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A Cooling and Heating solution for a house

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Abstract

The aim of this portfolio is to find the optimal solution for a cooling and heating system for a house in North Canberra using Systems Engineering approach. A whole-of-system approach was utilized to analyse the entire situation considering the requirement and limitations in order to find the most appropriate existing solution to this problem. The customer requirements were analysed and ranked using a HoQ, and the functionality and performance expected by the client was determined by carrying out functional analysis and it was decided that the optimal solution to this scenario is a Multi- split wall reverse cycle air conditioning system. This system was compared with several other feasible options in order to evaluate the satisfaction of the stakeholders' requirements. The entire portfolio highlights the Systems Engineering approach followed to arrive to the final solution using Systems Engineering concepts in order discover the ideal solution to the given scenario.

Introduction and problem background

The design problem addressed in this portfolio is a heating and a cooling system to a house. It is a two bedroom and a single brick (brick veneer) house which is approximately 180m^2. A brick veneer type of construction has an exterior brick skin on the outside and timber or a metal frame covered with plasterboard on inside [2, 3]. One of the main issues with this structure is the lack of insulation. Moreover the windows are single glazed and such glazing usually has a high U-value (U-value corresponds to the amount of heat/energy conducted through building materials or components under standard condition) reflecting low energy efficiency. It is also mentioned that the house receives afternoon sun.

The stakeholder in this problem is a university student and the main requirement of the design solution is heating and cooling facility considering low ongoing cost, aesthetics and safety. Based on the stakeholder's preferences and expectations on the solutions, the requirements for the design solution will be further analysed in the Requirements engineering concept.

Requirements Engineering

Based on the stakeholder's concerns on the heating and cooling system, the customer requirements were listed and analysed using pairwise analysis. During this process, low ongoing cost (cheap), aesthetics and safety were given priority as they were considered to be mandatory requirements by the client.

	cheap	looks good	safe	set-and-forget	cooling and heating	use heat to dry clothes in winter	low maintenance	durable	score	rank
cheap		1	0	1	0	1	0	1	5	3
aesthetics	0		0	1	0	1	0.5	1	4.5	4
safe	1	1		1	0	1	1	1	7	2
set-and-forget	0	0	0		0	1	1	0	3	7

cooling and heating	1	1	1	1		1	1	1	8	1
use heat to dry clothes in winter	0	0	0	0	0		0	0	0	8
low maintenance	1	0.5	0	0	0	1		0.5	4	5
durable	0	0	0	1	0	1	0.5		3.5	6

Table 1-pairwise analysis

In the pairwise analysis, 0.5 marks were assigned in order to assign separate ranks for durable, low maintenance and looks good customer requirements, since they all had the same rank of 4 in the initial analysis. The top customer requirements were ranked as follows.

1. Cooling and heating
2. Safe
3. Cheap
4. aesthetics
5. Low maintenance

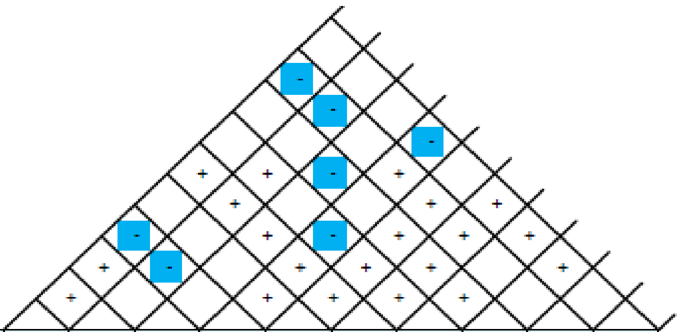
Although the customer has mentioned the system to be a ‘set-and-forget’ system, during the pairwise analysis, it was decided that the low maintenance and durability are more important than implementing a smart system considering the cost constraints

In addressing the design problem, several existing solutions that can be applied to the given scenario were consulted.

One of the common solutions is the installation of cavity wall insulation into the existing brick veneer wall as this can prevent up to 85% of heat transfer through the walls increasing the EER (energy efficiency rating) by 1 or 2 stars. Moreover this also increase the R value up to R3.4 [4]. The insulation instalment for existing brick veneer walls can be done either by removing the internal wall lining or insulating material such as rock wool, polystyrene boards; and polystyrene beads , glass wool can be pumped into the wall cavity via loose-fill cavity insulation[2]. Another possible solution is the replacement of single glazed windows by double glazed glass. However provided the customer is a tenant and the above mentioned solutions involve high installation cost, above mentioned solutions will be given a low priority.

Another feasible solution to this problem is the installation of a heating and a cooling system. Possible existing designs involve heaters and air conditioners. Since the customer requires both cooling and heating facilities, the design requirements and engineering characteristics will be determined for a reverse-cycle system in in order to produce a House of Quality for further analysis.

Figure 1- House of quality for the reverse cycle air conditioning system



Relative Importance	Column #	1	2	3	4	5	6	7	8	9	10
	Direction of Improvement	+	+	+	-	-	*	-	-	-	*
	Customer Requirements (Explicit and Implicit) / Functional Requirements	Air flow rate	Fan speed	height of outdoor air intake location	power consumption	number of parts	dimensions	start up time	user involvement	oprational noise level	performance of inverter DC motor
1	Effective cooling mechanism	9	9		-3		3	3			9
2	Effective heating mechanism	9	9		-3		3	3			9
3	Safe to operate			9					3		
4	Minimize ongoing cost	-3	-3	3	9	9	3	3	3		3
5	Minimize operational steps								9		3
6	Quiet	-1	-3		-1	-1				9	-1
7	Automatic temperature control	3	3		-3			9			9
8	Minimize temperature switching time	3	3		-3			9			9
9	measurement metric	[illegible]	rpm	m	kW	number	m	s	Joules	dB	Joules

The HoQ emphasizes several important points

- Height of the outdoor air intake location is important for the safety since it reduces the polluted air and dust intake, and also it minimizes the ongoing cost as it reduces the maintenance cost of the filters.
- A key observation from the HoQ is the large relationship between effective cooling/heating mechanisms with the functional requirements such as air flow rate, fan speed and inverter DC motor performance. Therefore it is clear that, improvement of those engineering characteristics will have a major improvement in the functionality. Moreover it is evident that optimized performance of the inverter DC motor has positive impacts on most of the DRs. It minimizes the temperature fluctuations and allows quick switching between cooling

and heating options by reducing the start-up (response) time and also increases the energy efficiency reducing the cost.

- Moreover, it is clear from the HoQ, that optimization of dimensions has a positive correlation on all the engineering characteristics. Due to the minimum contamination of dust and other pollutants, there is a correlation between height of outdoor air intake and the air flow rate. However there is a trade-off between this installation height and the user involvement, due to troublesome maintenance.
- More importantly, the HoQ highlights that low ongoing cost and effective cooling/heating are highly involved in the design requirements and this suggests that those DRs should be given priority in proposing a design solution.

Functional analysis

Functional Flow Block Diagram (FFBD)

The functional and performance requirements identified by the HoQ are transformed into a coherent description of system functions using functional analysis via a Functional Flow Block Diagram (FFBD). The following FFBD provides a description of the functional architecture of a reverse cycle air conditioning system in terms of functions and performance parameters [5] providing a logical sequence of the functions and performance requirements related to each function.

The top level of the FFBD indicates the general process that should be followed in order to heat or cool a space using a general reverse cycle air conditioner. The second level expands specifically targeting the way the top level functions are conducted. The process 1.0 to 2.0 indicates the 'GO' path and 'NO GO' path indicated from 5.0 to 11.0 demonstrates the MFBD (Maintenance Flow Block Diagram) for the design. Looking at the FFBD(2.0 to 3.0), it is obvious that the proposed technology is easy to use and provides the 'set-and-forget' option required by the stakeholder. Once the desired setting is chosen, the desired temperature will be maintained in the specified area until the system is switched off. (This is provided by the Graphical User Interface of the controller.). Moreover, this design supplies both heating and cooling facilities on the same devise under different options eliminating the costs for maintenance and installation of two separate devices for heating and cooling. Furthermore the system involves less frequent and simple troubleshooting /maintenance which don't require much technical knowledge.

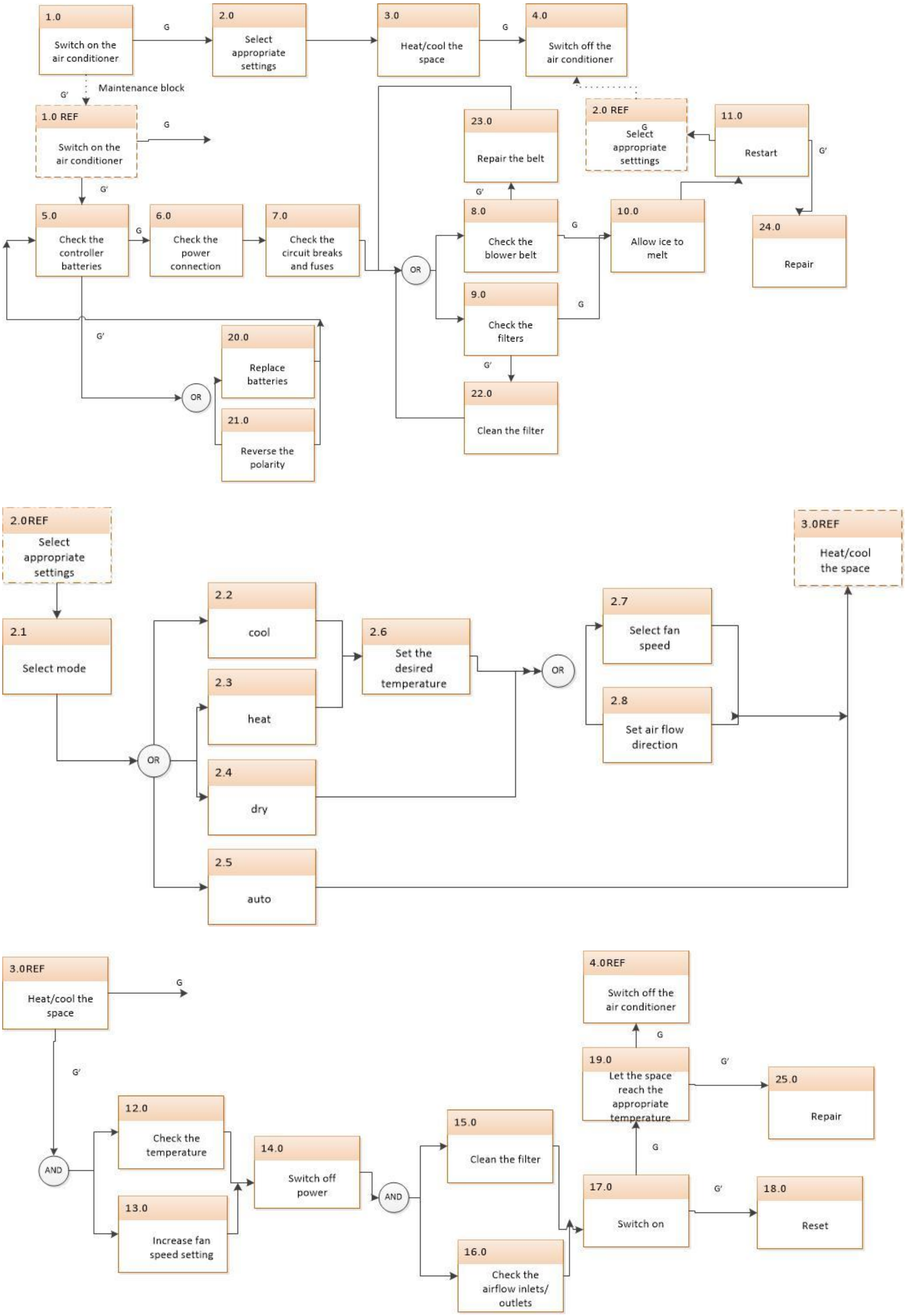


Figure 2-Functiinal Flow Block Diagram for the heat pump

Concept generation

Since ‘a conventional solution to one sub problem can frequently be combined with a novel solution to another sub problem to yield superior overall design [6]‘, products and technologies related to solving the mentioned engineering problem will be considered during the concept generation. Due to the high impact of the DRs such as effective cooling and heating on the functional requirements, the concepts will be generated around those DRs and then the search will be narrowed down by eliminating less feasible options based on the limitations in the problem and DRs.

1) cooling
   a) fans
   b) evaporative cooling
   c) air conditioning
      i) portable split air conditioning
      ii) portable single duct air conditioning
2) Heat exchangers[1]
   a) Reverse cycle system
   b) geothermal systems
   c) solar air cooling
3) wall insulation
4) window glazing
5) Electric slab heating
6) heating
   a) central heating
      i) duct air
      ii) hydronic systems
   b) space heating
      i) electric heater, electric portable heater, convector heaters with air, oil-filled column heaters
   c) electric fixed heater
   d) gas heater
   e) wood and other solid fuels
   f) heat shifter
   g) solar air heater

The options highlighted in blue were eliminated from the list due to various reasons. Wall insulation, heat shifter and window glazing were eliminated due to the customer being a tenant. Also electric slab heating can only be installed during construction. Space heating is only effective for smaller areas and are expensive to run and inefficient. Wood heaters were considered to be low in safety and inconvenient to use indoors. Solar air heater has a high initial investment cost, although it is considered to be energy efficient, it doesn’t necessarily adds heat to the house. Fans were also considered to be inefficient, since it is unable to lower the temperature by a significant amount. [1, 4].

Out of the feasible options, the most attractive heating/cooling systems are considered to be the reverse cycle air conditioning systems (heat pumps), as it provides both cooling and heating in a single system and are relatively high energy efficiency. Thus, these designs are also cost effective. Therefore from this point, this portfolio will only focus on multi split wall heat pumps which implement the same technology as the single standard split wall reverse cycle air conditioning system, with multiple indoor units attached to a single outdoor unit. This single standard split wall heat pump has an approximate coverage area of 100m^2, and it is fair to assume that an efficient heating and cooling can be obtained by a dual indoor unit – single outdoor unit system or more than two indoor units depending on the number of rooms and client's preferences.

Subsystems integration

In order to further analyse the proposed system, it was necessary to identify the required components, defining the individual subsystems with high internal complexity and minimise the external interactions with other packages[7]. This process was accomplished using a System Boundary Chart which was translated into a System-Subsystem Diagram via a Functional Block diagram.

System Boundary Chart

Endogenous	Exogenous	Excluded
inside coil	user input	price of electricity
outside coil	hot air	power failure
compressor	cold air	
reverse valve	electricity	
user interface		
power system		
control system		
motor system		

Table 2-System boundary chart for a heat pump

The internal variables of the design architecture consist of the subsystems of a general heat pump system. The exogenous variables of the system include the input and outputs to the system. Hot air will be considered as an output of the system under heating and whereas cold air will be considered as an output under cooling.

The excluded variables include the price of the electricity, since the price of the energy sources and rise of the price can't be controlled. The power pump can't be operated without electricity. Hence the system is not resistant to power failures and the heating and cooling terminate under a temporary withdrawal or failure of an electrical power supply. This defines the limitations of the proposed solution and a future improvement might be to introduce a heating/cooling system which is operates on a more effective source of energy.

Functional Block Diagram

According to Weilkiens, it's important to analyse the type of embedding for a proper integration system and surrounding to prevent negative consequences in the performance[8]. An elaborate system interface for the proposed solution is constructed by generating an FBD as shown in figure 2. The dotted line is the system boundary and surrounds the system blocks. In addition, all the currently known external variables are denoted all around the system and associations are used to link them[8].

The design architecture consists of 7 subsystems, some of which are partitioned further. Depending on the functionality (cooling or heating), inner unit and the outer unit interchangeably becomes either evaporator or condenser. This FBD illustrates the satisfaction of the product aesthetics mentioned under customer requirements due to interaction of user via the GUI. The control system consists of the software, circuitry and the thermostat sensors, and controls the entire system.

The two main functions of the heat pump are cooling and heating, and those two processes can be interpreted as follows. In the cooling mode, the compressor pumps the refrigerant to the reversing valve and then it will be directed to the outside coil, in which the refrigerant transfers its heat to the air flowing across the outside coil (condenser). Then the liquefied refrigerant flows into inside coil, then it absorbs heat from the air blown across the inside coil and that 'cool' air will be blown into the home. The refrigerant flows back to the reversing valve, then to the compressor, to continue the cycle. In the heating mode, the refrigerant will be pumped to the inside coil from the compressor via the reversed valve and heat is transferred from the refrigerant to the air and that 'hot' air will be circulated across the home. The liquefied refrigerant will flow back to the compressor and will continue the cycle [9, 10].

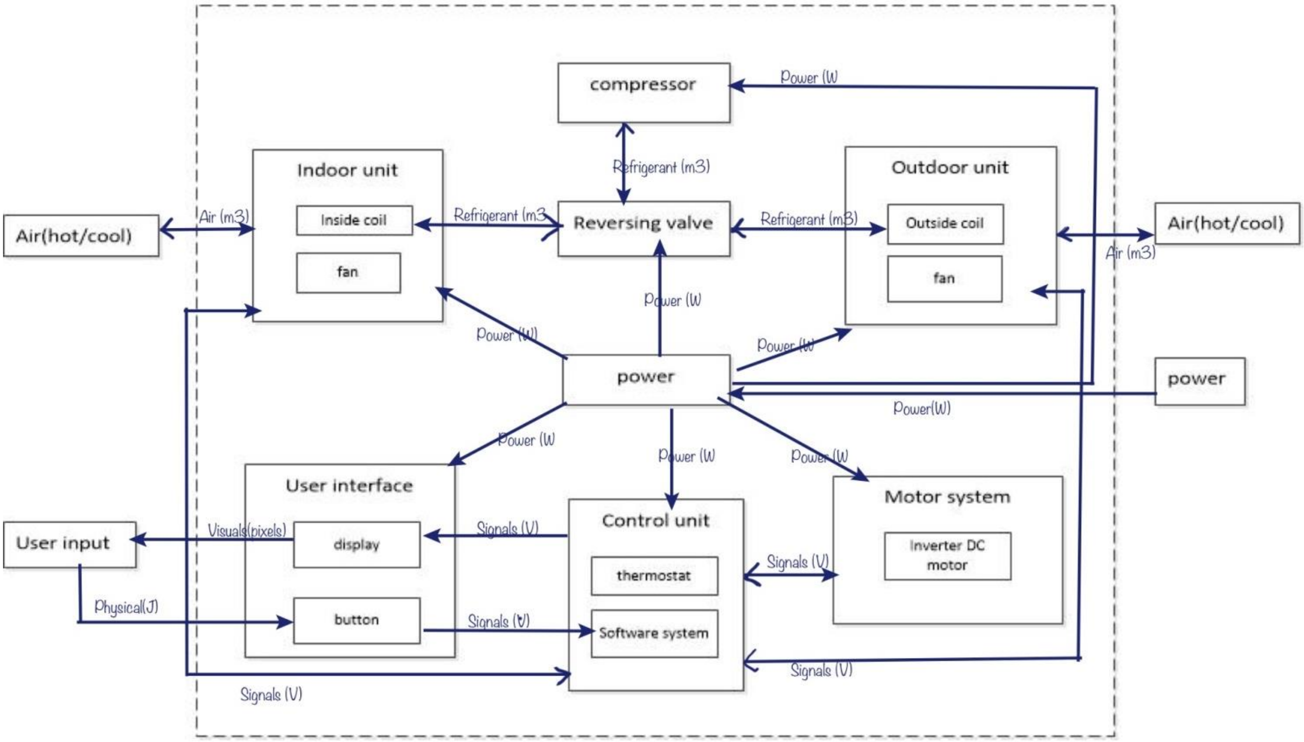


Figure 3-Functional Block diagram for the heat pump

Among the subsystems indicated in the FBD, the coils, compressor can be regarded as the predominate subsystems. It is clear from the diagram that, there exist strong relationships between those subsystems and can be integrated into a single subsystem due to its external complexity. However, for the sake of demonstrating the functionality of the heat pump and due to the physical architectural restraints (inside unit and outside unit are two physically separate subsystems in the actual design), those 3 will be left as separate subsystems.

System attributes

This section, relates the design requirements to the subsystems of the heat pump and these attributes define the non-functional operations or characteristics of the system[11].

Attributes Cascade

Primary attributes	Secondary attributes	Tertiary attributes	Subsystem

A1.0 Effective cooling mechanism	A1.1 automatic fan speed	A1.1.1 adjustable speed	IU,OU
		A1.1.2 Responsive speed	IU,OU
	A1.2Maximum air flow	A1.2.1 Appropriate auto swing design	IU,OU
A2.0 Effective heating mechanism	A2.1 automatic fan speed	A2.1.1 adjustable speed	IU,OU
		A2.1. 2 Responsive speed	IU,OU
	A2.2 Maximum air flow	A2.2.1 Appropriate auto swing design	IU,OU
A3.0 Safe to operate	A3.1 no current leakage	A3.1.1 proper insulation	all
A4.0 Low cost components	A4.1 low cost materials	A 4.1.1 low cost conductors for coils	IU,OU
A5.0 energy efficient	A5.1 minimum heat loss	A5.1.1 high thermal conductivity in coil	IU,OU
		A5.1.2 high thermal conductivity of refrigerant	IU,OU, compressor, reverse valve
	A5.2 reduce peak power consumption	A5.2.1 adjustable speed of compressor	compressor
A6.0 minimum operational steps	A6.1 simple user interface	A6.1.1 big display	interface
		A6.1.2 big buttons	interface
A7.0attractive design structure	A7.0 appropriate size	A7.1 minimum sized components	all
A8.0quiet	A8.0 minimum operational noise	A8.1.1 optimised fan speed	IU,OU
		A8.1.2 optimised inverted DC motor speed	motor
A9.0 easy to clean	A9.1 accessible parts	A9.1.1 Smooth panel surface	IU
A10.0 sturdy construction	A10.1 high quality materials	A10.1.1 long lasting materials	all
		A10.1.2 anti-corrosive materials	all
A11.0 automatic temperature control	A11.1 automatic restart	A11.1.1 effective memory usage	control
		A11.1.2inbuilt software	control
A12.0 minimum temperature switching time	A12.1 minimum time to reach desired temperature	A12.1.1 high performance of the inverter DC motor	motor
	A12.2 minimum temperature fluctuation	A12.2.1 high performance of the inverter DC motor	motor

Table 3-Attributes cascade for the heat pump (IU-inside unit, OU-outside unit)

Several conclusions can be drawn from the attributes cascade. Firstly the Inside coil and outside coil appear several times and this suggest that these subsystems are the most important subsystems in the design architecture. However the compressor subsystem appears only once in the attributes cascade and it is theoretically possible to merge this subsystem with another subsystem which is highly associated with the compressor subsystem. However in considering the physical architecture of the actual design, it is clear that this is not an appropriate suggestion since these modifications can change the system functionality. Furthermore this also reflects the satisfaction of the top most customer requirements, ‘effective cooling and heating’ as most frequently appearing subsystems are related to those DRs.

Verification and evaluation

In this section, the solution is validated through performance of few tests in order to evaluate the system performance against the customer requirements. Moreover evaluation matrices were constructed in order to evaluate different feasible design options against the stakeholder's requirements. Proof-of–concept and prototype tests are proposed to check if the suggested solution meets the CRs.

Validation

Proof-of-concept test

Attribute: A10.1.2 Anti-corrosive material

Test person: Chemist

Pass/fail criteria: +/- 5% change in the weight of the sample metal is deemed fail

Procedure:

1. Take 2 samples of the testing metal of same size, volume (high surface area) and weight.
2. Keep one sample (sample1) in a controlled environment and expose the other (sample2) to exact conditions present in/around the multi-split reverse cycle system.
3. Measure the percentage change in weight of the two samples every week.
4. Change the temperature and humidity surrounding sample 2.
5. Measure the percentage change in weight.

In this Proof-of-concept test method, a simple chemical test is used to find the corrosion of the selected metal. If the change in weight is -/+5% of its original weight, the test will be deemed fail due to the high rate of reaction of the metal which lower the performance and durability of the design.

Prototype test:

Attribute: A12.1Minimum time to reach desired temperature

Test person: Stakeholders

Pass/fail criteria: The rate of change of temperature less than 2'C/min is deemed fail

Procedure:

1. Set the temperature to the minimum value using the controller
2. Measure the temperature of the room using an appropriate thermometer
3. When the temperature comes to minimum stable value, increase the temperature by 2'C and measure the time take to achieve the chosen temperature.
4. Repeat the test starting from the maximum stable value and drop the temperature by 2'C.
5. Record the time taken.
6. Calculate the average rate of change of temperature.

Evaluation matrices

In this section several feasible options will be compared against several prioritized criteria inherited from the customer requirements in the pairwise analysis and HoQ. The evaluation process will be done in two levels under mandatory criteria and desired criteria.

First level Evaluation matrix against mandatory criteria

The top 4 customer requirements from the pairwise analysis are considered as the mandatory criteria for this evaluation matrix. The feasible options are listed as follows;

Option 1: multi split wall reverse cycle system
Option 2: ducted reverse cycle system
Option 3: cassette reverse cycle system

mandatory criteria	option1	option2	option3
effective cooling and heating	pass	pass	pass
safe	pass	pass	pass
low ongoing cost	pass	pass	fail
aesthetic	pass	pass	pass

Table 4-Evaluation matrix against mandatory criteria

According to the first evaluation, it is clear that cassette reverse cycle system is not considered as a feasible option since it fails to meet one of the mandatory criteria. Although the cassette reverse cycle system has a strong and effective cooling and a heating system, the overall system is expensive to operate and also has limited installation options which again leads to high installation cost[12]. Since cost efficiency was prioritized by the customer, this option will be excluded in the second evaluation.

Second level Evaluation matrix against mandatory + desired criteria

SCALE
5=Exceeds compliance
3=Full compliance
1=Partial compliance
0=Non-compliance

	weighting		option1		option2	
	rank	weighting	relative compliance	weighted value	relative compliance	weighted value
cooling and heating	1	8	5	40	3	24
safe	2	7	5	35	5	35
cheap	3	6	3	18	1	6
aesthetic	4	5	3	15	3	15
low maintenance	5	4	3	12	3	12
durable	6	3	3	9	3	9
set-and-forget	7	2	5	10	5	10
use heat to dry clothes in winter	8	1	0	1	0	0
	totals			139		111

Table 5-Second level evaluation

The approach utilized in scoring is given on the left hand side of the evaluation matrix. From the second level evaluation it is evident that the option 1 surpasses option 2 by approximately 25%. The approach utilized in scoring is given on the left hand side of the evaluation matrix. The greater score achieved by option 1 indicates that, split reverse cycle system satisfies more criteria that have been determined to be greater importance under the given limitations and conditions, than ducted reverse cycle system.

Note that the difference in the total scores for the two options was mainly caused in evaluating the satisfaction of effective cooling and heating and cost efficiency criteria. Given that the area of consideration is small, option 2 is more expensive than option 1. Moreover the option 2 uses more electricity even in their most economical modes and has a high installation cost. Although option 2 is able to cool and heat the entire house via a system of ducts, it might not be the best option in terms of the efficiency, provided that the client only requires to heat and cool certain spaces in the house and the house has a poor insulation. If the house had good insulation with double or triple glazed windows and the central heating/cooling were an customer requirement, ducted reverse cycle system might be a better option than multi-split reverse cycle system where several inside units are connected to a single outside unit.

Design communication

The final section of this portfolio focuses on the effective communication of this solution, since this enables to communicate the benefits of the solution to the customer. In order to make a convincing case for implementation of the given design, a meeting with the customer is required and also it is important to inspect the housing space where the system is being installed in order to suggest further modifications to improve the cost efficiency and energy efficiency, providing maximum customer satisfaction. Specially, in implementing a multi-split reverse cycle system, the number of inside units depends on the housing structure. Moreover, a flyer was produced in order to convey the proposed solution based on the provided customer requirements and limitations. Since the limitations were vaguely phrased by the stakeholder, the flyer will provide additional feasible options that can be applied to the problem along with some recommendations.

Conclusion

This portfolio highlights the use of Systems Engineering approach to find an optimal solution for a heating and a cooling method for a house in North Canberra. It was decided through a complete Systems Engineering design approach that the optimal solution for this problem is a Multi- split wall reverse cycle air conditioning system in order to satisfy the maximum customer requirements under the given conditions. A flyer was produced in order to educate and convince the stakeholders about this solution. However the implementation details and cost of the whole process is yet to be determined since it depends on the housing structure and it was decided that further implementation details and procedure will be considered after the physical examination of the architecture of the house.

Multi split reverse cycle air conditioning system

MULTI SPLIT REVERSE CYCLE SYSTEM

***This 2 in 1 cooling and heating system allows temperature* control for homes during climate changes.**

Another temperature controlling system which uses the same reverse cycle system or heat pump is, Ducted reverse cycle system. This system is also a potential candidate for climate control depending on the client's preference and physical limitations.

System advantages

- **Reverse cycle**

  The multi split reverse cycle system operates in both cooling mode and heating mode.
  Ideal for homes that experience seasonal low and high temperatures
  Can have multiple indoor units attached to a single outdoor unit allowing better temperature control for individual zones
- **Energy efficient**

  Consumes less electricity
  Smart control options are available to continually adjust power required for heating and cooling to suit the temperature.
  Better energy efficiency when multi units are used
- **Cost effective**

  Reduces the initial cost of purchase and installation cost since a single system will be installed instead of two separate cooling and heating systems.
  Efficient energy consumption of the system lowers the energy bill.
- **Safe**

  No exposed elements or flames in the indoor system
  Easy and simple maintenance
- **Aesthetic**

  These reverse cycle air conditioners are available in different sizes and this allows the client to choose the right size for the need, since the size of any cooling/ heating system directly effect on the performance.
  Quiet
  Easy to operate and usually comes with a user friendly controller
- **Set-and-forget**

  Automatic switch between heating and cooling modes
  Most of the split reverse cycle systems come with a timer
  Most of the systems have the ability to memorize the modes, air flow and temperature settings.
  Reaches the required temperature quickly with low start up time.

Comparison of Split reverse cycle system with Ducted reverse cycle system

split reverse cycle system	**Ducted reverse cycle system**
operates in both heating and cooling modes	operates in both heating and cooling modes
uses less electricity	uses more electricity
can be used in both small and large areas depending on the number of inner units	suitable for large areas (single solution for the entire house)
relatively low installation cost	relatively high installation cost
relatively simple to install	complicated to install

Recommendations to further increase the energy efficiency

- Addition of insulation to existing brick veneer walls using specially treated loose fill cavity insulation using rock wool, polyester, natural wool etc. as insulation batts.
- Replacing the single glazed windows with either double glazed or triple glazed glass.
- Managing the bright afternoon sun by installation of room darkening curtains, shutters or blinds.

Figure 4-The flyer produced for the effective communication of the solution

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