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An Efficient Heating and Cooling System for a Rented House

NAME: Gavin Saldanha

UNI ID: u5293105

TUTORIAL GROUP: W11R

Abstract

This report focuses on how an effective solution could be maintained to solve a heating or cooling system within a rented apartment in Canberra. This was best utilised via a systems engineering design through a multitude of analytical techniques to develop solutions and compare them via testing mechanisms. A seemingly holistic approach was undertaken upon designing systems so that every component works together with different interpretations, which would all be kept under constant corroboration and feedback to support the claims that would be aforementioned. Ergo, the theory and application for each step of the design process is constructed and applied to solve the client's heating/cooling system.

Introduction

Heating in Canberra has been considered as a necessitate luxury required by many to face the harsh winters that it imposes upon its people. Despite its dry climate due to the inland geographical location where Canberra is situated, the westerly winds can cause temperatures to hit 0 ºC, whereas the hotter months in the summer can cause temperatures to rise up to 40 ºC (Climate of Canberra Area, 2010). This can cause huge implications upon setting up an ideal heating system during the winters, yet retain its coolness during the summer as such systems could cost an exorbitant amount due to gas or electricity bills.

A systems approach must therefore be implemented to create a moderate room temperature within the apartment and with consideration of factors such as the expenses and the functionality. Our client had requested for a system which was not only just safe, but looked aesthetically pleasing and did not need to have an ongoing cost. Our client also expressed strong viewpoints for being cheap to maintain on a long run, as well as a system that would solve the heating and cooling solution once and for all. It shall also be assumed that the user already has a heating system installed and would like to reduce its consumption by proposal of an enhanced system. Unfortunately, more impactful systems will intuitively be discarded as the presence of the landlord hinders systems that could cause architectural changes. Hence, a complete and holistic systems method will be presented to exude how the insulation problem was dealt with.

Requirements Engineering

Upon receiving a set of prerequisites from the client, it was necessary to contrast the requirements with each other and observe for any notable changes and long-term effects in the system proposal. This requires a complete expansion of the prerequisites into more technical and engineering aspects such as a House of Quality, where it could expand on what factors of primary interest our system may need to convey (Shillito, 1994).

Since the customer had placed an urging need for numerous prerequisites, a comparison chart, also known as a Pairwise Analysis which ranks requirements individually was created to help grasp an enhanced opinion of what the client had requested (Dym & Little, 2008). The extension of such requirements were subdivided to design and engineering characteristics, where quantifiable measures were placed to assess the performance of the system via a Technical Measures System (Blanchard & Fabrycky, 2011).

1: More important **0: Less important**	Functionality	Cost	Aesthetics	Quick Installation / Setup	Safety	Score	Rank
Functionality		1	1	1	1	5	**1**
Cost	0		1	1	0	2	**3**
Aesthetics	0	0		1	0	2	**4**
Ease of Use	0	0	0		0	1	**5**
Safety	0	1	1	1		3	**2**

Table 1: A comparison chart to rank the requirements.

Customer Requirement	ID	Design Requirement
Functionality	DR01-01	Effective heat retainment
	DR01-02	Warms efficiently
Safety	DR02-01	Reduced risk of injury
Cost	DR03-01	Low initial cost
	DR03-02	Low ongoing cost
Ease of Use	DR05-01	Minimal installation time
	DR05-02	Easy to handle

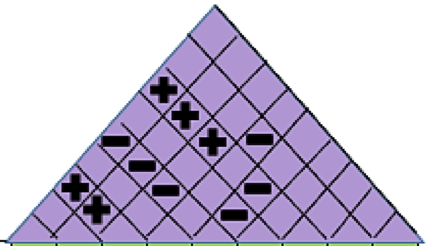
Table 2: Expansion towards design requirements in the new system.

ID	Design Requirements	Engineering Characteristics		TPM
DR01-01	Effective heat retainment	+	Thermal resistance	m^2K/W (meters squared Kelvin per Watt)
		+	Thermal capacity	J/K (Joules per Kelvin)
DR01-02	Warms efficiently	-	Heat loss	%
DR02-01	Reduced risk of injury	-	Fire/electricity hazards	%
DR03-01	Low ongoing cost	-	Maintenance cost	$ (AUD)
DR03-02	Low initial cost	-	Materials cost	$ (AUD)
DR05-01	Minimal installation time	-	Time for installation	Seconds
DR05-02	Easy to handle	-	Time taken in usage	Seconds

Table 3: Consideration of engineering ideals with how the system would perform them.

It can be observed that the initial requirements become less vague when they are expanded. A notable expansion would include the expenses within the system as these can be classified to initial costs when the new system is being implemented onto the apartment, or other ongoing costs which would occur in the long run such as how much would the expenses decrease to once the new system is implemented. It was assumed that the client would also want to easily manipulate the new system, which was why an easier usage handling with less installation time was characterized.

These design criteria were to provide more context for technical measures in the new system. Thermal engineering techniques were adopted to this consideration, as observed in thermal resistance and thermal capacity. These two aspects are very important in the field of thermodynamics – a higher thermal resistance would indicate a less reduction in heat transfer back to the surroundings, whereas a higher thermal capacity indicates that more amount of energy would be required to cause a change in temperature (Princeton, 2012). The reason why such options were desired is because Canberra is noted for its bright sunshine even during the winter (Climate of Canberra Area, 2010) which means that whilst thermal energy is preserved within the apartment, it would take a longer time to heat up further from the new system to the inside surroundings, thereby creating a cooler environment at the same time. Other quantifiable expansions include the maintenance cost and the time for installation, so that the initial setup is created rapidly with less hassle.



✚ : Positive (Correlation)
▬ : Negative (Trade off)

Relationships:
1: Weak
3: Medium
9: Strong

m^2K/Ws: metres squared Kelvin per watt
J/K: Joules per Kelvin
$: Australian Dollars
kW/s: kilowatts per second
s: seconds

ID	*DESIGN REQUIREMENT*	*RELATIVE IMPORTANCE*	Thermal Resistance	Thermal Capacity	Heat Loss	Fire/Electricity Risk	Materials Cost	Maintenance Cost	Electricity Usage Per Cost	Time for Installation	Time Taken in Usage
			+	+	-	-	-	-	-	-	-
DR01-01	Effective heat retainment	1	9	3	9		9		9		
DR01-02	Warms efficiently	5	9	3	9	1	9		9		
DR02-01	Reduced risk of injury	2				9	3	3			
DR03-01	Low ongoing cost	3	3		9		3	9	9		1
DR03-02	Low initial cost	4	3		9	3	9			1	
DR05-01	Minimal installation time	6			3					9	
DR05-02	Easy to handle	7									3
		TPMS	m^2K/W	J/K	%	Y/N	⇔	$	kW/S	s	s

Figure 1: A House of Quality matrix to analyse the requirements from the engineering characteristics.

A House of Quality matrix, which compares the design requirements to the engineering characteristics, can help stipulate the relationships and further importance in our design phase of the system (Hauser & Clauding, 1988). It is quite evident that thermal capacity and resistances must have strong relationships with most of the design requirements, however cost considers the most relationships as affecting the cost can not only affect what material type it is, but also the new system might be made of cheap impermanent material that can cause hazards. On the other hand, trade-offs and correlations between characteristics can provide a sense of corroboration to each other when the system will be instigated. As expected, cheap costs will always have a trade-off with thermally capacitive or resistant materials as these materials will remain expensive for its properties. Consequently, the latter will have correlations with electricity intake as this will decrease the usage of heaters or fans.

It might seem counter-effective over having a high thermally resistive material during the summer, as that would seemingly cause more heat to be trapped. However, due to the nature of the seasonal changes that causes high-angled sunlight to majorly occur during the summer, materials which successfully block high-angled sunlight and allow low-angled sunlight to flow through should be considered (Khavrus & Shelevytsky, 2010). Unfortunately, these materials are still hypothetical and will not be considered within the system, but will rather be a matter of discussion.

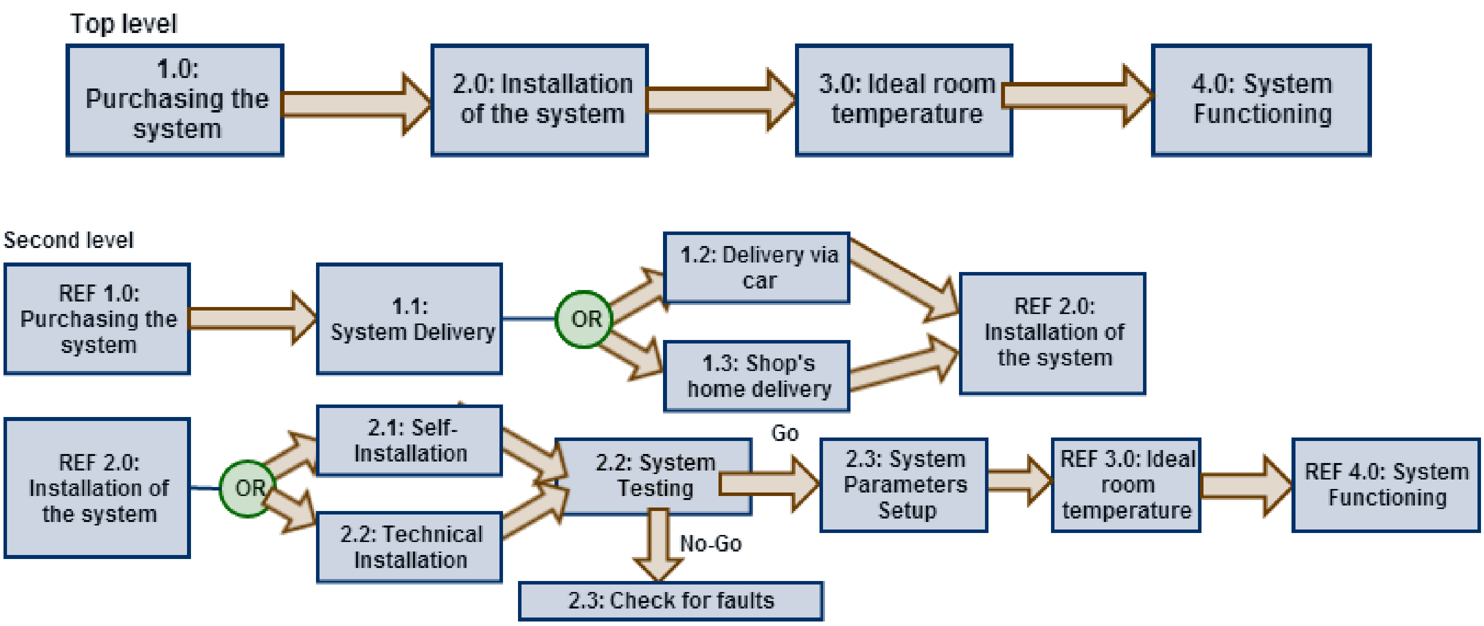
Defining the System's Functions

Using the tools that were previously used to create a refinement of the client's needs, the system must be defined to provide an overview of how the new system implementation should take place. Whilst a Use Case describes how the system would respond to a request from a stakeholder (Cockburn, 2001), further analytical techniques such as generating concepts to come up with solutions based on the structural flow of the new system via a functional flow block diagram would express a brief outcome of the new system (Ulrich & Eppinger, 1995), hence reducing the probability in overlooking requirements and design functions (NASA, 2007).

The Use Case might seem simplistic since the system to be reflected upon was only constrained to a student's house. Therefore, the system will primarily affect the "Client", or the university student. However, other "actors" might also play a role in the new system:-

- Guests of the university student will face similar use cases like the Client; however due to the temporary nature of their visit, they might exhibit different behaviour from the Client. Guests will also include family members and close friends of the Client.
- Landlords will play a more vital role as the house is currently under their name. Whilst the client normally influences what the design should be, the landlord will have more precedence as only certain concepts that require the redesign of the house will be discarded. If the concept is shown to cause more ongoing maintenance, those concepts could possibly be discarded too.

A vital aspect of systems engineering before discovering the various concepts is to have an impression of how the system will run through, or "flow". By creating functions sequentially and determining the lower-level functions, as well as the performance requirements that are coupled with the functions. These relationships are best defined with a Functional Flow Block Diagram (FFBD), as shown below. Due to the trivial and short-lived usage within the heating systems, a more generic FFBD with installation will be studied.



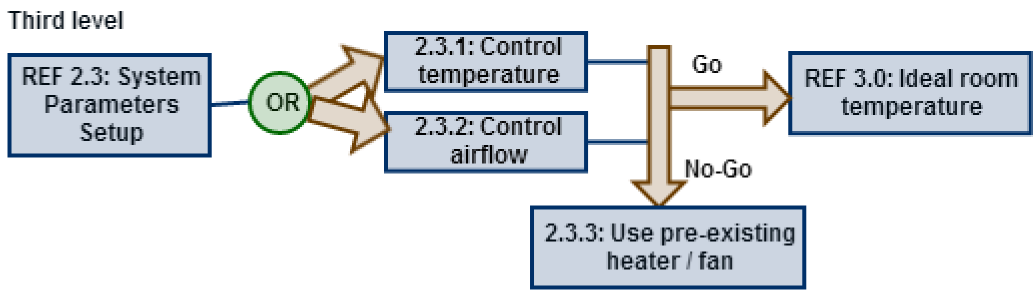


Figure 2: Functional flow block diagram of the new system processes.

The top level should iterate the basic needs once the concept is selected, i.e. purchase, installation, and reaching an ideal setting for the room temperature. As reiterated before, the student is assumed to already have a pre-existing heating/cooling system, however the new system will attempt in minimalizing (or even ceasing) as much of that system's usage due to the electricity costs involved with the pre-existing systems.

The purchase and delivery of the system is shown to be divided in two ways: if the delivery involves heavy tools or if the client does not have a car, it would make it more sensible to deliver it via the shop's own delivery service. The same division is also used for installation: complex systems will be technically installed, but small portable systems would rely on self.

As seen in the final third level, the setup of parameters is a matter of high regard. Since the client had requested for both, a heating and a cooling mechanism, parameters would have to be carefully optimisable such as temperature. Therefore, a Control Temperature and a Control Airflow were added to allow convenience towards the user. The pre-existing heating/cooling systems should still be considered in this system because the new system might not be entirely optimal to the client's subjective "ideal" temperature, and would therefore be used as a backup option.

Defining the system's functions also includes generating potential concepts that will be evaluated further in the report. Concepts are normally categorised based on their customer specifications, however, this report will focus on some of the main key aspects that each concept would have to offer:

1) **Passive solar designs such as double glazed windows:-**
   a) Increased thermal resistance and less heat loss due to an additional layer of glass and reflective layers that prevent further heat transfer. This is further enhanced by the thick curtains that are ensured to have a high R-value, which is an index of measuring thermal insulation. (Desjarlais, 2008)
   b) The certainty of injury might be likely such as trapping fingers whilst slamming the window shut, however this is very unlikely to cause any fire or electricity hazards.
   c) The initial cost might be a lot as the current rate of double-glazed windows in Canberra estimates to approximately 1300 $ (Canberra, 2014), however the ongoing cost should compensate for the initial cost over time.
   d) The fact that it is a rented house makes it increasingly difficult to ask the landlord for changes within the structure of the house.

2) **Thick curtains:-**
   a) Due to the nature of single-glazed windows, it gets increasingly feasible for cold or hot air to enter through during winter and summer respectively. Thicker curtains

would seem to be a smart option as the curtains can be undrawn to allow air in during summer and drawn to create heat retainment in winter.

b) Curtains are relatively safe from the other options, and can be designed to look aesthetically pleasing, but thicker options will remain expensive.

3) Cavity wall insulation:-

a) Apart from sharing similar thermal capacity and resistance ideals as double glazed windows, the certainty of injury is more possible during installation, which could possibly ruin the house such as the chance of asbestos infestation or even an electricity/fire malfunction.

b) The initial cost is exceedingly high and will probably not be accepted by the landlord as the place is rented and not owned.

4) Draught excluders on doors:-

a) The impact of thermal resistance and conductivity might not be as effective as the aforementioned concepts, but there is virtually no need for maintenance and minimal costs to setup or utilise.

b) Door draught sealers are relatively easy to manipulate and would hardly require any installation time, however their inefficiency might cause a somewhat similar heat loss.

Subsystem Integration

Often at times, a system can be too vague or ambiguous and certain aspects of the system must be assessed to see if it should lie within the system or not. These internal and external factors can play a huge impact on how the system is run, such as when the actors from the Use Case interacts with the components of the system. These correlations aid in corroborating certain system attributes when a concept is finalised. This method of integrating the various components of a system or a problem is known as subsystems integration (Torgerson et al., 2013).

A system boundary chart summarizes the scope of a model by listing the key variables that are found inside and outside of the system (Sterman, 2000). It can be observed that the Use Case are mostly considered outside of the system; this is because their interaction with the internal system and its manipulation will be undergone. Due to the relative uncategorisable nature of the concepts generated, a more generalised function will be attributed whilst discussing the system boundaries.

Inside	Outside
Infrastructure	User
Maintenance	Air
Product and Assembly	Sunlight
	Emissions
	Technicians

Table 4: System boundary chart.

As stated earlier, a critical analysis must be created to ensure what lies within the system and what lies outside. This is best clarified with a functional block diagram (FBD), which identifies how these interfaces interact with each other. The FBD identifies simplistic processes undergone in the system such as the inputs of air and sunlight to create cool air and warm heat respectively within the room. These interact with the subsystems defined within the system such as the maintenance and the assembly with the cooling and heating infrastructure. The factors external to the system such as emissions are emitted by the heating or cooling mechanisms, but these are not really quantifiable as the infrastructure doesn't really convert the energy to a measurable unit; rather, a transfer just occurs from emission which would then be reflected upon the user via temperature.

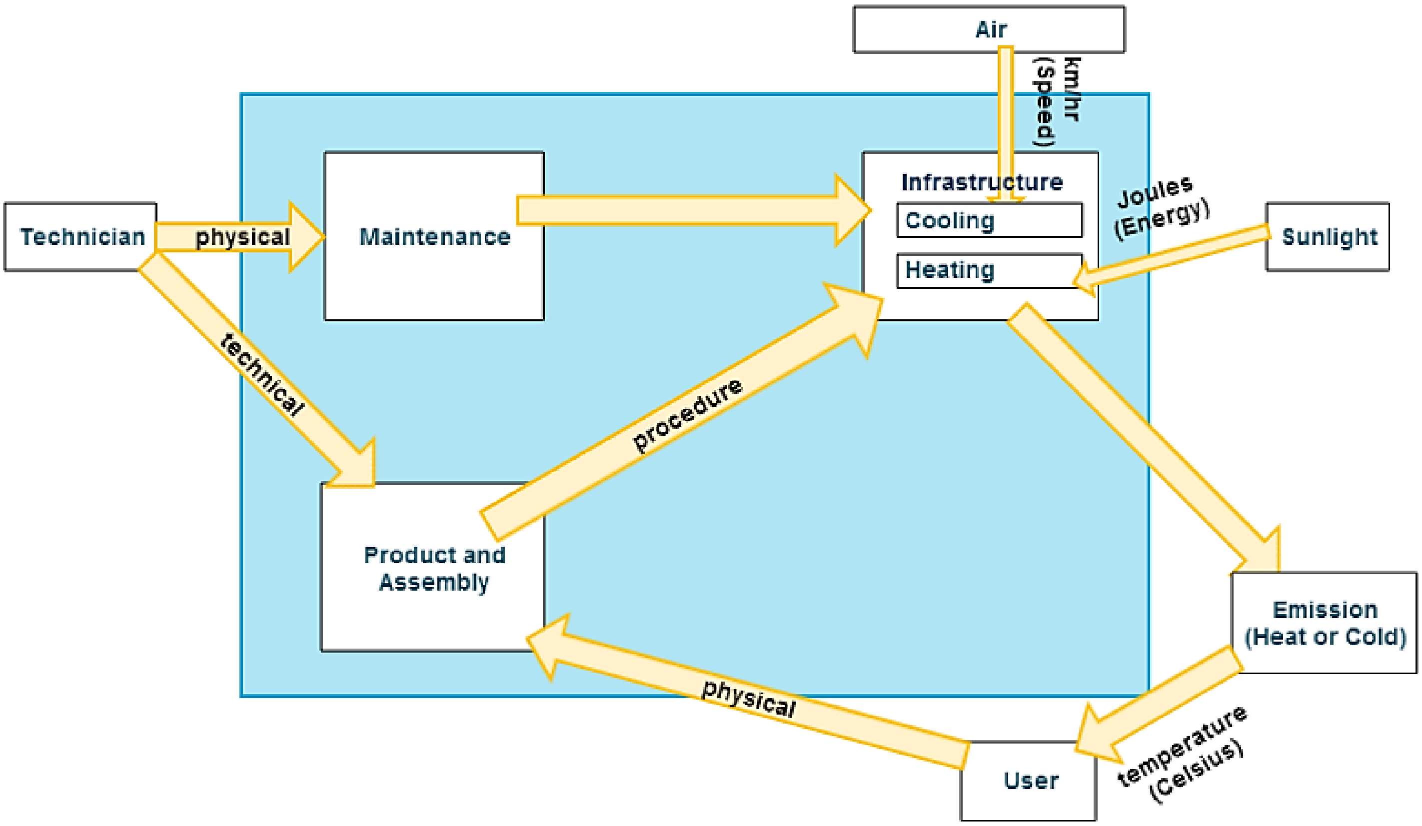


Figure 3: Functional block diagram indicating the interaction of subsystems.

It can be noted that the FBD proves a rather vague aspect of the system and its subsystem interactions. This is due to the fact that the concepts provided endure a much different process such as the curtains would provide a cooling and heating mechanism by drawing/undrawing it, but a cavity wall insulation provides heat within the system as a nature of its thermally resistive nature. Another discussable aspect is the fact that maintenance is not really required within the system for many concepts such as the draught excluders as the client would technically purchase a new one, and can therefore be partially excluded in the system.

System Attributes

After defining the boundaries of our system, a link should be made to see how the customer requirements fit the subsystems that we had earlier made. This can only be provided by divulging into how the requirement will be fulfilled by questioning more in depth and finding the root cause of the attributes (Serrat, 2010). Thereby, a more holistic approach will be taken where the alteration of customer requirements will now be traced back our subsystems, hence reinforcing the concepts that were discussed earlier (Smiths & Bahill, 2009).

The table below identifies the development of these attributes and the subsystems that relates to the design requirements that were initially mentioned.

PRIMARY ATTRIBUTE	SECONDARY ATTRIBUTE	TERTIARY ATTRIBUTE	RELATED SUBSYSTEMS
A1.0.0: **Effective heat treatment**	A1.1.0: Less rate of heat transfer	A1.1.1: Thickness of material	Infrastructure (Heating)
		A1.1.2: Heat retainment factor	Infrastructure (Heating)
A2.0.0: **Low ongoing cost**	A2.1.0: Reliable system	A2.1.1: High quality material	Product and Assembly/Maintenance
	A2.2.0: Less electricity usage	A2.1.2: High thermal mass	Infrastructure (Heating and Cooling)
A3.0.0: **Easy to handle**	A2.1.0: Less time to manipulate	A2.1.1 Materials with less weight properties	Product and Assembly

Whilst it might be considerably difficult to find the root cause of an "Easier to handle" attribute due to the ergonomic nature involved in utilising the system via a lighter material, the rest of the attributes are quite closely related to the Infrastructure – which involves the Heating mechanisms mostly. Thermal engineering aspects are accredited towards "Effective heat treatment" as these are best designated towards properties that influence the amount of heat flowing through such as the thickness of the material being used.

System attributes are notably known for its interconnection with other design requirements. This is prominently seen in the attribute "Low ongoing cost," where to minimize the usage of electricity, which would otherwise be used in a pre-existing heating/cooling system, a material with a high thermal mass would be necessitate. Thermal mass is considered as the ability of a material to store heat (Chiras, 2002), and whilst this might seem counter-intuitive because a high thermal mass would sound irrational during summer, materials which block high-angled sunlight could be sought after, as discussed earlier (Khavrus & Shelevytsky, 2010). This, in effect, corroborates the correlation between "Effective heat treatment" and the engineering characteristic of "Electricity Usage", thus revealing the interconnectivity of the system and its subsystems.

Certain attributes also shed light towards how some attributes could have a closer correlation or trade-off within the design requirements. Having a high thermal mass depends on high density (Chiras, 2002), but density is inversely proportional to mass and this will affect the lightweight properties that would be required of in the material ("A2.1.1: Materials with less weight properties."). Therefore, a compensation must be found to satisfy both criteria.

Verification and Evaluation

Before confirming the concept that should be implemented, the design standards that were set by the pre-determined systems attributes should be verified upon. The purpose of the verification is to ensure that the solution is valid and should be executed, as suggested by the user. The two testing methods that were initially proposed was the Operational Testing to rate the heat effectiveness attribute, but due to the high cost involved and the amount of time required, as opposed to the 'set-and-forget' attitude, a miniature yet concise Proof-of-Concept is preferred. (Blanchard & Fabrycky, 2011)

A Proof-of-Concept would not only rely on the aim and procedure of the test, but would also set certain benchmarks to be achieved within the system. This concept will not be technical as it is assumed that the university student will not pay for a detailed test, therefore a self-experiment is proposed for the heating system, as a different concept would be required for cooling. The benchmarks were hypothetically set up as the heat retainment factor is a concocted variable that was set to give the client a comprehensible statistical figure.

PROOF OF CONCEPT

Aim: Testing the heat retainment factor by comparing the temperature differences with and without the new system (Attribute 1.1.2: Heat Retainment Factor)

Testing by: Self (the client)

Criteria: To ensure the heat retainment factor with the new system is greater than 10% in contrast with the current system

Procedure:

1) Place a simple digital thermometer outside and inside the area whose temperature is to be tested before implementing the new system to attain the temperature difference
2) Account for any inconsistencies and ensure that other controls such as ovens, et cetera do not influence the temperature.
3) After implementing the system, measure the temperature with the same thermometer outside and inside.
4) The heat retainment factor is the percentage ratio of the pre-existing and current system.

Figure 4: Simplified proof-of-concept testing for the new system.

Last but not the least, a weighted matrix indicating how the concepts fair with the customer requirements are ranked before finalising the concept that will be communicated to the client. A "compliance" ranking is created as a comparison tool towards the customer requirements. It should be acknowledged that the evaluation sets up a feedback for the customer requirements as these requirements tend to change as the systems approach is divulged.

Scale
5 = Exceeds Compliance
3 = Full Compliance
1 = Partial Compliance
0 = Non-compliance

	Weighting		Double Glazed Windows		Cavity Wall Insulation		Thick Curtains		Draught Excluders	
	Rank	Weighting	Relative Compliance	Weighted Value	Relative Compliance	Weighted Value	Relative Compliance	Weighted Value	Relative Compliance	Weighted Value
Functionality	1	5	4	20	4	20	3	15	2	10
Safety	2	4	3	12	1	4	4	16	5	20
Cost	3	3	2	6	2	6	3	9	5	15
Aesthetics	4	2	3	6	3	6	4	8	4	8
	Totals			44		35		48		53

Table 5: Weightage matrix with system and their compliances.

Passive heating such as double glazed windows and cavity wall insulation received the least rating within the compliance matrix. Despite their effectiveness in reducing heat loss, the cost was primarily an important factor that came upon choosing the apt concept. Installing a thermal system architecturally instigates a higher expenditure as proper technicians would be present, where fire and safety hazards should be ensured.

Thick curtains and draught excluders, on the other hand, do not require safety measures and are relatively inexpensive. They can also be aesthetically pleasing if the client wishes to choose a more designed excluder or curtain. Conclusively, it can be seen that despite the functionality having a higher weightage, other factors that had low weightage gave draught excluder the concept to be pushed through due to the fact that it remains cheap, customisable and doesn’t harm the user.

Design Communication

The final stage in systems engineering is considered as an interactive component, where the final prototype from the list of system attributes and design requirements are presented to clients. This communication, in effect, aids in improving the design quality as further interviews or discussions enhances what should or should not be in the design (Shwom, 1999)

Due to the client’s background of being a university student, it would be a sensible approach to use graphs and diagrams to show a representation of how the new system could be an appropriate vehicle to explain the processes of the heat entrapment within the house. A Sankey diagram might sound like a technical way of explaining such procedures, but it can prove an effective mechanism for explaining how the current and new system would cause a huge fluctuation by decreasing the input electricity, whereas explaining where the draught excluders could be inserted at regions of major output heat leakages.

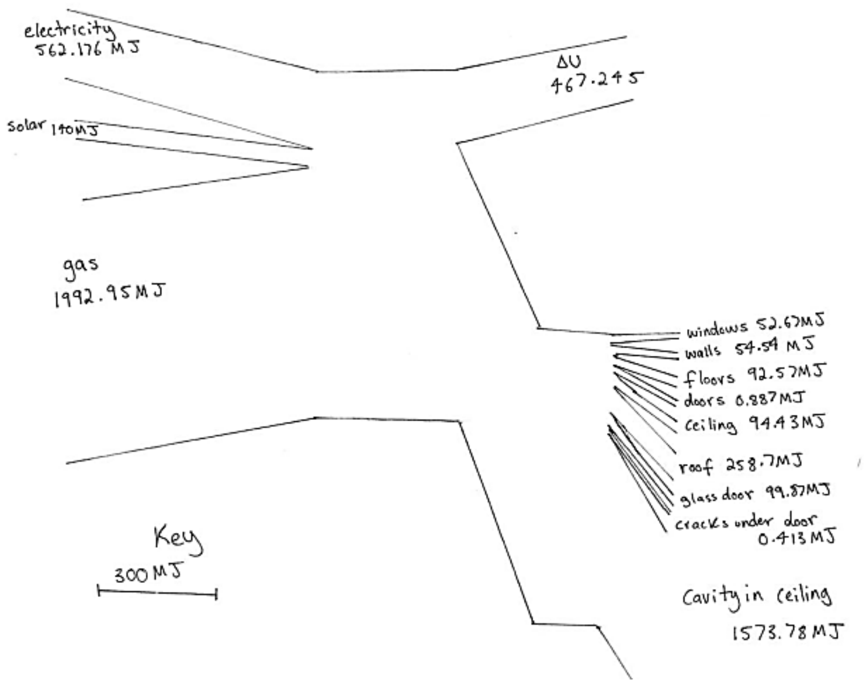


Figure 5: A sample Sankey diagram done for thermal behaviour within a home. (Deegan, 2010)

The customisability of the draught excluder contributes highly towards its aesthetics. As shown in Figure 6, designs of draught excluders could be brought upon. Reflecting upon the Use Case, since it does not cause significant damage to the door, this concept seems to be more relatively acceptable in contrast to the other concepts towards the Landlord, as well as the draught would not look unpleasant towards Guests who would casually visit the house.

Figure 6: Designable draught excluder to make it aesthetically pleasing. (EcoStore, 2014)

It may also occur that other concepts could also be simultaneously acceptable. Thick curtains would also seem appropriate as it falls relatively close to the draught in the weightage matrix, and therefore they should also be a matter of discussion towards the client. It might also be noteworthy to mention that the risk of safety is completely eliminated; in fact, soft draught excluders could prove as "cushion points" due to the common nature of bumping toes onto doors.'

The need for a technician and maintenance in the subsystems could be eliminated from the FBD discussed earlier as the draught excluder is fairly easy to install, whilst the Air Flow and the Temperature from the functional flow block diagram can be controlled via inserting or removal of the excluder. As a result, the "installation" of the system is merely just inserting the draught excluder onto the door. Ergonomically, having the draught excluder would not really create a ‘set-and-forget’ situation as the excluder would continuously be removed or inserted back when it is warm or cold respectively, and the fact that the excluder does not really provide any “effective emissions” would prove this concept to be peculiar, but as Occam’s Razor suggests, often the simplistic approaches would seem to be a more better solution.

Conclusion

With the six analytical techniques mentioned above, a succinct systems engineering approach was taken by dividing certain system techniques to create a better heating or cooling system. This led to the verification that a draught excluder was a seemingly better option.

However, this approach has also not considered the various ergonomic factors in depth. Whilst being very brief in the design communication aspect, issues such as if the client would appreciate such an ineffective system despite its aesthetics, cost and safety is a major issue. This system has also not approached the various relationships the client has maintained with such as the landlord as the most influential decision of the concept arises from the landlord. In conclusion, more analyses would still have to be considered before essentially employing the new system.

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