: if the entire building was modelled during the early design process would the façade design decisions differ to ones suggested by a performance sketch tool? A further test was whether practitioners building a performance sketch should be modelling the whole building using multiple zones from day one?

There are two different approaches to the development of an early design tool:

- Explore a range of building design ideas in detail (with simulation) and then summarise these in a book/tables of data/simple rule of thumb/another simplified software package – guidance thus derived is dependent on scenarios explored at the outset.
- Use a sophisticated and flexible modelling tool (e.g. EnergyPlus) but reduce the complexity of what it is modelling (e.g. COMFEN).

Energy simulation tools are essential in order to forecast a proposed building's thermal performance. However, the virtual representation of a building design can sometimes differ drastically from reality. Mazzarella & Pasini (2009) say:

> "Energy savings in buildings is today mandatory in developed countries, so it is imperative to perform, during the design stage, an accurate estimation of the energy used by buildings to assure different kinds of comfort."

1.2 Aim & Objectives

The aim of this research was to test whether the performance sketch can provide relevant advice. The objective was to compare the consistency of energy performance predictions derived from COMFEN with those from EnergyPlus. This was supplemented by use-case analyses of the value and relevance of COMFEN as an example of a performance sketch tool.

Ultimately the outcome of this research was to be a specification (based on the use-cases) of an ideal performance sketch tool supplemented by a decision-making diagram locating the performance sketch within practitioners' work flows.

The following questions are examined in this research:

1. **What are practitioners' needs from a performance sketch tool?**
   E.g. software capabilities and usability; graphical information; relevance of the tool's design predictions
2. **How relevant is the information predicted by a performance sketch tool?**
   E.g. accuracy and consistency of design predictions; lessons learnt from these design predictions
3. **Performance Sketch Early Design Tool – how simple is too simple?**
   E.g. ultimately define whether the design information within a performance sketch tool is too simple and its interface needs to be more comprehensive
4. **How close is close enough?**
   E.g. difference between early design lessons and detailed design lessons is significant especially when the design advice/feedback changes

Note: These questions will be addressed and analysed in the Conclusions chapter.

1.3 Lessons from The Architectural Sketch

Architectural ideas are expressed through simple and quick sketches (by architects) which represent the aesthetics of the building. The performance sketch tool has a similar basis: representing the energy concept of the building.

Figures 1~14 show examples of concept sketches and the completed buildings. These show that a sketch idea by an architect is expressed through particular principles which communicate with the client and developer (e.g. shape, scale & context). Practitioners transferred the design idea established during the early design stage into the physical built form. It is evident that there is a strong aesthetic relationship between the sketch and actual building. The designers carried the idea throughout the project. The early design decisions here clearly have had a huge influence on the final outcome.

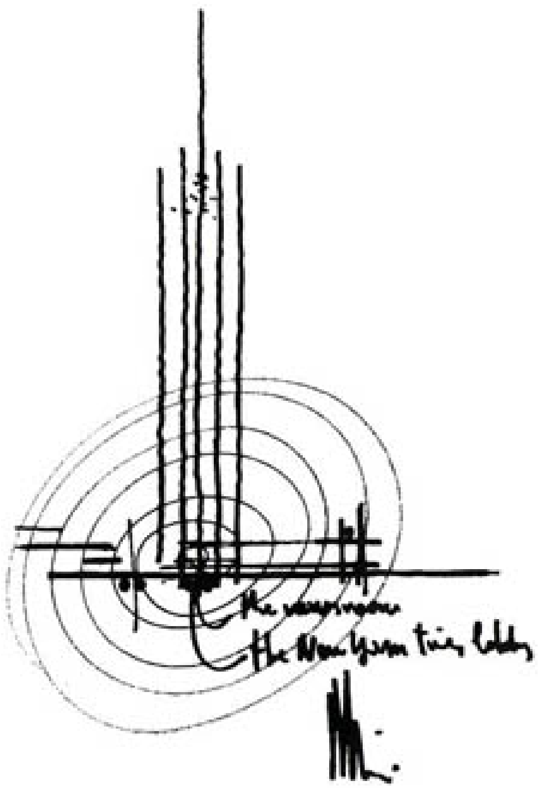

Figure 1 – Sketch of the New York Times building
Figure 2 – Exterior render of the New York Times building in New York, USA
Images © Renzo Piano Building Workshop (http://newyorktimesbuilding.com)

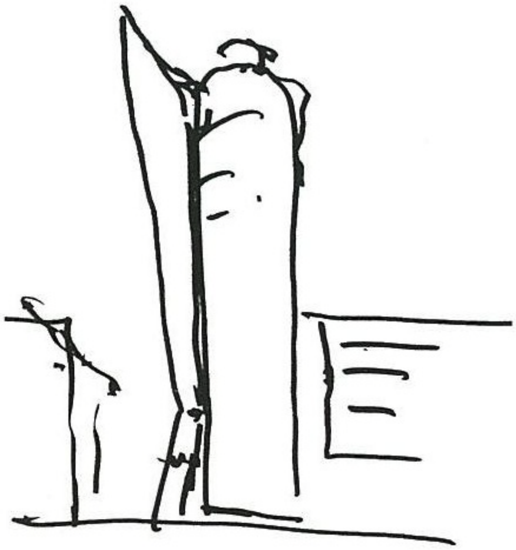
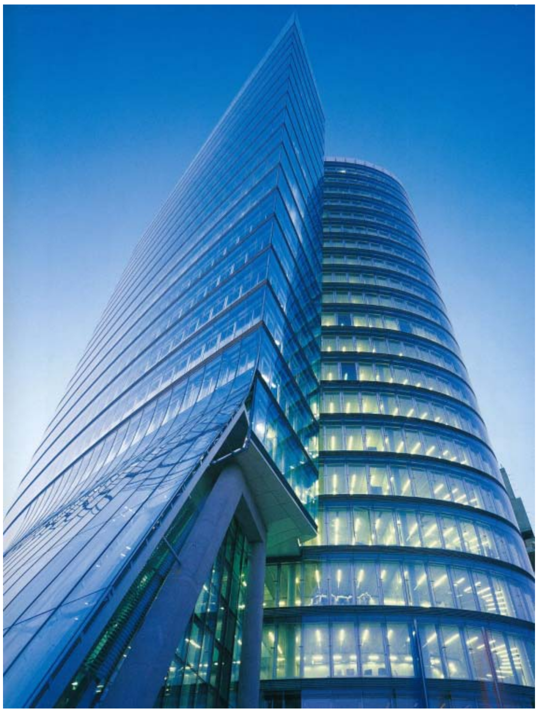

Figure 3 – Sketch of the UNIQA-Tower
Figure 4 – Exterior view of the UNIQA-Tower in Vienna, Austria
Images © Neumann + Partner, Architekten (Hindrichs & Heusler, 2010)

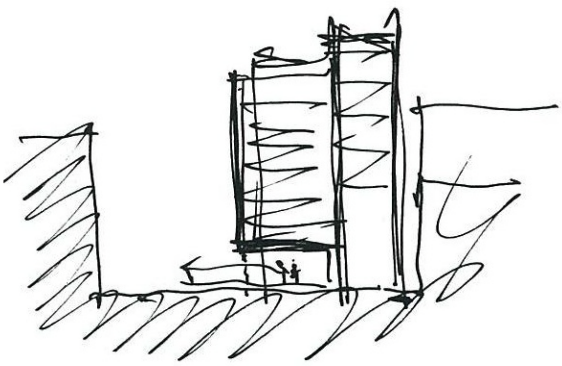


Figure 5 – Sketch of the Sentinel building
Figure 6 – Exterior view of the Sentinel building in Glasgow, UK
Images © Gordon Murray & Alan Dunlop, Architects (Hindrichs & Heusler, 2010)

Figure 7 – Sketch of the Tech Gate Tower
Figure 8 – Exterior view of the Tech Gate Tower in Vienna, Austria
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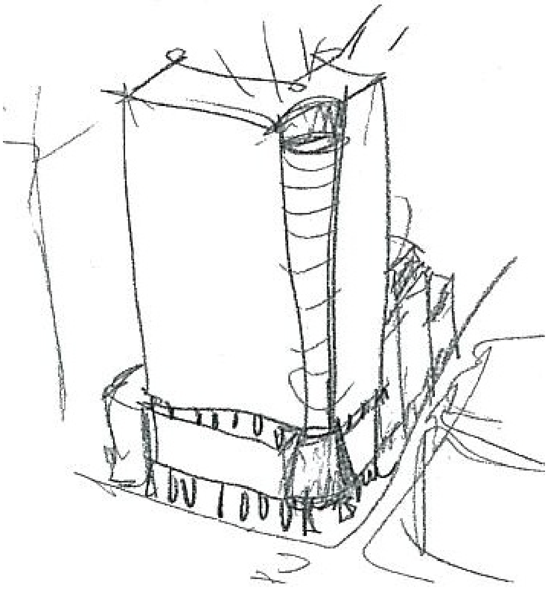

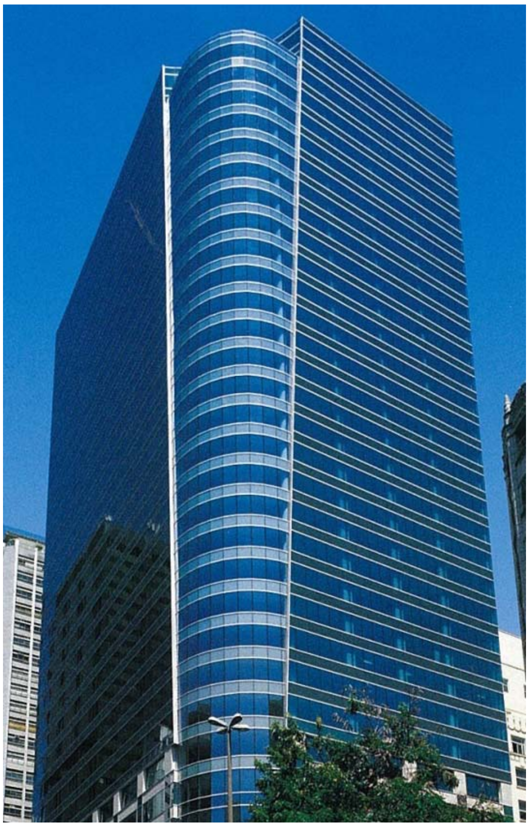

Figure 9 – Sketch of the Torre Almirante building
Figure 10 – Exterior view of the Torre Almirante building in Rio de Janeiro, Brazil
Images © Robert A. M. Stern (Hindrichs & Heusler, 2010)

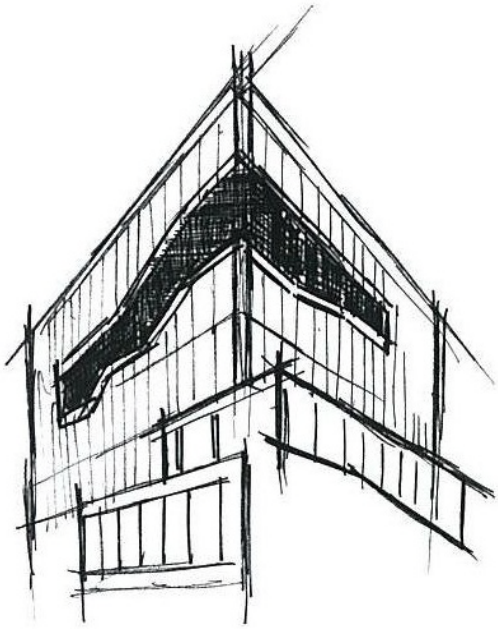 

Figure 11 – Sketch of the Koniglich-Niederlandische Botschaft building
Figure 12 – Exterior view of the Koniglich-Niederlandische Botschaft in Berlin, Germany
Images © Office for Metropolitan Architecture (Hindrichs & Heusler, 2010)

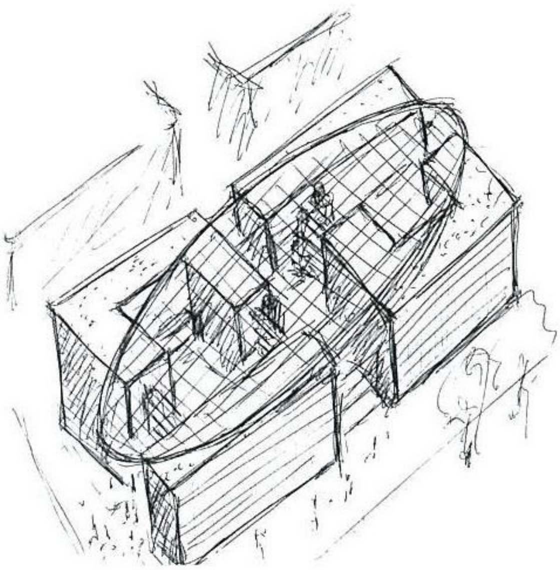 

Figure 13 – Sketch of the Spherion-Office building Deloitte
Figure 14 – Exterior view of the Spherion-Office building Deloitte in Dusseldorf, Germany
Images © Deilmann Koch, Architekten Stadtplaner (Hindrichs & Heusler, 2010)

Figures 1~14 show that the design lessons drawn from these sketches (simple ideas before studied in detail) have been carried out to completion. They suggest once a conceptual (sketch) idea is chosen it is apparent in the final product (i.e. completed building). This suggests why the performance sketch analogy may be useful. What is being sketched during the very early stages of design has a significant impact on a building project.

Early energy prediction is very much like the sketch of a building design (e.g. Figure 1). The ‘simple lines’ within a sketch are comparable to the performance sketch concept used to derive a theoretical idea of how the building design performs; by analogy, the performance sketch examines the environmental ideas in a building design. Like the architectural sketch, it must be simple and quick.

Generally, in early design the best concepts (aesthetic or energy performance) are selected for further development. As the building concept reaches the detailed design stage, those simple sketch lines are being replaced by specified dimensions, construction materials, mechanical systems and schedules etc (i.e. detailed simulation inputs) to paint a clearer/fuller picture of the proposed design.

The relationship between the design lessons of performance evaluation tools applied at sketch and detailed design phases has to be consistent in order for these tools to be viewed as providing plausible design advice/feedback. Hensen (1994) says:

> “Building energy simulation is considered to be a potentially powerful tool for decision support in energy efficient building design.”

All these building examples of sketch to completion have a common design characteristic: they all have heavily glazed façades. It is apparent that glass is a popular method of construction. In this research, COMFEN is used to evaluate sketch ideas of highly glazed commercial building design; it is an early design tool that focuses on sketches of fenestration design (i.e. help designers identify the optimum fenestration design for a building).

1.4 Research Overview

This first chapter is an introduction to the performance sketch idea and the research overall.

The next chapter looks into the literature of early design tools and their users. It discusses the evidence for the influence of early design tools. Also, this chapter focuses on commercial building façade design (aesthetics & energy performance) because of its role in occupants' well-being and the overall building energy consumption.

The third chapter describes the methodology of this research, from calculation methods/techniques used in simulations to structured interviews with practitioners. It describes the three-method approach, and how each method complements the others. The methods are:

1. Introduction of a Performance Sketch Tool to Practitioners
2. Consistency Test of a Performance Sketch Tool
3. Evaluating the Adequacy of the Sketch within a Performance Sketch Tool

The fourth chapter discusses the practitioner feedback from the use-case studies and the results derived from COMFEN and EnergyPlus simulations.

The fifth chapter contains a list of performance sketch tool specifications based on the use-case studies of chapter four.

The Conclusions chapter justifies the overall outcome of this research and examines each of the research questions in relation to the analyses of chapter four and the aims of the research.

The Future work chapter describes the potentials of Performance Sketch tools like COMFEN and reports research questions that require further testing and investigation.

The Appendices chapter includes all COMFEN (single-zone) simulation outputs, EnergyPlus results, façade material properties, and original interview feedback from practitioners.

2 LITERATURE REVIEW

This chapter looks into the literature of building energy simulation tools in relation to their role during early design and detailed design stages of building construction. There is a need for energy simulation tools because architecture practitioners utilise them to estimate energy performance of building designs. The chapter identifies the audience (users) of energy simulation tools and determines their simulation needs during different stages of design.

Also, the subject of heavily glazed façades is addressed. Section 1.3 illustrated a range of building designs that consist of highly glazed façades; designs driven by the conceptual sketch. The literature discussing the energy impact and the reasons why this method of construction is so popular in the commercial sector is extensive. The use of energy simulation tools is significant in this discussion because a building design is (ultimately) tested by these tools during design. This is where the aesthetic decisions about the façade which determine the overall energy impact can be evaluated.

2.1 Users of the Early Design Tool

Generally, the audience for early design tools for building energy performance are architects and engineers. The accuracy of these tools is essential in order to deliver a successful building project. Clevenger & Haymaker (2006) state that energy modelling accuracy (comparison between two models in the same simulation software) ranges from +/- 10% ~ 40% for non-residential models and general industry consensus is that comparisons of predicted performances are more useful than the absolute values themselves.

Many developers have the intention of knowing how a building design performs before construction begins, which is why practitioners (widely) use early design tools during the early stages of design; these tools allow practitioners to identify and evaluate the best concepts to show the developer which ideas are worth further development. Bordass & Leaman (1997) state:

> "Clients, naturally enough, hope that a new building will magic many of their building related problems away and leave them to concentrate on their businesses."

The intention of computer energy simulation is to create a virtual representation of the proposed design and determine its energy performance and environmental impact. However, various assumptions have to be made by the user (practitioner) in terms of building materials, lighting loads, building schedules and HVAC system which all require input data into the software. These design variables influence the results depending on the simulation assumptions made and the user's familiarity with the simulation tool. Therefore users of design tools need to have great understanding of just what is being simulated and the software's intended purpose. The user must recognise what the design tool is able to do and cannot do; using the appropriate tool to assess the proposed design is vital because a tool that is not intended for the desired type of analysis could produce estimations that are misleading to the user.

Like an architect's sketch, early design tools evaluate designs quickly. Detailed design tools require a much larger amount of data entry; they are therefore more time consuming.

Anytime during the early design phase the architect's concept sketch can be returned to the drawing table. Design alterations have to be made until the client is satisfied. The 'Performance Sketch' idea needs to be relevant to this early design stage; the capability of examining multiple designs quickly and accurately has to be time efficient for practitioners.

It is important to note that a simulation tool should work in favour of the user and not the other way around. The users of early design tools often base their opinion on software usability and capability (i.e. user-friendliness & options of analysis). The following sources express users' opinions of building energy simulation tools:

Attia, Beltrán, et al. (2009) mention:

> "Architects are looking for tools that can support sustainability design decisions and make detailed comparisons between different building design and equipment measures."

Tianzhen, Jinqian, & Yi, (1997) state:

> "From the perspective of many architects, most building performance simulation tools are judged as too complex and cumbersome."

Attia, Beltrán, et al. (2009) say:

> "Most architects who use building performance simulation tools in design practice are much more concerned with the (1) Usability and Information Management of interface and (2) the Integration of Intelligent design Knowledge-Base."

And, Punjabi & Miranda (2005) say:

> "However, despite the proliferation of many building simulation/energy analysis tools in the last ten years, architects and designers are still finding it difficult to use even basic tools."

"User-friendliness" is reported generally as playing a huge role in determining how the user perceives the design tool. It is vital that the design tool is user-friendly because then the user can integrate their professional knowledge and experiences into simulations of the proposed building design. "In order to create a simple building energy simulation tool that could help architects and engineers to calculate the impact of design choices the program had to be: highly user-friendly; need a minimum of data; and be very fast." (Gratia & De Herde 2002).

To Shaviv, Yezioro, et al. (1996) user-friendliness is ultimate flexibility in data entry:

> "Most parameters are not assigned specific values early in the design process. Therefore, the designer is free to choose almost any value for the parameter of his current concern. As the design progresses, the previously assigned values may restrict the designer's freedom in choosing the values that are assignable to parameters considered later."

User-friendliness is defined by this statement as ultimate flexibility. However, others argue that more flexibility means the tool becomes more complex; ultimately, it could be harder to understand and use. Bambardekar & Poerschke (2009) state that sophisticated simulation tools are used to test both macro and micro level performance parameters; but they have the following disadvantages:

- Steep learning curve and time intensive application
- Requires large amount of input data

Practitioners have virtually no limitations in terms of expressing their architecture or energy concepts during the early design stage because these are often firmed up during the detailed stage of design. The practitioner wishes to use early design tools to assess various design options with only few restrictions. Early design tools also require minimal information for the user to perform design simulations because during the early design stage the specified design information is not yet available (e.g. HVAC system, lighting load, & building schedules etc).

Each simulation tool has modelling restrictions/limitations. This research proposes there are two types of early design tool:

- **Traditional early design tool**: limited data entry is required due to restrictions on the design situations to which the tool can be applied: for example, limited building size, type, location, system.
- **Sophisticated early design tool**: allows access to a detailed design simulation tool is made available during the early design stage via a simplified model (i.e. a performance sketch tool).

One example of a traditional early design tool is a set of rules of thumb for building design based upon an experienced designers' documentation of their previous designs; or upon summaries of the results of multiple uses of a simulation package on multiple variants of a standard building. Ultimately, the predictions or rules of thumb derived are dependent on the nature of the standard building.

A sophisticated early design tool provides the user with the modelling flexibility of a comprehensive simulation package but reduces the complexity of data input. The user has the ability to assess a simple model with the option to adjust the essential 'detailed' simulation inputs (e.g. occupancy, lighting & interior equipment loads) during the very early stages of design.

The sophisticated early design tool allows the user to set the desired simulation inputs rather than working with defaults or standard designs not relevant to their site or client. Also, modelling flexibility allows the designer to explore a wider variety of concepts than the traditional tool.

It is essential to incorporate past experience (lessons learnt) to a new building project. In this sense every professional designer (Lain, Hensen, & Zmrhal 2009) performs some kind of optimization in each stage of the design process in order to ensure a good indoor environment quality while limiting or minimizing energy consumption. Making an actual design decision relies on the designer's ability to explicitly represent, and then reflect upon, the desirability of the performance of a certain constellation of form, function and context (Petersen & Svendsen 2010).

> "It is a matter of applying our technical knowledge and our long years of experience logically to create concepts for new and refurbished construction that will lead to low-energy buildings." Hermann Kaufmann (Hausladen, de Saldanha, & Liedl 2006).

These authors suggest that to design a sustainable building, all environmental factors have to be examined (taken into consideration) during the early design stage. They suggest use of early design tools is the most practical and effective method of testing for getting an indication of the proposed design's overall energy performance.

Some tools employ 'simplified' methods that address specific perceived needs of the early design phase while others adopt complex first-principle based engineering algorithms that can meet detailed design requirements (Lam, Huang, & Zhai 2004).

"Another important task is the issue of quality control, both for input and output. Input issues regarding internal loads are the most important since they are based on expertise (i.e. the data is not available from the product specifications). The output has to match in terms of expected results and common benchmarks, which are also based on experience." (Brahme, O'Neill, et al. 2009). Choosing the appropriate design tools for the desired analyses is very important:

> "A frequently encountered problem by engineers who would like to perform a simulation is that there is no single simulation environment that can cover the whole range of problems at hand. Certain performance aspects are available in one package while other aspects are only available in another package." (Hensen, Djunaedy, et al. 2004).

Some design tools require the user to have previous simulation experiences simply just to understand its basic principles. Not to mention the output data, the ability to understand and incorporate the predicted information to the design process depends on the user's level of simulation knowledge and their familiarity with the software.

Once the user understands the software principle it will become clearer to them just exactly what the predicted design message is indicating (i.e. simulation outputs) and really experiment with a variety of design options with confidence and trust in the software. Commission of the European Communities (1993) states:

> "The practical efficiency of building energy simulation tools is dependent not only on the facilities offered by the tools and the rigour of the underlying (dynamic thermal) calculations but depends also on the skills of the user in terms of abstracting the essence of a problem into a model, choosing appropriate boundary conditions, setting up simulations and interpreting the results."

Tools with built-in simulation examples allow the user to learn and understand the functionality side of the software (i.e. capabilities). As the user becomes more familiar with the software then the architectural drawings of the proposed design can be transferred into the virtual environment. It is essential to select the right tool for early design analysis. Having a design tool that is capable of exploring crucial design variables from an early design perspective is important to architects and engineers.

Early design tools have various audiences. Apart from the general users (e.g. architects & engineers), there is one other vital audience group and that is the clients. The information extracted from these early design tools must be presented to the client with clarity, so they understand the performance of the proposed design. Early design tools should therefore have the capability of providing the design information that practitioners require for client presentations. Often the output data predicted by the simulation software needs to be translated into graphs and tables and other information that the non-expert can understand. The process of creating those graphs and tables could be time consuming (and tedious) therefore tools that automate the provision of useful graphical information to represent the simulation data is extremely relevant for client meetings and progress reports.

Various authors suggest the importance of graphical output from an early design tool. "To understand the architects' perceptions about existing tools and the importance of using them during design phases." (Attia, Beltrán, et al. 2009). "It would be desirable to develop visualizations that would better facilitate a qualitative understanding of the design performance to the user and provide appropriate guidance in the context of early design decision making." (Lam, Huang, & Zhai 2004).

> "Architects need a tool that provides graphical representation of simulation input and output, simple navigation, flexible and customizable control, in addition to intelligent default features." (Attia, Beltrán, et al. 2009).

The relationship between software developers and users of their software is an area that lacks research and understanding. There needs to be a stronger link between the theory side of thermal calculation and real world (professional) practice. Understanding what practitioners/simulators need is very important for the role of a software developer. What may seem plausible to the developer at times might not be plausible to the user. It is crucial to know exactly what the users need during the development phase of these tools. In relation to building design, this research had access to information regarding to client desires and early design simulation needs through practitioners' interview feedback (i.e. use-cases).

2.2 Relevance of the Early Design Tool

The performance sketch tool uses a detailed design tool in a ‘sketch manner’ to evaluate a building design (i.e. like an architect’s sketch pad). Simplification of a detailed simulation application allows the user to sketch building ideas quickly and assess the essential design features during the very early stages of design (e.g. fenestration design & mechanical loads).

When writing about early design tools, it has been assumed by many of these authors that a complex computer simulation tool requires a complex and complete definition of a building; the simulation process is (often) slow and tedious due to the complexity of the required inputs. “The complexity of the data input is reduced by providing smart default values for solar systems and building elements, to broaden the use of this tool in the architects’ community.” (Witzig, Foradini, et al. 2009). They suggest that the use of smart default settings could replace the process of manual (simulation) data input entry which generally speaking is time consuming and complicated. This complexity has been perceived as a barrier to the use of complex computer simulation during the very early stages of design.

Ochoa & Capeluto (2008) state that early design decisions are based on vague ‘‘ideas’’ that cannot be evaluated with tools that rely on exact data. Many design tools have built-in example files within its application. Default settings used within the example files are very useful to designers because it allows them to perform simulations of their design concepts with very minimal information required. The advantage of smart default settings is that the user can alter these values to their liking. More detail can be incorporated into the simulation model as the design progresses. In other words, the user can adjust the settings to the desired values according to the finalised building specifications.

It is important to note that the performance sketch tool is of a different nature to the traditional type of early design tool proposed by Ochoa & Capeluto. The basic philosophy of the performance sketch tool is to use a comprehensive design simulation package in a much simpler manner. This provides the user with the power of a detailed design tool during the early stages of design, which comes with more modelling flexibility than the traditional approach where predictions derived are dependent on default settings within the application. The sophisticated early design tool allows the designer to explore various concepts in a sketch manner. The advantage of making some complex applications available from day one is that the sketch models can be duplicated, re-used and altered within the detailed design tool as the design progresses into the development phase.

Goulding (1993) noted that it is widely acknowledged that the best opportunity for improving a building’s energy performance occurs early in the design process when basic decisions are made. Many practitioners in today’s building industry use some kind of early design tool to estimate the performance of their proposed design. The predicted data is used to assist the design development process. Therefore, the accuracy and relevance of these design tools have a significant influence on the user’s trust.

Using computers to carry out load calculation and energy simulation is an important part of building design and energy efficiency research (Hui 1998). Once a project reaches the detailed design stage alterations to the building design may be extremely difficult. Therefore performance predictions by an early design tool are significant. If the basic requirement is not fulfilled (Eisele & Kloft 2003) all other attempts at creating a contented atmosphere through well-designed space are doomed to fail.

> "Decisions made in the very first stages of a building's design often have a significant impact on energy efficiency and internal environment of the building. Although many buildings have energy efficiency strategies embedded in their conceptual design, it is seldom that these concepts would be fully analysed at the initial design stages." (Pollock, Roderick, et al. 2009).

Design decisions are influenced by early design tools. Early design tools not only assist practitioners designing sustainable buildings but also allow designers to understand and explore the costs and benefits of alternative concepts. During the early stages of building design a number of decisions are made which have a strong influence on the performance of the building throughout the rest of the process (Petersen & Svendsen 2010).

> "Moreover, the penalty for not addressing climatic responsive design issues early in the process is that opportunity will be lost to make significant savings by relatively simple adjustments to the design. Increasingly sophisticated or costly efforts are needed to save energy." (Goulding 1993).

Lomanowski & Wright (2007) state that few tools exist that can aid the building designer in quantifying the impact of window shading on building loads. They suggest there is a clear need for an explicit treatment of window shading layers in building energy simulation especially during the early design stage. Many have proposed the essence of getting the building design right from day one; it should be common practice and take advantage of determining the ideal design before it is too late (i.e. during the stage when design is flexible not fixed). They emphasise that there is a desire for software capability and usability improvement, from a fenestration design analysis point of view.

When using early design tools to examine the energy performance of a proposed design, it is essential to differentiate design concepts that work and ones that perform inadequately. The predictions from these tools assist people with vital decisions that need to be made as the project progresses; predictions which help identify the best solutions to meet the project requirements.

> "An early analysis will help to establish the merits each design solution offer and help designers develop an optimum solution that meets all required criteria. Where problems with occupancy comfort can be identified early in the design process, passive or low energy solutions can be developed, tested and implemented into the final design." (Pollock, Roderick, et al. 2009).

Attia, Beltrán, et al. (2009) state the importance of realizing the impact on energy performance and cost from the early stages of design.

> "The value of computer simulation when used in early conceptual design lays in the opportunity to quantify the effect of design decisions on energy and comfort thereby reducing the time needed to turn-around design iterations." (Lain, Hensen, & Zmrhal 2009).

The general goal of energy analysis is to model the proposed design and see if it meets the desired energy performance and comfort levels (standards/codes and client requirements). Comparing the energy performance of various designs allows practitioners to narrow down to the best design options. Client dependent, the best concept(s) is later carried into the development phase of the project for further testing.

> "Simulation is much more effective when used for comparing the predicted performance of design alternatives, rather than when used to predict the performance of a single design solution in absolute sense." (Hensen, Djunaedy, et al. 2004).

There are many advantages using an early design tool – a virtual representation - because it:

- provides an early prediction of the proposed design's energy performance (e.g. EUI)
- can identify design problems earlier on in the project, so it can be solved/remedied
- helps the client and practitioners with the decision-making process

Architects rely on early design tools, they use early design tools to assess their designs and help them with decision-making. However, when it comes to building energy performance, predictions by an early design tool have to be plausible and consistent. The need for early design tools to be reliable is essential because it is too late to make changes after the building is completed; where changes to remedy defects could cost thousands of dollars.

> "Practitioners need early stage, strategic design decision support tools. In the area of indoor environment, building physics and building systems complex interactions exist which are very difficult – if not impossible – to capture and represent in rules or other forms of explicit knowledge for use in knowledge based systems. This is the main reason why many current knowledge based tools are often restricted to single issues." (Hensen, Djunaedy, et al. 2004).

The authors suggest the importance of selecting a relevant tool for the intended design analysis because each software application has its own simulation purpose(s).

Often when exploring a new building design that has not been simulated in the past, estimates and 'educated assumptions' have to be made based on the designer's past experiences. Brahme, O'Neill, et al. (2009) state:

> "Although many of the strategies can be simulated with current tools, there are some that have to be approximated, some have to be drastically simplified both for ease of modelling and time reasons."

The authors raise a key issue with some simulation tools being "drastically simplified" for user-friendliness and time efficiency purposes. The tendency with overly simplified tools is that they are not flexible, which restricts the designer from exploring various ideas from day one. This contrasts with the needs of a designer at the beginning of a building project when they should be identifying and evaluating the best solutions to carry into the detailed design stage.

Design parameters usually come from the project brief or the building budget. However, the simulation tool should never shape how the building is designed due to its software limitations. The designer needs a tool that is capable of testing the client's desired concept(s). The key is 'software capability' because it is important to distinguish what the tool can simulate and what it cannot. Lam, Huang, & Zhai (2004) suggest:

- "The user interface should be designed such that it is familiar, cognitive and compliments the concepts and processes of architectural design and energy modelling."
- "For a tool to be beneficial and remain relevant throughout the building delivery process, it would be advantageous if it is developed based on comprehensive and fundamental principles in modelling the building-environment interactions."

"It is essential that the simulation tools include an interface that supports such a knowledge-base. A knowledgebase that contains descriptive explanations, examples and procedural methods for determining appropriate installation and systems, e.g. guidelines, case studies, strategies etc." (Attia, Beltrán, et al. 2009). The authors state the importance of simulation interface. In this sense a simulation interface with clear documentation can help the user to understand software application and its outputs. It is essential for the user to understand the principles of a design tool; this can be achieved through the simulation interface proposed by Attia, Beltrán, et al.

"Computer modelling and simulation is a powerful technology for addressing interacting architectural, mechanical, and civil engineering issues in buildings." (Hensen, Djunaedy, et al. 2004). There are many current design tools that simulate various environmental factors in relation to building design (e.g. over-heating, glare & heat loss). However, it is essential for a design tool to be capable of simulating various design options that the user desires to assess; to address design aspects that influence the building's overall performance.

Building simulation tools allow today's practitioners to create a virtual model of their building design and assess its performance.

> "A design tool would go beyond calculating the energy performance to address other building design considerations like comfort, economics, and aesthetics. Also, a design tool would help its users formulate appropriate design criteria and improve building performance as the design evolves." (Papamichael & Ellington 1994).

It is clear that with the assistance of early design tools the designer will be able to identify what works well and areas that require improvement within a proposed building design. It is extremely important that practitioners understand the energy performance of their designs, and deal with issues/defects earlier on when mistakes can be fixed without major confrontation. Therefore these tools are the most practical solution for answering those early design questions by architects and engineers.

The performance sketch analysis approach of LBNL's COMFEN is of a similar nature to the user-friendly simulation tool (OPTI) proposed by Gratia & De Herde (2002); it is fast and requires minimal data. COMFEN focuses on the fenestration design of the building with simplified applications of a detailed simulation engine.

"With increasingly affordable computing power, it is argued that energy modelling tools should adopt rigorous physics and engineering-based algorithmic principles in the computational prediction of energy performance to ensure acceptable results." (Lam, Huang, & Zhai 2004). The authors suggest that from an early design assessment perspective there is a need for ensuring the plausibility of energy predictions derived from early designs tools.

The performance sketch tool allows the user to explore new ideas during the building design development phase, and has the added advantage of being compatible with a detailed design tool. Quick sketch analyses can be done parallel to the detailed comprehensive model if alterations are required during the detailed design stage; the sketch approach is time efficient.

2.3 The Relationship between Early Design Lessons and Detailed Design Lessons

In this research COMFEN is the selected example of an early design (Performance Sketch) tool that determines the energy performance of various façade sketches. These early design messages are incorporated into detailed simulations using EnergyPlus.

Architects and engineers depend on energy simulation tools to provide them with predictions on how their proposed design performs before it is built. Hui & Cheung (1998) wrote:

> “The purpose of energy calculation is to estimate the annual energy consumption of buildings so as to provide information for energy and economic analysis which aims at improving the building design.”

As a practitioner you would expect the best proposed concept developed during the early design stage to perform in a similar/plausible manner as the comprehensive model when specified details are incorporated into the simulations. Early design predictions have to be consistent with results derived from the detailed design stage. If the early design message is inconsistent there is a possibility of misleading practitioners during the early design stage; defects that occur during the detailed design stage could be expensive to remedy. Therefore, the relationship between early design tool and detailed design tool is significant.

The transition process from the early design stage of a building to the detailed design stage is a significant phase in a building project. Ultimately, the decisions made during the early design stage determine/shape the final performance of a building project.

> “The early stages of this process characterize themselves by a constant search for a design direction. But as demonstrated by specialists in design methods, decisions taken in those moments can determine the success or failure of the end product.” (Hari 2001).

Early design tools are suitable for the preliminary (early) design stage because simulation settings are often based on defaults until the building design specifications are determined, which are specified later in the project (i.e. development phase). The ‘sketch’ design considerations during the preliminary design phase is important because of its effect on the detailed design stage.

> “The fragmented nature of the building process, in which no member of the design team considers the overall optimization of the indoor environment, further compounds the problem. Since the façade and fenestration design relates to different aspects of building performance (heating, cooling, lighting) and human comfort (thermal, visual), an integrated approach should be followed from the early design stage.” (Tzempelikos, Athienitis, & Karava 2007).

Fabrizio, Corrado, & Filippi (2010) state that it is well known that the potential benefits of the design inputs taken at the design concept stage are much higher than the benefits of design choices taken at the design development and construction document phase. “The cost of implementing concepts to improve the energy performance of a building is also lower at the earliest stages.” (Lewis 2004).

Early decisions made in a project play a huge role in the relationship between early and detailed design. All aspects of the design must be examined as early as possible, from the (exterior) building envelope to comfort of occupants in the internal environment. The ideal is to carry the best concept(s) from early design analysis into the detailed (development) stage and apply specified details into the simulation model for in-depth analyses before finalising the building design.

Some simulation tools can be difficult to understand because of software complexity. Hong & Tianzhen (1997) state that the procedure of building energy simulation is not simple and there are a lot of factors to consider. Architects and engineers may not able to master it without proper training beforehand. In general, the procedure of the simulation will be as follows:

- **a)** mastering of the simulation tools;
- **b)** description of the building design and the assumptions;
- **c)** preparing of the simulation inputs;
- **d)** carrying out of the simulation; and
- **e)** interpretation of the simulation results.

Walton (1989) & Feustel (1989) pointed out most existing tools are either too “simplistic” or too “complicated” to provide effective design support. The simplistic ones are often too limiting, in that they apply only to highly generic situations regarding building geometry and operation. Twenty years after Walton & Feustel’s statement the situation has not changed; the following are others suggesting that simulation tools are too complex for early design simulations:

- “The currently available design advice tools tend to focus on the development of a platform for the evaluation of alternative designs rather than giving actual design advice.” (Petersen & Svendsen 2010).
- “Most tools are dedicated to evaluate and model a certain finished alternative, not to suggest and evaluate different design options and directions. This implies fitting an idea to the modelling tool, thus filtering out information that could be useful or distorting the process.” (Ochoa & Capeluto 2008).
- “The sophisticated ones typically demand too much information, time, and expertise to be helpful to the primary building designers (usually architects) in the early stages of building design.” (Gan 2000 and Papakonstantinou, Kiranoudis, & Markatos 2000).

From an early design perspective, to sketch what needs to be accomplished is more important than the specific details. The detailed specifications can be applied once the overall concept has been established.

Obviously, the simpler the tool, the easier it would be for the user to perform design simulations. When less detail is applied, the predictions are simply a quick indication of the design performance. This is ideal for early design analyses because practitioners can simulate various designs quickly and narrow down the proposed options for development phase.

However, if more specified details are incorporated into the simulations, the more relevant these predictions would be to the completed building; the only issue is that those kinds of information are not fixed (determined) during early design. Lam, Huang, & Zhai (2004) say:

> "The conceptual approaches adopted and technical implementation of these tools varies significantly. Some tools employ 'simplified' methods that address specific perceived needs of the early design phase while others adopt complex first-principle based engineering algorithms that can meet detailed design requirements."

Also, Petersen & Svendsen (2010) point out:

> "Making informed design decisions requires the management of a large amount of information on the detailed properties of design options and the simulation of their performance."

The key issue studied in this research is the need to develop a trust in the relationship between the predictions of tools used during the early and detailed design stages. Possible design defects investigated and solved during the conceptual stage must remain design issues for which the solutions are valid at the detailed design stage. "The tendency to adopt abstraction and rule-of thumb approaches in an attempt to meet the time and resource constraints encountered in early design should be avoided." (Lam, Huang, & Zhai 2004).

Early design predictions produce design concepts which are incorporated into detailed simulations for further testing with specified building specifications (e.g. HVAC & lighting). Brahme, O'Neill, et al. (2009) wrote:

> "Simulation tools are mostly used during the detailed design stage when most of the decisions regarding building massing and system types are already made. The tools in this case allow one to understand the impact of various building and system component efficiencies."

The urgency to meet the initial design deadline during the 'sketch' design stage can often rush the decision-making process. It is paramount to get the design correct from day one and avoid shortcuts that could potentially lead up to further problems somewhere down the line during the design development phase; by that stage additional cost to remedy those design defects is inevitable.

The following diagram proposed by Kalay (1999) describes decision-making during the early design stage before the project progresses onto the detailed design phase:

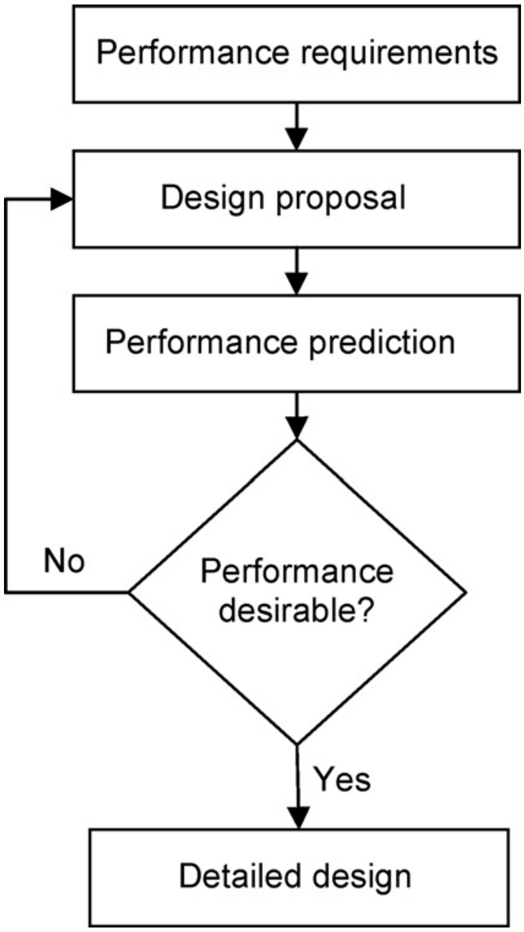

Figure 15 – Workflow and subtasks in performance-based design (Kalay, 1999)

Figure 15 portrays the notion of getting the preliminary design right before moving onto the detailed design stage. No further project development is undertaken before the desired design performance has been met. To meet the desired performance is the responsibility of the practitioners who use early design tools to predict performance of building designs, which also need to meet the design concept that the client is looking for. When the project enters the detailed design stage, any mistakes discovered can be extremely difficult and expensive to remedy; not to mention time consuming. Petersen & Svendsen (2010) state:

> “The workflow in Figure 15 is an attempt to improve the ability of the designer to facilitate the design activities in the conceptual design phase.”

2.4 Commercial Building Façade Design

The discussion in Section 1.3 shows a range of building designs typical of modern high rise buildings where highly glazed façades are popular. This research has focused on fenestration design for these types of buildings because they are clearly popular and because their performance is widely debated. More than many other buildings, this performance in use is critically dependent on design decisions made during the early design stages.

> "Fenestration systems are major elements in the energy balance of office buildings, and their design is a critical part of the building design process. The selection of glazing materials, systems and window treatments such as overhangs and shading devices can have major impacts on building energy use." (Persily 1993).

It is possible to find various references to the desirability of glass as an envelope material in commercial building façade design, even though this type of construction method can require an immense amount energy to maintain comfort indoors. The system is perceived to enhance the building façade's appearance and provide occupants with natural light in the work environment. For example:

- "Glass is one of the best construction materials for giving a building a homogenous appearance. This look is associated with dynamism, precision, prestige and progress. Also: The trend for as much transparency as possible in architecture embraces the wish to dissolve the outer skin and make the building appear light and open." (Hausladen, de Saldanha, & Liedl 2006).
- Lomanowski & Wright (2007) discuss the importance of solar gain management in energy efficient building design: "Given the current architectural trend toward highly glazed façades in commercial buildings."

Energy simulation tools can determine the most energy efficient concepts. Therefore, if the client decides to have a 'glass box' (building) design these tools can assist the design team in establishing the best solution. Early predictions of heat loss/gain derived from energy performance modelling of the building design can help the designers to determine the best combination of shading system and type of glazing that would minimise the energy consumption and still maintain the desired exterior appearance. The practitioners' responsibility is to integrate any client-desired features into the building design; if you have to build this way (e.g. for aesthetics purposes) it is essential to identify energy and cost efficient concepts from the early stages of design.

Heavily glazed façades are neither bad nor good. They are just one of many building features that have to be simulated and evaluated during the design phase. It is important to note, in a simulation approach there should be very few shortcuts or assumptions connecting general building design features and performance. The early decisions made are very influential to the project overall.

> "Often the building services engineer will be involved later in the project where many of the decisions over fabric, shape, layout, glazing and orientation have been made and fixed. Therefore by this stage the ability to utilise the most appropriate passive measures may have been heavily restricted and mechanical conditioning systems are needed to maintain occupancy comfort." (Pollock, Roderick, et al. 2009).

Environmental Factors which are generally agreed to have a large impact on a commercial building's energy consumption and occupants' wellbeing and which are governed by the amount of glass in a building façade are:

- Building over-heating potential
- Heat loss of interior space
- Glare from daylight/sunlight
- Glare from neighbouring heavily glazed buildings

In 2006, the US Department of Energy reported that buildings consumed 40% of the energy in the United States and 12% of the water (DoE 2007). And, Prasad & Bhat (2005) say:

> "Approximately one third of our primary energy supply is consumed in buildings. Consequently, buildings are a primary contributor to global warming and ozone depletion. Therefore, achieving better energy efficiency in buildings has become one of the world's major challenges."

These authors suggest the negative effects of designing building façades that are dominated by glass for aesthetics purposes. Whereas the sustainability side of the design can sometimes be overshadowed by the overall building image. Bannister (2009) emphasised the significance of building design during the preliminary design phase:

> "…there are some buildings that are doomed from day one to perform poorly. In some cases this is because the basic design is poor, but the problem can also affect buildings that have apparently reasonable design and construction, at least at the macro level."

If the tendency is to clad the building envelope with glass to enhance its aesthetic appearance, then it is vital to examine all environmental factors during the early design stage. Glass buildings provide occupants with daylight and connection to the exterior environment. In this sense glass façades are perceived as an important design feature in a building:

> "The importance of glass as a cladding material cannot be underestimated. With the exception of plastics, it is the only transparent cladding material, providing daylighting and connection with the outside. It is rare client who desires less light-transmitting glass on a project." (Brock 1948).

"Numerous office buildings of the 1980s were designed to isolate the internal conditions from the outdoor climate as far as possible; this at the cost of high energy consumption." (Voss, Herkel, et al. 2007). The authors back up Brock's opinion on the importance of glass cladding. It is suggested that for this reason it is important to retrofit old buildings to achieve sufficient access to daylight that can help minimise electric lighting energy consumption (i.e. optimum Window-to-Wall Ratio).

There are many aesthetic and other reasons encouraging architects to build with glass façades. Despite the environmental factors and energy impact, there are several reasons why glass façades are so popular (by practitioners' demand) in the commercial building sector:

1. Aesthetic of the building is appealing
2. Access to natural light provides occupants with the indoor-outdoor connection, which result in higher productivity (healthy work environment)
3. Speed of construction allows the tenant to move in the property as soon as possible
   (e.g. unitised system – curtain wall construction)
4. It enables the firm to secure building projects

These reasons have a significant influence on the decisions made by the design team and client, hence the familiar trend of glass buildings in cities around the world. Architects are almost forced to design this way to secure projects:

> "Building façade design is developed at a very early stage of the design process. It is often the basis for the award of the contract to a particular firm of architects or developers." (Kolokotroni, Robinson-Gayle, et al. 2004).

Figures 16~18 show examples of highly glazed commercial buildings. What they have in common is that their 'glass skin' building aesthetics make them a landmark within their own city. There are two main aspects that make these buildings stand out, their scale and geometry.

Scale: towering expression of Taipei 101 (height of 508m) and International Finance Centre (height of 416m)

Geometry: angled façades of the Audi Forum building and Taipei 101's bamboo exterior appearance

Ultimately, these two design aspects express the architectural idea envisioned by the design team.

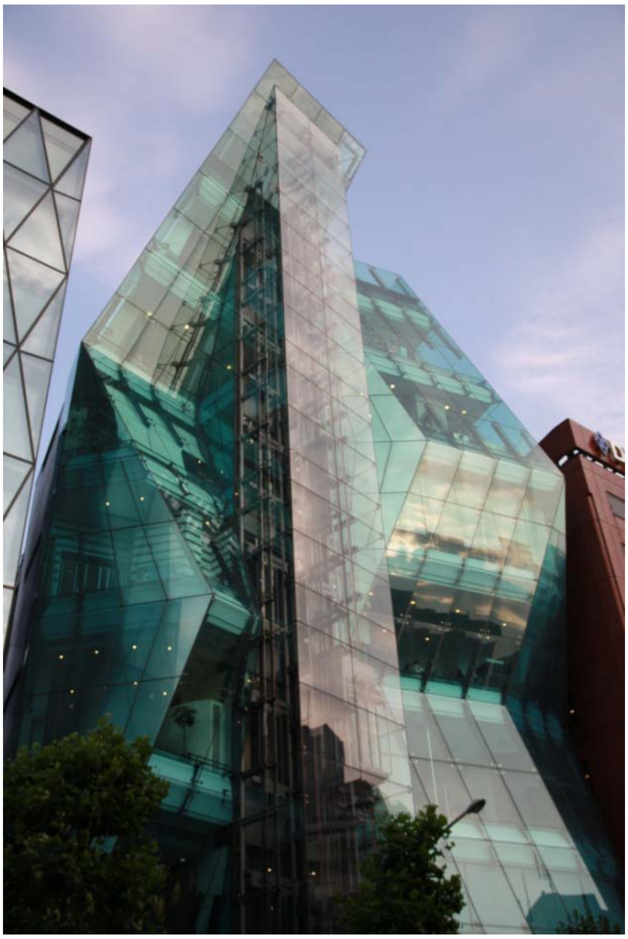

Figure 16 – Exterior view of Taipei 101 in Taipei, Taiwan
Figure 17 – Exterior view of the Audi Forum building in Tokyo, Japan
Photographs © Chi-Yao Hsu

Figure 18 – International Finance Centre in Hong Kong. Image © (Crosbie, 2005)

Despite the poor thermal properties of glass (which cause overheating & heat loss), these examples (Figures 16~18) are demonstrations of the popularity of glass amongst clients and design practitioners. Often, designs of heavily glazed (high-rise) commercial buildings rely on mechanical systems to condition the interior spaces. In other words, as long as the building aesthetics meet the design brief in relation to image and prestige other design aspects (such as energy use and envelope thermal performance) can be compromised. Many people argue that a simple glass façade causes internal comfort and energy performance issues:

- "Although the user enjoys more of a view out, there is an increased risk of glare and overheating in summer." (Hausladen, de Saldanha, & Liedl 2006).
- "In terms of energy consumption, much of the existing commercial building stock is made up of multi-storey, highly-glazed, thermally-lightweight developments that are totally dependent on non-renewable energy for heating, cooling and lighting." (Fernandez 2008).
- "There is just too much glass used on these curtain wall systems, all because of the aesthetic and this makes it very difficult to enclose conditioned air; the building relies on the mechanical systems to maintain comfort. Fenestration and shading systems have a major impact on visual and thermal comfort in perimeter spaces but also on energy consumption, peak loads, and possibly HVAC system sizing." (Tzempelikos & Athienitis 2005).

The authors suggest that heavily glazed buildings (like Figures 16~18) rely on mechanical systems to condition its internal environment to keep the building occupied from day to day.

This is not a new issue and the debate about it is ever growing. Hausladen, de Saldanha, & Liedl (2006) wrote:

> "The objective in the design of façades is to find the optimum compromise between the specific location and the various requirements of the planned building use."

The reality is that research of this type might not have the ability to control how people design their buildings, but it can forward the message to designers that the use of simulation tools from day one will emphasise just how much energy glass-greedy buildings can (potentially) chew up each year and throughout their lifetime. When designing a building it is argued that the analysis should be focused on long term use, not short term. Often, long term effects are ignored, as Flanagan & Norman (1983) stated:

> "The difficulty of forecasting future events in the life of a building and its components, which is part of the reason why LCC considerations are often overshadowed during the design process."

"Transparent façade components allow for passive heating of the interior through insolation. Far more frequently, however, solar heat gains will contribute to overheating and increased cooling loads. The total window area on the exterior wall and the efficiency of the shading system are key factors." (Eisele & Kloft 2003). There are ways (potentially) of making all glass façades work at least as well as other systems if they incorporate active shading device etc. The following are some solutions proposed by Hausladen, de Saldanha, & Liedl:

- "The use of natural light has a considerable influence on the energy demand of a building. The direct saving comes from the reduction in electricity used for lighting."
- "External solar screening is the most effective system because the solar radiation is blocked before it can reach the façade. However, initial and maintenance costs are higher because the system is exposed to weather and wind."
- "Internal solar screening is protected from the weather, can be operated in all wind conditions and provides glare protection."

Winfried Heusler (Hausladen, de Saldanha, & Liedl, 2006) adds that for glass façades to work they require some type of active shading system to adapt according to the weather:

> "Building skins that have been properly designed to meet their climatic and usage requirements react to changing outside conditions as a semi-permeable membrane with dynamic properties instead of presenting a rigid, impenetrable barrier between the room and the outside environment."

Also, there are cost implications of active glass façades. However, Hausladen, de Saldanha, & Liedl (2006) point out:

> "Room climate can be considerably improved at little extra cost if the characteristics of a façade arising from its orientation are taken into account in the strategies for providing solar screening and adequate ventilation."

Hausladen, de Saldanha, & Liedl (2006) argue building façades should adapt to their environment so the complexity of mechanical systems can be reduced:

- "Façades must be able to react and vary themselves in response to the dynamic outdoor climate and ever-changing indoor climatic conditions."
- And, "The more adaptable the façade is, the less complex the building technical systems need to be and the lower the associated energy demand is."

However, Leaman & Bordass (1999) argue that active façades which are well-tuned to their climate could have potential failure risks:

> "Bigger and more complex buildings demand subtler strategies for managing this complexity and different design strategies and technologies to support them. Where this is successful, performance gains are possible, but where management does not properly compensate for the extra diligence that technology needs, chronic problems usually result."
>
> And: "No begged questions, Keep it as simple as possible, but not more so; Make it adaptable; If in doubt, leave it out; and What if...so what?; can be appropriate rallying cries." (Bordass & Leaman 1997).

One way to avoid this is to get better information during the early design. This can be achieved with an early design tool that produces advice/feedback consistent with that produced later in the design process from a detailed design tool. Bordass & Leaman (1997) state that designers sometimes collude in this fantasy and do not make it clear that many measures require vigilance in use, sometimes more than the measure deserves.

2.5 Integration of Aesthetics & Performance

Among building performance and aesthetics there is one vital variable that is controlled (shaped) by these two design factors, and that is the comfort of building occupants. Hausladen, de Saldanha, & Liedl (2006) say:

> "As people nowadays spend most of their time in rooms and hardly any time outdoors, room climate has become increasingly important to our feeling of well-being."

And, Eisele & Kloft (2003) write:

> "Comfort is measured in dynamic quantities, which must take the frequency and type of activity as well as the location of the occupants into consideration."

These authors suggest that it is essential to provide the building occupants with a healthy work environment which can help with their wellbeing and productivity.

From an environmental perspective, some may argue that the energy/thermal performance of a building is more important than its aesthetics. The following source supports this argument:

> "Do you want to save serious energy and serious money? That's easy. Use less glass. Windows and curtain walls are the most expensive component in a building and provide the worst energy performance." (Lstiburek 2008).

However, there are many people arguing that from a building design of view, aesthetics is very important. Hausladen, de Saldanha, & Liedl (2006) say:

> "In additional to acting as a skin, façades have considerable influence on the external appearance of a building. They can be used to provide information or project an image to the public."

Simulations tools can estimate the overall performance of a building design to guide designers in the direction of maximising energy efficiency; testing various solutions to determine the best design (in terms of energy performance).

> "Building design should be no longer merely dominated by aesthetic and functional considerations. Environmental performance based concern needs to be considered at the planning stage, which can help to deliver valuable information on the viability of a design approach." (Pollock, Roderick, et al 2009).

The envelope of the building should assist the mechanical systems and work together as one to provide a comfortable environment for the occupants. In order to be energy efficient, it should never come down to full reliance on the mechanical systems.

> "The aesthetic appearance of the exterior envelope need not conflict with the other performance requirements, but as is the case with other performance requirements, aesthetic considerations should not be allowed to predominate over the achievement of other requirements." (Persily 1993).

Early design tools enable a real balance to be achieved – not just a strong aesthetic gesture and estimation of performance. Early design tools permit the integration of design, aesthetics and performance. For example, a certain aesthetic could be achieved through an alternative construction method that would benefit the building performance as well. The desired building appearance and performance can be simulated by early design tools to assist practitioners on making decisions, Flanagan & Norman (1983) wrote:

> "A decision is being made to acquire assets that are intended to last and to be used for a number of years. These assets will commit the owner or user not only to initial capital costs, but also to subsequent running costs, day to day operating, cleaning and maintenance costs, and periodic repair or replacement costs."

Figures 19 & 20 show two unique (glass) buildings that speak for themselves through their exterior aesthetics. They are examples of rhetoric building design about strong aesthetics integrated with performance.

Figure 19 – Exterior view of the Mode Gakuen Cocoon Tower in Tokyo, Japan
Photograph © Tange Associates (Wood, 2010)

Figure 20 – Exterior view of the Mode Gakuen Spiral Towers in Nagoya-shi, Japan
Photograph © Nikken Sekkei Ltd (Wood, 2010)

The Cocoon Tower in Figure 19 is 50 stories (204m high) with its primary use being a school and commercial retail. Tim Johnson (NBBJ) quoted:

> "This is a great example of using a rich program to create a wide variety of spaces that take advantage of natural light and inspiring views." (Wood 2010).

Wood (2010) mentioned:

> "The tower is designed specifically with the environment in mind. This includes a cogeneration system, installed within the building, that produces about 40% of the structure's power and thermal energy. "
>
> Also, "The elliptic shape allows for even distribution of sunlight, thereby limiting heat radiation to the surrounding area."

The Spiral Towers in Figure 20 is 36 stories (170m high). Its primary use is school with some retail as well. Gordon Gill, Adrian Smith + Gordon Gill Architecture quoted:

> "Finally we see a rotated tower scheme that has real integrity. It is well planned and creatively varied in its spatial experiences." (Wood 2010).

Wood (2010) says:

> "The unique design of the three wings of the tower, twisted in helical form, appear to change shape when viewed from different angles, giving an elegant yet dynamic impression."
>
> Also, "Double-glazed windows and air-flow windows are employed to reduce heat loads created by the sun around the perimeter zone."

Wood (2010) noted that both of these buildings maintained their architectural integrity and utilised different methods to help reduce energy consumption.

In summary, the factors of aesthetics and performance are just as important as each other in a building design. Essentially, they are both part of the vital formula for designing a good commercial building. Practitioners should express their architecture through performance of design and through performance of design the aesthetics will emerge; if that is achieved, comfort of occupants will automatically follow. However, if the aesthetics overshadows the building performance, it is inevitable that the mechanical systems will be responsible for dealing with the environmental factors such as excessive heat gain/loss throughout the year.

3 METHODOLOGY

In order to improve the relevance and consistency of the overall research method, this research methodology consists of three separate individual research methods. The purpose is to examine and explore the capability of the performance sketch early design tool concept. The three methods used are: to develop a use-case study using COMFEN (LBNL 2010) as an example; and then to explore whether a performance sketch tool can predict energy performance estimations in a plausible manner; and finally to explore the impact on design predictions of different levels of complexity of the performance sketch.

3.1 Overall Hypotheses

The following are the hypotheses for this research project:

- Performance sketch tool COMFEN can predict plausible energy performance estimations that are consistent with results derived from detailed design tool EnergyPlus.
- Use-case studies of COMFEN with practitioners will provide an evaluation of the concept of the Performance Sketch concept resulting in a definition of the properties of an ‘ideal’ early design tool.

The methodology examines these hypotheses by testing the single-zone (simulation) method of COMFEN to see whether its predictions are plausible for energy analyses of commercial building designs from an early design perspective.

For some forms of early design tool there are such simplifications that determining the reason for implausible performance predictions is tricky. In this research, the advantage is the underlying calculation engine for the early design tool is a simulation engine and the same simulator (EnergyPlus) can be used to test consistency with detailed design predictions. The differences revealed are thus most likely to be about the (performance) sketch – the simplification process.

Ultimately, the results will demonstrate the potentials of COMFEN as a performance sketch tool and identify areas that require improvement. It could eventually benefit many practitioners in the building industry and help reduce energy consumption in heavily glazed commercial buildings. The three-method approach used for this research is explained in the next section; these three methods interlock together as one with the main focus on assessing the performance sketch concept.

3.2 Methodology Overview

The research methodology used the following three research methods:

1. **Use-case study of a Performance Sketch Tool with Practitioners**

   Seek feedback from a number of practitioners in the building industry on the subject of COMFEN – the performance sketch tool; via interviews, the practitioners' feedback are 'use-cases' (Haumer 2004) in this research.

2. **Consistency Test of a Performance Sketch Tool**

   Testing of COMFEN example façades under contrasting climates to examine the consistency between its energy predictions and results derived from the EnergyPlus detailed model.

3. **Evaluating the Adequacy of the Sketch within a Performance Sketch Tool**

   Explore practical application in COMFEN of users' ideas where these are not already in COMFEN (i.e. testing of some suggestions from the use-cases in EnergyPlus).

All three research methods are relevant in terms of improving the energy predictions by a performance sketch early design tool. The outcome of each section is described in the results chapter.

3.3 An Example of a Performance Sketch Early Design Tool: COMFEN 3.0

COMFEN was selected as an example of a performance sketch tool for this research. This early design application matches the performance sketch concept. Using a performance sketch tool like COMFEN can be very helpful during the early design stage where very little design detail/information is available.

COMFEN uses the sophisticated detailed design performance analysis program (EnergyPlus) in a simpler more constrained – sketch-like – manner. This comes with the advantage of ensuring that the sketch analysis calculation engine improves at the same rate as the detailed design tool; and, it ensures that the performance information generated in COMFEN can be duplicated and re-used as the model and the design itself get more sophisticated during the building project.

The following statement is the definition/intention of the COMFEN software from its developer (http://windows.lbl.gov/software/comfen/3/index.html):

> "Lawrence Berkeley National Laboratory's (LBNL) software – COMFEN (COMmercial FENestration) is a tool designed to support the systematic evaluation of alternative fenestration systems for project-specific commercial building applications. COMFEN provides a simplified user interface that focuses attention on key variables in fenestration design. Under the hood is EnergyPlus, a sophisticated analysis engine that dynamically simulates the effects of these key fenestration variables on energy consumption, peak energy demand, and thermal and visual comfort."

Figure 21 shows the typical COMFEN simulation interface. It displays the fenestration analyses in simple (sketch) graphical form; it is capable of comparing multiple designs at once.

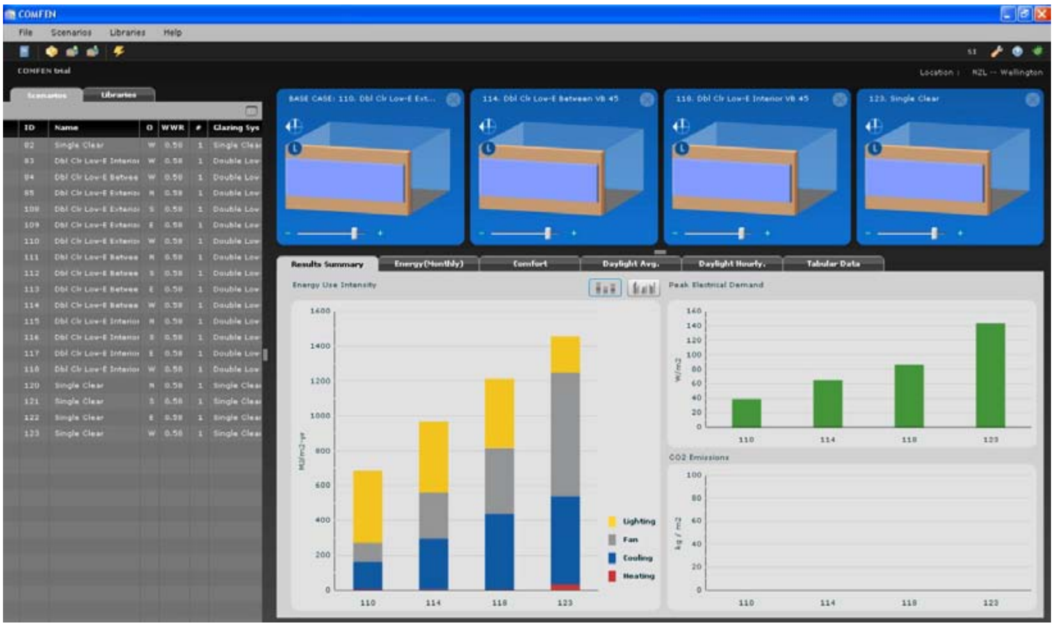

Figure 21 – COMFEN 3.0 simulation interface

COMFEN is an early design interface to the EnergyPlus detailed simulation engine. It provides the user with a performance sketch interface which includes many vital simulation functions required for an early design analysis.

COMFEN provides the user with a simplified diagram and energy performance graphs (i.e. energy distribution) of each façade design option. It simulates one façade orientation and one zone at a time for each fenestration scenario. It can simulate façades facing any desired orientation. COMFEN 3.0 is capable of the following analyses through its graphical interface:

- Energy use distribution of HVAC, electric lighting and interior equipment loads
- Peak energy estimation
- Carbon dioxide (CO2) emission of each design scenario
- Daylight predictions (annual average illuminance)
- Discomfort glare index analyses
- Thermal comfort predictions – Predicted Percentage of Dissatisfied (PPD)
- Tabular data (percentage difference between base design and other scenarios)

COMFEN's speed of calculation is significant; quick and efficient due to its single-zone calculation method. It is a performance sketch tool that allows the user to assess fenestration designs quickly without detailed design information.

This research focuses on the Energy Use Index (EUI) of the façade design derived from COMFEN and EnergyPlus (i.e. energy end-use of electric lighting, interior equipment & HVAC) for each façade design tested. The reason for this focus is that the research is about determining the consistency of energy performance (advice/feedback) between early and detailed design tools.

The following figures show the edit scenario windows within COMFEN where the building project can be altered through elevation, plan and section views.

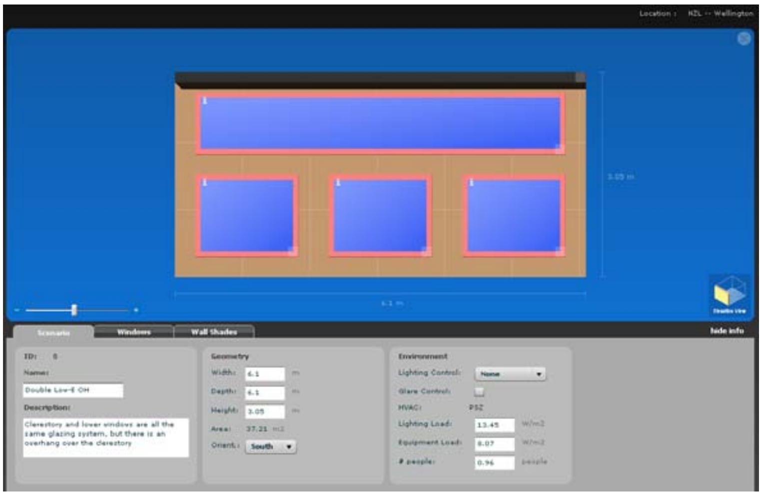

Figure 22 – COMFEN fenestration editing view in elevation

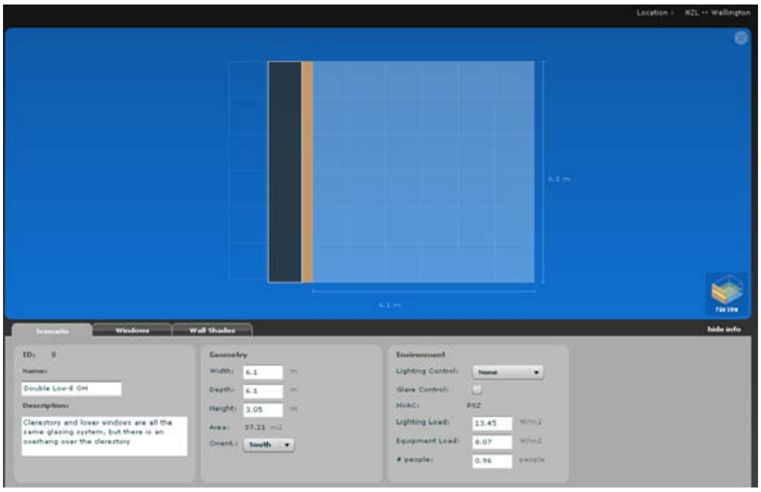

Figure 23 – COMFEN fenestration editing view in plan

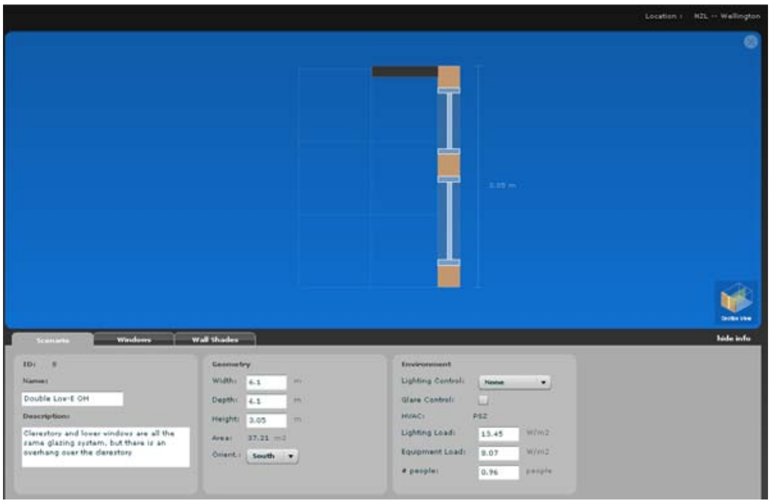

Figure 24 – COMFEN fenestration editing view in section

Elevation view (Figure 22) allows the user to alter the fenestration design. For example, the user can quickly sketch/assess various window sizes, glazing types, adding shading devices and fins/overhangs. It facilitates the comparison of various combinations of glazing and shading device to identify the best design concept(s) in a particular climate. The plan and section views (Figures 23 & 24) provide a visualisation of the fenestration design (i.e. visual reference for the location of windows/shading devices). Below each view, there are (white) boxes for simulation input entry. These input options are just capabilities of the detailed design tool EnergyPlus. COMFEN capabilities are made available for sketch/early design assessment purposes. The user can alter the fenestration geometry, floor area, lighting & equipment loads (Watts per metre square) and number of occupants. Also, the user can select the compass orientation they desire to simulate and the type of lighting/glare control settings. The user can record the description of each sketch, therefore different scenarios can be easily differentiated and documented.

There are built-in example files within COMFEN that help the user to learn the software; these are examples of fenestration design scenarios/projects. Also, there are libraries of glazing type and shading device system which allows the user to create their own fenestration designs (i.e. combinations of glazing and shading device). The purpose of these example files is to help the user understand the sketch application and its simulation inputs/outputs. When they become more familiar with the software, the user can quickly duplicate and alter these example files to form combinations of fenestration design to suit a specified project brief.

In summary, architects and engineers can pin-point the best fenestration concept designs with COMFEN multiple façade comparison capability. The lessons learnt from the early design predictions calculated by COMFEN can assist practitioners in making design decisions from day one of the building project. Hitchcock, Mitchell, Yazdanian, Lee, & Huizenga (2008) state:

- The overall objective of COMFEN is to promote the design and deployment of high performance fenestration systems by making complex simulation comparisons of alternative fenestration design choices accessible to a wide audience of users.

- The primary audience of COMFEN is architects during early design. A second primary audience of COMFEN is fenestration manufacturers.

- The main objective of COMFEN in this respect is to analyse new complex fenestration products in an unbiased manner so that those products that enhance the overall performance of fenestration systems can be promoted to consumers.

COMFEN is a performance sketch tool specifically designed to assess ‘commercial fenestration’ during the early stages of design.

3.4 An Example of a Detailed Design Tool: EnergyPlus 4.0

EnergyPlus is a comprehensive (multi-zone) building energy simulation engine. The desired building design determined by an early design tool can be carried into EnergyPlus for further and more complex simulations (i.e. during detailed design stage).

> "EnergyPlus is a whole building energy simulation program that engineers, architects and researchers use to model energy and water use in buildings. Modelling the performance of a building with EnergyPlus enables building professionals to optimise the building design to use less energy and water." (US DoE 2010).

EnergyPlus has the power to model (simulate) complex details within a building design (e.g. finalized geometries, materials, mechanical systems & building schedules).

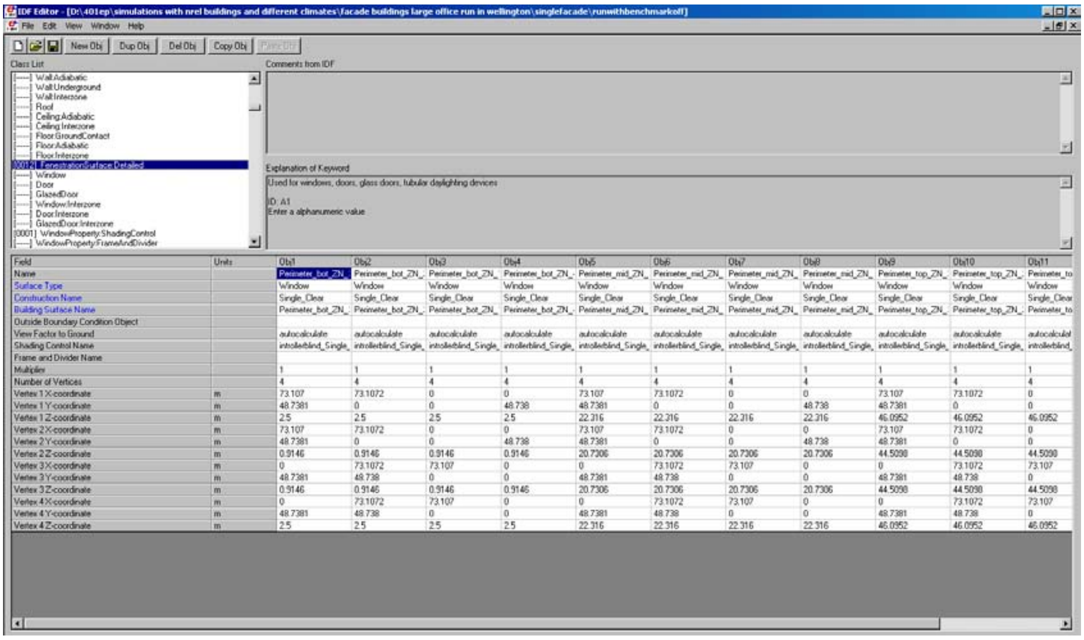

Figure 25 – EnergyPlus 4.0 idf-Editor

The detailed design stage for a building is the process before the actual construction begins. No physical work can begin until every detail of the building design is examined and approved. Areas that are specifically related to this research are HVAC and lighting energy predictions (i.e. EUI predicted by COMFEN and EnergyPlus). All the EnergyPlus simulation models in used by COMFEN and EnergyPlus are of '.idf' file type.

The EnergyPlus 'idf-Editor' interface is displayed in a spreadsheet-like format as can be seen in Figure 25. Hundreds of design variables can be entered by the user to the desired settings (e.g. HVAC system, lighting loads, occupancy & building schedules etc). The idf-Editor does not have a graphical representation of the simulation inputs (i.e. model geometry). However, there is a Plug-in for SketchUp that makes EnergyPlus modelling much more user-friendly. The following section explains why the OpenStudio Plug-in was used in this study.

EnergyPlus allows the designer to simulate and predict through hour by hour calculations for a year how a building would perform when completed. Its link to COMFEN is a powerful relationship (i.e. software compatibility) that allows practitioners to apply more (or less) detail to a simulation model during any time throughout the design phase; it offers the advantage of referring back to the performance sketch tool during the detailed design stage, when necessary, secure in the knowledge that the calculation engine in both cases is EnergyPlus and thus the calculation process will be consistent.

3.4.1 OpenStudio Plug-in

OpenStudio was used in this research because it is an essential visual integrity check on the geometry modelled in EnergyPlus. Figure 25 shows the spreadsheet-like format in which geometry and all other data describing a building is entered into EnergyPlus. The visual cross-reference provided by OpenStudio would be a very useful check of the data as a visualizer of the data. The advantage of OpenStudio is that the geometry can also be edited.

The following statement is the definition of the OpenStudio Plug-in from its developers (http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm):

> “OpenStudio Plug-in allows you to use the standard SketchUp tools to create and edit EnergyPlus zones and surfaces. You can explore your EnergyPlus input files by using all of the native SketchUp 3D capabilities to view the geometry from any vantage point, apply different rendering styles, and perform shadowing studies. The plug-in allows you to mix EnergyPlus simulation content with decorative content such as background images, landscaping, people, and architectural finish details – all within the same SketchUp model.”

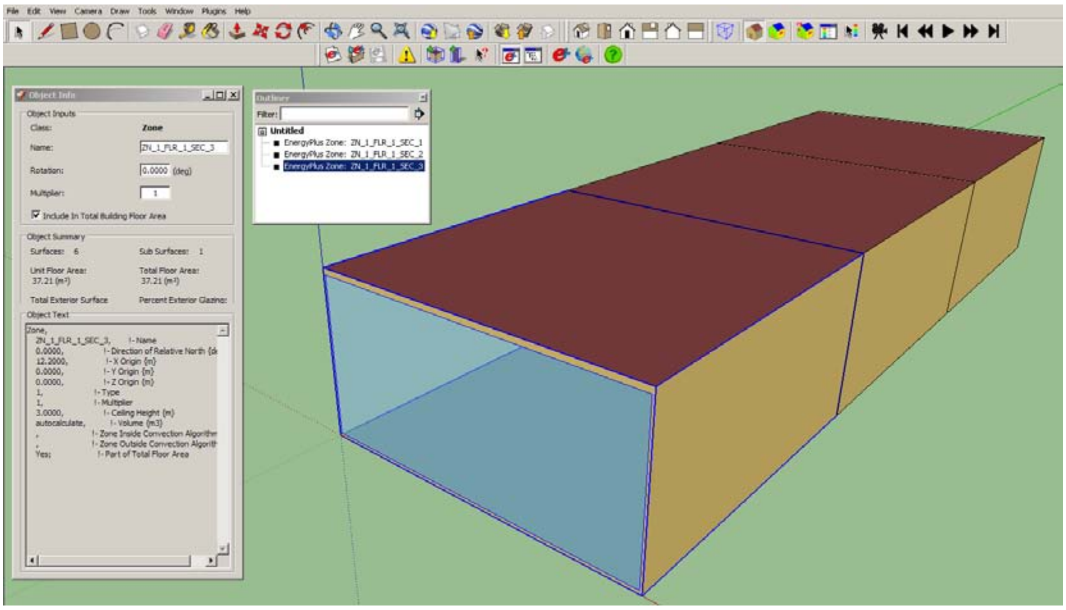

Figure 26 – OpenStudio within SketchUp

Figure 26 is an example of the building geometry of an EnergyPlus file viewed via the OpenStudio Plug-in within Google SketchUp. In this research OpenStudio was mainly used for the geometry modelling, minor changes to building envelope materials and shading devices. This enabled a more consistent modelling of geometry within the idf-Editor, which can become difficult when purely handled via numerical data entry. All inputs excluding geometry coordinates were entered within the spreadsheet-like format of the idf-Editor. For example, some of these details were: HVAC system, lighting loads, occupancy, and building schedules.

3.5 Introduction of a Performance Sketch Tool to Practitioners

The approach of the first method of this research is to present COMFEN to practitioners as an example of a performance sketch tool. The selection of practitioners was from as wide a range of backgrounds as possible. Their feedback on the concept of the Performance Sketch was collated into a specification of their 'ideal' early design tool.

The intention was to show the potentials of COMFEN to practitioners and through structured questioning to gather their opinions on the performance sketch tool idea. Feedback from architects and engineers from New Zealand, Japan, and Taiwan and the USA was obtained.

The use-cases play a central role in the analysis of the Performance Sketch. The practitioners' feedback on their early design needs was based on past and current project experiences.

Structured interviews were held with practitioners centred on a list of questions relating to COMFEN as an example of a performance sketch early design tool. The use-cases were intended to determine what worked and what additional capabilities were desired. The research design allowed the possibility that if a consensus list of desirable design options could be compiled for COMFEN then these design options could be tested within EnergyPlus and thus be validated for future versions of COMFEN.

The ultimate objective is to have an early design tool that architects and engineers can trust and use to deliver their design to a client. To do that the tool has to minimise its design limitations, because project bids are often won or lost based on the building's aesthetic; so having the freedom to analyse a wide range of architectural concepts is essential.

In this research, an information sheet and consent form regarding this research were distributed (emailed) to various architectural/engineering firms around the world. The practitioners selected for the interviews were based on their personal interest/response to the performance sketch idea. The practitioners interviewed were all new to the COMFEN software and they were asked to provide feedback after an introduction to the software.

The use-cases illustrate a wide range of views stated by professionals from different backgrounds, countries, cultures, and practices.

3.5.1 Interview Sample Size

Turner, Lewis, & Nielsen (2006) state that:

- most usability problems are detected with the first three to five subjects
- running additional subjects during the same test is unlikely to reveal new information
- return on investment (ROI) in usability testing is maximized when testing with small groups using an iterative test-and-design methodology

These claims are determined in the studies by Virzi (1992), Nielsen & Landauer (1993) and Lewis (1994). On the basis of these sources, it was decided that only a small number of participants would be sufficient to carry out this research. The first five practitioners who responded to the research information sheet were chosen for face-to-face interviews. Sometimes more than one practitioner attended the use-case study interviews so the data represents the views of 6 firms, but 9 people.

3.5.2 Delphi-like Review of Responses

The 'Delphi' method was incorporated into the interviews with practitioners. This allowed them during the use-case visits to freely express their opinion on COMFEN as an example of a performance sketch early design tool. Then the Delphi review process allowed for consultation about the form and content of the notes taken, and to consider others' views and contribute to the development of a consensus view based on professional work experiences. Rowe & Wright (1999) characterised the Delphi method with four key features:

1. ***Anonymity*****:** allows the participants to freely express their opinions without undue social pressures to conform from others in the group. Decisions are evaluated on their merit, rather than who has proposed the idea.
2. ***Iteration*****:** allows the participants to refine their views in light of the progress of the group's work from round to round.
3. ***Controlled feedback*****:** informs the participants of the other participant's perspectives, and provides the opportunity for participants to clarify or change their views.
4. ***Statistical aggregation of group response*****:** allows for a quantitative analysis and interpretation of data.

> "The Delphi method is an iterative process used to collect and distill the judgments of experts using a series of questionnaires interspersed with feedback. The questionnaires are designed to focus on problems, opportunities, solutions, or forecasts." (Skulmoski, Hartman, & Krahn 2007).

Interview questions are stated in Section 4.1.1 in the Results Chapter.

3.5.3 Process of Interviewing Practitioners: Introduction of COMFEN

COMFEN was introduced to various practitioners as an example of a performance sketch early design tool. The interview use-cases were from:

- 6 different architecture & engineering firms around the world; which includes a USA interview – recorded in 2008 prior to the commencement of this thesis (Donn 2010)
- Total practitioners contributed in uses-cases = 9 male professionals (5 architects & 4 engineers).

The interview process comprised four phases:

1. Research topic information sheet and consent form were approved by the ethics committee of Victoria University of Wellington, New Zealand.

2. Information sheet and consent form were distributed by email to various architectural/engineering firms around the world.

3. Practitioners (architects & engineers) in Wellington, Japan and Taiwan agreed to take part in the research. Their feedback is the use-cases in this thesis.

4. Interview arrangements (visit selected practitioners)

Note: The participants were selected based on their personal interest in the Performance Sketch Concept (i.e. not randomly selected).

There are always barriers when the research goal involves gathering feedback from working professionals in the building industry. There are many factors that influence the participant on taking part in the research such as: personal interest on the research; their availability of time; the firm's rules on design confidentiality.

All interview participants were new to the COMFEN software. They are male architects and engineers in the building industry. They were encouraged to express their opinions on COMFEN based purely on their own perspectives. APPENDIX A & APPENDIX B contain, respectively, the information sheet sent to practitioners.

3.6 Consistency Test of a Performance Sketch Tool

This section describes the second method of this research. The purpose of this test was to assess COMFEN as an example of a performance sketch early design tool, to see whether its single-zone predictions are consistent with results derived from detailed multi-zone simulations. It was assumed that for COMFEN to be viewed as a plausible early design analysis tool, the predicted performance should be carried into the detailed design stage.

COMFEN is EnergyPlus, it only makes certain functions of EnergyPlus available for early design purposes. The great advantage of this sketch tool is that more detail can be applied to a model (as the design progresses) because of its relationship/compatibility to EnergyPlus. And it provides the user with the capability/functionality of a complex simulation tool during the preliminary design phase.

COMFEN (version 3.0) was specifically designed to analyse façade designs for single perimeter zones only; the performance sketch used by COMFEN to make the calculations quick is that of the single zone in a building. And detailed simulations in EnergyPlus (version 4.0) can examine the entire building.

The methodology adopted for this test examines COMFEN with four of its built-in example façade designs (various glazing types and shading combinations) under four climate zones. It compares the COMFEN performance predictions with those from EnergyPlus when these façade designs are applied to full scale buildings. The geometry selected for the full scale buildings is the geometry of DoE's small & large benchmark offices (US DoE 2010). They were modelled under the same climates.

This test examines COMFEN as an example of a performance sketch tool by assessing the consistency of single-zone predictions with results derived from multi-zone simulations in EnergyPlus. The simulation analyses performed in this test are:

- COMFEN analysis of four façade designs (built-in examples see section 3.6.2).
- COMFEN façades incorporated to full scale DoE office buildings in EnergyPlus.

The full scale (multi-zone) buildings use the same default settings as COMFEN. The only difference between the single-zone and multi-zone models is the scale (i.e. floor area).

If COMFEN's single-zone method can produce energy results that are consistent with multi-zone (detailed) simulations it would be beneficial to the users.

3.6.1 The Definition of Consistency

The building energy simulations focused on the Energy Use Index (EUI) of the façade design derived from COMFEN and EnergyPlus. It was used to determine the ranking of energy performance (electric lighting load, interior equipment load & HVAC load) for each façade design tested. It is important to note that the significance of the simulation results lies within the relative values (i.e. distribution of energy end-uses), not the absolute value of a fenestration design's total EUI.

The rankings of façade performance predictions in COMFEN and EnergyPlus determine the consistency of single-zone calculation method to the multi-zone method. Energy performance ranking was determined by fenestration energy predictions; façade design with the lowest total EUI (kWh/m^2.yr) is ranked first.

The definition of consistency is:

- COMFEN (single-zone) and EnergyPlus (multi-zone) predictions of energy performance will produce the same design advice/feedback (i.e. the ranking of the façade ideas will be the same, as well as similarity in distribution of energy end-uses).

Distribution of energy end-uses determines the consistency of performance sketch advice/feedback. For example, while total energy use might be the same, the distribution of energy end-uses has to be consistent between single-zone and multi-zone models. In order the design advice/feedback to be consistent there should be consistency in HVAC & Lighting energy demand.

3.6.2 Consistency Test: Fenestration Design Scenarios

In the first stage of this test, four generic fenestration designs were simulated in COMFEN. The following are the chosen COMFEN façade designs:

- **A.** Double clear Low-E glazing with exterior venetian blinds (permanently fixed) at 45°
- **B.** Double clear Low-E glazing with between venetian blinds (permanently fixed) at 45°
- **C.** Double clear Low-E glazing with interior venetian blinds (permanently fixed) at 45°
- **D.** Single clear glazing

Figure 27 shows the section details of the façade designs modelled in COMFEN (for the full description of the designs, refer to APPENDIX I – Façade Constructions & Material Properties).

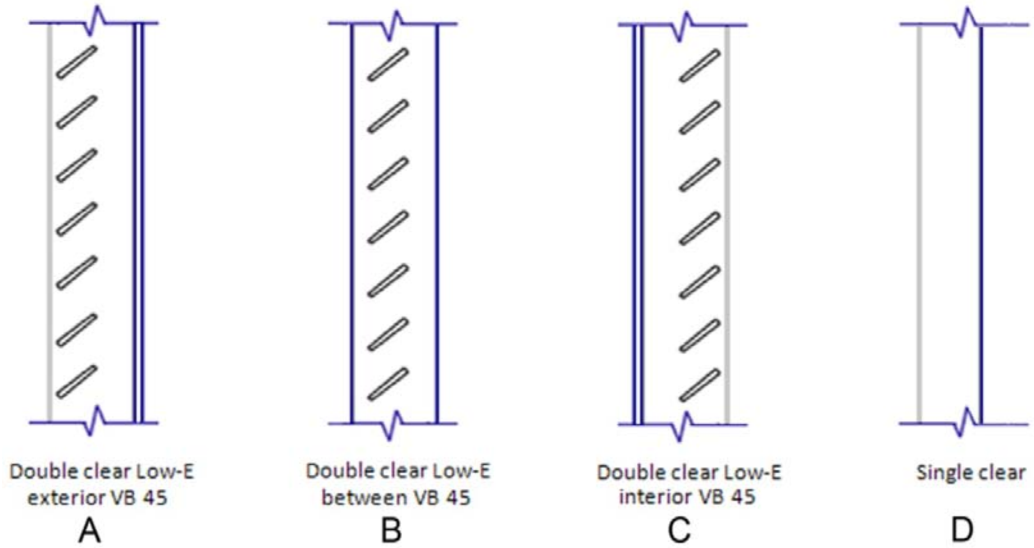

Figure 27 – Façade designs simulated in COMFEN & EnergyPlus

The reason for these fenestration selections is to create façades with the potential for radical differences in energy performance. The façade designs are similar to each other apart from the position of Venetian blinds, which can lead to a simple interpretation of the performance differences. In Figure 27, the left of each fenestration option represents the exterior environment and the right is the interior. The letter code of each façade design (Figure 27) links to graphs in the results chapter.

These following locations were chosen for this test:

- Wellington, New Zealand – *mixed, marine climate zone (IWEC.epw)*
- Melbourne, Australia – *warm, marine climate zone (IWEC.epw)*
- Minneapolis-St Paul, USA – *cold, humid climate zone (TMY2.epw)*
- Bombay, India – *mixed, dry climate zone (IWEC.epw)*

Note: TMY2 weather file was from NREL and IWEC files were from ASHRAE (for each location the same weather file was used in both COMFEN and EnergyPlus simulations).

There is a possibility that design predictions are consistent in one climate zone and inconsistent in another. Therefore a range of different locations were selected. Contrasting climate zones were selected for testing in order to assess particular single-zone/multi-zone design issues/properties; examine how COMFEN fenestration designs perform in the best/worst scenarios.

In COMFEN, simulations are performed in single zones only, so there is a zone for each façade orientation (Figure 28). The following figure is a default COMFEN zone which has a total floor area of $37m^2$. The R-value of COMFEN default walls = 2.29 m^2-K/W; Window-to-Wall Ratio (WWR) was set to 58% in all models.

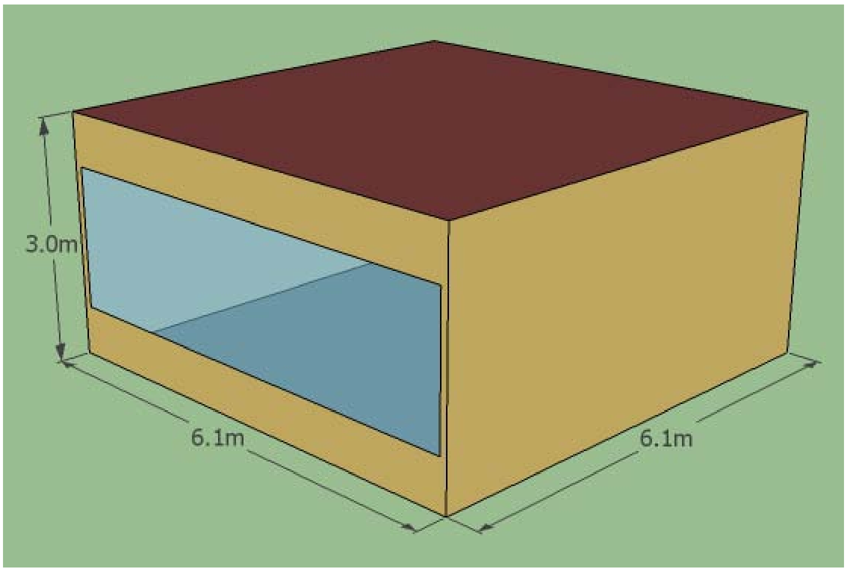

Figure 28 – Typical COMFEN single-zone model and its dimensions

For each fenestration design, four orientations (4 zones) were simulated to calculate the average of the north, south, east and west-facing zones of a whole building. The average fenestration energy predictions were used to develop an energy performance ranking (1^{st}~4^{th}) because the average of four (COMFEN) perimeter zones represents an entire building for each façade design. The ranking was developed to show which façade design is the most energy efficient. This was intended to mirror the way in which a designer would use a performance sketch to determine the optimum façade for a building.

3.6.3 Fenestration Design Scenarios Integrated into DoE Benchmark Models

The façade designs used in the COMFEN simulations were integrated into the US Department of Energy's (DoE) small and large benchmark offices (US DoE 2010) under the same climate zones as the COMFEN designs.

In order to ensure the EUI comparison between COMFEN and EnergyPlus predictions was focused only on the two programs' ranking of the façade designs the models in each program had a consistent Window-to-Wall Ratio. All models in this test had a WWR of 58% which originated from the DoE large office model.

The façades' energy performance was ranked from 1st to 4th in both programs. Figures 29 & 30 are SketchUp's representation of the benchmark offices in three dimensional (X-ray views) forms within OpenStudio; dividing walls in Figures 29 & 30 show the separation of zones in each office building.

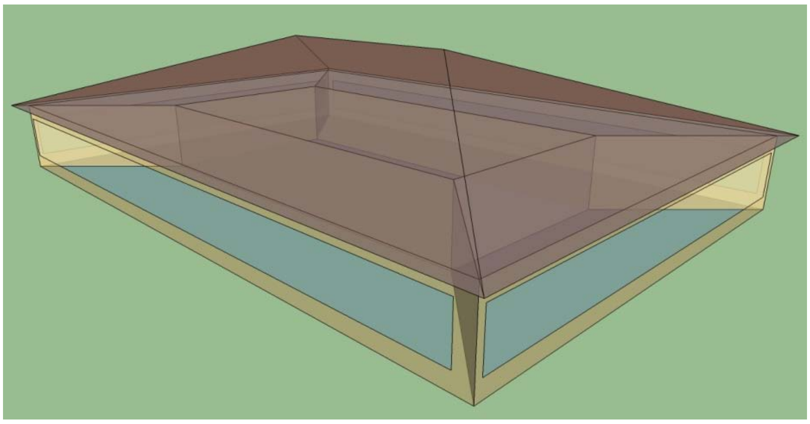

Figure 29 – Geometry of DoE small benchmark office

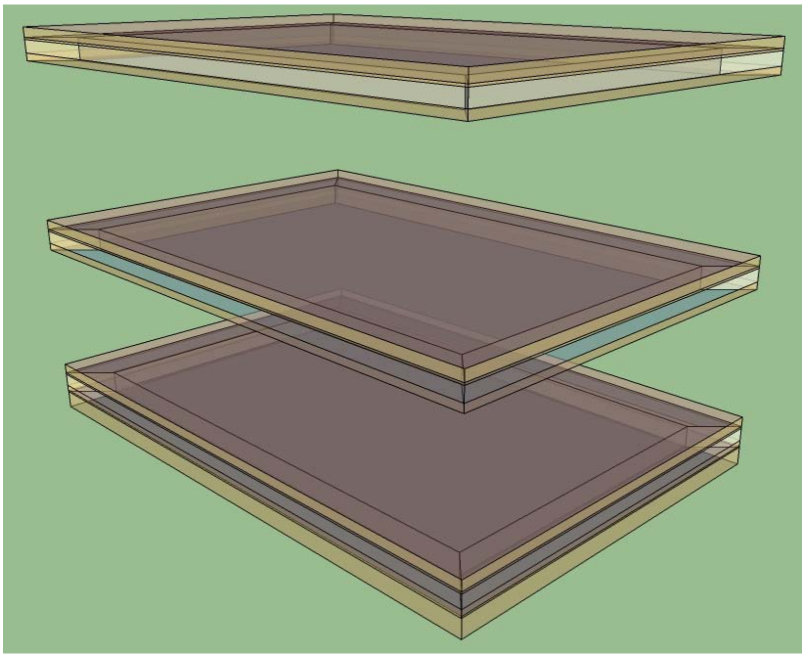

Figure 30 – Geometry of DoE large benchmark office

In the large office, EnergyPlus divides up floors into top, middle and bottom for its calculation because energy use will vary in each floor level. The method of energy calculation consists of top, bottom and basement floors (each multiplied by 1) plus middle floors (multiplied by 10) to represent the 13 storey benchmark large office. The small office is simply displayed as a single storey building in OpenStudio.

The benchmark offices consist of multiple zones, where each floor is made up of a single core zone and four perimeter zones. A core zone (internal space) does not have as much daylight exposure (solar gain) compared to perimeter zones. Figure 31 shows the plan of the zones in the small office. The 5 zones have the same arrangement as the 5 zones on each floor of the large office. The principal differences between small and large office are the scale of the building and its zones (CZ = core zone & PZ = perimeter zone). Figure 32 shows the floor layout of the large benchmark office.

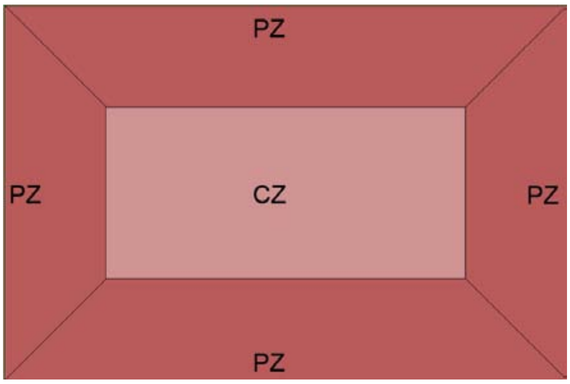

Figure 31 – Floor layout of perimeter zones and core zone in the small benchmark office

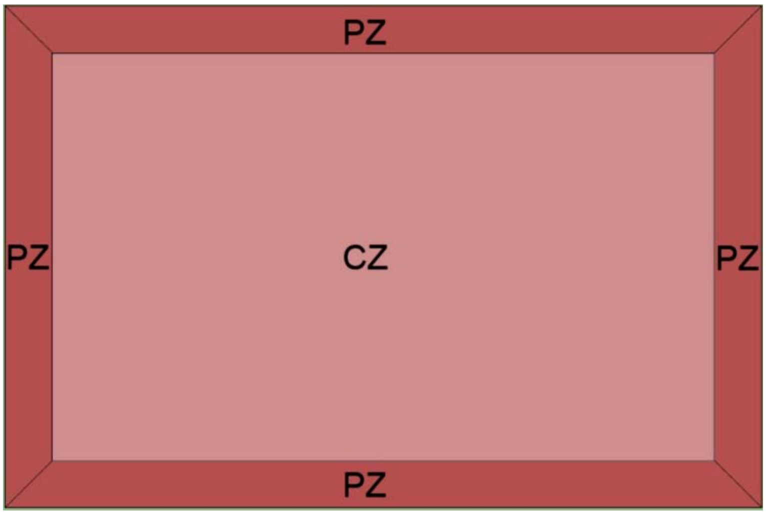

Figure 32 – Floor layout of perimeter zones and core zone in the large benchmark office

The floor area of the DoE benchmark offices simulated in EnergyPlus is:

- Small office: 510m² - total of 1 storey (attic excluded in EUI) Figure 29 & Figure 31
- Large office: 46,320m² - total of 13 stories (basement included) Figure 30 & Figure 32

The difference in floor area between small and large offices is immense and it is likely to be significant in any energy performance calculations. Figure 32 shows that the large office's perimeter zones have a depth which is much smaller as a proportion of the whole floor area compared to the perimeter zones in the small office. The distribution of core zone(s) and perimeter zones could have a significant influence on the energy performance predictions as the energy needs of a zone in contact with the outside climate are very different than the energy needs of a zone almost completely isolated from the outside. The reason for assessing these two different office models is to examine whether this scale difference in a building makes a difference in terms of overall energy performance and façade ranking.

Table 1 below shows how the floor area percentage of perimeter zones versus core zone(s) varies in the DoE offices.

DoE Office	**m² % of Perimeter Zones**	**m² % of Core Zone(s)**	**Total m² % of building**
Small	71% (362m²)	29% (148m²)	100% (510m²)
Large	29% (13,433m²)	71% (32,887m²)	100% (46,320m²)

Table 1 – Floor area percentage of perimeter zones versus core zones

The energy use of the perimeter zones varies depending on their façade orientations. The core zone is not directly connected to daylight therefore it has a higher electric lighting energy demand than perimeter zones. One of the principal focuses of this research is therefore examination of the influence on the consistency of energy use predictions of the COMFEN model with no core zones when compared to full scale (multi-zone) models.

The integration of COMFEN façade designs into the DoE offices created four different buildings in each office category because of the four fenestration designs examined in this test. Each façade design represents an individual model with identical fenestration design on all orientations (e.g. Small office with design A, Small office with design B, Large office with design A etc). A total of two building types and four façades, therefore eight multi-zone buildings were tested across four climate zones. The results are compared with COMFEN predictions to see if the single-zone design messages are consistent.

3.6.4 Simulation Settings

The following are the general simulation settings applied to the COMFEN and EnergyPlus models:

Location: according to weather file
North Axis: 0 degrees
Terrain: suburbs (COMFEN default)
Daylight control: daylight used when working surface exceeds 538 Lux which reduces the electric lighting load during that period. Electric lighting is switched on when working surface drops below 538 Lux (538 Lux is derived from COMFEN which is approximately 50fc)
Shading Control Type: always on
HVAC: fully HVAC conditioned zones
Fenestration construction: see Figure 27 & APPENDIX I
Building envelope: COMFEN default construction settings (Wall R-value = 2.29 m^2-K/W)

Table 2 – General simulation settings used in the consistent test of COMFEN

The type of HVAC system and targeted standards used in the simulation models are:

- **PSZ-AC:** DoE's Packaged Single Zone – Air Conditioner HVAC system
- **Targeted Standard:** ASHRAE Standard 90.1-2004 & 62-1999 (energy standard for buildings except low-rise residential buildings)

Table 3 shows the detailed settings used in COMFEN and EnergyPlus models:

Modelling setting	COMFEN & EP models
Window-to-Wall Ratio (%)	58
Occupancy (people/m^2)	0.03
Interior Lighting (W/m^2)	13.5
Interior Equipment (W/m^2)	8.1
Infiltration (ACH)	0.3
HVAC System	PSZ-AC
Building Schedules	COMFEN Small office
Targeted Standard	ASHRAE 90.1-2004

Table 3 – Further detailed simulation settings in COMFEN and DoE offices

As many simulation settings as possible were made consistent between the COMFEN and EnergyPlus models to ensure that any observed differences in energy use prediction would focus on the modelling approach – the single zone of COMFEN versus the multi-zone of EnergyPlus.

3.7 Evaluating the Adequacy of the Sketch within a Performance Sketch Tool

This section describes the third method of this research. It examines the use-cases (interview feedback) by exploring the complexity of COMFEN as an example of a performance sketch tool. The main suggestions regarding COMFEN improvements are (see Table 7 on page 69):

- the ability to examine/understand the performance of adjacent zones (i.e. multi-zones)
- the ability to simulate ‘Natural Ventilation’

The simple 1-zone simulation approach of COMFEN has its benefits. These are: quick calculations and the ability to compare multiple façade designs at once. However, its current application does not allow the user to assess designs with natural ventilation, which rules out this energy saving opportunity. Also, focusing on perimeter zones of a building design could be misleading because core zones could have a huge effect on the overall energy consumption.

The goal of this method was to use EnergyPlus to “mock up” a COMFEN run to examine the design options reported as desired during the use-cases. This method relies on the fact that EnergyPlus is the calculation engine for COMFEN. If a COMFEN single-zone model were to be simulated in EnergyPlus the results would be the same. This mock-up process examined how one might create a performance sketch early design tool based upon a more complex model than the single perimeter zone of COMFEN.

3.7.1 Adding Complexity to the Performance Sketch Tool

Two particular aspects of Performance Sketch complexity were modelled with full version of EnergyPlus; they were:

Is a multi-zone sketch model different to a generic COMFEN single-zone model? Does it produce the same design lessons/feedback?

The multi-zone sketch is assumed to be a more accurate method (i.e. modelling of associated spaces within a building design) than the single-zone approach when modelling building energy performance. The purpose of this analysis is to examine whether it is possible to calculate results similar to multi-zone simulations based on COMFEN’s (single-zone) method. Multi-zone tests were performed in EnergyPlus to explore the multi-zone design option. Also, to prove that single-zone (simulation) is enough from an early design perspective.

Could COMFEN run a single-zone/multi-zone natural ventilation model?

The purpose of this analysis is to assess the design option of natural ventilation with single and multi-zone models in EnergyPlus. Tests were performed in EnergyPlus because the current COMFEN interface cannot simulate natural ventilation. Potentially, natural ventilation could be incorporated into future versions (depending on verification of results).

This analysis addressed two simulation types for each category of modelling method:

- **HAVC Only models** (current intention of COMFEN)
- **Mixed Mode models** (desired feature of Natural Ventilation incorporated with HVAC)

The following are the categories of modelling method explored in this analysis:

- **COMFEN model:** Single-zone in COMFEN. Consists of north & south facing zones simulated separately (for HVAC Only model).
- **1-zone model:** Single zones in EnergyPlus to assess Natural Ventilation option (for Mixed Mode model: north & south zones simulated separately).
- **2-zone model:** Consists of 2 zones in EP (north & south zones).
- **3-zone model:** Consists of north, south and core zones in EP. The 3-zone model is the equivalent of three generic COMFEN single zones, each zone with the same width, length and height (3m).

Note: all models have the same height, width, and length with identical glazing percentage. The only difference is the zone layout and connections from zone to zone. It is significant to have the same dimensions across the modelling method categories because they are likely to have a large effect on the final calculated performance.

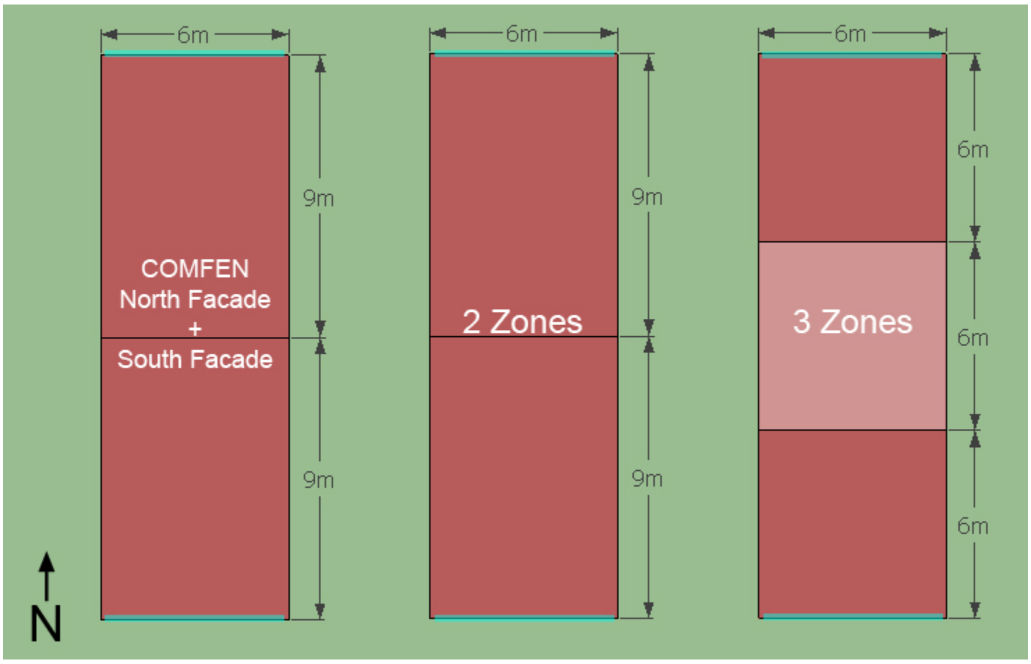

Figure 33 – Plan view: modelling categories

Figure 33 shows the zone layouts modelled. On the left is a 'single-zone' model – the North and the South facing zones are modelled in separate COMFEN like runs and the total energy use is the sum of the two zone energy uses; in the centre is a 2-zone model – one model comprising two zones connected by an internal wall; on the right is a 3-zone model where the interior zone has no fenestration connection to the outdoor climate. The floor areas are the same in all models at 112m² (equivalent of 3 standard COMFEN zones).

The only difference between the mock up COMFEN model and the real one is that you cannot model the Natural Ventilation and multi-zone use-case suggestions through the current COMFEN interface.

The 2-zone test questions whether 1-zone is enough to assess a fenestration design. The 3-zone model illustrates the effect of an interior (core) zone. The results will determine whether the simplest approach to creating a performance sketch (1-zone calculations) is adequate for early design analyses.

The energy use index (EUI: $kWh/m^2.yr$) of each modelling category was assessed to determine the EUI percentage difference between the calculation methods (i.e. single-zone vs. 2-zone model & single-zone vs. 3-zone model).

3.7.1.1 Simulation Settings:

The following simulation assumptions are kept consistent throughout the modelling categories; these settings are significant because they could have a huge effect on the calculated performance of each modelling category. Therefore the simulation settings need to be: a) the same for every simulation; b) in ranges that make the building convincing models of actual commercial building use (i.e. heavily glazed buildings illustrated in Section 1.3).

The following are the general simulation settings applied to models within this analysis:

Location: Wellington, New Zealand
North Axis: 0 degrees
Terrain: suburbs (COMFEN default)
Daylight control: daylight used when working surface exceeds 538 Lux which reduces the electric lighting load during that period. Electric lighting is switched on when working surface drops below 538 Lux (538 Lux is derived from COMFEN which is approximately 50fc)
HVAC only models: fully HVAC conditioned zones
Mixed Mode models: natural ventilation used when indoor temperature exceeds 25°C and switched off when interior temperature drops below 18°C
Fenestration construction: 6mm single clear glazing (see APPENDIX I)
Building envelope: COMFEN default construction settings (Wall R-value = 2.29 m^2-K/W)

Table 4 – General simulation settings for 1~3-zone models

The following table shows detailed simulation settings derived from a COMFEN curtain wall example:

Modelling settings	**1~3-zone models**
Single Glazed Façade (mm)	6
Glazing Percentage (%) North & South façades	97% (relate to buildings in Section 1.3)
Occupancy (people/m^2)	0.03
Interior Lighting (W/m^2)	13.5
Interior Equipment (W/m^2)	8.1
Infiltration (ACH)	0.3
HVAC System	PSZ-AC: Packaged Single Zone – Air Conditioner HVAC system
Building Schedules	COMFEN Small office
Targeted Standard	ASHRAE 90.1-2004

Table 5 – Detailed simulation settings for 1~3-zone models

3.7.2 Individual Zone Comparison: Results of Adding Complexity to the Performance Sketch Tool

The purpose of this test is to examine each individual zone simulated using a range of different, more complex performance sketches. The goal is to determine whether a multi-zone approach to creating the performance sketch is better or worse than the current one. The distribution of energy use (kWh/m^2.yr) between each individual zone within the models is examined. The analysis illustrates the amount of energy consumed by each zone in relation to its façade orientation. This includes the five major energy components: Heating, Cooling, Ventilation, Interior Lighting, and Interior Equipment. Figure 33 shows the zone layout of each modelling category.

The question asked is: Is a single-zone sufficient for early design analyses? Is it capable of producing similar design lessons (i.e. distribution of HVAC & lighting loads) to multi-zone models?

The distribution of energy use between each zone for a fenestration design is as critical as the EUI ranking. Consistent early design advice/feedback is not just predictions of a consistent ranking of the EUI but also an indication of where the energy performance varies. The designer could still be lead to an erroneous design decision if the distribution of energy end-uses is inconsistent with what will happen in reality. For example, a designer could view the energy performance of a three zone ‘sketch’ and note that the zone facing the noonday sun has the tendency to overheat (i.e. high cooling demand). Their response could be radically different if they viewed outputs from a one zone model which will not overheat even though it has the same window and floor area as the three zone model. The following is how the percentage of energy use index (EUI %) is determined in each modelling category:

- **COMFEN model:** Total EUI % = North zone EUI % + South zone EUI %
- **2-zone model:** Total EUI % = North zone EUI % + South zone EUI %
- **3-zone model:** Total EUI % = North Zone EUI % + Core zone EUI % + South Zone EUI %

E.g. North zone total EUI % = total kWh/m^2.yr (EUI) of north zone / total kWh/m^2.yr (EUI) of model. South zone total EUI % = total kWh/m^2.yr of south zone / total kWh/m^2.yr of model.

Note: Total EUI = Total (annual) energy consumption of all zones within a model.

3.7.3 A Consistency Test for the Study of Adding Complexity to the Performance Sketch Tool

Some of the concerns of the use-case interviewees related to the need for natural ventilation and multi-zone simulation during early design analyses. These cannot be currently modelled with COMFEN. They can be modelled with EnergyPlus. EnergyPlus was therefore used to mock up the operation of COMFEN with these features. This was a test of adding a different sort of complexity to the performance sketch tool.

The analysis is similar to the consistency test for COMFEN. The purpose of this analysis is to examine single-zone and multi-zone models with natural ventilation incorporated. This was to determine whether it is possible for single-zone models to produce the same design advice/feedback as multi-zone models.

In this test two fenestration designs (Figure 34) were simulated to see if the single-zone energy predictions are consistent with the multi-zone results (2-zone and 3-zone models). Therefore, each fenestration design is simulated in all modelling categories; Mixed Mode is the only mode assessed in this test (i.e. HVAC & Natural Ventilation).

Two fenestration designs were selected in order to explore the potential differences in energy performance in the single-zone and multi-zone models with Mixed Mode incorporated. The following are façade design details for this test (see). Figure 33 shows the zone layout of each modelling category.

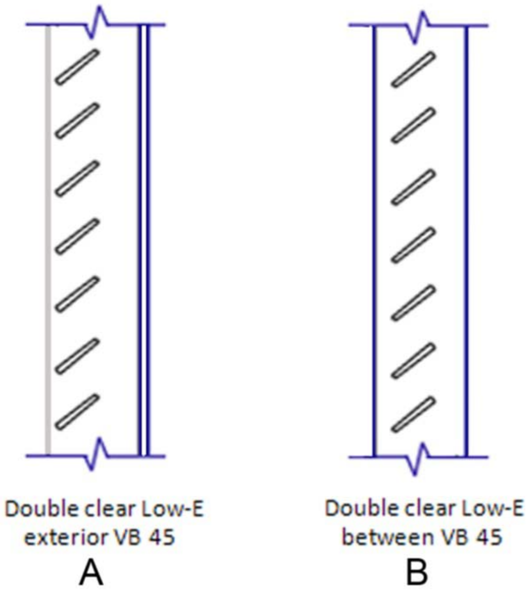

Figure 34 – Façade designs simulated in consistency test

- **A.** Double clear Low-E glazing with exterior venetian blinds (permanently fixed) at 45°
- **B.** Double clear Low-E glazing with between venetian blinds (permanently fixed) at 45°

Fenestration design with the lowest energy consumption ($kWh/m^2.yr$) was ranked 1st in COMFEN and EnergyPlus (e.g. 100 $kWh/m^2.yr$ is ranked above 150 $kWh/m^2.yr$ etc).

Similar to the consistency test for COMFEN, consistency is achieved if single-zone and multi-zone energy predictions are the same design advice/feedback. For example, energy performance of a three zone 'sketch' has to be similar to a one zone model for the design advice/feedback to be consistent; therefore the calculated results need to be consistent in: a) ranking; b) distribution of energy-end-uses.

3.7.3.1 Simulation Settings

Simulation settings are kept the same throughout this consistency test between single-zone and multi-zone models; these settings are significant because they could have a huge effect on the calculated performance of each modelling category. The results illustrate the difference in energy performance between fenestration designs tested in single-zone and multi-zone models. Refer to Tables 4 & 5 for simulation settings.

4 RESULTS

This chapter reports the results of the three research methods described in the previous chapter. It deals in turn with the interview use-case studies; the consistency test; and the study of the complexity of a performance sketch tool.

4.1 Use-cases: Introduction of a Performance Sketch Tool to Practitioners

This section analyses each practitioner's interview feedback. Practitioners' anonymity was maintained by reporting their responses under labels A through F. The appendix chapter lists their occupation within the firm, as architect or engineer. In relation to COMFEN as an example of the performance sketch tool, initial feedback from each interview was also recorded in APPENDICES C to H.

4.1.1 Interview Questions

The following questions were used to structure the interview with each practitioner after the introduction of the COMFEN software:

1. What do you think of COMFEN?
2. Was there enough information in the graphical results?
3. Areas that need improvement?
4. Any further comments?

A practitioner was asked to provided further feedback if their comments challenged the performance sketch tool idea. This was to determine not just the challenge, but also their rationale for their feedback. Gathering further feedback on what would be the ideal 'sketch' design tool (i.e. its capability and usability) will help improve the relevance of COMFEN predictions.

The following questions were asked in the 2nd round of feedback (if required):

1. If you were to design an early design tool (performance sketch tool), what would you incorporate into the tool? How complex is too complex?
2. As a practitioner (keep in mind the performance sketch tool idea), what would be a good early design tool to you? What is useful in very early sketch design?
3. After a better understanding of the performance sketch tool idea, does the feedback on COMFEN change in anyway? Or the original interview feedback still stands?

The next few pages summarise the analysis of the use-cases and the subsequent feedback. **Note:** If no further feedback was provided by the practitioner, the first round of feedback was taken to be their final statement on COMFEN as a performance sketch tool.

4.1.2 Overall Analysis of Conclusions: Use-cases

Tables 6 & 7 summarise the practitioners' views of the advantages of COMFEN (Table 6) and the desired features for a performance sketch tool (Table 7). The reference column in each table links to APPENDICES C~H which contain initial feedback recordings and individual analysis of each use-case.

The following table is a summary of COMFEN advantages:

Advantages of COMFEN	Reference to Appendix
Ability to compare multiple façade designs simultaneously which are supported by good graphical information	D, E, F, H
The software is simple, quick and user-friendly from an early design perspective	C, E, F, G
The program is compatible with EnergyPlus (detailed design tool) which can carry the design into the detailed design stage	E
Good for communicating with the client through its graphical interface (e.g. energy performance of the design)	G
It would be useful for window manufacturers (i.e. input various products into the software)	G

Table 6 – Advantages of COMFEN

The results in Table 6 show the main advantages of COMFEN quoted by practitioners; these were:

- The ability to compare multiple façade designs simultaneously which are supported by good graphical information (4/6 use-cases).
- The software is simple, quick and user-friendly from an early design perspective (4/6 use-cases).

Overall, practitioners had similar comments on COMFEN as a performance sketch tool. The majority of the practitioners believe these advantages are great from a performance sketch design perspective.

The following table is a summary drawn from practitioner feedback of the desired features for future versions of the performance sketch tool:

Desired Features	Reference to Appendix
Double façade design option	C, D, E, G, H
Sketch/Simulate what you want *E.g. ability to sketch desired geometries and draw in shading elements rather than just define dimensions.*	C, D, F, H
Aesthetics visualisation: realistic sketch of design scenarios *E.g. colour of glass, fins, shading devices & orbit around the 3D model.*	C, D, F, H
Annual cost analysis *E.g. option to plot in cost of energy per kilowatt-hour, life cycle cost calculation & material costs.*	D, E, F, G
Multi-zone simulations *E.g. to assess the whole building, air/heat movement between the perimeter zones & core zones – could influence the design predictions dramatically.*	D, E, F
Natural ventilation option *E.g. mixed mode option, control over size & schedule of openings.*	C, D, F
Atrium design option	D, E, G
Automatically compare to desired standard(s)	C.2, H
Importing complex architectural geometry into the software *E.g. import drawings from Revit & other CAD programs.*	D, F
Simulating external shading and sun path study *E.g. neighbouring buildings & trees.*	C, H
Apply materials to opaque areas *E.g.* walls/ceiling/floor.	D, G
HVAC system control options *E.g. summer & winter - seasonal efficiency, temperature settings and more detail/information on the type of system – Package Single Zone-AC.*	C.2, F
Export models to other common detailed design tools (not just EnergyPlus) *I.e. compatible file format.*	F
Control over internal gains *E.g. option to enter desired values.*	C.2
Automatically convert simulation outputs to desired unit *E.g.* $kWh/m^2.yr$ *&* W/m^2 *etc.*	C.2
Automatically include a small image of each façade option on charts as well *I.e. not just a number reference to design scenario.*	C.2
Automatically produce charts comparing designs that allow the user to bring into MS Excel	C.2
Light (Lux) measurement on ceiling *E.g. light bouncing off shading device – opportunity to use daylight with electric lights.*	D
Solar gain & heat gain analyses	H

Table 7 – Desired design features in future versions

Table 7 shows all the desired feedback reported during the use-cases. The features that were most commonly referred to in the 6 use-cases, and thus might be viewed as of highest priority, in sketch performance tools development beyond what COMFEN provides were:

- **Double façade design option** (5/6 use-cases).
- **Sketch/Simulate what you want** (4/6 use-cases).
- **Aesthetics visualisation: realistic sketch of design scenarios** (4/6 use-cases).
- **Annual cost analysis** (4/6 use-cases).
- **Multi-zone simulations** (3/6 use-cases).
- **Natural ventilation option** (3/6 use-cases).
- **Atrium design option** (3/6 use-cases).

Having the ability to sketch freely seems to be the essential feature proposed by the practitioners. In order for the user to explore/express their architectural ideas, sketch limitations must be kept at a minimum. Multi-zone simulations, natural ventilation, double façade and atrium design features could be perceived as part of the 'sketch/simulate what you want' desired feature category. These desired features are for analysis purposes helping practitioners identify and evaluate the best (sustainable) design solutions from very early stages of design. For example, the ability to assess a building with natural ventilation was stated to be an important design option that needs to be incorporated in to any performance sketch tool. That the COMFEN performance sketch tool was not able to model this design feature made this a highlighted desirable feature in the feedback.

Building visualisation in the early design interface is significant according to the use-case feedback. It is important to practitioners – whether architects or engineers – that the interface provides a realistic representation of the sketch design scenarios. The representation is important for analysis and for client presentation purposes.

Cost analysis permits comparison of energy cost in use with construction costs. They were desirable because they can help the design team to persuade the client and sell the proposed idea (i.e. secure a design contract).

The practitioner feedback from the use-cases suggests that they want a more complex model when using a performance sketch tool. A more complex model (e.g. imported Revit/AutoCAD geometry or modelling of multi-zones), will take longer for the simulation engine to calculate façade designs. Potentially, it creates a difficulty in learning/understanding how the software works. Ultimately this complexity challenges the fundamental basis of the performance sketch concept.

Despite this, and in contradiction to the performance sketch introduction to the use-case sessions, the majority of the practitioners suggested that this extra precision (e.g. ability to sketch desired geometries) in the modelling interface would be really relevant from an early design perspective.

In summary, the outcome of this analysis determined three design features that require improvement in a performance sketch tool by comparison with the COMFEN example. A diagram of decision-making for performance sketch analysis was also established. The following sections make up the resulting performance sketch tool specifications:

1. **Freedom of Aesthetics** – ability to sketch (basic) desired building geometry
2. **Sustainable Designs** – relevant/plausible early design performance predictions
3. **Delivering the Design** – realistic interface visualisation for client presentations
4. **Diagram of Decision-making** – guideline for performance sketch analysis

Practitioners often begin their design on a sketch pad because free-hand sketching allows them to fully express their inspiration, aesthetically. Various designs can be sketched quickly on paper and then presented to the client. COMFEN has the capability of comparing multiple façades simultaneously, so was presented in the use-cases as very much a ‘sketch pad’ of early design simulations. The presentation showed that a tool like COMFEN could be really useful because practitioners can readily transfer their sketches into the software. Also, COMFEN delivers the building design in a manner that is easy for the client to understand. Its performance reporting has the potential to impress the client by quickly and graphically presenting the costs and benefits of different design concepts.

4.2 Consistency Test of a Performance Sketch Tool

The consistency of design advice/feedback between performance sketch tool and detailed design tool was evaluated by comparing the energy performance ranking of the fenestration scenarios specified in the methodology chapter.

The following points summarise the process of energy performance ranking:

- The ranking of façades was determined by calculating the annual energy performance in COMFEN using its one zone model and in EnergyPlus using the DoE benchmark small and large office models (US DoE 2010) for four radically different climate zones.
- In COMFEN: the façade design with the lowest energy consumption (average kWh/m^2.yr across all orientations) was ranked 1st and the façade design that consumed the most energy per year (average kWh/m^2.yr across all orientations) was ranked 4th.
- In EnergyPlus: the building design with the lowest energy consumption (kWh/m^2.yr) was ranked 1st and the building that consumed the most energy per year was ranked 4th.
- Plotting these façade designs left to right from first to fourth ensures that consistency of design predictions equals 'letter order' in the graphs: if the ranking in the COMFEN & EnergyPlus results has the same order then the predictions are consistent.

4.2.1 Exploration of Possible Climatic Differences

The following table illustrates the consistency of COMFEN fenestration ranking across all four climate zones. The table represents an overall comparison of ranking trends from country to country; the consistency of COMFEN's sketch advice/feedback on fenestration designs are shown as C = Consistent Ranking (green) and I = Inconsistent Ranking (red).

Location/Climate Zone	COMFEN vs. Small Office	COMFEN vs. Large Office
Wellington (mixed, marine)	C	I
Melbourne (warm, marine)	C	C
Minneapolis (cold, humid)	I	C
Bombay (mixed, dry)	C	C

Table 8 – Consistency of COMFEN fenestration ranking

The results in Table 8 show that across all climate zones examined in this research COMFEN produced consistent fenestration performance advice/feedback as multi-zone offices in Melbourne and Bombay. However, inconsistent design messages occurred in some scenarios in Wellington and Minneapolis.

The results in Figures 35~38 show the energy performance of fenestration designs in four radically different climate zones. These locations were selected to represent a range of climate zones around the world. They explore the differences in energy performance during sketch and detailed design simulations.

The following are the COMFEN fenestration design scenarios which link to graphs and tables in this section:

- **A.** Double clear Low-E glazing with exterior venetian blinds (permanently fixed) at 45°
- **B.** Double clear Low-E glazing with between venetian blinds (permanently fixed) at 45°
- **C.** Double clear Low-E glazing with interior venetian blinds (permanently fixed) at 45°
- **D.** Single clear glazing

The results in Figures 35 & 36 show the two locations where COMFEN's calculation of the energy performance of fenestration designs is consistent (i.e. the same letter order) with that of EnergyPlus. However, these graphs compare the breakdown of the energy consumption from COMFEN with the similar breakdown in EnergyPlus (EP), not just the overall total energy use. These show that COMFEN has a very different pattern of energy use than the small office as cooling is more important than heating. Whilst more consistent with the large office trends, COMFEN still appears to exaggerate the importance of cooling in that the differences in cooling energy use and ventilation between fenestration designs is far greater as a proportion of the total energy use.

This has serious implications for the consistency of design advice. If, for example, the designer decides to focus on what appear to be the important lessons from the COMFEN indication of which are the most important end-uses of energy they may place too much emphasis on the items (like ventilation in Figure 35) where the design choices appear to make a large difference in overall energy use.

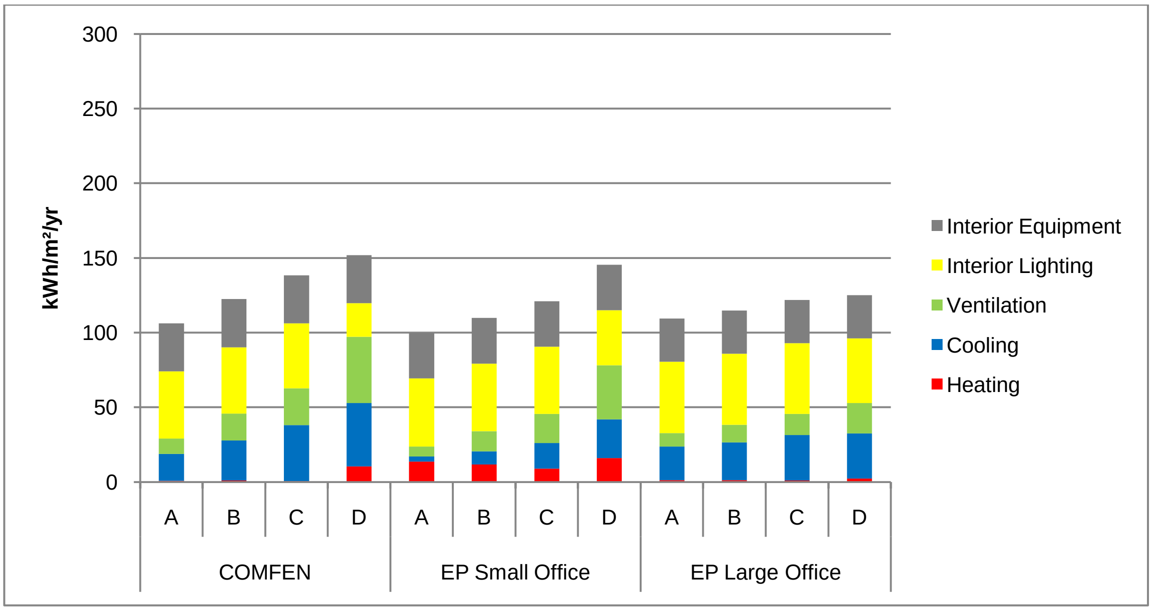

Figure 35 – COMFEN and EP simulations in Melbourne

Figure 35 shows that the COMFEN energy performance ranking for Melbourne is consistent with all office scenarios. Table (APPENDIX K.1) contains the results of the annual energy distribution of designs simulated in Melbourne.

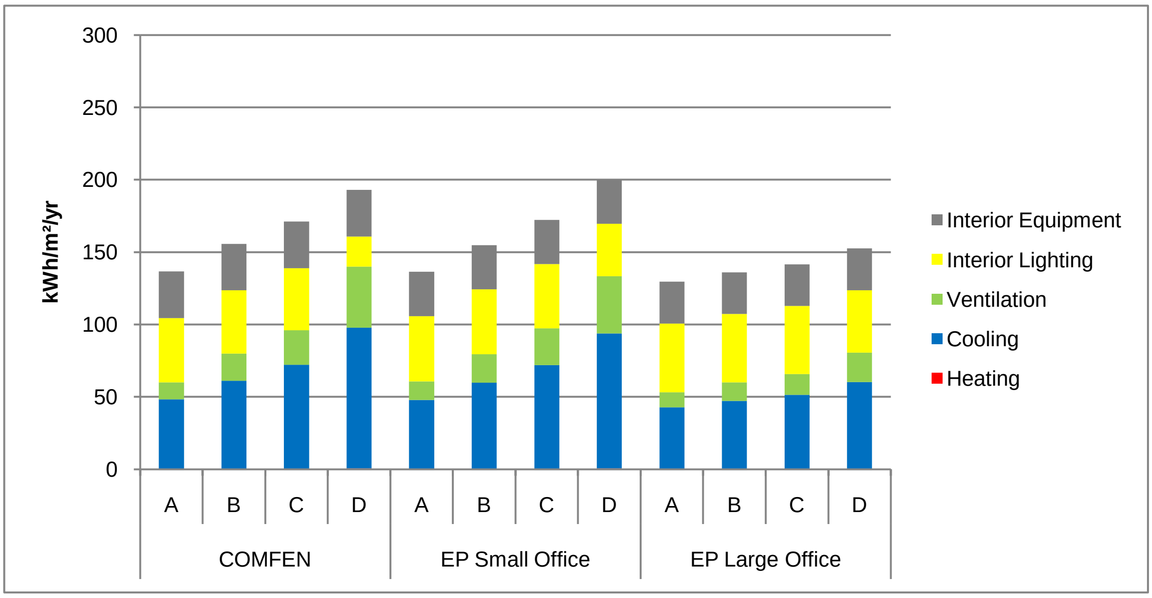

Figure 36 – COMFEN and EP simulations in Bombay

The Bombay results in Figure 36 show that COMFEN overall ranking is consistent with all results derived from EnergyPlus. Table (APPENDIX M.1) contains the results of the annual energy distribution of designs simulated in Bombay. The general lessons of the individual breakdowns of the end-uses of energy are mostly consistent, except for case D (Single clear glazing) where COMFEN indicates the Interior Lighting is significantly lower than EnergyPlus suggests.

The results in Figures 37 & 38 show the locations where COMFEN's ranking of energy performance is inconsistent (i.e. a different letter order). It is evident here also that the single-zone approach has exaggerated the distribution of energy end-uses in some scenarios.

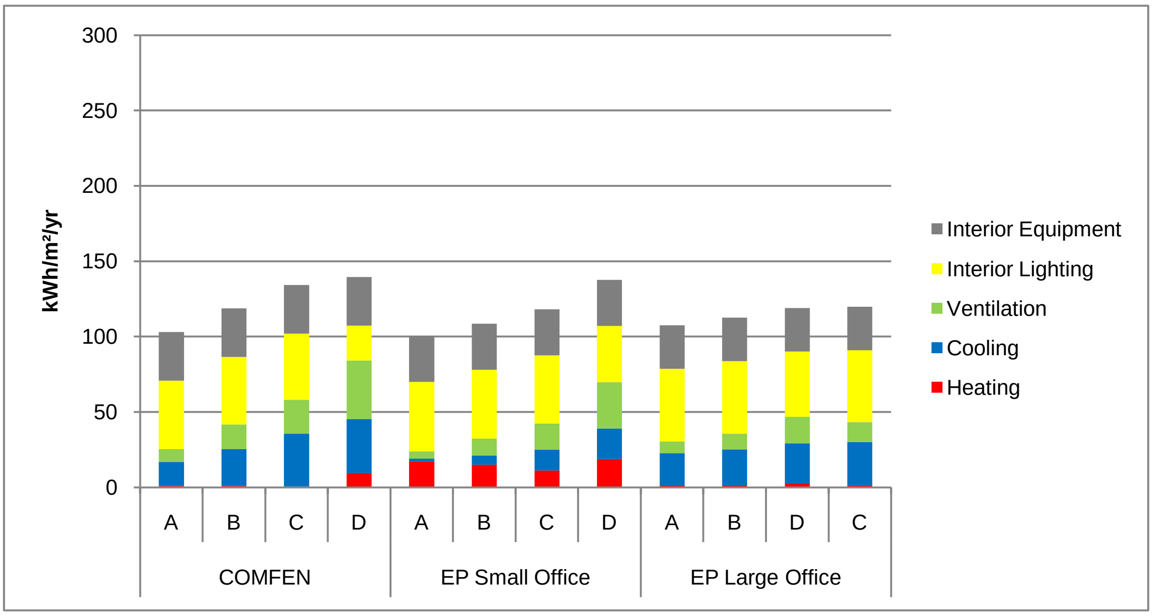

Figure 37 – COMFEN and EP simulations in Wellington

Wellington COMFEN ranking (Figure 37) is consistent with majority of EnergyPlus scenarios. However, the letter order for the large office scenario does not match COMFEN's letter order; Façades C & D were inconsistent (Double clear Low-E with interior venetian blinds & Single Clear). Table (APPENDIX J.1) contains the results of the annual energy distribution of designs simulated in Wellington. It is noticeable again that despite the consistency of the ranking of the total energy use predictions for the different scenarios, the Heating Energy Use for the Small Office is a significant design issue, while it is not for COMFEN or for the Large Office.

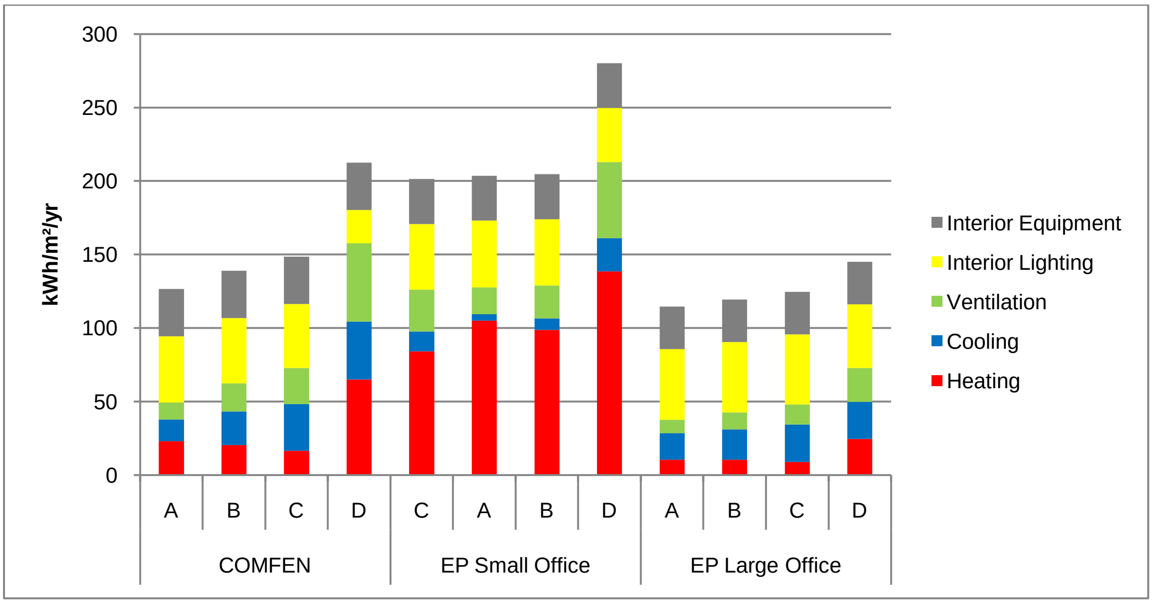

Figure 38 – COMFEN and EP simulations in Minneapolis

The Minneapolis results in Figure 38 show that the COMFEN rankings were consistent only with the large office EnergyPlus results. The letter order was inconsistent with the small office scenario; only fenestration D was consistent throughout all office scenarios. Table (APPENDIX L.1) contains the results of annual energy distribution of designs simulated in Minneapolis. Again, the underlying pattern of the energy end-uses was hugely different for the COMFEN and Small Office cases. Even where the results and much of the breakdown patterns were similar between COMFEN and the Large Office case, the relative significance of Heating Energy Use was radically inconsistent (see fenestration type D).

There is an apparent trend in terms of the locations that produced consistent fenestration ranking. Melbourne and Bombay are both hot climate zones that require a high cooling load. Locations where inconsistent ranking occurred had cooler climatic characteristic which means higher heating requirements: Wellington and Minneapolis.

Large amounts of energy can be saved by using appropriate fenestration design within the building's context. The consistency test results show that façade designs perform differently in each location. For example, small office results in Minneapolis show some signs of inconsistency (i.e. different ranking to COMFEN). Façade option C appears to be the most energy efficient, which is different to other climates where façade option A is ranked first. Slight inconsistency occurred in Wellington where option D was ranked in front of option C in the large office scenario; COMFEN did not produce the same ranking as the large office.

It is important to note that fenestration ranking and overall energy use are only parts of any early design advice/feedback. Distribution of energy end-uses is also highly significant because it can influence the designer's decisions about how to further improve the building energy performance. Across all climates, COMFEN has the tendency to exaggerate different energy end-uses compared to the multi-zone scenarios. This could potentially mislead designers during early stages of design.

The scale of the building may play a large role in the determination of the distribution of energy end-uses. For example, the distribution of floor area (i.e. percentage of perimeter & core zones) could be a factor influencing the occurrence of inconsistencies. COMFEN does not calculate the core zone's energy use because it fully focuses on fenestration design with a single perimeter zone.

The following table mines further into the data shown in Figure 36 for Bombay. The ranking produced by COMFEN for Bombay (an example of a warm climate) was consistent with the detailed model calculations:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	A	B	C	D	A	B	C	D
Heating	0.2	0.3	0.4	0.7	0	0	0	1	0	0	0	0
Cooling	48	61	72	97	48	60	72	93	43	47	51	60
Ventilation	12	19	24	42	13	20	25	39	10	13	14	20
Interior Lighting	44	44	43	21	45	45	44	36	48	47	47	43
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	137	156	171	193	136	155	172	200	130	136	142	152
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
%Difference	-	14%	10%	13%	-	13%	11%	16%	-	5%	4%	8%

Table 9 – Annual energy distribution of designs simulated in Bombay

The data bars in Table 9 show the hierarchy of energy end-uses within each fenestration design (widest bar being the dominant consumption of energy or vice versa). Also, the table portrays the percentage difference between fenestration designs. For example, 14% represents that the lower ranked design (e.g. 2nd) uses 14% more energy compared to the next higher ranked design (e.g. 1st). APPENDIX M contains COMFEN/EnergyPlus data and notes relating to Bombay simulations.

Across all the climates studied, COMFEN in Bombay produced ranking of design scenario performance predictions that were the most consistent with the multi-zone results. However, the individual energy loads in Table 9 are exaggerated in some scenarios. It shows that COMFEN (single-zone) exaggerates energy use in some small office scenarios:

- interior lighting load for option D is much lower (i.e. probably due to the absence of a core zone)

The following table illustrates the inconsistent fenestration ranking produced by COMFEN in Wellington (an example of a cool climate); COMFEN's different distribution of energy end-uses is evident:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	A	B	C	D	A	B	D	C
Heating	0.9	1.0	0.6	9.4	17	15	11	19	1	1	2	1
Cooling	16	25	35	36	2	6	14	20	21	24	27	29
Ventilation	9	16	22	39	5	11	17	31	8	10	18	13
Interior Lighting	45	45	44	23	46	46	45	37	48	48	43	48
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	103	119	134	139	100	109	118	138	108	113	119	120
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
%Difference	-	15%	13%	4%	-	8%	9%	16%	-	5%	6%	1%

Table 10 – Annual energy distribution of designs simulated in Wellington

The data bars in Table 10 also show the hierarchy of energy end-uses within each fenestration design. APPENDIX J contains data and notes relating to Wellington simulations.

At first glance, COMFEN's overall performance ranking is consistent with the small office scenario. It leads to the simple conclusion that perhaps it is the floor distribution of the small office (29% core & 79% perimeter) which is much closer to COMFEN's perimeter zone approach. However, the ranking order does not signify that COMFEN produces consistent advice/feedback across the categories of energy end-use (e.g. heating & cooling requirements). The design advice drawn from the patterns of energy end-use is shown for all the climates to be most different for the Small Office scenario. It seems that if the single zone simulation approach of a performance sketch tool like COMFEN is to be used, it should normally be used to model Large Office types of building.

Early design lessons are critical. From fenestration analyses to sizing of mechanical systems, predictions of early design performance must be reliable; the wrong design message from day one could jeopardise the entire building project.

The simplest performance sketch approach of the single zone is apparently not adequate for early design analyses of a multi-zone design. When examining each end-use, it is clear that the 1-zone model exaggerates some energy end-uses compared to others in the multi-zone approach. This is undesirable, because design advice/feedback needs to be consistent in all stages of the design process in order to help designers to identify/evaluate the best building solutions during early stages of design.

Single zone sketch simulations require careful scrutiny to avoid the pitfalls indicated by some of the inconsistencies that occurred in this test. Energy performance predictions derived from COMFEN have more often than not generated fenestration rankings that are consistent across different scenarios.

In summary, the results indicate that one zone and one façade is not enough in terms of calculating plausible energy distribution for the whole building. The designer needs to focus on the right design aspects from day one (e.g. cooling requirement), therefore an imprecise distribution of the load predictions derived from a single-zone calculation is a huge issue; this raises the question of whether it is possible to use the 1-zone approach to sketch/evaluate a whole building, accurately.

4.3 Evaluating the Adequacy of the Sketch within a Performance Sketch Tool

This section summarises the results of the analysis of the complexity of the COMFEN model as an example of a performance sketch tool. The analysis examines how useful more complex models might be compared to the single zone model could be in early design analyses. Options of multi-zone simulation and natural ventilation were assessed because they were the most commonly requested model enhancements mentioned in the conclusions of use-case studies (also see Table 7 on page 69).

The current COMFEN interface cannot simulate multi-zone or natural ventilation models. HVAC Only & Mixed Mode models were simulated in this study because the results illustrate whether a multi-zone model is different to a single-zone model (i.e. does a single-zone model produce the same design lessons/feedback with these modes incorporated?).

4.3.1 Adding Complexity to the Performance Sketch Tool

The HVAC Only models are fully conditioned by mechanical systems without any use of natural ventilation.

The results in Figure 39 & Table 11 show the energy distribution of the 'HVAC Only' simulations in Wellington. The table also illustrates the percentage differences between each modelling method (i.e. difference between HVAC, lighting & equipment loads).

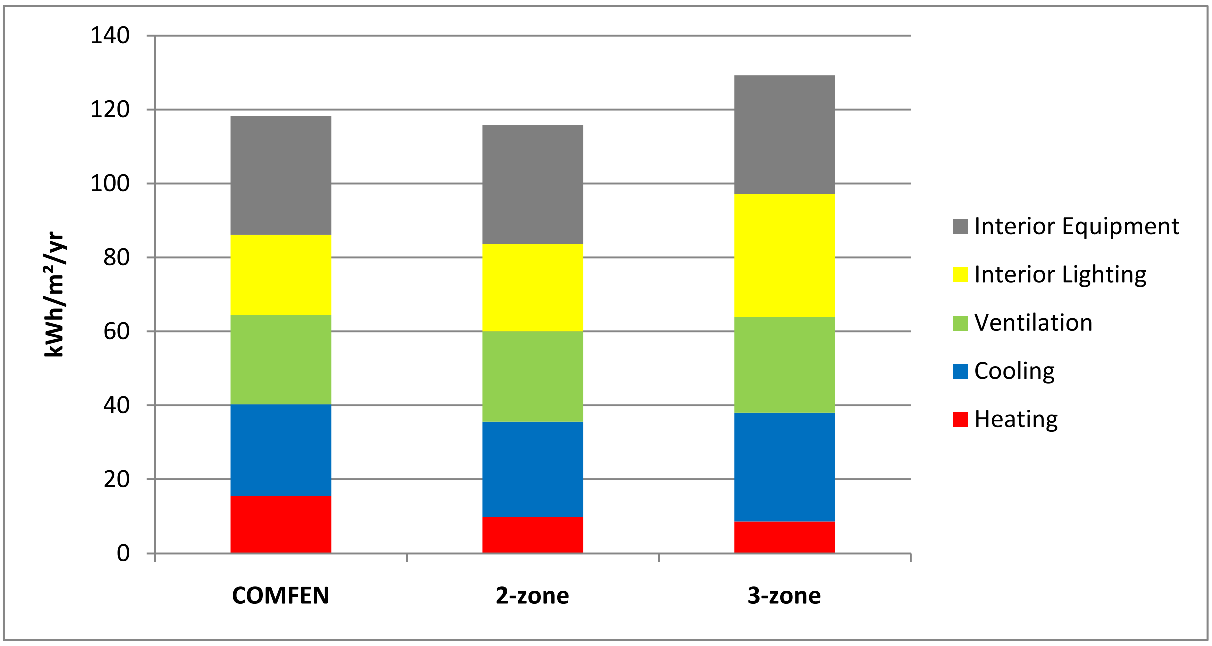

Figure 39 – HVAC Only with daylight control simulations

HVAC Only	1-zone	2-zone	3-zone	% Difference (+/-) 1-zone vs. 2-zone	% Difference (+/-) 1-zone vs. 3-zone
Heating	15.5	9.8	8.6	+58%	+80%
Cooling	24.8	25.8	29.4	-4%	-19%
Ventilation	24.1	24.4	25.8	-1%	-7%
Interior Lighting	21.8	23.6	33.3	-9%	-53%
Interior Equipment	32.1	32.1	32.1	0%	0%
Total ($kWh/m^2.yr$)	118	116	129	+2%	-9%

Table 11 – Annual energy distribution of HVAC Only models simulated in Wellington

Table 11 shows that the EUI difference between 1-zone and 2-zone models is +2%. And the energy difference between 1-zone and 3-zone models is -9% (i.e. the COMFEN single-zone model consumed 9% less energy than the 3-zone model).

COMFEN's (quick) single-zone simulation method is capable of predicting overall energy performance that is similar to the 2-zone EnergyPlus model. However, the energy differences between 1-zone and 3-zone models are considerably larger. This is the effect of the core zone associated to the 3-zone model, which is a zone that does not have daylight control.

The results illustrate that single-zone and multi-zone models are capable of producing similar overall energy predictions. However, there are lessons derived from single-zone calculations that have been exaggerated (i.e. over/below 10%) compared to multi-zone results; these are:

- 58% more heating than 2-zone; 80% more heating than 3-zone
- 19% less cooling than 3-zone
- 53% less interior lighting than 3-zone (due to no core zone in 1-zone model)

Other energy end-use differences were less than 10%.

The 1-zone model energy use was the total energy use of a north and a south facing façade (i.e. 2 single zones), simulated separately in COMFEN. The 2-zone and 3-zone models had lower heating load resulting from the modelling of the two zones together.

The 1-zone model consumed 53% less lighting energy than the 3-zone model because of the daylight control. The 3-zone model contains a core zone which means daylight control is used only in the perimeter zones. Electric lights are always used in the core zone during working hours. Hence, the lighting load in the 3-zone model is much higher compared to the 1-zone and 2-zone models.

The Interior equipment loads across all approaches of simulation are the same because they were based on a fixed simulation input (i.e. 8.1 W/m^2).

If design advice/feedback is to be consistent, then it requires the distribution of energy end-uses to be similar between single-zone and multi-zone models (Table 11). The results suggest that multiple zones are required for early design analyses because the single-zone approach has the tendency to overemphasise some energy end-uses. Potentially, the designer could be misled (e.g. high heating requirement suggested by COMFEN).

The results in Figure 40 and Table 12 show the energy distribution of the 'Mixed Mode' simulations in Wellington. Mixed Mode models use natural ventilation when indoor temperature exceeds 25°C and switched off when interior temperature drops below 18°C (i.e. HVAC is switched off when natural ventilation is in use).

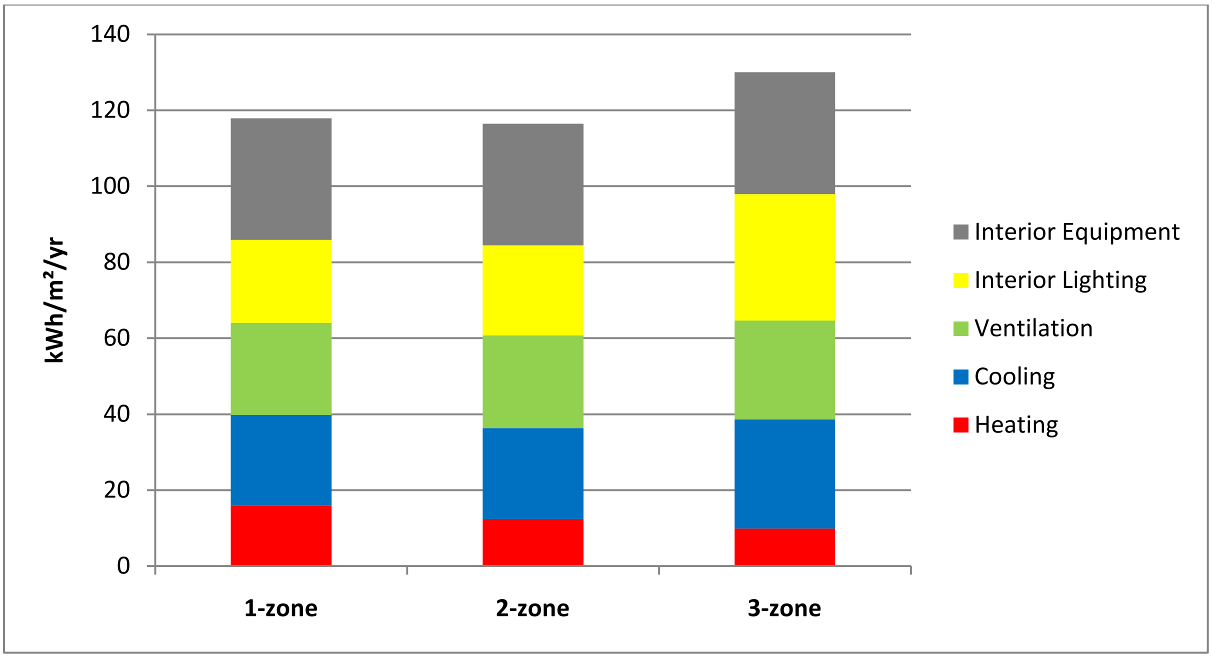

Figure 40 – Mixed Mode with daylight control simulations

Mixed Mode	1-zone	2-zone	3-zone	% Difference (+/-) 1-zone vs. 2-zone	% Difference (+/-) 1-zone vs. 3-zone
Heating	15.9	12.4	9.9	+28%	+61%
Cooling	23.8	23.9	28.7	0%	-20%
Ventilation	24.3	24.4	26.0	0%	-7%
Interior Lighting	21.8	23.6	33.3	-9%	-53%
Interior Equipment	32.1	32.1	32.1	0%	0%
Total (kWh/m^2.yr)	118	116	130	+1%	-10%

Table 12 – Annual energy distribution of Mixed Mode models simulated in Wellington

Table 12 shows that there is a +1% EUI difference between 1-zone and 2-zone models. And the energy difference between 1-zone and 3-zone models is -10% (i.e. 1-zone model consumed 10% less energy compared to the 3-zone model). Again, there was virtually no difference between 1-zone and 2-zone models. And, the energy differences between 1-zone and 3-zone models are still considerably larger.

The results illustrate that the distribution of energy end-uses is considerably different between single-zone and multi-zone models (Table 12). The Mixed Mode results also suggest that the single-zone approach has the tendency to overemphasise some energy end-uses.

Just how close is close enough to determine that COMFEN energy predictions are plausible for early design analyses? Clevenger & Haymaker (2006) stated:

> "Energy modelling accuracy ranges from +/- 10%~40% for non-residential models and general industry consensus is that comparisons of predicted performances are more useful than the absolute values themselves."

Based on this source, the single-zone prediction looks plausible as a total EUI because the estimation (kWh/m^2.yr) was within the suggested threshold. However, some end-use differences were above or below (+/-) the maximum value of 40% (e.g. heating & lighting energy requirements).

Overall, the results derived from both modes illustrated that the single-zone approach has the tendency to distort distribution of energy end-uses compared to multi-zone sketches. Inconsistent distribution of the load predictions shows that the single-zone calculation method is an inaccurate approach to forecast the energy distribution of a multi-zone model.

4.3.2 Individual Zone Comparison: Results of Adding Complexity to the Performance Sketch Tool

This section examines the distribution of energy use within the simulation output of the 'HVAC Only' models examined in the previous section. They were selected for further analysis to illustrate the amount of energy consumed by each zone in relation to its façade orientation.

This time the energy use was broken into five major components: Heating, Cooling, Ventilation, Interior Lighting, and Interior Equipment. The purpose was to see the energy performance of each individual zone.

The following tables illustrate the energy consumption of each zone within all modelling categories simulated in Wellington:

HVAC Only	North Zone	South Zone	Total EUI ($kWh/m^2.yr$)	EUI %
Heating	4.2	11.3	15.5	13%
Cooling	21.0	3.8	24.8	21%
Ventilation	18.6	5.5	24.1	20%
Interior Lighting	11.6	10.1	21.8	18%
Interior Equipment	16.0	16.0	32.1	27%
Total EUI ($kWh/m^2.yr$)	71.5	46.7	118	100%
EUI %	61%	39%	100%	-

Table 13 – Distribution of energy use for each zone within the COMFEN model

HVAC Only	North Zone	South Zone	Total EUI ($kWh/m^2.yr$)	EUI %
Heating	2.6	7.1	9.7	8%
Cooling	22.0	3.9	25.9	22%
Ventilation	18.8	5.6	24.4	21%
Interior Lighting	13.4	10.2	23.6	20%
Interior Equipment	16.0	16.0	32.1	28%
Total EUI ($kWh/m^2.yr$)	72.9	42.8	116	100%
EUI %	63%	37%	100%	-

Table 14 – Distribution of energy use for each zone within the 2-zone model

HVAC Only	North Zone	Core Zone	South Zone	Total EUI ($kWh/m^2.yr$)	EUI %
Heating	2.9	0.5	5.2	8.6	7%
Cooling	19.3	7.3	2.8	29.4	23%
Ventilation	18.1	5.3	2.5	25.9	20%
Interior Lighting	6.6	16.7	10.0	33.2	26%
Interior Equipment	10.7	10.7	10.7	32.1	25%
Total EUI ($kWh/m^2.yr$)	57.5	40.5	31.2	129	100%
EUI %	45%	31%	24%	100%	-

Table 15 – Distribution of energy use for each zone within the 3-zone model

The total energy use (kWh/m^2.yr) is the sum of all the zones in a model. The EUI percentage column in the tables indicates what proportion each end-use is of the total EUI. The EUI percentage row at the bottom of each table shows the fraction of the total EUI contributed by each zone. There are some large differences in the EUI percentage columns between the 1-, 2- and 3-zone models, communicating in particular very different messages about the significance of heating energy use.

Results in Table 13 show that COMFEN's north zone utilizes 61% of the total EUI. And, the south zone consumes approximately 39% of the total annual energy.

Table 14 illustrates that the 2-zone model's north zone utilises 63% of the total EUI; and the south zone consumes approximately 37% of the total annual energy.

Table 15 shows that the 3-zone model's north zone utilizes 45% of the total EUI. The south zone consumes 24% of the total energy and the core zone at approximately 31%.

It is apparent that the core zone has a significant effect on the distribution of energy end-uses. The lesson learned from the modelling categories is that a multi-zone model (i.e. zones simulated together) behaves differently to a model with zones simulated separately. This suggests that the single-zone approach is missing the connection between thermal zones; it is simply not enough to sum up the total of 'two' single zones.

The major difference can be seen in the heating, cooling and ventilation loads. In general, perimeter zones require more energy to condition because they are closer to the exterior elements compared to the core zone space. The heat gains and losses are greater, particularly through the fenestration. The north zone consumes more cooling and ventilation energy (kWh/m^2.yr) because in Wellington the north facing zone is exposed to direct sunlight more throughout the year compared to the south facing zone. By contrast, the core zone relies on electric lighting the entire day. This is because there is minimal or no natural light entering the space.

The following table summarises the EUI percentage of energy distribution within each modelling category in Tables 13~15.

HVAC Only	**1-zone**	**2-zone**	**3-zone**
Heating	13% (16)	8% (10)	7% (9)
Cooling	21% (25)	22% (26)	23% (29)
Ventilation	20% (24)	21% (24)	20% (26)
Interior Lighting	18% (22)	20% (24)	26% (33)
Interior Equipment	27% (32)	28% (32)	25% (32)
Total EUI % & (Total EUI kWh/m^2.yr)	100% (118)	100% (116)	100% (129)

Table 16 – EUI percentage comparison of the modelling categories simulated in Wellington

Table 16 illustrates that the COMFEN single zone model can produce similar total EUI as multi-zone models. Ventilation and interior equipment loads are similar across all modelling categories. However, some design lessons derived from COMFEN are not the same in the multi-zone models. These are:

- The 1-zone model has a much higher heating load than 2-zone & 3-zone models
- The cooling load is considerably lower than the 3-zone approach
- The interior lighting load is much lower than that shown by the 3-zone approach: the core zone is critical.

Results in Table 16 illustrate the benefit of daylighting in 1-zone and 2-zone models. These models therefore had a lower percentage of lighting energy use compared to the 3-zone model.

In general, the EUI of all modelling categories were similar. However, it is clear that the percentage of energy distribution changes considerably in multi-zone simulations; especially when a core zone is modelled (i.e. heating & lighting requirements).

Overestimated/underestimated predictions could potentially mislead the designer from day one. The option to simulate multiple zones needs to be incorporated into COMFEN and other similar tools in order performance sketch predictions to be more relevant during the early design stage.

4.3.3 A Consistency Test for the Study of Adding Complexity to the Performance Sketch Tool

The analysis examines single-zone and multi-zone models with natural ventilation incorporated. The results illustrate the consistency of sketch design advice/feedback between single-zone and multi-zone models.

The following are the fenestration designs examined in this test (see Figure 34):

- **A.** Double clear Low-E glazing with exterior venetian blinds at 45° (permanently fixed)
- **B.** Double clear Low-E glazing with between venetian blinds at 45° (permanently fixed)

The façade design with the lowest EUI (kWh/m^2.yr) is ranked 1st. Consistency is achieved if single-zone and multi-zone predictions of energy performance generate the same design advice/feedback (i.e. the façade ranking and the distribution of energy end-uses is similar).

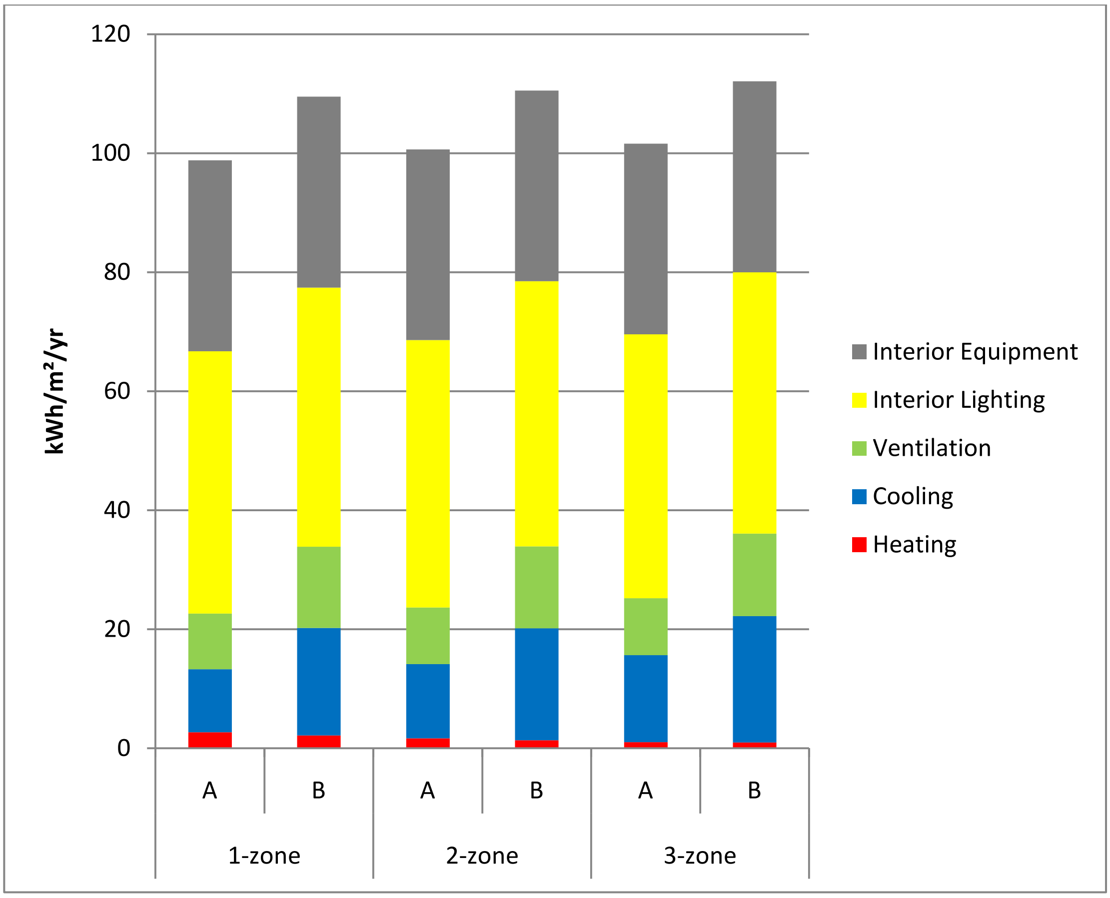

Figure 41 – Consistency test: Mixed Mode models with daylight control

The following table illustrates façade ranking and energy consumption (EUI percentages) of the fenestration designs tested in the Wellington:

Simulation Category	1-zone		2-zone		3-zone	
Façade Code	**A**	**B**	**A**	**B**	**A**	**B**
Heating	2.7 (3%)	2.2 (2%)	1.7 (2%)	1.4 (1%)	1.0 (1%)	1.0 (1%)
Cooling	11 (11%)	18 (16%)	12 (12%)	19 (17%)	15 (14%)	21 (19%)
Ventilation	9 (9%)	14 (12%)	10 (9%)	14 (12%)	10 (9%)	14 (12%)
Interior Lighting	44 (45%)	44 (40%)	45 (45%)	45 (40%)	44 (44%)	44 (39%)
Interior Equipment	32 (32%)	32 (29%)	32 (32%)	32 (29%)	32 (32%)	32 (29%)
Total EUI (kWh/m^2.yr) & EUI%	99 (100%)	109 (100%)	101 (100%)	111 (100%)	102 (100%)	112 (100%)
Ranking	1	2	1	2	1	2
% Difference	-	11%	-	10%	-	10%

Table 17 – Consistency test: Mixed Mode models with daylight control

The results in Figure 41 & Table 17 show that the façade rankings (letter orders) are consistent throughout the categories of modelling method (i.e. ranked 1st = Double clear Low-E with exterior venetian blinds & ranked 2nd = Double clear Low-E with between venetian blinds).

Results in Table 17 illustrates that the 1-zone Performance Sketch can produce fenestration ideas consistent with those from multi-zone models. However, some design lessons derived from the 1-zone model are different. These are:

- much higher 1-zone heating load than 2-zone & 3-zone models
- 1-zone cooling load lower than the 3-zone model

Ventilation, interior equipment and lighting loads are similar across the modelling categories.

In this test the Interior Lighting percentages were really similar across all simulation categories; fenestration designs had a huge influence on the distribution of energy end-uses (i.e. effect of permanently fixed venetian blinds).

Overall, results illustrate that a one zone model can produce a similar Total EUI as multi-zone sketches. However, similar to other performance sketch tests in this research the multi-zone models produced a different design message when the focus is on the distribution of load predictions. The differences might be small in this test, but as the scale of a model increases, there is a possibility that the differences could be immense; this suggests the importance of modelling multiple zones during performance sketch analyses.

5 Practitioner-based Performance Sketch Tool Specifications

The use-cases suggested a user desire for increased modelling complexity in future versions of a performance sketch tool. The study of the influence of the complexity of the performance sketch tool model, suggested there is a need for that complexity if the energy performance is to relate to full scale. At their simplest, actions resulting from these recommended actions would make more technological functions of EnergyPlus available in COMFEN simulation. If the detail of the sketch tool is increased users will be able to simulate more complex façade designs and derive extra relevant predictions to utilise in the detailed design.

The Performance sketch concept requires a simplified model of a building - a (performance) sketch. However, the exploration of the single-zone COMFEN model as an example of a performance sketch tool suggests the single-zone approach is inadequate. Possibly, it can be a misleading sketch of the thermal performance of a whole building.

The use-cases suggest that despite understanding the performance sketch concept the practitioners still desired a more detailed sketch. This raises a serious question as to whether any simple approach to evaluating the essential features of a building could be used in association with a detailed thermal model.

The outcome of the use-case analyses determined three areas of design feature in COMFEN that users suggested required improvement in future versions. As a summary of this, a diagram of decision-making for performance sketch analysis was also established. The final sections of this chapter describe in turn each of these individual areas within the performance sketch tool specifications:

1. **Freedom of Aesthetics** – ability to sketch (basic) desired building geometry
2. **Sustainable Designs** – relevant/plausible early design messages/predictions
3. **Delivering the Design** – good interface graphical visualisation for client presentations
4. **Diagram of Decision-making** – guideline for performance sketch analysis

The specifications are based on the desired COMFEN features suggested in the use-case studies. These specifications can help the development of future versions of performance sketch tools; and assist users during the early stages of design.

5.1 Freedom of Aesthetics

The use-cases suggest that it is vital for users of the performance sketch tool to have the ability to express (sketch) their desired building geometry. The following specifications are related to freedom of aesthetics in early design tools.

Ability to sketch any desired building geometry:

- The designer should be able to express their ideas without restrictions during the sketch design phase.

Visualisation of the sketched design within the interface:

- The sketched building geometry should be realistic, visual elements such as glass colour, solar shading devices, and surface materiality are important to the user.

Ability to apply/select construction materials:

- A performance sketch tool should allow the user to pick construction material for each building surface in the sketched geometry (i.e. walls/ceiling/floor/roof).

Capability of importing complex architectural geometry:

- The performance sketch tool should allow the user to sketch complex shapes in software such as Revit and ArchiCAD/AutoCAD, and then import the file into COMFEN for performance analysis.

Ability to export COMFEN models:

- The performance sketch tool should allow the user to export the sketched design to other common detailed design tools (e.g. EnergyPlus – compatible file format).

5.2 Sustainable Designs

Practitioners suggested that it is vital for an early design tool to have the capability of examining a wider range of design scenarios than COMFEN can currently analyse. This they recognised is at variance with the fundamentals of the performance sketch concept. Ultimately, this new approach to modelling would add huge complexity to a performance sketch tool.

The following specifications are related to analysis options required by COMFEN users in early design tools:

Cost analysis:

- A performance sketch tool should allow the user to plot in cost of energy (e.g. $/kWh)

Design options:

- Natural ventilation, double façade and atrium options should be available in a tool for more sustainable building designs.

Shading devices:

- Freedom of geometry in designing of custom shading devices.

External shading:

- A performance sketch tool should allow the user to simulate the proposed design in context, with neighbouring buildings and trees etc.

HVAC systems:

- Option to select the type of HVAC system and (at least) set seasonal efficiency for summer & winter.

Multi-zone simulations:

- A performance sketch tool should allow the user to understand the effects of air and heat movement between perimeter and core zones in the building design. And, it should have the ability to simulate floor sections within a building design (i.e. top, middle & bottom floors).
- In Figure 42, illustrates the option of a 'Generic Core Zone', where the user can plot in mechanical load values per metre square (W/m^2) for the electricity consumption (i.e. HVAC, lighting & interior equipment etc). Essentially, with the additional core zone plus four perimeter zones, energy performance of a whole (multi-zone) floor/building could be examined in COMFEN (i.e. stated in the use-cases).

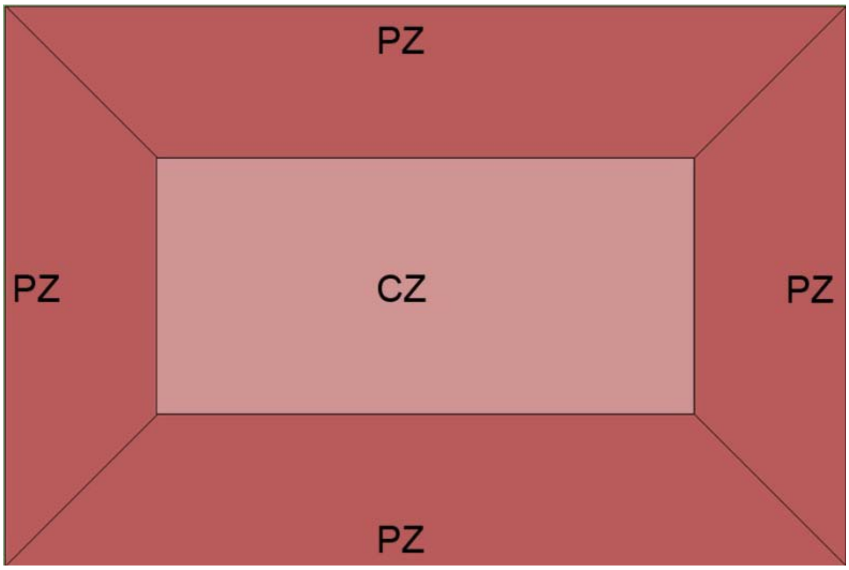

Figure 42 – COMFEN perimeter zones with an additional generic core zone

CZ = Core Zone & PZ = Perimeter Zone

Modelling environment:

- A performance sketch tool should allow the user to examine the proposed design in context with surrounding buildings and trees (present) in the simulation model; this will truly show the effects of the surrounding elements on the proposed design's performance.

5.3 Delivering the Design

The use-case results suggest that communication with the client is paramount in order for the project to progress smoothly. The following specifications are related to visualisation (for the client in particular) of predictions within early design tools.

Visualisation of design:

- A performance sketch tool should allow the user to explore the building design (i.e. orbit around the 3D model).
- A performance sketch tool should allow the user to clearly present the proposed design to the client, aesthetically.
- The proposed design should be supported by easy to understand graphical information relating to overall performance (i.e. tables & figures).

5.4 Diagram of Decision-making for Performance Sketch Analysis

The following is an expanded version of Kalay's diagram (Figure 15) of workflow and subtasks in performance-based design. The original diagram has been modified to incorporate performance sketch tools. It should be noted that this diagram identifies two parts of the overall design process where the performance sketch tool might be applied: i) conventionally – during sketch design; and ii) during detailed design when some design option that could be sketched can be studied rapidly through the sketch.

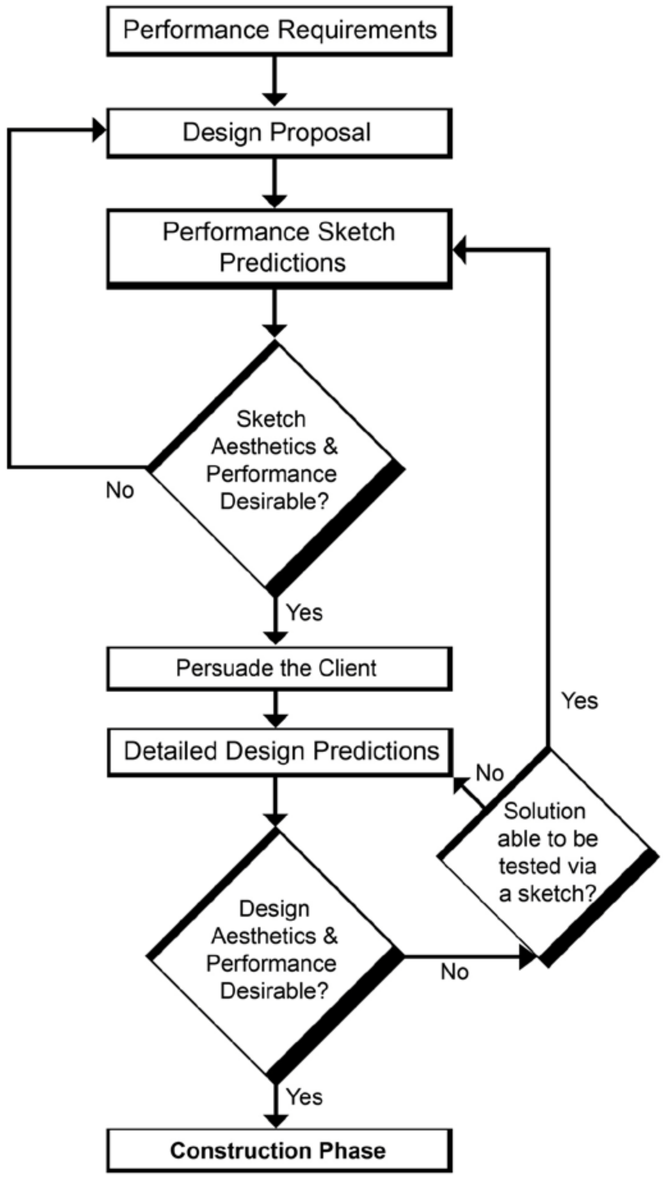

Figure 43 – Diagram of decision-making for performance sketch analysis

This diagram reflects the way in which architects and engineers perform performance sketch analysis. It is intended that it guide tool developers in production of new (performance sketch) analytical tools. It provides a framework in which detailed design tools like Energy Plus and OpenStudio can be planned and developed in a parallel manner.

6 CONCLUSIONS

The following returns to the research questions stated in the aim & objectives section of Chapter 1:

1. **What are practitioners' needs from a performance sketch tool?**

   Specifications in Chapter 5 illustrate the ideal model of a performance sketch early design tool.

2. **How relevant is the information predicted by a performance sketch tool?**

   The use-cases suggest that COMFEN predictions are valuable. However, the capability of only sketching orthogonal-shaped designs and not being able to model the gamut of sustainable design ideas (e.g. atrium design & natural ventilation etc) is a big restriction for practitioners (i.e. less relevant to complex designs).

3. **Performance Sketch Early Design Tool – how simple is too simple?**

   Currently, based on the use-cases single-zone is said to be efficient (quick) and easy to understand. However, many have suggested that there is a need to increase the complexity in geometry modelling (i.e. freedom to sketch anything).

4. **How close is close enough?**

   The single-zone sketch has the tendency to over emphasise (distort) distribution of energy load predictions when compared to multi-zone results derived from EnergyPlus.

The use-case studies in this research established the definition of an ideal Performance Sketch early design (simulation) tool. Despite understanding the intention of the performance sketch concept, architects and engineers still desire that extra precision in the COMFEN modelling interface. The use-cases suggested that in order the sketch design advice/feedback to be more relevant, the designer must have the freedom to sketch/evaluate design elements such as building geometry, HVAC system, building schedules, lighting loads and occupancy.

COMFEN and EnergyPlus fenestration design ranking comparison determined the consistency between sketch predictions and detailed calculations. In summary, the tests in this research indicate that it is inadequate to solely focus on the fenestration design when examining the energy performance of a whole building, accurately (i.e. multiple zones have to be assessed during the early design stage). The calculation method of one zone and one façade has demonstrated that it cannot produce plausible distribution of energy load predictions; this imprecise design message could mislead the designer from day one.

The Performance Sketch Specifications can help improve future simulation tools' usability and capability by applying suggestions stated in the interview use-cases; also assist designers performing sketch analyses.

Practitioners rely on early design tools to forecast the energy performance of a proposed design. It is crucial to get the basic fundamentals right from day one of the project, because problems that occur later on could be costly to the client and design team.

COMFEN could evolve (develop) into a software that sketches 'multi-zone buildings' from the early design stage. Also, the possibility of having natural ventilation calculations in COMFEN, by having (blank) boxes for users to enter (the desired) input values; basic (natural ventilation) equation that links with the modelled geometry. Therefore, architects and engineers can take these sketch (multi-zone) predictions into the detailed design stage for further development.

In conclusion, it is clear that the performance sketch tool requires further improvements (i.e. plausible distribution of energy end-uses). And experience is required in order to examine real building designs with COMFEN and EnergyPlus. However, COMFEN can certainly develop into a powerful performance sketch tool in the future because of its compatibility with the EnergyPlus simulation engine.

FUTURE WORK

The outcome of this thesis suggests that the following research questions require further testing and investigation:

- Test a wide range of climate zones within COMFEN to see whether inconsistent design advice/feedback only occurs in the climate zones demonstrated in this research; with detailed examination of the distribution of energy end-uses.

- Design features such as double façade and natural ventilation being incorporated into upcoming versions of COMFEN.

- Development of a performance sketch early design tool that is capable of testing 'Non-linear' shaped building designs (i.e. increase complexity in geometry modelling).

COMFEN has the potential to be a power simulation tool for early design analyses; in the course of further development, COMFEN could be a very efficient way to sketch/evaluate the energy performance of numerous commercial buildings in New Zealand.

BRANZ's Building Energy End-use Study (BEES) will produce reliable data on building schedules, material properties, equipment loads, and occupancy. For the first time anywhere it will be possible to simulate/test a building based upon the median/mean, standard deviation; or some percentile expression of the real measured data of New Zealand commercial buildings.

The BEES data is important for the Performance Sketch because it offers the opportunity to critique the performance sketch concept with real buildings/data; this will help improve software usability and capability.

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APPENDICES

APPENDIX A – Selection of Practitioners: Information Sheet

Project Title – Commercial Building Façade Design: Improving the Consistency of Early Design Tool Predictions and Detailed Design Tool Calculations

To whom it may concern,

I am a student from The School of Architecture at Victoria University of Wellington, planning to work with practitioners to determine their simulation needs during the early stages of design. These are use-cases, which are interview feedback from users of COMFEN (building energy simulation program). The use-cases will play a huge role in terms of improvements to early design tools like COMFEN. The feedback is based on the introduction of COMFEN to practitioners, so they will determine their needs based on past/current project experiences by stating the essential information they need for the early and detailed stages of design. These improvements will make the early design tool more user-friendly. The aim of this research project is to improve the consistency between early design tools and detailed design tools and to develop a list of façade design specifications (template models) for early design tools that are based on feedback from interviews with practitioners (use-cases).

Improvements in early design tool simulations has the potential to save money and time during the early design stage. The capability to simulate multiple façade designs quickly and accurately will benefit clients and practitioners in the New Zealand building industry. It will provide architects and engineers with trust, confidence and reliable design messages that can be carried out into the detailed design stage.

Your approval is required to undertake this research project. I am interviewing practitioners like yourself from various firms. You will answer a series of questions. Notes will be taken during the interviews and also a voice recording. The introduction of COMFEN and interview will take approximately 40 minutes (single visit).

Should any participants feel the need to withdraw from the project, they may do so without question at any time before the data is analysed. Email or call me if that's the case.

The gathered information and voice recordings will remain confidential and deleted at the completion of the report (it will not be possible for you to be identified personally in the report). No other person besides myself and my supervisor, Michael Donn, will see the raw interview feedback.

A copy of the final report can be provided to you, if you wish.

Yours sincerely,
Henry Hsu

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APPENDIX B – Selection of Practitioners: Consent Form

Victoria University of Wellington
Consent to Participation in Research

Project Title – Commercial Building Façade Design: improving the relevance of early design tools to detailed design tools

Please tick:

- ☐ I agree to take part in this research
- ☐ I consent to information or opinions which I have given being quoted anonymously in any reports on this research
- ☐ I would like the tape recordings of my interview returned to me at the conclusion of the project
- ☐ I understand that I will have an opportunity to check the transcripts of the interview before publication
- ☐ I understand that the data I provide will not be used for any other purpose or released to others without my written consent
- ☐ I would like to receive a summary of the results of this research when it is completed
- ☐ To receive a copy of the report

Name of participant (please print clearly)...

Signature... **Date**...

APPENDIX C – Practitioner A: Initial Interview Feedback

9th July 2010

COMFEN Advantages:

- COMFEN Narrow down façade options quickly, so practitioners can move on to the next design phase.

Desired features in future versions of COMFEN:

- The design options costed
- Double skin façade option needed
- Need for natural ventilation simulations
- Adjust natural ventilation openings
- External shading, neighbouring buildings and trees etc needed
- Ability to have angled fins and shades
- The option to plot in values
- Able to change pump and fan values, W/m^2 etc
- Fan energy, it's detailed for a simple tool
- Visual drawing of the fins and shading devices, glazing on the section and plan views etc, realistic image to convince the people view the results and design
- Visual feedback, shading device needs to be visible on the interface
- Peak heating and cooling for summer and winter (seasonal efficiency)

Comments which challenge the idea of a Performance sketch tool:

- HVAC, what type is it in detailed, more description and info
- Simulate what you want, reduce limitation of COMFEN
- Variables in the HVAC system (various systems to choose from)

APPENDIX C.1 – Practitioner A: Analysis of Initial Interview Feedback

Occupation: Architect & Engineer

Summary of COMFEN Advantages:

- COMFEN narrow down façade options quickly, so practitioners can move on to the next design phase.

Summary of Conclusions:

- Desire of cost analysis in the interface.
- Desire of natural ventilation, double façade and atrium design option.
- Desire of more complex HVAC systems available in COMFEN. Currently, the program lacks precision from the HVAC system perspective.
- Option of simulating external shading, neighbouring buildings and trees.
- Realistic image of shading devices and fins shown on the sketched scenarios for aesthetics visualisation.
- Simulate what you want in terms of geometry, reduce limitations in COMFEN.

Analysis of Conclusions:

- A complex (HVAC) model will take more time for the simulation engine to calculate façade designs. Also, it will create difficulty on learning/understanding how the software works (i.e. time consuming), which ultimately challenges the performance sketch idea. However, the question is (if possible): just how helpful would this extra precision in the modelling procedure be to the early design stage?
- For example, if a curved façade is graphically represented differently on the interface (i.e. with multiple straight lines), is that a big problem in terms of the aesthetics? Or as a practitioner, it is absolutely vital for the digital model to look realistic? Regardless if the simplified shape represents the equivalent idea of the actual design.

APPENDIX C.2 – Practitioner A: 2nd Round of Feedback

I definitely think that if it is to be a successful tool for early façade analysis there shouldn't be much limitation on façade options in which to compare. So all types of glazing, external shading, double façade options should be available. Agree that HVAC system type isn't as important for just façade performance analysis.

I don't think that cost analysis of options needs to be included. My revised comments are as follows:

Design conditions

- Need to have control over design room heating and cooling temperatures and not rely on COMFEN defaults
- Need to have control over design ambient temperatures for peak heating and cooling load calc
- Should be able to use NIWA weather files for NZ site locations for energy calc

Glazing

- Allow simple definition as Window to Wall Ratio (WWR), G-value, Overall U-value (including frame effect)

Wall

- Allow option to define as simple R-value

External shading

At a minimum external shading should capture the following:

- Fixed vertical elements
- Fixed horizontal elements
- Movable shading - open or closed based on incident solar radiation
- Should be able to see in 3D model and orbit around

It also would be good to be able to "draw in" shading elements rather than just define dimensions.

Internal blinds

- Define by shading coefficient
- Control operation based on incident solar radiation

Internal gains

- Need to have control over inputs and operational profiles and not just rely on COMFEN defaults

HVAC

Don't think the actual HVAC system type is required to compare façade options but in order to benchmark annual energy use it is important to be able to input both:

- Heating system seasonal efficiency e.g. boiler = 0.95, heat pump = 3.0
- Cooling system seasonal efficiency e.g. chiller = 5.0

Otherwise if they are both assumed to have an efficiency of 1.0 it can change the comparative performance between options and resulting hierarchy of façade performance.

Would then be good to have the option to model an HVAC system in slightly more detail by including:

- Outdoor air rate lit/s per m^2
- Annual pump and fan energy kWh/m^2
- Heat recovery effectiveness % (may require additional inputs to define)
- Economiser cycle (may require additional inputs to define)

That is a simple way to capture different HVAC systems and in terms of calculation shouldn't be too complex

Ventilation

- As above don't think necessary to include outdoor air rate for just façade performance comparisons
- Need to include natural ventilation option - define as free net open-able area (m^2), operation profile based on internal temperature and wind speed at a minimum
- Mixed mode ventilation option should also be available

If I were to design a tool it would also have these additional features:

- Produce easy to read printout of all model inputs (or notional inputs selected by the user)
- Calculate frequency of thermal comfort range (PMV) during occupied hours
- Automatically compare to NZBC (NZS4243) reference model performance for site location
- Convert peak heating and cooling loads to W/m^2 format and show on the same chart
- Automatically combine annual heating and cooling energy and convert to kWh/m^2 per year format
- Automatically produce charts comparing multiple façade options. Also allow output in table format to bring into MS Excel
- Automatically include façade summary description of each option on chart e.g. WWR, glazing U-value, glazing G-value, shading description
- Automatically include a small image of each façade option on charts as well

APPENDIX C.3 – Practitioner A: Analysis of 2nd Round of Feedback

Judging by the feedback of Practitioner A, it is very clear that the performance sketch tool needs to increase its complexity. However, compromises can be made through incorporating the essentials stated in the 2nd round of feedback without losing the sketch characteristic of COMFEN (i.e. features noted in the summary of conclusions).

The question asked after the 1st round of feedback was: just how helpful would this extra precision in the (HVAC) modelling process be to the early design stage? The question was asked because it challenged the idea of performance sketch. Practitioner A has pointed out the importance of the option for HVAC seasonal efficiency, because without it (i.e. current version of COMFEN) the default settings could cause hierarchy in the façade performance predictions. Therefore, this feature is essential for future versions of COMFEN (i.e. more input options for HVAC modelling). In this case, longer calculation time with increase of HVAC complexity is preferred over the speed provided by general default settings. Hindsight, it might take the user longer to learn/understand how the software works.

Another question asked after the initial feedback was: it is absolutely vital for the model to look realistic? Practitioner A emphasised in the 2nd round of feedback that various design options should be available in the software (e.g. double façade & natural ventilation). Visualisation of the designs in the interface is vital. The user should not be restricted to only modelling orthogonal shaped designs. Essentially, allow the user to freely sketch the desired building geometry or the equivalent shape. Restrictions of sketching should be avoided during design stage because it will result in aesthetics limitation.

In summary, Practitioner A agreed (settled) with most of the conclusions stated in the initial feedback in relation to HVAC complexity and freedom of sketching; whereas, the costing option was later said to be unnecessary. The feedback pointed out the significance of the need to simulate the desired building shape and its mechanical system (i.e. more relevant predictions). Also, the relationship between visual presentation and simulation results is paramount in order the user to understand the predicted data.

APPENDIX D – Practitioner B: Initial Interview Feedback

3rd August 2010

COMFEN Advantages:

- It is very good to have the ability to compare multiple façade designs at once that are supported by graphical results.

Desired features in future versions of COMFEN:

- Costing and material analysis
- Natural ventilation needed
- Shading device modelling (its effects). Modelling of complex shapes (curved), analysis of its transmission level and solar gain, thermal mass
- Double façade and atrium design option
- Lux level on the ceiling, light bouncing off the shading device, opportunity to use the combination of electric lighting and natural lighting
- colour of glass shown on the sketched scenario

Comments which challenge the idea of a Performance sketch tool:

- Option to alter the interior wall/ceiling/floor material and colour
- Ability to import Revit (or other drawing software) complex geometries into COMFEN (at the moment it lacks of precision from the modelling perspective)
- Limited in terms of shape capable of modelling
- Need to analyse the air movement, heat movement between perimeter zones and core zone, because it may be a different result once the core zone is incorporated in detailed design, which is too late. Therefore need multi-zone simulation during early design stage.
- It's just a comparative tool at the moment, will move on quickly from here, we need to know what the full building would behave like earlier on

APPENDIX D.1 – Practitioner B: Analysis of Initial Interview Feedback

Occupation: Architect

Summary of COMFEN Advantages:

- It is very good to have the ability to compare multiple façade designs at once that are supported by graphical results.

Summary of Conclusions:

- Desire of cost analysis in the interface.
- Desire of natural ventilation, double façade and atrium design option.
- Desire of importing complex architectural geometry into COMFEN (e.g. curved shading devices drawn in Revit or other drawing software). COMFEN currently lacks precision from the modelling perspective.
- Colour of glass should be shown on the sketched scenario for aesthetics visualisation.
- The need to have multi-zone simulations because the air/heat movement between the perimeter zones and core zones could influence the design predictions dramatically. Therefore we need to know how the ‘full building’ would behave like.

Analysis of Conclusions:

- A complex (Revit) model will take more time for the simulation engine to calculate façade designs. Also, it will create difficulty on learning/understanding how the software works, which ultimately challenges the performance sketch idea. However, just how helpful would this extra precision in geometry modelling be to the early design stage?
- So if a curved shading device is graphically represented differently on the interface (i.e. with straight lines instead), is that a big problem in terms of visualisation? Is it enough to have simplified shapes that represent the equivalent design idea? Or as practitioner, it is absolutely vital for the shading device to look realistic within a digital model?

No further feedback was given by Practitioner B, therefore initial feedback remains as their final statement on COMFEN as a performance sketch tool.

APPENDIX E – Practitioner C: Initial Interview Feedback

25th June 2010

COMFEN Advantages:

- It is great that COMFEN (early design tool) is compatible with EnergyPlus.
- Also, the plugin with Google SketchUp makes sketch design user-friendly. The COMFEN program seems user-friendly which is a plus.
- The information generated by COMFEN is enough and useful from an early design perspective. CO2 analysis very useful during early design stage.
- COMFEN and EnergyPlus can be used at the same time to determine the desired/optimum glazing type and building geometry.

Desired features in future versions of COMFEN:

- Double façade and atrium design option
- Adding costs to the program is a good idea

Comments which challenge the idea of a Performance sketch tool:

- to have full building simulation during early design stage (multi-zone simulation in COMFEN not available).
- be more complex, desire of doing simple “full” building simulations in COMFEN. Because COMFEN at the moment seems just like a program that determines the façade design (that’s what it is for), however, it is not all about glazing/façade type because the core zone(s) of the building design will affect the overall energy consumption, as well as atrium spaces.

APPENDIX E.1 – Practitioner C: Analysis of Initial Interview Feedback

Occupation: Architect & Engineer

Summary of COMFEN Advantages:

- Compatible with EnergyPlus.
- Opentstudio Plug-in with Google SketchUp makes sketch design user-friendly.
- COMFEN predictions is enough and useful from an early design perspective.
- CO2 analysis very useful.
- COMFEN and EnergyPlus can be used at the same time to determine the desired/optimum glazing type and building geometry.

Summary of Conclusions:

- Desire of cost analysis in the interface.
- Desire of double façade and atrium design option.
- Desire of doing simple "full" building simulations in COMFEN.

Analysis of Conclusions:

- A complex (multi-zone) model will take more time for the simulation engine to calculate façade designs. Also, it will create difficulty on learning/understanding how the software works, which ultimately challenges the performance sketch idea. However, just how helpful would this extra precision in 'building zoning' be to the early design analysis?

No further feedback was given by Practitioner C, therefore initial feedback remains as their final statement on COMFEN as a performance sketch tool.

APPENDIX F – Practitioner D: Initial Interview Feedback

6th September 2010

COMFEN Advantages:

- Speed of simulation is fast, quick analysis
- ASHRAE PoE comfort calculation good for Green Star PoE assessment. Also, the daylight tab is good information. Good for early design stage decision making.
- COMFEN provides enough info from an early design stage perspective. Good balance.

Desired features in future versions of COMFEN:

- Need natural ventilation option (multi-zone when have NV), define openable windows. Dynamic model, mechanical windows that adjust according to the temperature and weather.
- HVAC type, its parameters, more info on exactly what the HVAC package is.
- Ability to define set points temperature etc winter summer
- Need more geometry freedom for aesthetics purposes
- Import geometry from different drawing software
- Export COMFEN model into common detailed design tool that are used by firms in the world, file format that is compatible.
- Architects like to have a realistic image of the design – freedom of sketching and displayed on the interface. Sections and elevations. Ability to alter the façade, angles and aesthetic pleasing shapes.

Comments which challenge the idea of a Performance sketch tool:

N/A

APPENDIX F.1 – Practitioner D: Analysis of Initial Interview Feedback

Occupation: Engineer

Summary of COMFEN Advantages:

- Speed of simulation
- ASHRAE Post Occupancy Evaluation (POE) comfort calculation is good for Green Star POE assessments.
- Daylight predictions are good for early design stage decision making.
- COMFEN provides enough information from an early design stage perspective (i.e. good balance).

Summary of Conclusions:

- Need natural ventilation option (multi-zone when have NV), define open-able windows. Dynamic model, mechanical windows that adjust according to the temperature and weather.
- HVAC type, its parameters, more info on exactly what the HVAC package is.
- Ability to define set points temperature etc winter summer
- Need more geometry freedom for aesthetics purposes
- Import geometry from different drawing software
- Export COMFEN model into common DDT that are used by firms in the world, file format that is compatible.
- Architects like to have a realistic image of the design – freedom of sketching and displayed on the interface. Sections and elevations. Ability to alter the façade, angles and aesthetic pleasing shapes.

Analysis of Conclusions:

- Practitioner D stated that COMFEN is a good simulation tool overall for the sketch design phase. However, there were several design options that need to be incorporated into future versions of COMFEN in order to meet the desires (seen in summary of conclusions). Freedom of sketch and realistic visualisation are vital design aspects for Practitioner D; this suggests there is a need for improvements in these areas.

Practitioner D had no further feedback, therefore initial feedback remains as their final statement on COMFEN as a performance sketch tool.

APPENDIX G – Practitioner E: Initial Interview Feedback

2nd June 2010

COMFEN Advantages:

If design is more complex then COMFEN is good tool for sketch design, non symmetrical windows etc.

COMFEN is a good tool for communicating with the client, seal the deal with client with its graphical interface.

If cost too high, but still needs to meet the client's requirement, therefore minor changes will be done on the façade design, this is where COMFEN can come in handy/useful.

More useful/suitable for material/window manufacture

Desired features in future versions of COMFEN:

- Double façade and atrium design option
- Need Life Cycle Cost calculation in COMFEN (more detail), way to convince client (the proposed design) with the interface, LCC graphs, design benefits etc.
- Cost estimation, annual cost estimation, benefits to client, payback cost/time
- Façade material (need to have the option to change - the opaque areas)
- Cost of materials etc, thermal performance, its life expectancy (blank box to fill in value)

Comments which challenge the idea of a Performance sketch tool:

- It's useful (COMFEN) for architects but it's not really part of my job. I will recommend various designs, but the performance analysis is for engineers/manufactures.

APPENDIX G.1 – Practitioner E: Analysis of Initial Interview Feedback

Occupation: Architect

Summary of COMFEN Advantages:

- A good tool for sketch design (e.g. non-symmetrical windows on building façade).
- COMFEN is a good for communicating with the client, with its graphical interface.
- If cost too high, but still needs to meet the client's requirement, this is where COMFEN can come in handy/useful.
- More useful/suitable for window manufacture

Summary of Conclusions:

- Desire of Life Cycle Cost analysis in the interface.
- Desire of double façade and atrium design option.
- COMFEN is useful for architects, but it's not really part of my job.

Analysis of Conclusions:

- Practitioner E suggests that COMFEN is a useful tool for what it is, but its current functionality is more relevant to window manufactures rather than architects.
- For example, if it was possible to simulate 'anything you want' but the graphics of these design choices are not displayed exactly in COMFEN (i.e. simplified geometry of the actual design), is that a big problem in terms of the aesthetics? Or as practitioners, it is absolutely vital for the model to look realistic? Regardless the simplified shape which represents the equivalent idea of the actual design. Also, would it be more 'part of your job' if the program expands its design capability?

No further feedback was given by Practitioner E, therefore initial feedback remains as their final statement on COMFEN as a performance sketch tool.

APPENDIX H – Practitioner F: Initial Interview Feedback

16/09/2008 (recorded USA interview)

COMFEN Advantages:

Good comparison options, ability to compare four designs/scenarios at once (neat).

Interface – how façade designs link to graphs and simulation output data: very important for architects, understanding the data and good graphic presentation.

Desired features in future versions of COMFEN:

- Current design opinions – limitation of aesthetics? (Modelling parameters)
- Aesthetic pleasing & sustainable designs that look good and perform well
- Sell the idea to the client by indicating the benefits of their investment, short term & long term (design punch line).
- Glass fins, rotating shading devices, double façade option
- Solar gain and heat gain analyses
- Selection of glass colour (aesthetic visualisation of design)
- Selection of building standards (design requirements)
- Shading and sun path study

Comments which challenge the idea of a Performance sketch tool:

- Why is one zone enough?

APPENDIX H.1 – Practitioner F: Analysis of Initial Interview Feedback

Occupation: Architect

Summary of COMFEN Advantages:

- Ability to compare four designs/scenarios at once
- Graphical information

Summary of Conclusions:

- Ability to sketch freely
- Glass fins, rotating shading devices, double façade option
- Solar gain and heat gain analyses
- Selection of glass colour (aesthetic visualisation of design)
- Selection of building standards (design requirements)
- Shading and sun path study

Analysis of Conclusions:

- Practitioner F suggests that COMFEN is a neat tool. However, raised a question: why is one zone enough? The 1-zone method is specifically for analyses of façade performance; focusing on types of glazing & shading device.
- Freedom of sketch and visualisation are vital aspects for the interface; this suggests there is a need for improvements in these areas.

APPENDIX I – Façade Constructions & Material Properties

Each fenestration option was constructed by a list of building materials and the chosen shading device. The following fenestration options were used in the consistency test of COMFEN 3.0, where the layers of construction go from outer layer to inner layer in each list:

(A) Double clear Low-E glazing with exterior venetian blinds at 45°

- Exterior shading device = horizontal metal venetian blinds, permanently fixed at 45 degrees (1mm thick)
- Outer layer = 3.175mm Low-E glazing
- Air gap = 12.7mm (argon & air)
- Inner layer = 5.715mm Low-E glazing

(B) Double clear Low-E glazing with between venetian blinds at 45°

- Outer layer = 3.175mm Low-E glazing
- Air gap = 6.4mm (argon & air)
- Between shading device = horizontal metal venetian blinds, permanently fixed at 45 degrees (1mm thick)
- Air gap = 6.4mm (argon & air)
- Inner layer = 5.715mm Low-E glazing

(C) Double clear Low-E glazing with interior venetian blinds at 45°

- Outer layer = 3.175mm Low-E glazing
- Air gap = 12.7mm (argon & air)
- Inner layer = 5.715mm Low-E glazing
- Interior shading device = horizontal metal venetian blinds, permanently fixed at 45 degrees (1mm thick)

(D) Single clear glazing

- Outer layer = 5.664mm clear glazing
- Air gap = none
- Inner layer = none
- Shading device = none

APPENDIX J – Simulation Location: Wellington, New Zealand

(Mixed, marine climate zone)

Façade Code: A	North	South	East	West	Average
Heating	0.7	1.1	0.9	0.9	0.9
Cooling	17	15	16	16	16
Ventilation	9	8	8	9	9
Interior Lighting	44	48	45	45	45
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	102	104	103	104	103

J. 1 – COMFEN Double clear Low-E exterior VB 45 simulated in Wellington

Façade Code: B	North	South	East	West	Average
Heating	0.6	1.4	0.9	0.9	1.0
Cooling	28	16	26	28	25
Ventilation	17	9	17	23	16
Interior Lighting	43	48	45	44	45
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	120	106	121	128	119

J. 2 – COMFEN Double clear Low-E between VB 45 simulated in Wellington

Façade Code: C	North	South	East	West	Average
Heating	0.4	0.8	0.6	0.7	0.6
Cooling	40	22	37	41	35
Ventilation	22	10	24	33	22
Interior Lighting	42	47	44	43	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	137	112	138	150	134

J. 3 – COMFEN Double clear Low-E interior VB 45 simulated in Wellington

Façade Code: D	North	South	East	West	Average
Heating	8	15	8	8	9.4
Cooling	49	10	40	45	36
Ventilation	40	11	43	61	39
Interior Lighting	22	24	23	23	23
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	150	92	147	169	139

J. 4 – COMFEN Single clear simulated in Wellington

APPENDIX J.1 – Simulation Location: Wellington, New Zealand

The following table shows the energy performance ranking and energy distribution of each fenestration design in the Wellington climate zone:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	A	B	C	D	A	B	D	C
Heating	0.9	1.0	0.6	9.4	17	15	11	19	1	1	2	1
Cooling	16	25	35	36	2	6	14	20	21	24	27	29
Ventilation	9	16	22	39	5	11	17	31	8	10	18	13
Interior Lighting	45	45	44	23	46	46	45	37	48	48	43	48
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	103	119	134	139	100	109	118	138	108	113	119	120
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
%Difference	-	15%	13%	4%	-	8%	9%	16%	-	5%	6%	1%

J. 1. 1 – Annual energy distribution of designs simulated in Wellington

The percentage difference illustrates the amount of energy consumed more by the lower ranked fenestration design. In other words, 15% represents that the lower ranked design (e.g. 2nd) uses 15% more energy (annually) compared to the higher ranked design (e.g. 1st).

The COMFEN results show that there is a 15% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 13% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is very close at 4% (Double clear Low-E with interior venetian blinds vs. Single Clear).

The EnergyPus results of the small office show that there is an 8% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 9% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 16% (Double clear Low-E with interior venetian blinds vs. Single Clear).

The EnergyPus results of the large office show that there is a 5% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). There is a 6% difference between the 2nd (B) and 3rd (D) options (Double clear Low-E with between venetian blinds vs. Single clear). The difference between the 3rd (D) and 4th (C) options is 1% (Single clear vs. Double clear Low-E with interior venetian blinds).

COMFEN predictions were consistent across all scenarios in the small office category; the performance advice/feedback was the same. Slight inconsistency occurred when option D was ranked in front of option C in the large office category; COMFEN did not produce the same (consistent) design advice/feedback as the large (multi-zone) office. The table illustrates that COMFEN tends to exaggerate distribution of energy end-uses compared to some multi-zone scenarios (e.g. higher cooling requirements).

The following shows the energy end-use ranking within each COMFEN fenestration design in the Wellington climate zone:

1st Fenestration A: interior lighting was the dominant end-use, followed by cooling, interior equipment, ventilation and heating.

2nd Fenestration B: interior lighting was the dominant end-use, followed by cooling, ventilation, interior equipment, and heating.

3rd Fenestration C: interior lighting was the dominant end-use, followed by cooling, interior equipment, ventilation, and heating.

4th Fenestration D: ventilation was the dominant end-use, followed by cooling, interior equipment, interior lighting, and heating.

The following shows the energy end-use ranking within each fenestration design in the small office category in the Wellington climate zone.

1st Fenestration A: interior lighting was the dominant end-use, followed by interior equipment, heating, ventilation, and cooling.

2nd Fenestration B: interior lighting was the dominant end-use, followed by interior equipment, heating, ventilation, and cooling.

3rd Fenestration C: interior lighting was the dominant end-use, followed by interior equipment, ventilation, cooling, and heating.

4th Fenestration D: interior lighting was the dominant end-use, followed by interior equipment/ventilation, cooling, and heating.

The following shows the energy end-use ranking of each fenestration design in the large office category in the Wellington climate zone:

1st Fenestration A: interior lighting was the dominant end-use, followed by interior equipment, cooling, ventilation, and heating.

2nd Fenestration B: interior lighting was the dominant end-use, followed by interior equipment, cooling, ventilation, and heating.

3rd Fenestration D: interior lighting was the dominant end-use, followed by interior equipment, cooling, ventilation, and heating.

4th Fenestration C: interior lighting was the dominant end-use, followed by interior equipment/cooling, ventilation, and heating.

APPENDIX K – Simulation Location: Melbourne, Australia

(Warm, marine climate zone)

Façade Code: A	North	South	East	West	Average
Heating	0.6	1	0.9	0.9	0.8
Cooling	19	17	18	18	18
Ventilation	10	10	10	11	10
Interior Lighting	43	47	45	45	45
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	105	107	106	107	106

K. 1 – COMFEN Double clear Low-E exterior VB 45 simulated in Melbourne

Façade Code: B	North	South	East	West	Average
Heating	0.5	1.3	0.9	0.9	0.9
Cooling	30	19	28	31	27
Ventilation	18	11	19	26	18
Interior Lighting	42	47	44	44	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	122	110	124	133	122

K. 2 – COMFEN Double clear Low-E between VB 45 simulated in Melbourne

Façade Code: C	North	South	East	West	Average
Heating	0.4	0.7	0.6	0.8	0.6
Cooling	42	25	40	44	37
Ventilation	23	13	27	36	25
Interior Lighting	41	47	43	43	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	139	117	143	156	138

K. 3 – COMFEN Double clear Low-E interior VB 45 simulated in Melbourne

Façade Code: D	North	South	East	West	Average
Heating	9	15	9	9	10
Cooling	54	16	47	53	42
Ventilation	43	16	49	69	44
Interior Lighting	22	23	23	22	22
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	159	103	160	185	152

K. 4 – COMFEN Single clear simulated in Melbourne

APPENDIX K.1 – Simulation Location: Melbourne, Australia

The following table shows the energy performance ranking and energy distribution of each fenestration design in the Melbourne climate zone:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	A	B	C	D	A	B	C	D
Heating	0.8	0.9	0.6	10.4	14	12	9	16	1	1	1	2
Cooling	18	27	37	42	3	9	17	26	23	25	30	30
Ventilation	10	18	25	44	7	13	20	36	9	12	14	20
Interior Lighting	45	44	44	22	46	45	45	37	48	48	47	43
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	106	122	138	152	100	110	121	145	109	115	122	125
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
% Difference	-	15%	13%	10%	-	10%	10%	20%	-	5%	6%	3%

K. 1. 1 – Annual energy distribution of designs simulated in Melbourne

In the COMFEN results there is a 15% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 13% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 10% (Double clear Low-E with interior venetian blinds vs. Single Clear).

In EnergyPus results of the DoE small office there is a 10% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 10% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 20% (Double clear Low-E with interior venetian blinds vs. Single Clear).

In EnergyPus results of the DoE large office there is a 5% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). There is a 6% difference between the 2nd (B) and 3rd (C) options (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 3% (Double clear Low-E with interior venetian blinds vs. Single clear).

Overall, COMFEN energy performance predictions in Melbourne were consistent with all office scenarios. However, the table illustrates that COMFEN tends to exaggerate distribution of energy end-uses compared some multi-zone scenarios (e.g. lower heating requirements).

APPENDIX L – Simulation Location: Minneapolis-St Paul, USA

(Cold, humid climate zone)

Façade Code: A	North	South	East	West	Average
Heating	25	21	23	23	23
Cooling	14	15	15	15	15
Ventilation	11	11	11	13	12
Interior Lighting	48	43	45	45	45
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	130	122	127	128	127

L. 1 – COMFEN Double clear Low-E exterior VB 45 simulated in Minneapolis

Façade Code: B	North	South	East	West	Average
Heating	27	15	19	20	20
Cooling	15	25	25	26	23
Ventilation	12	17	21	27	19
Interior Lighting	48	42	44	44	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	135	131	141	149	139

L. 2 – COMFEN Double clear Low-E between VB 45 simulated in Minneapolis

Façade Code: C	North	South	East	West	Average
Heating	24	12	14	16	16
Cooling	20	36	34	37	32
Ventilation	14	21	27	36	25
Interior Lighting	47	41	43	43	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	137	142	152	164	149

L. 3 – COMFEN Double clear Low-E interior VB 45 simulated in Minneapolis

Façade Code: D	North	South	East	West	Average
Heating	98	52	55	54	65
Cooling	15	51	44	47	39
Ventilation	22	45	63	84	53
Interior Lighting	24	22	23	22	23
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	192	201	218	240	212

L. 4 – COMFEN Single clear simulated in Minneapolis

APPENDIX L.1 – Simulation Location: Minneapolis-St Paul, USA

The following table shows the energy performance ranking and energy distribution of each fenestration design in the Minneapolis climate zone:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	C	A	B	D	A	B	C	D
Heating	23	20	16	65	84	105	99	138	10	10	9	24
Cooling	15	23	32	39	14	4	8	23	18	21	25	25
Ventilation	12	19	25	53	28	18	23	52	9	12	14	23
Interior Lighting	45	44	44	23	45	45	45	37	48	48	48	43
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	127	139	149	213	201	204	205	280	115	119	125	145
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
% Difference	-	10%	7%	43%	-	1%	1%	37%	-	4%	4%	16%

L. 1. 1 – Annual energy distribution of designs simulated in Minneapolis

In the COMFEN results there is a 10% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 7% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 43% (Double clear Low-E with interior venetian blinds vs. Single Clear).

In EnergyPus results of the DoE small office there is a 1% difference between the 1st (C) and 2nd (A) fenestration options (Double clear Low-E with interior venetian blinds vs. Double clear Low-E with exterior venetian blinds). The difference between the 2nd (A) and 3rd (B) options is 1% (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 3rd (B) and 4th (D) options is 37% (Double clear Low-E with between venetian blinds vs. Single Clear).

In EnergyPus results of the DoE large office there is a 4% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). There is a 4% difference between the 2nd (B) and 3rd (C) options (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 16% (Double clear Low-E with interior venetian blinds vs. Single clear).

The percentage difference between fenestration designs closes drastically in the office categories (i.e. there is almost no difference between designs A, B & C).

Overall, COMFEN energy performance predictions were consistent with the large office EnergyPlus results. However, the COMFEN letter order was inconsistent with the small office category; only fenestration D was consistent throughout all office scenarios. However, the table illustrates that COMFEN tends to exaggerate distribution of energy end-uses compared to some multi-zone office scenarios (e.g. lower heating requirements).

APPENDIX M – Simulation Location: Bombay, India

(Mixed, dry climate zone)

Façade Code: A	North	South	East	West	Average
Heating	0.2	0.2	0.2	0.2	0.2
Cooling	47	48	48	49	48
Ventilation	11	11	12	13	12
Interior Lighting	46	43	44	44	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	137	135	136	139	137

M. 1 – COMFEN Double clear Low-E exterior VB 45 simulated in Bombay

Façade Code: B	North	South	East	West	Average
Heating	0.2	0.2	0.3	0.5	0.3
Cooling	52	58	64	69	61
Ventilation	13	13	21	28	19
Interior Lighting	46	42	43	43	44
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	144	145	161	173	156

M. 2 – COMFEN Double clear Low-E between VB 45 simulated in Bombay

Façade Code: C	North	South	East	West	Average
Heating	0.3	0.2	0.4	0.7	0.4
Cooling	58	67	77	85	72
Ventilation	15	15	27	38	24
Interior Lighting	46	41	43	42	43
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	152	155	180	198	171

M. 3 – COMFEN Double clear Low-E interior VB 45 simulated in Bombay

Façade Code: D	North	South	East	West	Average
Heating	0.4	0.3	0.9	1.3	0.7
Cooling	68	85	112	124	97
Ventilation	22	20	53	74	42
Interior Lighting	21	20	21	21	21
Interior Equipment	32	32	32	32	32
Total (kWh/m^2.yr)	143	158	219	252	193

M. 4 – COMFEN Single clear simulated in Bombay

APPENDIX M.1 – Simulation Location: Bombay, India

The following table shows the energy performance ranking and energy distribution of each fenestration design in the Bombay climate zone:

Simulation Category	COMFEN				EP Small Office				EP Large Office			
Facade Code	A	B	C	D	A	B	C	D	A	B	C	D
Heating	0.2	0.3	0.4	0.7	0	0	0	1	0	0	0	0
Cooling	48	61	72	97	48	60	72	93	43	47	51	60
Ventilation	12	19	24	42	13	20	25	39	10	13	14	20
Interior Lighting	44	44	43	21	45	45	44	36	48	47	47	43
Interior Equipment	32	32	32	32	31	31	31	31	29	29	29	29
Total (kWh/m2.yr)	137	156	171	193	136	155	172	200	130	136	142	152
Ranking	1	2	3	4	1	2	3	4	1	2	3	4
% Difference	-	14%	10%	13%	-	13%	11%	16%	-	5%	4%	8%

M. 1. 1 – Annual energy distribution of designs simulated in Bombay

In the COMFEN results there is a 14% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 10% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 13% (Double clear Low-E with interior venetian blinds vs. Single Clear).

In EnergyPus results of the DoE small office there is a 13% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). The difference between the 2nd (B) and 3rd (C) options is 11% (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 16% (Double clear Low-E with interior venetian blinds vs. Single Clear).

In EnergyPus results of the DoE large office there is a 5% difference between the 1st (A) and 2nd (B) fenestration options (Double clear Low-E with exterior venetian blinds vs. Double clear Low-E with between venetian blinds). There is a 4% difference between the 2nd (B) and 3rd (C) options (Double clear Low-E with between venetian blinds vs. Double clear Low-E with interior venetian blinds). The difference between the 3rd (C) and 4th (D) options is 8% (Double clear Low-E with interior venetian blinds vs. Single clear).

Overall, COMFEN energy performance predictions were consistent with all results derived from EnergyPlus. Bombay and Melbourne were the only locations where COMFEN predictions were entirely consistent with the office scenarios.

However, the table illustrates that COMFEN tends to exaggerate distribution of energy end-uses compared to some multi-zone office scenarios (e.g. higher cooling requirements).