DEEP DIVE CASE STUDY:
Building Energy Use Analysis and System Design for Energy Efficiency and Sustainability

Project EEERE:
Energy **E**fficiency **E**ducation **R**esources for **E**ngineering

Consortium Partners:

Project Partners:

DEEP DIVE CASE STUDY:

Building Energy Use Analysis and System Design for Energy Efficiency and Sustainability

Supporting Material

Project EEERE:

Energy **E**fficiency **E**ducation **R**esources for **E**ngineering

Consortium Partners:

Project Partners:

Produced by the University of Wollongong

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Acknowledgements

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Project Background

Energy efficiency is widely recognised as the simplest and most cost-effective way to manage rising energy costs and reduce Australia's greenhouse gas emissions. Promoting and implementing energy efficiency measures across multiple sectors requires significant development and advancement of the knowledge and skills base in Australia. Engineering has been specifically identified as a profession with opportunities to make substantial contributions to a clean and energy-efficient future. To further enable skills development in this field, the Department of Industry commissioned a consortium of Australian universities to collaboratively develop four innovative and highly targeted resources on energy efficiency assessments, for use within engineering curricula. This includes:

1. Ten short **'multi-media bite'** videos for each engineering college of Engineers Australia and an introduction (led by Queensland University of Technology with the University of Adelaide);
2. Ten **'flat-pack'** supporting teaching and learning notes (led by University of Adelaide with QUT);
3. Two **'deep-dive case studies'** including worked calculations (led by University of Wollongong); and
4. A '**virtual reality experience'** in an energy efficiency assessment (led by Victoria University).

Specifically, these resources address the graduate attributes of '**identifying**', '**evaluating**' and '**implementing**' energy efficiency opportunities in the workplace, incorporating a range of common and discipline specific, technical and enabling (non-technical) knowledge and skill areas. The four resources were developed with reference to the 2012 Industry Consultation Report and Briefing Note [1] funded by the Australian Government's former Department of Resources, Energy and Tourism (RET), and through further consultation workshops with project partners and industry stakeholders. At these workshops, participants confirmed the need for urgent capacity building in energy efficiency assessments, accompanied by **clear guidance for any resources developed**, to readily incorporate them into existing courses and programs. Industry also confirmed three key graduate attributes of priority focus for these education resources, comprising the ability to: **think in systems**; **communicate between and beyond engineering disciplines**; and **develop a business case** for energy efficiency opportunities.

[1] Desha, C. and Hargroves, K. (2012) *Report on Engineering Education Consultation 2012*, a report and accompanying Briefing Note, Australian Government Department of Resources, Energy and Tourism, Canberra.

Contents

1 Introduction

Australia generates about 1.5% of global greenhouse gas emissions. However, on a per capita basis, Australia is one of the world's largest polluters[2]. It is reported that 23% of Australia's total greenhouse gas emissions are a result of energy demand in buildings[3]. The rapid enhancement of energy efficiency in the building sector is essential for a timely reduction in global energy use and promotion of environmental sustainability. Appropriate building energy use analysis and system design are among the key steps towards building energy efficiency and sustainability.

This document outlines a *Deep Dive Case Study* analysing energy efficiency in commercial building services design. Based on provided or selected building parameters (location, geometry, etc.), the case study looks at building energy use, water pumping system design, and air duct system design and the subsequent impact on energy efficiency. While the latter of these technologies are specific within a building, the approach of the case study attempts to remain holistic to establish the impact of specific design decisions on the overall energy use, and subsequently, energy efficiency in the broader sense as an engineering challenge.

This deep dive case study will demonstrate how to analyse building energy use to identify possible technical options to reduce building energy consumption, and optimise the design of the air duct system and water pumping systems in heating, ventilation, and air-conditioning (HVAC) systems. It will illustrate how to determine the optimal pipe/duct size and select appropriate water pumps/ventilation fans under the given design conditions to achieve energy efficiency.

This document provides an overview and objectives for engineering faculties, addressing:

- Graduate attributes and learning outcomes (both technical and enabling) to be developed through using this resource.
- Potential learning pathways for developing the identified knowledge and skills.
- How the learning outcomes link to Engineers Australia accreditation requirements and Stage 1 competencies.
- How the learning outcomes link to other high order competencies, such as improvements in graduates' abilities to conceptualise energy efficiency issues, and to work in multi-disciplinary teams to assess and implement energy efficiency opportunities (e.g. with accountants etc.).
- How the resources and the learning outcomes will produce graduates that are more job-ready in relation to energy efficiency assessment, management, monitoring, project analysis and implementation.
- The engineering sub-disciplines for which the resources are relevant.

The document also provides information regarding guidance documents or advice for lecturers to:

- Provide practical guidance or advice to lecturers and faculties wishing to incorporate the resources, and
- Support lecturers' practical understanding of energy efficiency in an industrial context, and their capacity to teach it effectively.

[2] http://www.carbonneutral.com.au/climate-change/australian-emissions.html, accessed 10 Dec. 2013
[3] CIE, Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut, Centre for International Economics (CIE), Canberra & Sydney, Australia, September 2007

2 Statement of coverage

2.1 Resource focus

The case study was developed with three different levels of technical details, knowledge and skills, as illustrated in Figure 2.1. Level 1 focuses on building energy use analysis. Based on given building geometry and design conditions, the students can act as a building services system designer to estimate the energy use of different building components, such as lighting, air-conditioning, office equipment, etc. The students can also estimate building energy performance enhancement through changing lighting energy use intensity, window-to-wall ratio, the inclusion of additional insulation layers for building façade, etc.

Level 2 mainly focuses on the water pumping system design, including pressure drop calculation, pipe sizing and water pump selection. Level 3 focuses on the air duct system design, including calculation of pressure drop across each individual component in an air duct system and selection of appropriate ventilation fans for energy efficiency. Level 2 and Level 3 will use a problem-based learning approach to highlighting engineering considerations in the design of water pumping systems/air duct systems and selection of water pumps/ventilation fans.

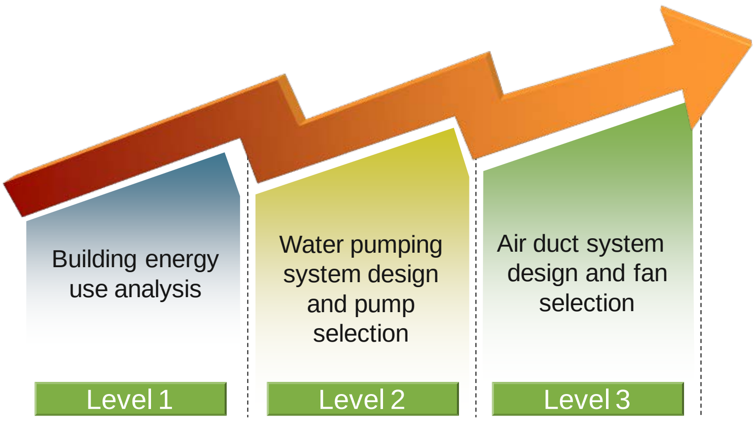

Figure 2.1 - Illustration of the three-level deep dive case study

The *Deep Dive Case Study* simulation and software platform utilises Microsoft Office Excel (2010 and above) and Visual Basic Application. The software platform is provided “unlocked” to ensure educators and students can investigate all aspects of calculation and simulation. This platform is utilised to enable the case study to be expanded through the creation of additional themes or entirely new case studies, e.g.:

- Integration of different control strategies for water pumps and ventilation fans;
- Tuning of the parameters of the PID controllers for variable speed fans and water pumps; and
- Integration of the central plant such as chillers, heat pumps, etc.

Level 1 of the *Deep Dive Case Study* software is a single level worksheet and provides a general understanding of the impacts on building energy usage from different aspects including building constructions, internal gains and operation schedules. The software is able to run simulation according to user defined inputs and demonstrate current and last run results graphically in terms of total annual energy consumption and energy breakdown. This part of the software is also designed to calculate design cooling load based on the design conditions which will be used in the air duct and water pumping system design and optimisation.

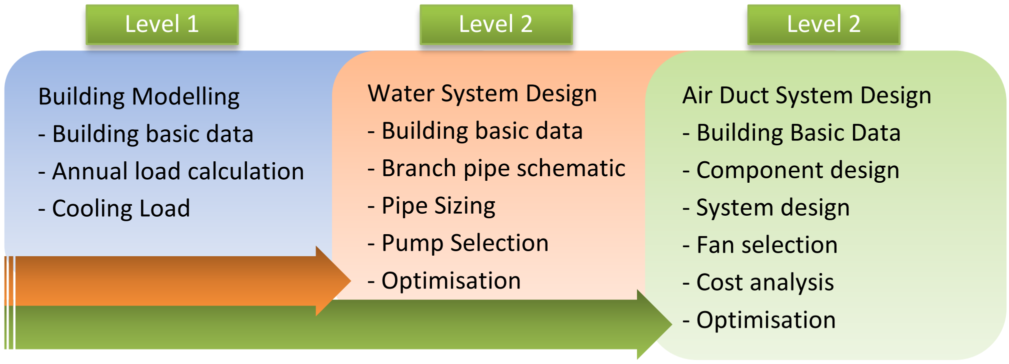

Figure 2.2 - Illustration of the three-level deep dive case study

Level 2 of the software enables the design and optimisation of the water pumping system in an air-conditioning system of the *Deep Dive Case Study*. Chilled water pumping system design and optimisation mainly include the water pipe sizing and pump selection based on the given design load. There are two parts in the water pumping system design, i.e. inputs and outputs. With the correct inputs, the index circuit, initial and operating costs will be determined.

Level 3 of the software summarises the design and optimisation of the air duct system in an air-conditioning system. The air system design is achieved as a multi-level process, by navigating through three separate spreadsheets, i.e. 'System Design', 'Fan Selection' and 'Cost Analysis'. Users can select different duct sizes, duct materials and fittings in the system design to determine the best design option based on life-cycle cost analysis. Determining a suitable design or optimising for energy efficiency (or other targets) enables the task to be either simple or a higher level of complexity.

Level 1 and Level 3 worksheets utilise data from Level 1 to ensure continuity of the *Deep Dive Case Study*. Further details of the operation and background theory for the *Deep Dive Case Study* simulation software are provided in the *Companion Document*.

2.2 Relevant industry sectors

The industry sectors included within this *Deep Dive Case Study* are the following:

- Commercial building design
- Building services
- HVAC systems
- Mechanical design

2.3 Relevant technologies

The key technologies to be covered in the *Deep Dive Case Study* include ventilation systems, lighting systems, fans, water pumps and HVAC systems. A range of scenarios below can be covered and tested in this case study:

- Estimate the energy use of different building components based on given design conditions and current building design standards;
- Analyse building energy performance enhancement through using different energy efficiency lighting products and the inclusion of additional insulation layers for building facades;
- Calculate the pressure drop across each individual component of an chilled/hot water system under different pipe sizes;

- ➢ Determine the optimal pipe size and select the best water pump by using life-cycle cost analysis; and
- ➢ Determine the pressure drop across each individual component of an air duct and distribution system.

Visual display of component and system design is included in the *Deep Dive Case Study* simulation and software platform to ensure the students have obtain some authenticity to the design decisions they are making. Refer to example below.

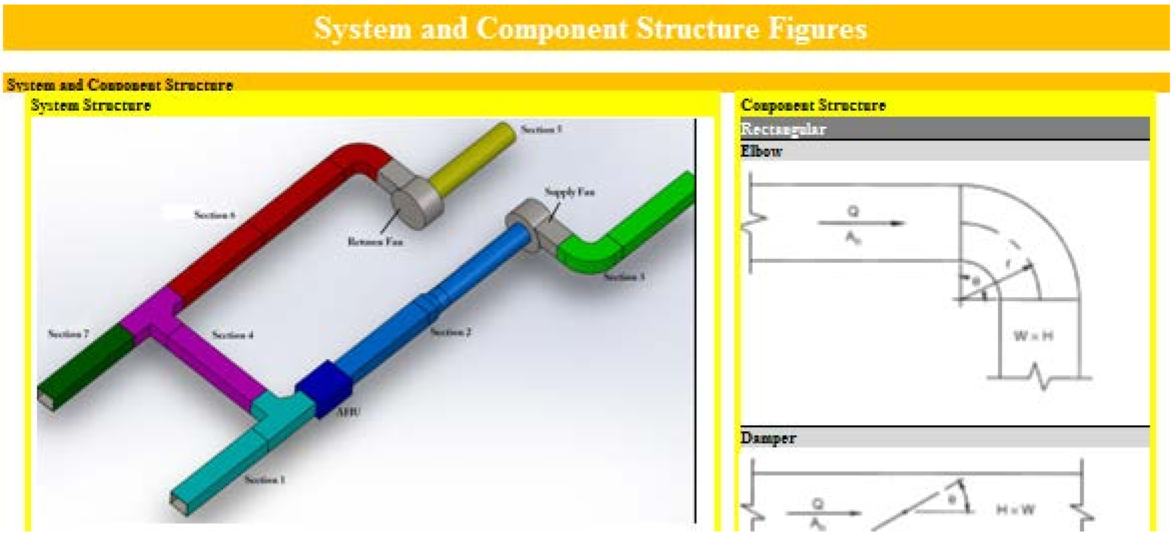

Figure 2.3 - Some information in the "Help" sheet.

2.4 Graduate outcomes

The learning outcomes achieved from students will be dependent on how educators choose to utilise the *Deep Dive Case Study* simulation and software platform. Generally, students completing tasks utilising the *Deep Dive Case Study* will gain an understanding of the impact of various design decisions on commercial building services energy use and gained knowledge of building design principles in general.

In the area of building energy use the key learning activities are as follows:

- ➢ Understand the effects of a range of variables (e.g. insulation, windows-to- wall ratio, operation schedule, etc.) on building energy use;
- ➢ Understand how to optimise the building design to reduce energy consumption; and
- ➢ Understand how to determine the design heating and cooling load under a given condition.

In the area of water pumping system design and pump selection, the key learning activities are as follows:

- ➢ Understand the effects of a range of variables (e.g. pipe sizes and fittings) on a water pumping system design and pump selection;
- ➢ Understand how to calculate the pressure drop across each individual component in a water pumping system;
- ➢ Understand how to appropriate size a water pumping system and select appropriate pumps based on the given design flow rate and system pressure drop calculations; and
- ➢ Compare the performance of a water pumping system under different design options.

In the area of air duct system design and fan selection, the key learning activities are as follows:

- Understand the effects of a range of variables (e.g. duct sizes, materials and fittings) on an air duct system design and fan selection;
- Understand how to calculate the pressure drop across each individual component in an air duct system; and
- Understand how to appropriate size an air duct system and select appropriate fans based on the given design flow rate and system pressure drop calculations; and
- Compare the performance of an air duct system under different design options.

Mapping of graduate attributes to the Engineers Australia Stage 1 Competencies will be dependent on the manner and extent to which the *Deep Dive Case Study* is utilised. Preliminary mapping of competences against the perceived energy efficiency 'gap' attributes identified in 2012 Energy Efficiency in Engineering Briefing Note for participating in energy assessments and evaluating energy efficiency opportunities (Tables 1 and 2)[4] are provided below:

Table 2.1 – Engineers Australia Stage 1 Competencies addressed by *Deep Dive Case Study*

Selected perceived critical gaps (industry clustered themes) and mapping to EA Stage 1 Competencies[4]	EA Stage 1 Competencies[5]
Systems awareness, whole systems thinking, holistic approaches (Framing systems)	1.1, 1.2, 1.5, 2.1, 2.2, 2.3, 3.1
Collaboration, cross-disciplinary approaches, ability to work in a group	3.5, 3.6
Knowledge of measuring technologies and metrics, ability to identify inputs/outputs/losses	1.2, 2.1
Knowledge of energy principles, energy & relative amounts of energy needed for certain processes	1.1
Research skills	2.1, 3.4
Systems thinking - Identify all inputs and outputs, measurement and verification, create a baseline	1.5
Diagnostic skills, Critical thinking	1.5, 2.2, 2.3
Understanding of core engineering principles, including basic physics, thermodynamics and heat transfer, fluid mechanics, electrical machines	1.1, 1.2
Knowledge of EE technology	1.1, 1.3, 1.4
Financial education and evaluation skills, economic and business case analysis skills, ability to calculate expected Return on Investment (ROI)	1.1, 1.3, 1.4
Creative/ lateral thinking / Innovative thought processes, understand how and where to draw on external knowledge sources, capitalising on collaborative approaches/ team work	2.1, 2.3, 2.6
Reporting skills / documentations skills (potential opportunities, recording calculations)	3.2, 3.3, 3.4

[4] Desha, C. and Hargroves, K. (2012) *Report on Engineering Education Consultation 2012*, a report and accompanying Briefing Note, Australian Government Department of Resources, Energy and Tourism, Canberra.
[5] Stage 1 Competency Standard for Professional Engineer, Engineers Australia, available from http://www.engineersaustralia.org.au/, [date accessed March 2014].

2.5 Engineering sub-disciplines

The engineering disciplines included within this case study are the following:

- Civil
- Mechanical
- Process

3 Teaching guide

The *Deep Dive Case Study: Building Energy Use Analysis and System Design for Energy Efficiency and Sustainability* teaching resource is designed to be delivered as either a self-guided learning tool, tutorial task, workshop activity, or subject assignment.

The *Deep Dive Case Study* software allows the student to investigate and evaluate the impact of various design decisions in regards to commercial building energy efficiency and sustainability. The software aims to be able to provide an understanding of design outcomes due to parameter and material changes without having to laboriously perform a number of intermediate detailed calculations. To this regard it enables the user to establish a more holistic viewpoint of design outcomes in relation to energy efficiency and sustainability.

3.1 Pre-requisite knowledge

As indicated in Section 2.1, the resource incorporates three different levels of technical details, knowledge and skills. The resource may therefore be utilised for demonstration purposes, short tutorial problems, or detailed investigations. The resource however is not designed to be an introduction into the commercial building energy efficiency and sustainability topic area, and some previous knowledge of concepts related to commercial building operation and energy requirements is required to be delivered before implementation. Alternatively, the resource could be utilised in the later stages of sustainability related topics or later stages of the engineering degree program without introduction.

3.2 Embedding within existing programs

The *Deep Dive Case Study* is designed to be implemented at the practise and demonstrate phases of the undergraduate programme[6]. To this regard it is expected to be embedded into 3rd and 4th year subjects of the undergraduate degree programme. However, educators may wish to implement components during the learning phase of the respective engineering degree if used for demonstration purposes or guided tutorials, following introductory knowledge of commercial building operation and energy requirements.

An example task utilising the *Deep Dive Case Study* is provided in the *Companion Document*. The task is specifically designed for an initial high level of classroom discussion, followed by individual work or activity in small groups, and then reporting back to the larger group. This structure suits workshop styled tutorials. Initial high level discussion could be used to outline the scope of the activity (rather than it being provided). Detail in the task is left vague specifically to promote this purpose. The procedure of defining scope with a client, undertaking investigation and analysis, and reporting back

[6] C. Desha, *Energy Efficiency & Engineering Education: Increasing Energy Efficiency Knowledge & Skills*, Briefing Note for Engineering Practitioners and Educators, Report for Engineers Australia and DRET, 31 August 2012.

to the client, fulfils the requirement to emulate a typical energy efficiency related engineering problem.

3.3 Catering for different audiences

3.3.1 Varying class sizes

The *Deep Dive Case Study* software has been developed using Visual Basic and Microsoft Excel. The software has a reasonably large file size (10-15 MB) but is otherwise easily portable to individual computers or distributed via web based applications. Thus implementation into varying class sizes is only restricted by the number of computers accessible by the students.

3.3.2 Multi-disciplinary audiences

Use of the *Deep Dive Case Study* with multi-disciplinary audiences is encouraged and was part of the design brief during development. The detailed calculations within the software are based around building technology, civil, mechanical and process engineering. Depending on the relative experience of the students the detailed calculations may be analysed as part of the activity or omitted from the learning process (e.g. focus on lifecycle analysis). It is to be noted that the learning outcomes are focused towards engineering students specifically. Implementation beyond lower levels such as use as a demonstration tool to illustrate relationship between energy efficiency and material selection will require some knowledge of building physical elements to be established.

3.3.3 Dealing with multi-disciplinary audiences

For multi-disciplinary audiences, depending on the experience levels of students, the Level 1 and Level 2 stages of the *Deep Dive Case Study* are proposed to be most appropriate. Energy use analysis will be relevant to all disciplines to establish knowledge of the basic energy efficiency proposition. Tangible and effective measures to alter the energy use of the building provide a suitable discussion activity for all disciplines.

DEEP DIVE CASE STUDY:

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Companion Guide

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Specifically, these resources address the graduate attributes of '**identifying**', '**evaluating**' and '**implementing**' energy efficiency opportunities in the workplace, incorporating a range of common and discipline specific, technical and enabling (non-technical) knowledge and skill areas. The four resources were developed with reference to the 2012 Industry Consultation Report and Briefing Note [1] funded by the Australian Government's former Department of Resources, Energy and Tourism (RET), and through further consultation workshops with project partners and industry stakeholders. At these workshops, participants confirmed the need for urgent capacity building in energy efficiency assessments, accompanied by **clear guidance for any resources developed**, to readily incorporate them into existing courses and programs. Industry also confirmed three key graduate attributes of priority focus for these education resources, comprising the ability to: **think in systems**; **communicate between and beyond engineering disciplines**; and **develop a business case** for energy efficiency opportunities.

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Contents

1 Overview

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This document is the *Companion Guide* to a *Deep Dive Case Study* analysing energy efficiency in commercial building services design. Based on provided or selected building parameters (location, geometry, etc.), the case study looks at building energy use, water pumping system design, and air duct system design and the subsequent impact on energy efficiency. While the latter of these technologies are specific within a building, the approach of the case study attempts to remain holistic to establish the impact of specific design decisions on the overall energy use, and subsequently, energy efficiency in the broader sense as an engineering challenge.

This deep dive case study will demonstrate how to analyse building energy use to identify possible technical options to reduce building energy consumption, and optimise the design of the air duct system and water pumping systems in heating, ventilation, and air-conditioning (HVAC) systems. It will illustrate how to determine the optimal pipe/duct size and select appropriate water pumps/ventilation fans under the given design conditions to achieve energy efficiency.

2 Benefits you will gain

The case study was developed with three different levels of technical details, knowledge and skills, as illustrated in Figure 2.1. Level 1 focuses on building energy use analysis. Based on given building geometry and design conditions, you can act as a building services system designer to estimate the energy use of different building components, such as lighting, air-conditioning, office equipment, etc. You can also estimate building energy performance enhancement through changing lighting energy use intensity, window-to-wall ratio, the inclusion of additional insulation layers for building façade, etc.

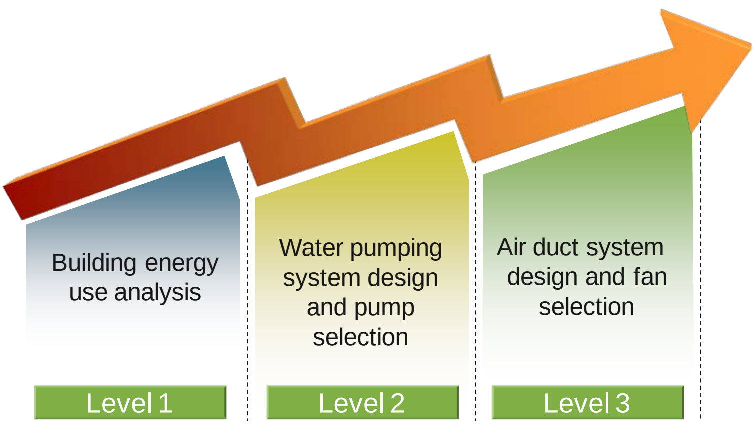


Figure 2.1- Illustration of the three-level deep dive case study

[2] http://www.carbonneutral.com.au/climate-change/australian-emissions.html, accessed 10 Dec. 2013.
[3] CIE, Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut, Centre for International Economics (CIE), Canberra & Sydney, Australia, September 2007.

Level 2 mainly focuses on the water pumping system design, including pressure drop calculation, pipe sizing and water pump selection. Level 3 focuses on the air duct system design, including calculation of pressure drop across each individual component in an air duct system and selection of appropriate ventilation fans for energy efficiency. Level 2 and Level 3 will use a problem-based learning approach to highlighting engineering considerations in the design of water pumping systems/air duct systems and selection of water pumps/ventilation fans.

Through utilising the case study at various levels you will develop a holistic understanding of the impact of various design decisions on commercial building services energy use and gain knowledge of building design principles in general.

3 The case study task

You are to assume the role of a building services design engineer. By analysing the scenarios available to you in the case study software, you are to evaluate the design options put to you in the design brief (Section 3. 1) and provide suitable justification for your selected set of design parameters.

The range of scenarios below can be covered and tested utilising the case study software:

- Estimate the energy use of different building components based on given design conditions and current building design standards;
- Analyse building energy performance enhancement through using different energy efficiency lighting products and the inclusion of additional insulation layers for building facades;
- Calculate the pressure drop across each individual component of an chilled system under different pipe sizes;
- Determine the optimal pipe size and select the best water pump by using life-cycle cost analysis; and
- Determine the pressure drop across each individual component of an air duct and distribution system;

The background details (assumptions, methodology and calculations) of each level of the case study software (refer to Figure 2.1) can be found in Section 4 to Section 6.

3.1 The design brief

As a building design services engineer you are charged with the design and analysis of new building stock for a particular client (*Client A*). *Client A* is a national company and accordingly will have buildings within three different states/territories. It is assumed that the configuration of the buildings in each state/territory will be approximately the same. You are to complete the activities outlined below related to the design of building services. Assistance in defining the detailed scope of the task related to *Client A*'s buildings will be provided through workshop discussion.

3.1.1 Establish building parameters

Select three suitable state/territory locations for *Client A*'s buildings (refer to drop down list in case study software), for which you will analyse the building services design. Select a suitable footprint, number of storeys, general use of the buildings, and a standard set of design parameters to uniformly apply to each of the three buildings.

3.1.2 Building energy use analysis

For the each of the three different state/territory climatic conditions, analyse the building energy use and comment on the appropriateness of the selected set of design parameters which have been uniformly applied to each of the three buildings.

3.1.3 Design of water pumping system

For the uniform set of selected design parameters, determine a suitable design of the water pumping system for *Client A*'s buildings. Through the various options available in the case study software, provide some comment on the alternative design options for the water pumping system, including discussion on the impact on overall energy use. Also investigate to what extent the water pumping system design is dependent on the climatic conditions at each location.

3.1.4 Heating, ventilation and air conditioning (HVAC) system design

For the uniform set of selected design parameters, determine a suitable design of the air ventilation system for *Client A*'s buildings. Through the various options available in the case study software, provide some comment on the alternative design options for the ventilation system, including discussion on the impact on overall energy use and life cycle cost. Also investigate to what extent the air ventilation system design is dependent on the climatic conditions at each location.

3.2 Task outcomes

On completing this task, you will have gained understanding of the impact of various design decisions on commercial building services energy use and gained knowledge of building design principles in general.

In the area of building energy use the key learning activities are as follows:

- Understand the effects of a range of variables (e.g. insulation, windows-to- wall ratio, operation schedule, etc.) on building energy use;
- Understand how to optimise the building design to reduce energy consumption; and
- Understand how to determine the design heating and cooling load under a given condition.

In the area of water pumping system design and pump selection, the key learning activities are as follows:

- Understand the effects of a range of variables (e.g. pipe sizes and fittings) on a water pumping system design and pump selection;
- Understand how to calculate the pressure drop across each individual component in a water pumping system;
- Understand how to appropriate size a water pumping system and select appropriate pumps based on the given design flow rate and system pressure drop calculations; and
- Compare the performance of a water pumping system under different design options.

In the area of air duct system design and fan selection, the key learning activities are as follows:

- Understand the effects of a range of variables (e.g. duct sizes, materials and fittings) on an air duct system design and fan selection;
- Understand how to calculate the pressure drop across each individual component in an air duct system; and
- Understand how to appropriate size an air duct system and select appropriate fans based on the given design flow rate and system pressure drop calculations; and

- Compare the performance of an air duct system under different design options.

3.3 Task outputs

The deliverable output of this task is to be a summary report (limited to six pages) which details the considerations and design options outlined in the design brief. Specific outputs generated from case study calculations are to be included in the report to justify design parameter selections and/or verify impact of design alternatives (where applicable). Discussion and/or recommendations for optimal building services design with respect to the various climatic conditions are to be included in the summary report. Include any external factors (beyond the case study software options) which you think would be important in regards to minimising building energy use.

Where activities are undertaken in a group, the summary report must indicate the contributions from each member. Presentation of results will be required during tutorial discussion.

4 Building energy usage estimation

This part of software provides a general understanding of the impacts on building energy usage from different aspects including building constructions, internal gains and operation schedules. The software is able to run simulation according to user defined inputs and demonstrate current and last run results graphically in terms of total annual energy consumption and energy breakdown. This part of the software is also designed to calculate design cooling load based on the design conditions which will be used in the air duct and water pumping system design and optimisation.

4.1 Software introduction

The software estimates the energy consumption of a simplified building model with a square floor plan but user can define the building levels and single floor areas. Figure 4.1 shows the user interface with following parameters, which can be adjusted within the input ranges specified in brackets.

- Building location (Darwin, Sydney and Melbourne)
- Building levels (1 – 20)
- Floor area (100m^2-2000m^2)
- Window to wall ratio (1% to 50%)
- R-value of building fabric (R1 – R8)
- U-value of windows (U0.5 – U5)
- Windows solar heat gain coefficient (SHGC) (0.2-0.8)
- Lighting intensity (4W/m^2 to 15W/m^2)
- Computer intensity (4W/m^2 to 20W/m^2)
- Occupancy intensity (5m^2/people to 15m^2/people)
- Cooling and heating set-point (18^{o}C to 22^{o}C for heating, 23^{o}C to 25^{o}C for cooling)

Once all required parameters are provided, user can click the “Run Simulation” button at the left bottom corner to run the simulation. The simulation will take about 20 seconds to obtain the results. After the simulation is completed, the breakdown of energy use in different systems can be shown in the right top side of the interface automatically, which includes the cooling energy consumption, heating energy consumption, lighting energy consumption, equipment energy consumption and others (i.e. lift, hot water, etc.). The bar chart below demonstrates the absolute energy consumption values. User can compare the current simulation results with the last simulation results in order to understand the impact of changing design variables on building energy consumption quantitatively.

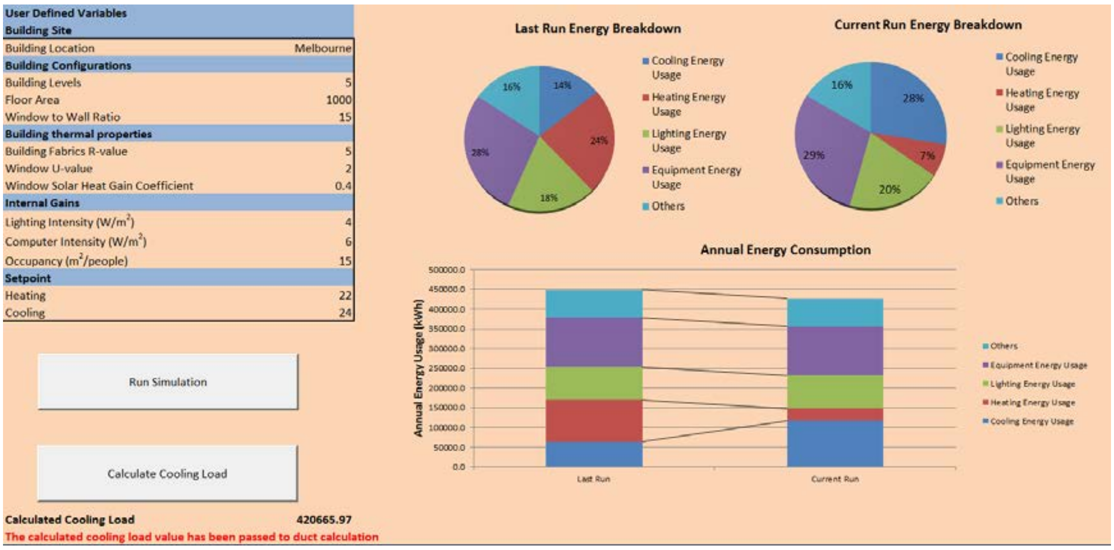


Figure 4.1 - User interface of the building energy consumption estimation.

User can also click the "Calculate Cooling Load" button to determine the building design cooling load according to the building properties specified. The estimated results will be displayed below the button and also be automatically passed to "Air duct system design and optimisation" and "Water pumping system design and optimisation" as the design target.

4.2 Description of calculation procedures

4.2.1 Building geometry

The simplified building model is a square box with user defined levels, single level floor area and windows to wall ratio. All floors except the ground floor are considered as perfect thermal conductor.

4.2.2 Building energy

The major part of the building energy calculation is the heating and cooling energy calculation. As illustrated in Figure 4.2, the calculation is based on the calculated heating and cooling load with the heat balance method and then convert the load to energy with a fixed coefficient of Performance (COP).

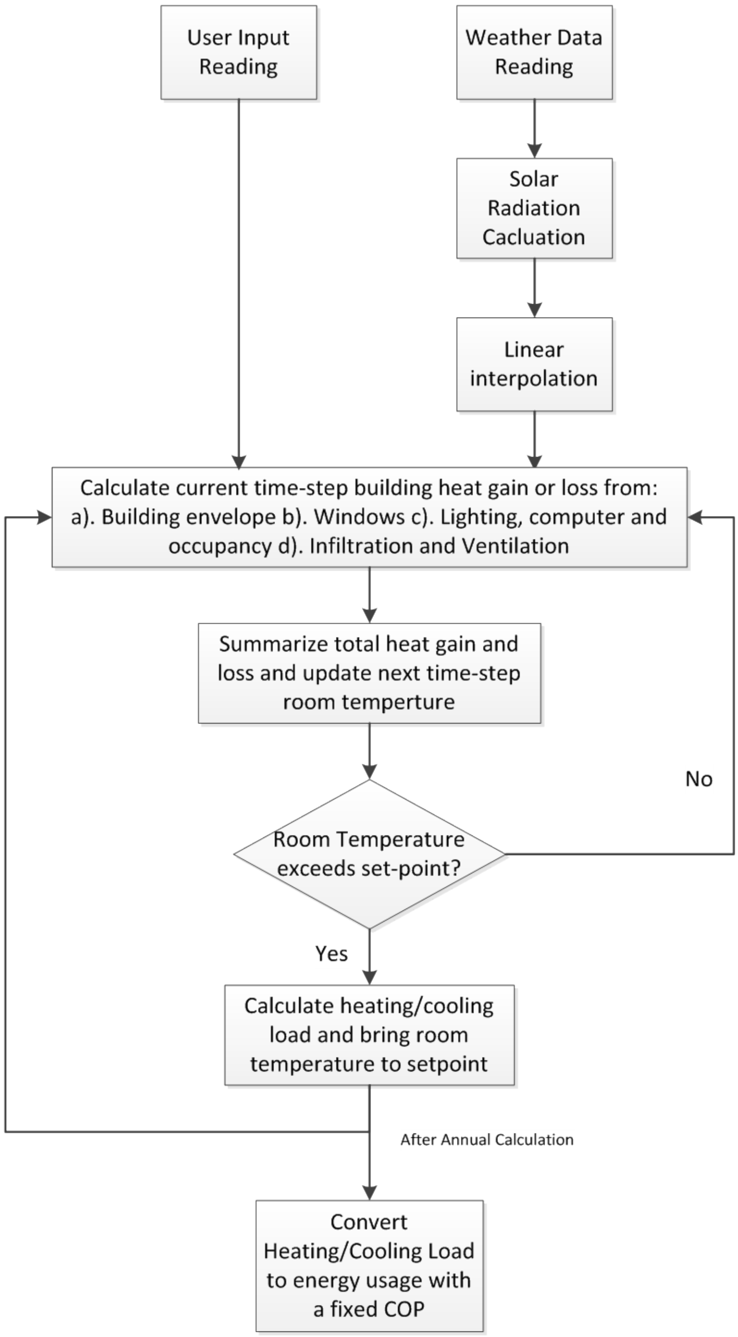


Figure 4.2 - Procedures of building heating/cooling energy calculations.

After necessary calculation initialization, the first step in the procedure is to read weather data and calculates the radiation intensity on four (4) building orientations as well as the top roof. The software calculates the solar incidence angle at current time-step and then finds out the radiation intensity on different surfaces with direct, diffuse and ground reflected radiation data from weather file considered.

The next step is to interpolate weather data and radiation intensity linearly to 0.1 hour time-step in order to avoid accumulated error because of long time-step. Then the software will calculate the heat gain or loss from four (4) major aspects including:

a) building envelope;
b) Windows;
c) Internal gains; and
d) Infiltration and scheduled natural ventilation.

After the determination of current time-step heat gain or loss, the software will update the room temperature based on the results. Then the software will judge whether the new room temperature exceeds the heating or cooling set-point. If the room temperature still remains in the heating and cooling set-point, this time step is finished and the calculation goes to the next time-step. Otherwise, the software will calculate the required heating or cooling load to bring the temperature back to the desired set-point while the heating or cooling load is accumulated into the total heating or cooling load.

Once the annual calculation is completed, the software will convert the heating and cooling load to energy usage with a fixed Coefficient of Performance (COP).

5 Water system design and optimization

This section summarises the design and optimisation of the water pumping system in an air-conditioning system. Chilled water pumping system design and optimisation mainly include the water pipe sizing and pump selection based on the given design load. There are two parts in the water pumping system design, i.e. inputs and outputs. With the correct inputs, the index circuit, initial and operating costs will be determined.

5.1 Instructions for an air duct system design and optimisation

By clicking “Water Pumping System Design and Optimisation” button in the main interface, user will enter the sub-interface of “Water Pumping System Design and Optimisation” (see Figure 5.1).

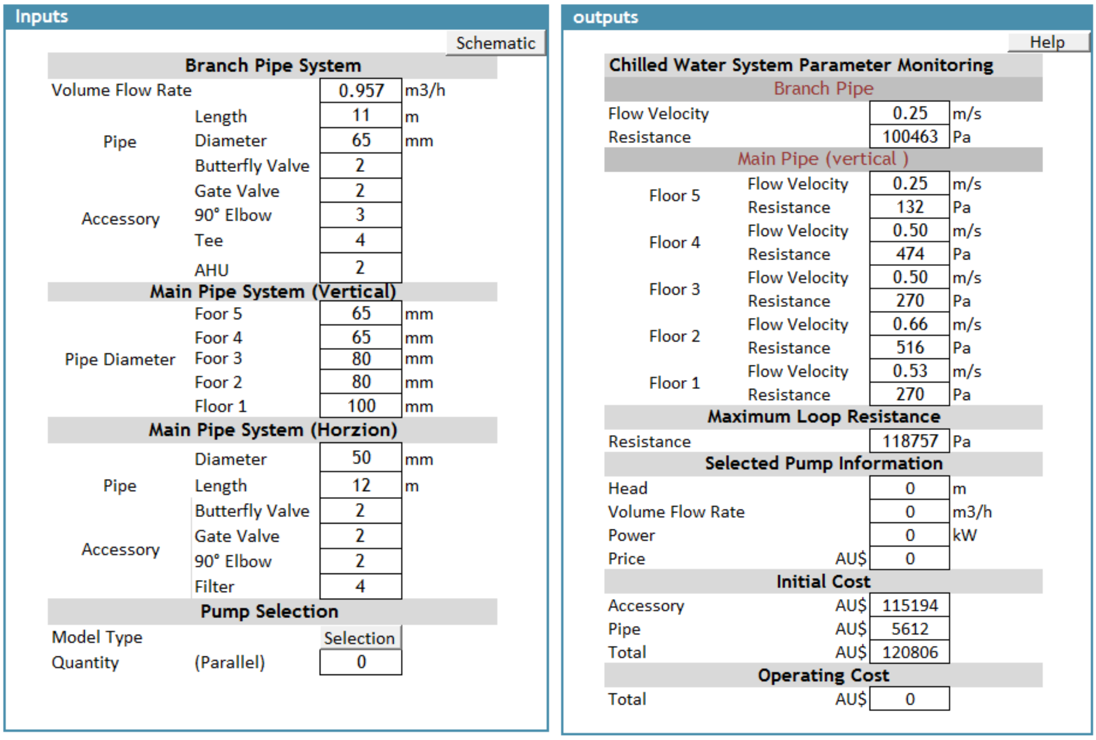


Figure 5.1 - Water Pumping System Design and Optimisation

Figure 5.2 shows the input data/steps required for design and optimisation of water pumping systems, including basic building data, main supply and return pipeline design, pump selection, electricity price and terminal loop design. The key design parameter monitoring can help user to select appropriate values in the design process.

Building basic data → Branch pipe system → Main pipe design → Pump selection

Figure 5.2 - Major input data/steps required for design and optimisation of the water pumping system

By clicking on "Schematic" button, a general design blueprint on a typical water pumping system, as shown in Figure 5.3, will be displayed to help the users without prior knowledge on water pumping systems to understand how to define the variables in the water pumping system design and better understand the inputs required in the user interface.

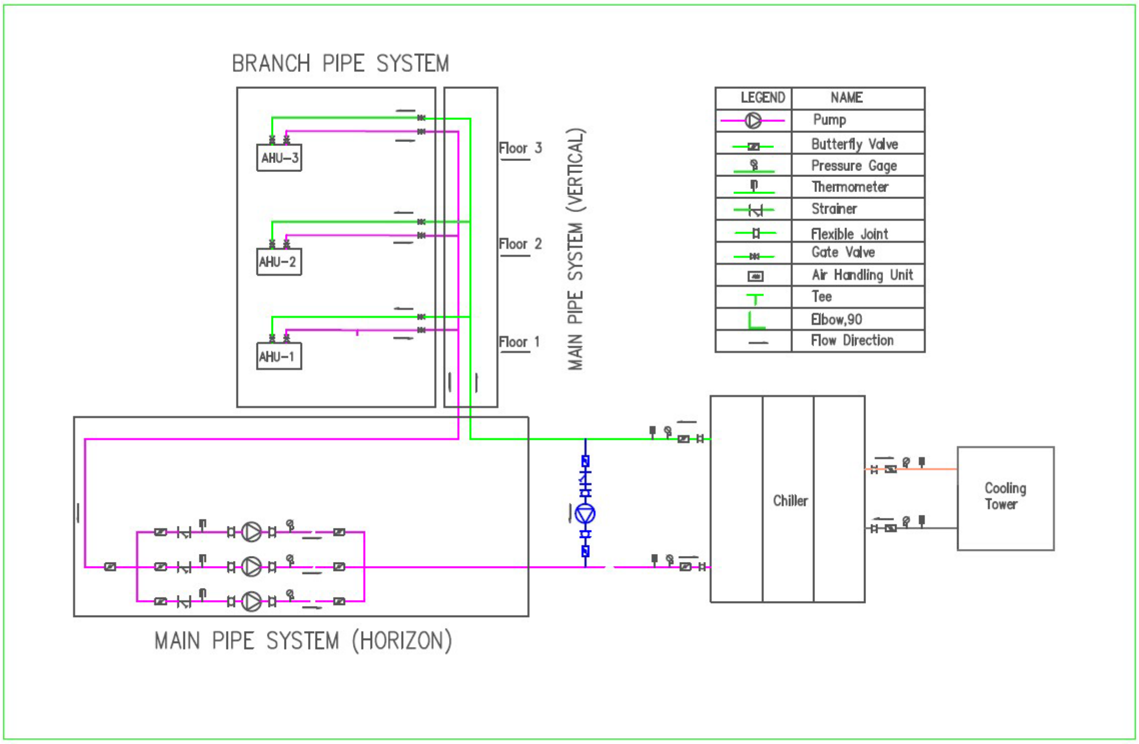


Figure 5.3 - Schematic of a typical water pumping system.

Based on the building design cooling load, user can estimate the water flow requirement of the water pumping system, which will be used to size the water pipes and pump selection. User needs to estimate the length of main supply and return pipelines, the length of the pipelines in each terminal loop and the numbers of necessary fittings based on the building floor plan. The electricity price is also designed as a user input variable to determine the operational cost of the water pumping system. In this process, user can monitor the water velocity in the main supply and return pipelines and flow resistance to ensure the pipe sizing selected is reasonable. The "Help" button recommends the range of the water flow velocity and flow resistance commonly used in water pumping system design. Once the pipe sizing completes, user can select appropriate water pumps from the pump database, in which a total of 187 different water pumps are included.

For each design option, the results will be displayed in "Outputs". User can store the results by pressing "Save" button. The system can save a maximum of 5 sets of simulation results. By clicking the "Create" Button, the system will provide a comparison among the data sets saved in a PDF file.

5.2 Pump selection

Clicking "Selection" button can unhide the "Water Pump Selection" interface. There are two ways to select a pump: selecting a pump from the database and define a pump according to the required water flow rate and pump head. Figure 5.4 shows the interface of "Water Pump Selection". User can choose the pump type by entering the pump head and flow rate to find out the most suitable pump. If there is no suitable pump in the database, user can define the pump head, flow rate and associated cost to determine the appropriate pump suitable for the case studied.

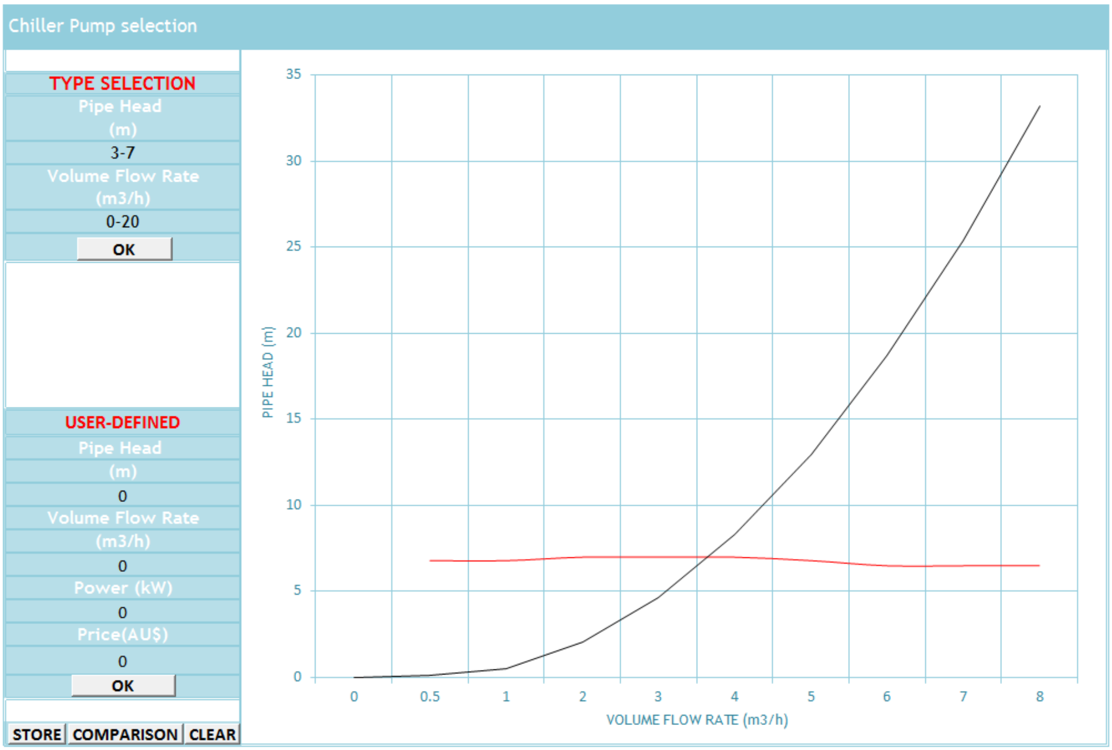


Figure 5.4 – Pump selection

For each design option, user can save the results by clicking "Save" button. A total of five design options can be saved, which can help user to easily compare the difference among different water pumping system design options to determine the best option via clicking "Create" button as shown in Figure 5.5

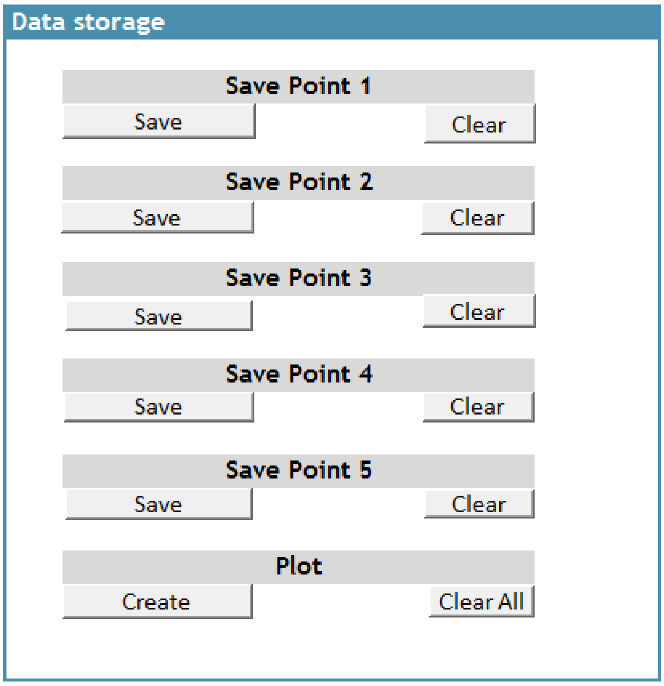
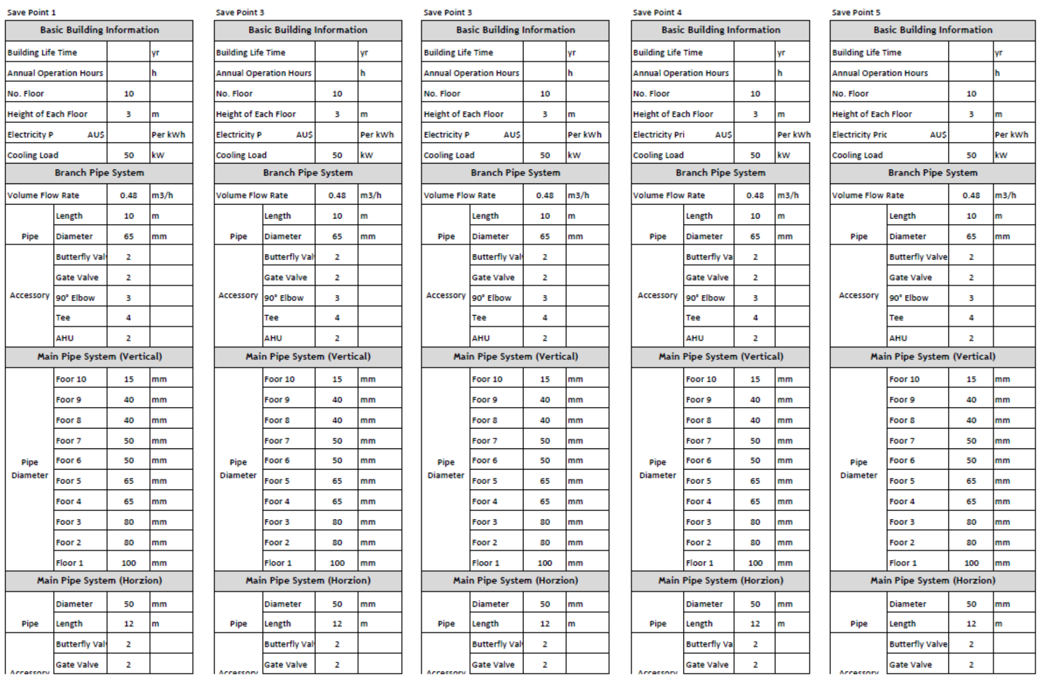


Figure 5.5 –Data storage

The results of life-cycle cost analysis will be provided in a pdf file.



Save Point 1

Basic Building Information			
Building Life Time			yr
Annual Operation Hours			h
No. Floor		10	
Height of Each Floor		3	m
Electricity P	AU$		Per kWh
Cooling Load		50	kW
Branch Pipe System			
Volume Flow Rate		0.48	m3/h
Pipe	Length	10	m
	Diameter	65	mm
Accessory	Butterfly Val	2	
	Gate Valve	2	
	90° Elbow	3	
	Tee	4	
	AHU	2	
Main Pipe System (Vertical)			
Pipe Diameter	Foor 10	15	mm
	Foor 9	40	mm
	Foor 8	40	mm
	Foor 7	50	mm
	Foor 6	50	mm
	Foor 5	65	mm
	Foor 4	65	mm
	Foor 3	80	mm
	Foor 2	80	mm
	Floor 1	100	mm
Main Pipe System (Horzion)			
Pipe	Diameter	50	mm
	Length	12	m
Accessory	Butterfly Val	2	
	Gate Valve	2	

Save Point 3

Basic Building Information			
Building Life Time			yr
Annual Operation Hours			h
No. Floor		10	
Height of Each Floor		3	m
Electricity P	AU$		Per kWh
Cooling Load		50	kW
Branch Pipe System			
Volume Flow Rate		0.48	m3/h
Pipe	Length	10	m
	Diameter	65	mm
Accessory	Butterfly Val	2	
	Gate Valve	2	
	90° Elbow	3	
	Tee	4	
	AHU	2	
Main Pipe System (Vertical)			
Pipe Diameter	Foor 10	15	mm
	Foor 9	40	mm
	Foor 8	40	mm
	Foor 7	50	mm
	Foor 6	50	mm
	Foor 5	65	mm
	Foor 4	65	mm
	Foor 3	80	mm
	Foor 2	80	mm
	Floor 1	100	mm
Main Pipe System (Horzion)			
Pipe	Diameter	50	mm
	Length	12	m
Accessory	Butterfly Val	2	
	Gate Valve	2	

Save Point 3

Basic Building Information			
Building Life Time			yr
Annual Operation Hours			h
No. Floor		10	
Height of Each Floor		3	m
Electricity P	AU$		Per kWh
Cooling Load		50	kW
Branch Pipe System			
Volume Flow Rate		0.48	m3/h
Pipe	Length	10	m
	Diameter	65	mm
Accessory	Butterfly Val	2	
	Gate Valve	2	
	90° Elbow	3	
	Tee	4	
	AHU	2	
Main Pipe System (Vertical)			
Pipe Diameter	Foor 10	15	mm
	Foor 9	40	mm
	Foor 8	40	mm
	Foor 7	50	mm
	Foor 6	50	mm
	Foor 5	65	mm
	Foor 4	65	mm
	Foor 3	80	mm
	Foor 2	80	mm
	Floor 1	100	mm
Main Pipe System (Horzion)			
Pipe	Diameter	50	mm
	Length	12	m
Accessory	Butterfly Val	2	
	Gate Valve	2	

Save Point 4

Basic Building Information			
Building Life Time			yr
Annual Operation Hours			h
No. Floor		10	
Height of Each Floor		3	m
Electricity Pri	AU$		Per kWh
Cooling Load		50	kW
Branch Pipe System			
Volume Flow Rate		0.48	m3/h
Pipe	Length	10	m
	Diameter	65	mm
Accessory	Butterfly Va	2	
	Gate Valve	2	
	90° Elbow	3	
	Tee	4	
	AHU	2	
Main Pipe System (Vertical)			
Pipe Diameter	Foor 10	15	mm
	Foor 9	40	mm
	Foor 8	40	mm
	Foor 7	50	mm
	Foor 6	50	mm
	Foor 5	65	mm
	Foor 4	65	mm
	Foor 3	80	mm
	Foor 2	80	mm
	Floor 1	100	mm
Main Pipe System (Horzion)			
Pipe	Diameter	50	mm
	Length	12	m
Accessory	Butterfly Va	2	
	Gate Valve	2	

Save Point 5

Basic Building Information			
Building Life Time			yr
Annual Operation Hours			h
No. Floor		10	
Height of Each Floor		3	m
Electricity Pric	AU$		Per kWh
Cooling Load		50	kW
Branch Pipe System			
Volume Flow Rate		0.48	m3/h
Pipe	Length	10	m
	Diameter	65	mm
Accessory	Butterfly Valve	2	
	Gate Valve	2	
	90° Elbow	3	
	Tee	4	
	AHU	2	
Main Pipe System (Vertical)			
Pipe Diameter	Foor 10	15	mm
	Foor 9	40	mm
	Foor 8	40	mm
	Foor 7	50	mm
	Foor 6	50	mm
	Foor 5	65	mm
	Foor 4	65	mm
	Foor 3	80	mm
	Foor 2	80	mm
	Floor 1	100	mm
Main Pipe System (Horzion)			
Pipe	Diameter	50	mm
	Length	12	m
Accessory	Butterfly Valve	2	
	Gate Valve	2	

Figure 5.6 – Results from Life cycle cost analysis

5.3 Key calculation equations used

The frictional resistance of a water pipe system is determined by Equation (5-1).

$$\Delta p_f = \lambda \frac{l}{d}\frac{\rho v^2}{2} = \left(\frac{\lambda}{d}\frac{\rho v^2}{2}\right) l = Rl \qquad (5\text{-}1)$$

Where, Δp_f is the frictional resistance loss, λ is the frictional resistance coefficient (dimensionless quantity), *l* is the straight pipe length, *d* is the pipe diameter, ρ is the water density, υ is the water velocity, i_L is the frictional resistance per unit length, d_N is the inner diameter, and g is the design flow.

The local resistance of a water pipe system can be determined by Equation (5-2).

$$\Delta p_l = \xi \frac{\rho v^2}{2} \quad (5\text{-}2)$$

where, Δp_1 is the local resistance loss, and ξ is the local resistance coefficient.

The total resistance loss in the water pumping system can be determined by Equation (5-3). The chilled water flow can be determined by Equation (5-4).

$$p = \sum(\Delta p_f + \Delta p_l + \Delta p_e) \quad (5\text{-}3)$$

$$q_m = \frac{\Phi}{c\Delta t} \quad (5\text{-}4)$$

where, P is the total resistance loss, Δp_e is the equipment resistance loss, q_m is the chilled water flow rate, Φ is the cooling load, Δt is the supply and return temperature difference, and c is the specific heat capacity.

6 Air duct system design and optimisation

6.1 Design flow

This section summarises the design and optimisation of the air duct system in an air-conditioning system. The air system design was achieved through six steps below. User can select different duct sizes, duct materials and fittings in the system design to determine the best design option based on life-cycle cost analysis.

1) Study building plan and sketch the duct system layout;
2) Divide the duct system into different sections and number each section, as shown in Figure 6.1;
3) Select a duct size based on the recommended velocity used in design practice (e.g. 1-10m/s);
4) Calculate the total pressure losses and lay out the pressure distribution;
5) Fan selection; and
6) Life cycle cost analysis.

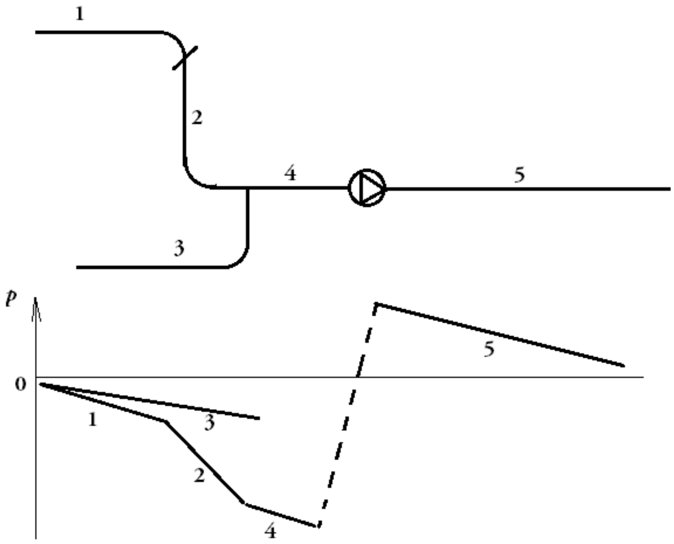


Figure 6.1 - Number each section in an air duct system.

6.2 Instructions for an air duct system design and optimisation

By clicking "Air Duct System Design and Optimisation" button in the main interface, user will enter the interface of "Air Duct System Design and Optimization" (see Figure 6.2). The air duct system design and optimisation are performed through three different activities as the three buttons shown in the left side of this page, i.e. 'System Design', 'Fan Selection' and 'Cost Analysis'. At the right bottom corner, a "Back to Main Interface" button was designed to reopen the main interface.

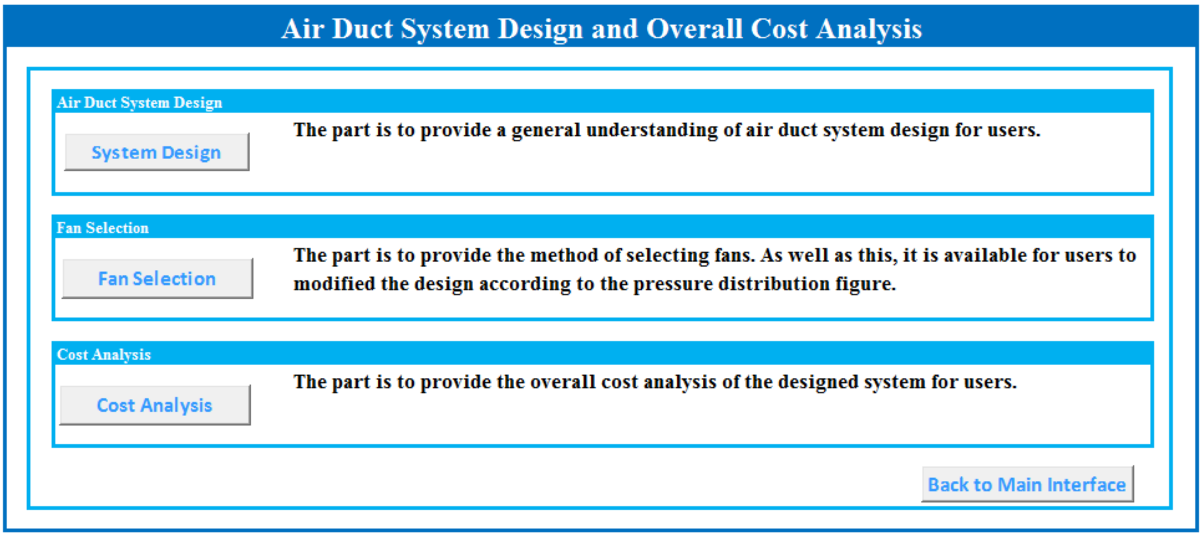


Figure 6.2 - Interface of the air duct system design and optimization.

6.3 System design

By clicking the "System Design" button, two separate sheets, "Air_Duct_System_Design" and "Air_Duct_System_Help", will be opened. There two boxes in the "Air_Duct_System_Design" sheet (as shown in Figure 6.3). One is the input box and the other is the output box. In the input box, user can specify the duct sizes, materials and fittings to be used in the air duct system. The pressure losses across each individual component and the total pressure drop will be displayed in the output box. By clicking the "Return" button at the right bottom corner, user will return to the sub-interface of "Air Duct System Design and Optimisation". By clicking the "Next Step" button, user will enter "Fan_selection" sheet. The "Air_Duct_System_Help" sheet (as shown in Figure 6.4) provides user necessary information on the design of an air duct system such as the elbows, dampers, etc.

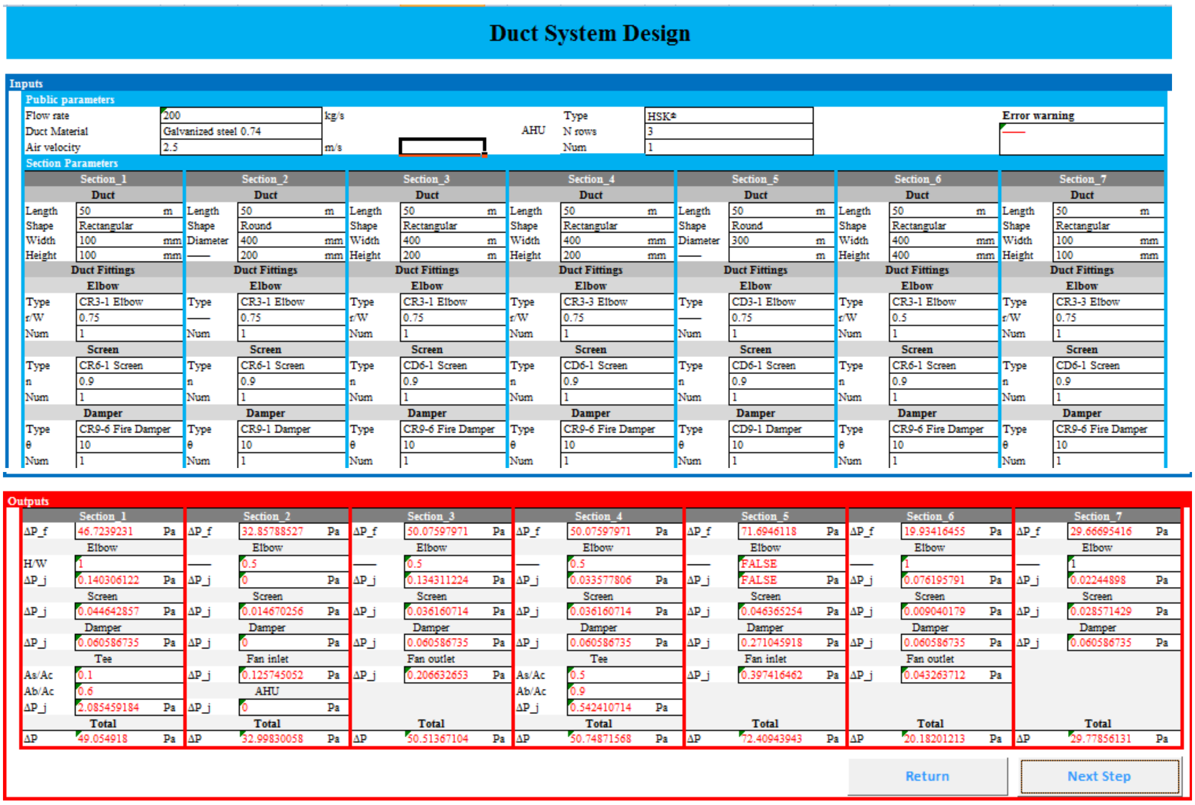


Figure 6.3 - Duct system design sheet.

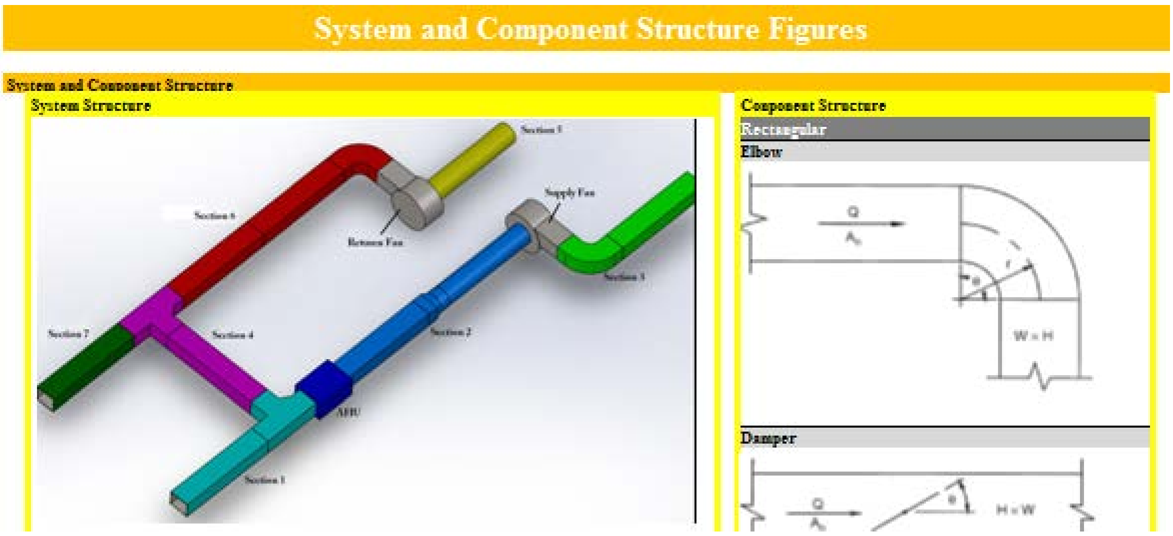


Figure 6.4 - Some information in the "Help" sheet.

6.4 Fan selection

There are two ways to enter the "Fan_Selection" sheet. One is from the sub-interface of "Air Duct System Design and Optimisation" and the other is from "Air Duct System Design" sheet. In this sheet, user can select appropriate fans and analyse the design results. Figure 6.5 illustrates an example of the pressure distribution along each section of an air duct system and the operation curves of the supply fan. The fan types and efficiency can be selected from this sheet. If user would like to define a fan type and efficiency, the blank options in "Fan type" and "Efficiency type" can be selected and then user can assign appropriate values (i.e. flow rate and fan head) for both parameters. The figure in the right side will show the fan curve automatically. At the same time, in the case, user needs to define the price of the fans. If the design results are not satisfactory, user can go back to the "Air_Duct_System_Design" interface to modify the design parameters.

Figure 6.5 - Sheet of Fan Selection.

There are three buttons in this sheet, i.e. “Return” button, “Nest Step” button and “Previous Step” button at the bottom of the sheet. By clicking the “Previous Step” button, user can go back to the sheet of “Air_Duct_System_Design” to change the design parameters. The “Return” button allows the user to reopen the sub-interface of “Air Duct System Design and Optimisation”.

6.5 Life-cycle cost analysis

By clicking the “Cost Analysis” button in the sub-interface of “Air Duct System Design and Optimisation” or by clicking the “Next step” button in the sheet of “Fan_Selection”, user will enter the sheet of “Life-cycle_Cost_Analysis”. In this sheet, use can specify the life time of the building and electricity price. The system will automatically determine the first capital investment cost and life-time operational cost. User can also compare the performance of different design options (a maximum of 5 is allowed), as shown in Figure 6.6.

Figure 6.6 - Life cycle cost analysis sheet.

6.6 Major inputs and fittings

6.6.1 Major inputs

- ***Flow rate***: derives from the "Building Energy Usage Estimation".
- ***Duct material***: Duct types and materials determine the roughness factor, which impacts the friction losses (refer to Table 1 for more details).
- ***AHU (Air Handling Unit)***: enter the number of heat transfer tube rows (N rows∈(1,8)) and the number of AHU.

Table 1 - Duct roughness factor

Duct Material	Roughness Category	Absolute Roughness ε, ft
Uncoated carbon steel, clean (Moody 1944) (0.05 mm)	Smooth	0.03
PVC plastic pipe (Swim 1982) (0.01 to 0.05 mm)		
Aluminum (Hutchinson 1953) 0.04 to 0.06 mm)		
Galvanized steel, longitudinal seams, 200 mm joints (Griggs et al. 1987) (0.05 to 0.10 mm)	Medium-smooth	0.09
Galvanized steel, continuously rolled, spiral seams, 3000 mm joints (Jones 1979) (0.06 to 0.12 mm)		
Galvanized steel, spiral seam with 1, 2, and 3 ribs, 3600 mm joints (Griggs et al. 1987) (0.09 to 0.12 mm)		
Galvanized steel, longitudinal seams, 760 mm joints (Wright 1945) (0.15 mm)	Average	0.15
Galvanized steel, spiral, corrugated, 3600 mm joints (Kulkarni et al. 2009) (0.74 mm)	Medium-rough	0.9
Fibrous glass duct, rigid		
Fibrous glass duct liner, air side with facing material (Swim 1978) (1.5 mm)		
Flexible duct, fabric and wire, fully extended		
Fibrous glass duct liner, air side spray coated (Swim 1978) (4.6 mm)	Rough	3.0
Flexible duct, metallic (1.2 to 2.1 mm when fully extended)		
Concrete (Moody 1944) (1.3 to 3.0 mm)		

As shown in Figure 6.7 and Figure 6.8, each floor has the same air duct system. There are two (2) tees in Section 1 and Section 4, respectively. The supply fan and return fan are located between Section 2 and Section 3, and Section 5 and Section 6 respectively. The AHU is placed between Section 1 and Section 2. In terms of other duct fittings, user can define the number as they wish.

Section Parameters	Section_1		Section_2		Section_3		Section_4		Section_5		Section_6		Section_7
Duct													
Length	50 m	Length	50 m	Length	50 m	Length	50 m	Length	50 m	Length	50 m	Length	50 m
Shape	Rectangular	Shape	Round	Shape	Rectangular	Shape	Rectangular	Shape	Round	Shape	Rectangular	Shape	Rectangular
Width	100 mm	Diameter	400 mm	Width	400 m	Width	400 mm	Diameter	300 m	Width	400 mm	Width	100 mm
Height	100 mm	——	200 mm	Height	200 m	Height	200 mm	——	m	Height	400 mm	Height	100 mm
Duct Fittings – Elbow													
Type	CR3-1 Elbow	Type	CR3-1 Elbow	Type	CR3-1 Elbow	Type	CR3-3 Elbow	Type	CD3-1 Elbow	Type	CR3-1 Elbow	Type	CR3-3 Elbow
r/W	0.75	——	0.75	r/W	0.75	r/W	0.75	——	0.75	r/W	0.5	r/W	0.75
Num	1	Num	1	Num	1	Num	1	Num	1	Num	1	Num	1
Screen													
Type	CR6-1 Screen	Type	CR6-1 Screen	Type	CD6-1 Screen	Type	CD6-1 Screen	Type	CD6-1 Screen	Type	CR6-1 Screen	Type	CD6-1 Screen
n	0.9	n	0.9	n	0.9	n	0.9	n	0.9	n	0.9	n	0.9
Num	1	Num	1	Num	1	Num	1	Num	1	Num	1	Num	1

Figure 6.7 - Illustration of input parameters in the air duct system design interface for fittings.

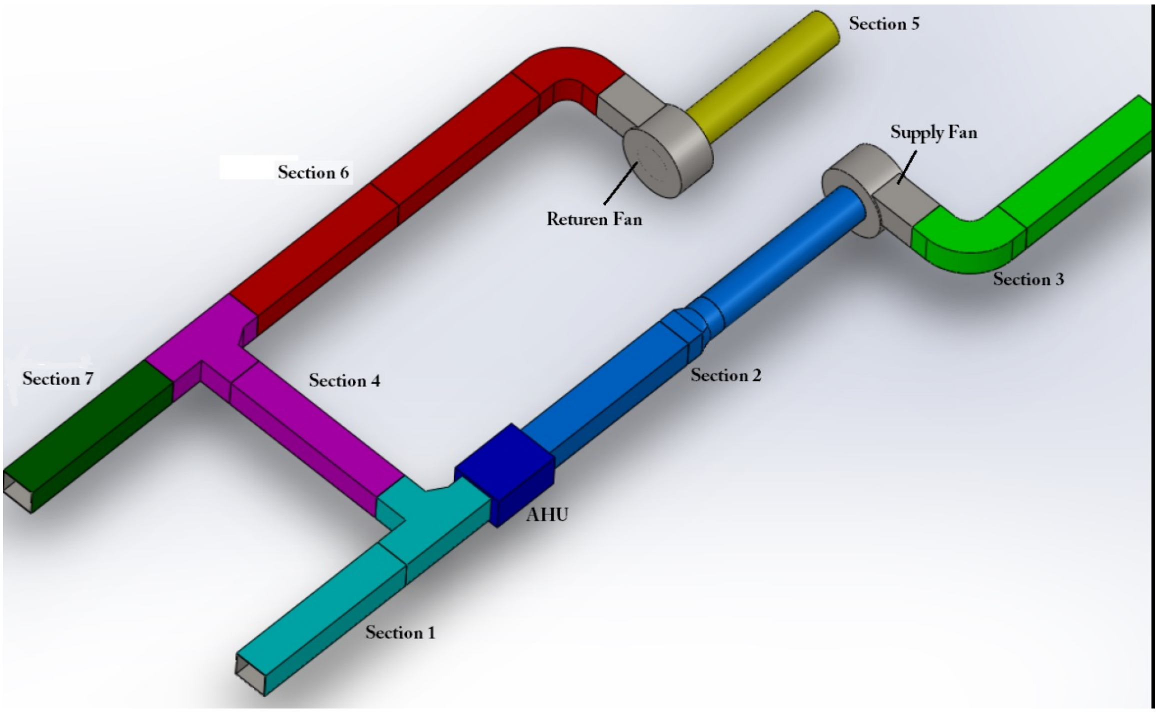


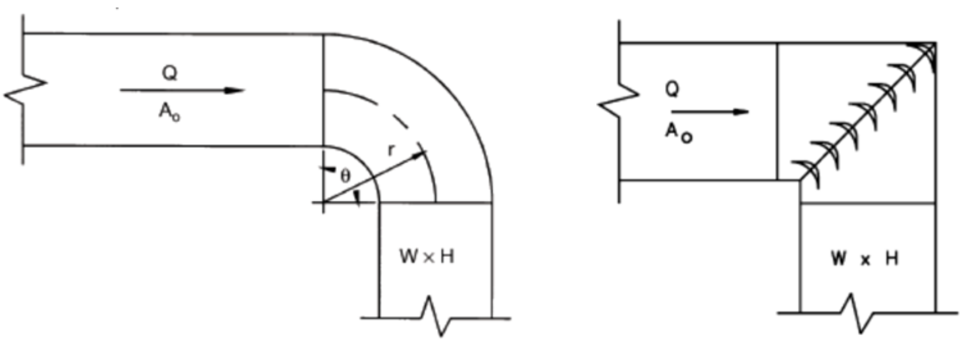
Figure 6.8 - Air duct system structure

- ***Length***: Enter the duct section length (taking the area of building into account);
- ***Shape***: Two shapes of 'Round' and 'Rectangular' are available for most of sections except Section 5. This parameter determines the duct fitting type;
- ***Width and Height/Diameter***: If the shape of "Round" is selected, the label of "Diameter" will show, and user needs to enter the diameter of the duct. Otherwise, the width and height of the duct need to be entered if user defines "Rectangular" as the duct shape;

These parameters will be used to calculate the cross section of a duct. As the cross sections of different duct sections are interacted with each other, special attention should be paid to define the duct size. For instance, the cross section of Section 2 should be larger than that of Section 1 and Section 4, and the cross section of Section 6 should be larger than that of Section 7 and Section 4.

6.6.2 Major fittings

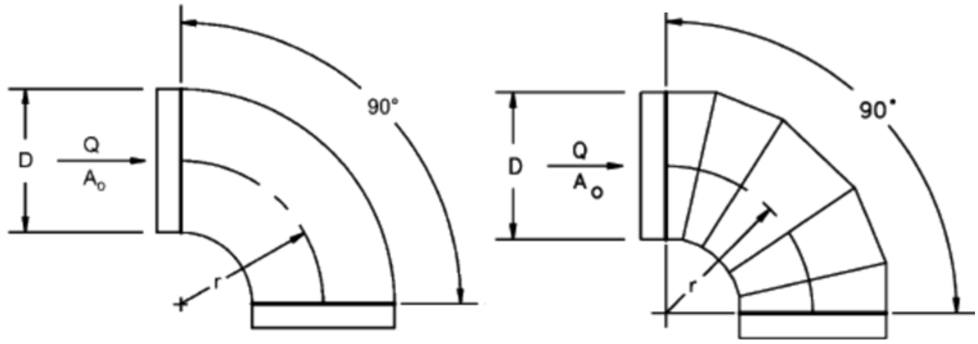
- ***Elbow***: often used in an air duct system. It can be rectangular or round. There are only six (6) types of 90° rectangular elbow (CR1, CR3, CR9, CR12, CR15 and CR16) available in the software database to reduce the complexity. The parameters for CR1 and CR3 are shown in Figure 6.9 a). The radius of the elbow is designed as an input variable. No additional input is required if user selects CR9, CR12, CR15 and CR16 (See Figure 6.9 b)).



a) b)

Figure 6.9 - Rectangular elbows.

There are four (4) types of 90°round elbow (e.g. CD1, CD5, CD9 and CD10), as shown in Figure 6.10, included in the software database. The dynamic loss of the round duct elbow is determined by its diameter. Therefore, no input is required by user.



a) b)

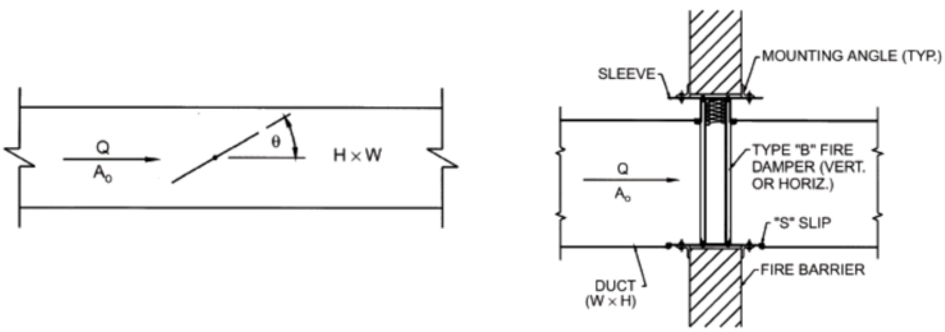
Figure 6.10 - Round elbows.

- ***Screen***: screens are recommended to be installed at the inlet of fans, or any location in a duct where needs to filter dust. There are two types of screens, i.e. rectangular and round (see Figure 6.11). Only CR6-1 and CD6-1 were used in the software database.

a) Rectangular screen b) Round screen

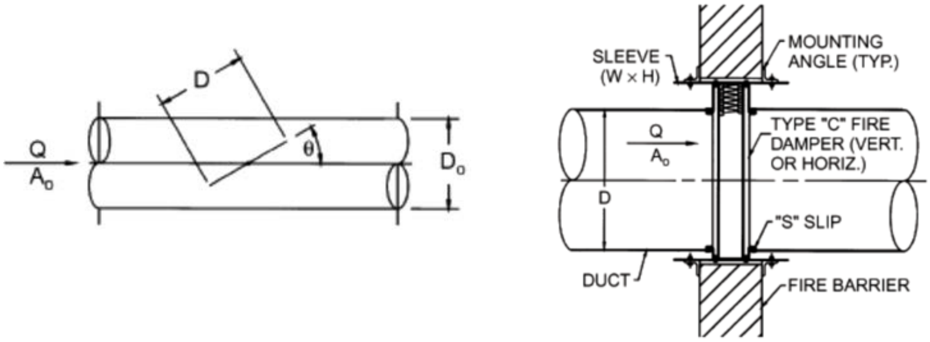
Figure 6.11 - Screens.

- ***Damper***: There are four (4) types of rectangular dampers are available in the software database (i.e. CR1, CR3, CR4 and CR6). CR6 is a fire damper, as shown in Figure 6.12, and no any input is required in this type of damper. However, the angle (θ) is an input variable for other types of dampers. Two types of round dampers are used in the software (i.e. CD9-1 and CD9-3). The latter is a fire damper, as shown in Figure 6.13. The input parameters for them are similar to that of the rectangular dampers.



a) Ordinary damper b) Fire damper

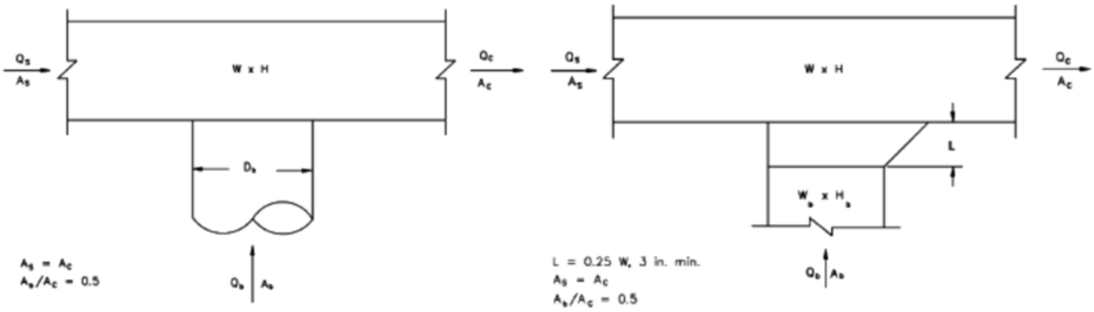
Figure 6.12 - Rectangular dampers.



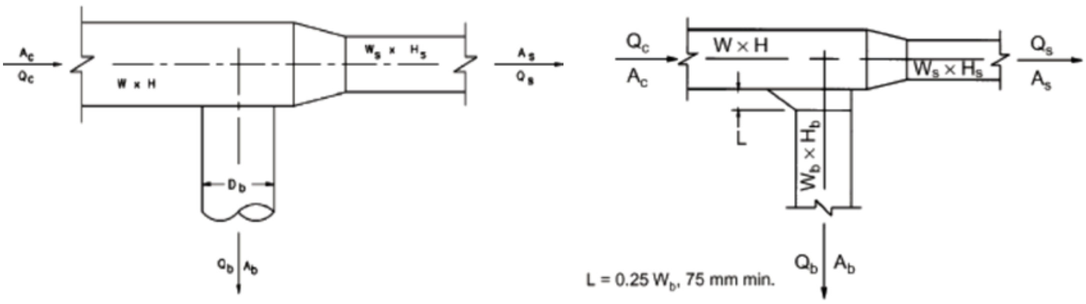
a) Ordinary damper b) Fire damper

Figure 6.13 - Round dampers.

- ***Tee***: Four (4) rectangular tees are available in the software (i.e. ER5-2, ER5-3 and SR5-13, SR5-15). The first two are for exhaust systems (see Figure 6.14 a) and Figure 6.14 b)) and the other two are for supply systems, as shown in Figure 6.14 c) and Figure 6.14 d). The flow rate ratio is also designed as an input parameter.



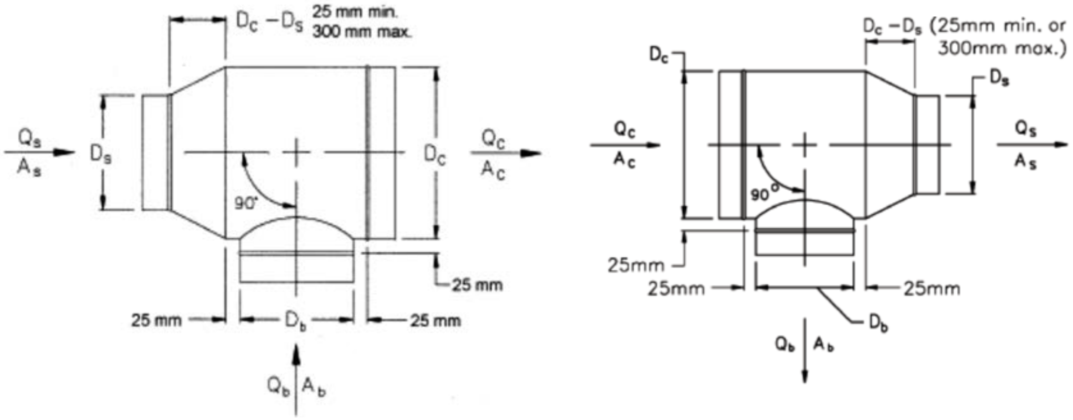
a) ER5-2 b) ER5-3



c) SR5-13 d) SR5-15

Figure 6.14 - Different types of tees.

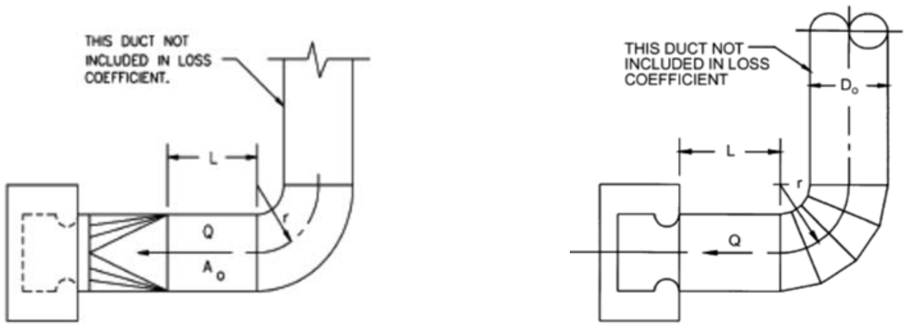
Three round tees are available in the system (i.e. ED5-3, D5-3 and SD5-9), as shown in Figure 6.15. The first two are for exhaust systems. ED5-3 is for the duct diameter less than 250mm, while D5-3 is for the duct diameter larger than 250mm. In contrast, the other one is for supply systems. The flow rate ratio is needed as an input parameter.



a) ED5-3, D-5 b) SD5-9

Figure 6.15 - Round tees.

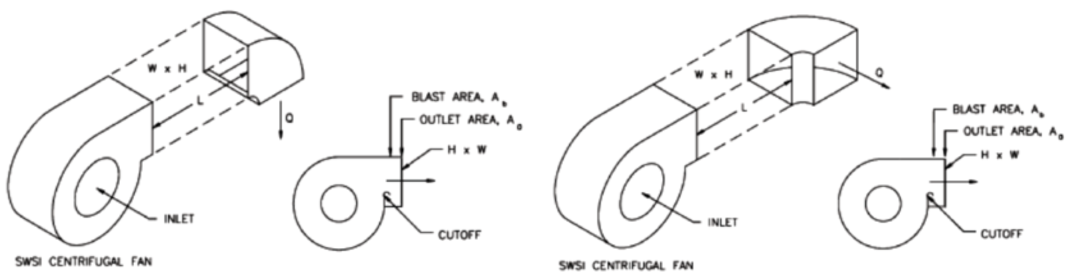
- ***Fan inlet***: only one rectangular fan inlet and round fan inlet are available in the software tool (i.e. ER7-1 and ED7-2), as shown in Figure 6.16. The parameters of the ratio of the duct section radium and height, and the inlet length and height are designed as the input variables.



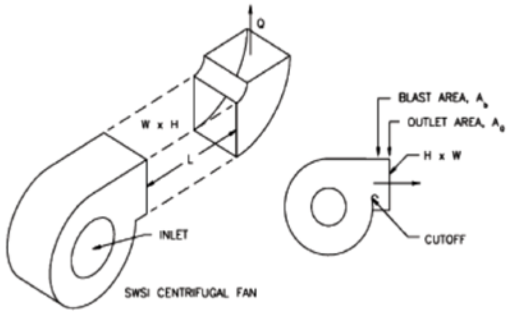
a) Rectangular fan inlet b) Round fan inlet

Figure 6.16 - Fan inlet

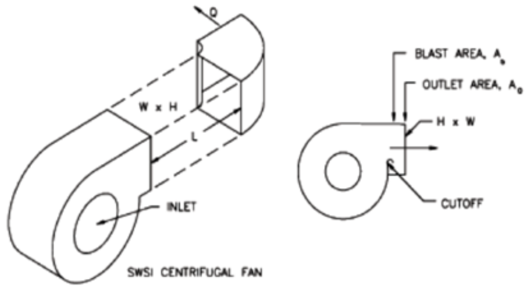
- ***Fan outlet***: only rectangular fan outlets are available. For a centrifugal fan, the inlet should be round, while the outlet should be rectangular. The outlets with different directions, as shown in Figure 6.17 should be selected. The ratio of the blast area and outlet area, and a special parameter named L/Le are designed as the inputs. The recommended value for L/Le is from 0 to 10.



a) A b) B



c) C



d) D

Figure 6.17 - Different rectangular fan outlets.

6.7 Major equations used

The Bernoulli equation as shown in Equation (6-1) was used to determine the pressure loss across an individual component in an air duct system.

$$\frac{1}{2}\rho V^2 + p + \rho g z = C \tag{6-1}$$

Assuming the constant fluid density in the system and considering the friction of fluid, Equation (6-1) can be re-written as Equation (6-2).

$$\frac{1}{2}\rho V_1^2 + p_1 + \rho g z_1 = \frac{1}{2}\rho V_2^2 + p_2 + \rho g z_2 + \Delta p_{t,1-2} \tag{6-2}$$

where Δp_t is the pressure loss of the air duct system caused by the fluid resistance, which should be conquered by the pressure difference supplied by fans.

The friction loss in each individual component is calculated by using Darcy equation below.

$$\Delta p_f = \frac{1000 fL}{D_h} \cdot \frac{\rho V^2}{2} \tag{6-3}$$

where, $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right)$; $\mathrm{Re} = \frac{VD_h}{1000\nu}$; $D_h = \frac{4A}{P}$ is the hydraulic diameter; ε is the roughness factor, dependent on materials and configuration of the ducts (Table.1).

The dynamic losses resulted from the flow disturbances caused by the duct mounted equipment and fittings that change the airflow path's direction and/or area can be determined by Equation (6-4).

$$\Delta p_j = C \cdot \frac{\rho V^2}{2} \tag{6-4}$$

where, C is the local loss coefficient, which varies with different fittings of components.

The total losses in the system can then be determined by Equation (6-5).

$$\Delta p_t = \Delta p_f + \Delta p_j = \left[\frac{1000\, fL}{D_h} + C \right] \cdot \frac{\rho V^2}{2} \tag{6-5}$$