Comparing Approaches to Improving Energy Efficiency of Lighting a House

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Abstract

In the context of increasing power bills and the presence of climate change, improving lighting efficiency is a pertinent topic for consideration. Three alternative approaches to improving the efficiency of lighting in a typical family home are: switching light bulbs for LEDs (Light Emitting Diodes), having motion sensing lights that turn on with motion and having a home controlled computer network connected to lights and sensors. From the requirements of the client (a typical Canberra family) it was found that useability, efficiency and cost were important considerations. Through an examination of solutions considering implementation and feasibility, the design chosen was a house lighting network controlled by a computer but with the possibility of user input using a smartphone as a remote. Nevertheless, every solution considered would be an improvement over the current system and if the requirements changed another solution might be more appropriate.

Contents

Introduction

With 19% of the world's energy used for lighting and 6% of the world's greenhouse emissions produced as a consequence, improving lighting efficiency is in everyone's best interest (Bahga & Madisetti 2014). With the rise of technology increased efficiency can be achieved with increased automation as well as increased efficacy in the bulbs themselves. This automation also increases useability. Smart lighting can allow light to be controlled remotely from a smartphone, turn on and off according to occupancy and respond to ambient conditions, namely sunlight intensity (Byun & Park 2001).

Furthermore, studies have shown that combining occupancy sensors with personal controls in an office environment reduced energy usage by 32% even with an improved lighting power density of approximately 50% higher (Galasiu & Newsham 2009). Similarly, 40% energy savings were found in a study by Enscoe and Rubinstein in 2010. Consequently, it is clear that that automated lighting has the potential to provide significant benefits in terms of energy efficiency.

This paper examines how automation would work in a typical family home, which approach is best and even questions whether automation is the correct way to go. There are already commercial systems on the market using many different approaches from individual sockets replaced by sensor sockets that self-control, to Wi-Fi enabled bulbs, to rewiring the home and connecting to a central computer. This portfolio follows the systems design approach to compare alternatives against the requirements and with the consideration of trade-offs, determine the best solution for the client.

Client and Context

The examination of how to improve energy efficiency of lighting in the home is quite broad. The scope of the paper has been narrowed down to look specifically at changing the lighting using the existing sockets and not the source of the energy itself (Loe 2003). The project title can be rephrased into a question which gives a basis for ideas: "How might we improve the energy efficiency of lighting a family home?" There are many approaches that can be used to answer this question. The three types that this project will focus on are changing the light source, having occupancy controlled individual room lights and having a home networked with computer controlled lights. All these approaches have the potential for significant improvement in energy efficiency.

In order for specific design criteria to be used to compare and evaluate the best solution the situation of the client needs to be considered. The client is a relatively typical Canberra couple with a 19 year old child living in a 40 year old double brick four bedroom house. In discussions with the client it became apparent that they desired an efficient system that was user friendly. They also did not want a huge cost and they wanted the system to be as green as possible. The simplicity of the design, its safety and unobtrusiveness were lesser concerns but it needed to be feasible to install.

The information the client provided was taken in the context of a typical Canberra family so that the solution would be broadly applicable. From the Australian Bureau of Statistics the following data was obtained for Canberra: An average family size of 2.6 and average children per family of 1.8 suggest fairly small families with some families only having a single parent. Of two parent families 31.2% have both partners working full time and a further 20.5% have one partner full time and the other part time suggesting very busy lives and the lack of time for most Canberrans. A weekly household income of $1920 often coupled with either a median $380 weekly rent or $2167 monthly mortgage repayment suggests the high cost of living and lack of disposable cash. (Australian Bureau of Statistics 2011). All together this data suggests that a user friendly system which takes up limited time but does not cost an excessive amount would be appealing to the typical Canberra family.

Stakeholders

In order to understand the problem and form a solution it is important to determine the stakeholders involved. In the figure a stakeholder map has been produced showing the relationship between the various parties involved in the creation and use of an efficient home lighting system. The bottom part of the figure shows a breakdown of one particular party, the home user, into more specific subgroups which are all important to consider in the design generation. The focus on the home users is due to the fact that they will use the system every day as well as be responsible for the initial purchase.

The process of examining stakeholders has demonstrated that there are many groups with greatly diverging interests and aims invested in the topic. On the one side are the designers of the lighting system itself who want to design and sell a profitable item. There are regulatory groups such as the government and environmentalists with their own agenda desiring safety and low environmental impact. The electricity company on the other hand wants to generate as much revenue as possible desiring greater electricity bills but its profits are affected by the cost of fuel. The architect, builder and electrician are the ones who determine the lighting layout to suit the home user and need to install the system. The influence of all groups on the final design needs to be recognised.

A more detailed analysis of the home user determines that different users have different needs and interact with lights in a different way. Children may leave lights on, forgetting to turn them off. Guests need to be able to find how to easily turn on and off lights. Certain motion sensors might irritate pets' hearing (U.S. National Library of Medicine 2016). The home owner may be concerned with the cost of the system and also its effect on the resale value of the property. A suitable system must be adaptable enough to fulfil the needs of each category of users.

This analysis makes clear that the project's lighting system must satisfy a number of groups, being relatively simple to install, safe, environmentally friendly, useable by adults, guest, children and pets.

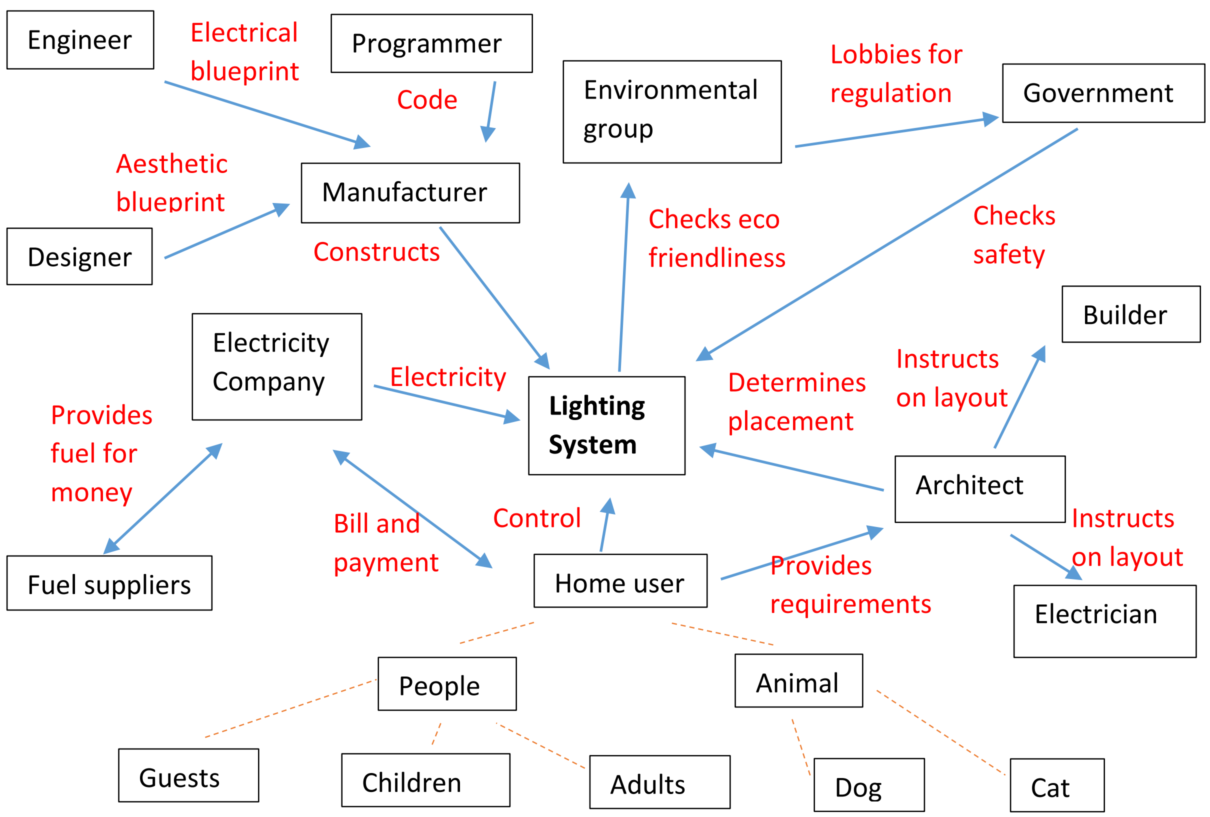


Figure 1: Stakeholder Analysis with an emphasis on the user

Determining Approaches

With the understanding of the problem from problem scoping and needs and opportunities, solutions can now be examined in a systematic manner. Two concept classification trees were used in coordination to both look at various potential solutions as well as different sensor types.

The first concept classification tree was used to examine in greater detail three solutions to improving the lighting efficiency of the home. These three quite different solutions were changing the light source, having lights that sense motion and turn on and off or have an automated home network which can control the lights.

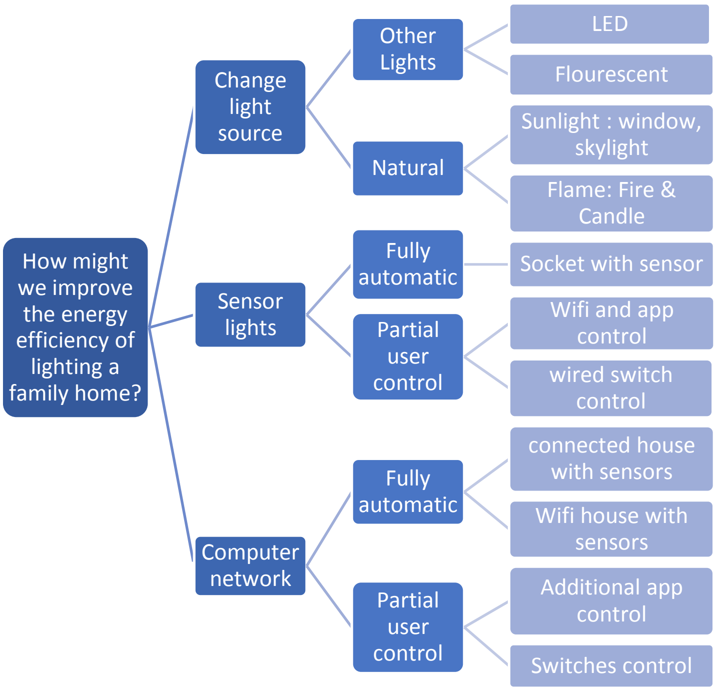


Figure 2: Concept classification tree of approaches to lighting efficiency

It is interesting to note that the light source can be changed both with natural light or changing the bulb. The issue with natural light is it cannot be controlled by a program or the user and so it was discounted as an option. LEDs are on average slightly more efficient than fluorescents so are preferable. (Doulos & Tsangrassoulis & Topalis 2008) The other two branches both raised the same two important questions: should the system be fully automatic or should it have partial user control and should it be a wired system or should it be connected via a home Wi-Fi network. Taking the system completely out of the users' control does not allow for the unexpected and cannot adapt in specific circumstances. Furthermore, rewiring the old wires for a home lighting system would be costly and complex, making Wi-Fi controlled components preferable. Hence the three options to be considered further were simply changing the lights for LED bulbs, Wi-Fi connected lights with sensors and app control and a home computer networked Wi-Fi system with smartphone user control.

Separately the best type of control sensor for the light had to be considered. For the sensor lights a single occupancy sensor needed to be attached to each one. The passive ultrasonics could be falsely triggered by many sounds such as wind, rain, ringing phones, pets or the television. Similarly, image sensors require complex processing of data. Hence, the active ultrasonic would be the best option. However, the sending out of ultrasonics waves could cause discomfort to pets as disused in problem scoping. As a result an infrared thermal imaging sensor would work best. (Pan et al. 2008)

For a home networked system more different sensors can be used in an integrated approach that provides more capabilities and a reduced probability of erroneous input: Optical trip sensors could be used at doors, light intensity sensors at windows along with a combination of passive ultrasonic and infrared sensors in the ceiling. This information could then be processed by a programed computer and along with a timetable control could adjust home lighting efficiently and unobtrusively to suit the user. The use of multiple sensors would reduce the risk of false triggering due to the misinterpretation of input data (Wen & Agogino 2011). Further, multiple sensors would improve functional capability with more diverse situational control meaning that the lighting at any given time would be more suited to the user's needs.

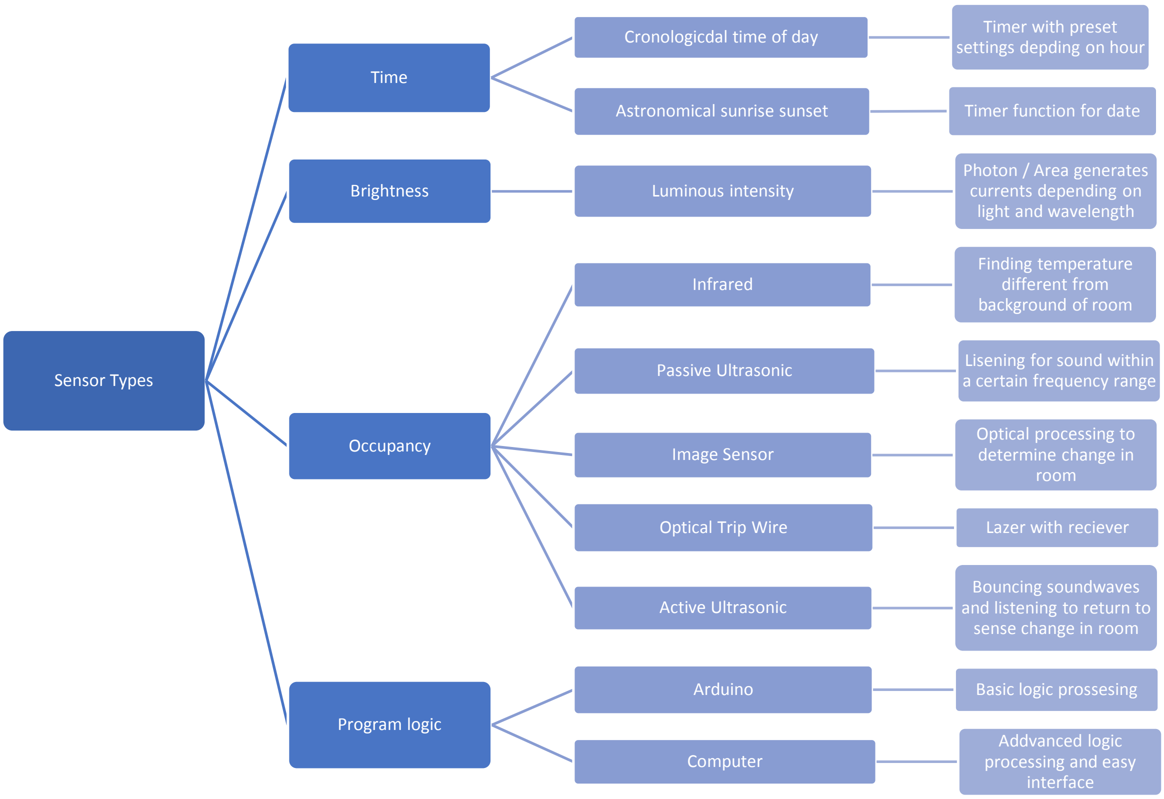


Figure 3: Breakdown of different sensor types and explanation of how they function.

System Requirements

For the concepts previously considered to be evaluated it is necessary to examine the requirements. Requirements analysis is an important tool that looks at what precisely is the project trying to achieve and provides an indication of how to achieve this. The alternative proposals need to be refined and considered in within certain constraints: both customer desires and practical considerations. The client had a number of customer requirements which served to give a clear direction to the project. The client desired a low cost, efficient and environmentally friendly system. Further the client would also like the system to be relatively simple, unobtrusive and safe. These client 'wants' were broken down into design requirements that were more specific and could be measured in a clear metric. This breakdown into design requirements allowed the project to optimise specific elements.

It is important to understand the relative importance of each of the customer requirements. A pairwise analysis with the input of the client provided this data (appendix 1). From most to least important the requirements are: efficient, user friendly, cheap, environmental, simple, safe and unobtrusive. From this it can be concluded that efficiency and useability are more important than any of the other requirements, meaning a design convincingly fulfilling these requirements is vital.

The customer requirements give rise to the consideration of the metrics used to measure how each concept measures in achieving each criteria. As a result in figure 4 each customer requirement is broken down into two or three specific technical or design requirements which can then be optimised. For instance the criteria of cheap is broken down into components cost, maintenance cost and installation cost. Clearly each of these criteria would be measured in dollars and preferably the amount they would cost would go down. The chosen 17 design requirements provide the rubric to evaluate the three design approaches proposed but to determine the significance and weighting of each criteria the further tool of House of Quality becomes necessary.

Customer Requirement		Design Requirement	Metric	Direction
Cheap	1.01	Components cost	Dollars ($)	Down
	1.02	Installation cost	Dollars ($)	Down
	1.03	Maintenance cost	Dollars ($)/year	Down
Simple	2.01	Installation time	Hours (h)	Down
	2.02	Number of components	Integer	Down
	2.03	Length of additional wiring	Meters (m)	Down
User Friendly	3.01	Time of user interaction	Seconds / day	Down
	3.02	Automation percentage	Percentage 0-100%	Up
Environmental	4.01	Carbon footprint including production	MJ/ lighting unit	Down
	4.02	Length of lifetime	Years	Up
	4.03	Amount recyclable components	% of total mass	Up
Efficient	5.01	Cost of power for lights	Dollars ($) / year	Down
	5.02	Bulb efficiency	Brightness/Watts	Up
Unobtrusive	6.01	Contrast of colour to surroundings	Darkness	Down
	6.02	Size per unit	cm^2	Down
Safe	7.01	Voltage in wires	Volts (V)	Down
	7.02	Heat of light 1cm from light	Degrees Celsius	Down

Figure 4: Customer and Design Requirements with measurement metric and desired direction of improvement

A House of Quality is used to determine the relative importance of the design requirements and any trade-offs between them. For instance it shows that decreasing the component cost also decreases the lifespan and that cost is only slightly more significant than lifetime so it is necessary not to alter either requirement extremely. Such discoveries were achieved in the process of creating the House of Quality. First the client requirements were given a score out of 10 and while the order was the same as the pairwise rank this gave a more meaningful and precise result which could be converted into a percentage. By mapping each customer requirement to all the design requirements it could be seen which design requirements have the most influence. Comparing design requirements also allowed for their relationship to be seen by indicating either a positive or negative correlation in the pyramid above the matrix. Using the scores of each design requirement information a ranking and thus percentage importance of the design requirements were determined. The five most important design requirements are: automation %, bulb efficiency, cost of power, component cost and lifetime.

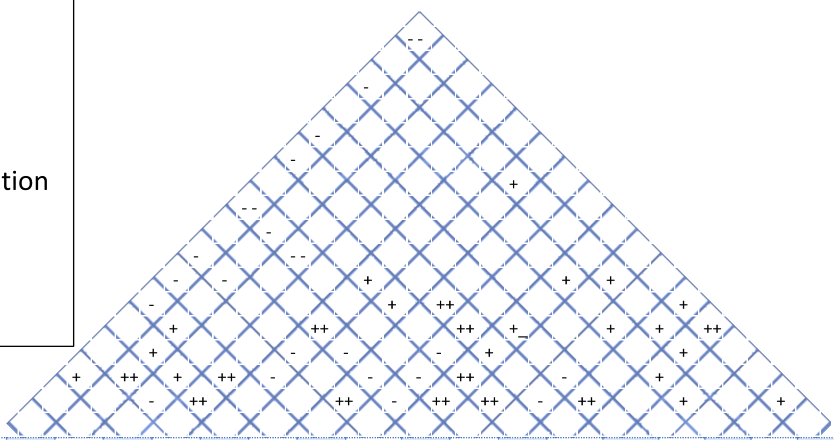
Some important observations can be drawn with the help of the House of Quality. Four design requirements map broadly to customer requirements: lifetime, automation percentage, length of wiring and number of components. The broad mapping of these four shows both the deep relationship with the functioning properties of the final system and the feasibility of implementing the system showing consideration of the context of old wiring and complexity of multiple components. Further the realistic benchmarks suggest a relatively large initial cost that would take some time to be offset by energy and power bill savings. This leads to the realisation that useability for the client is just as important as efficiency and as such the design must not only improve efficiency but make the user’s life easier.

Each of the 17 design criteria has a numeric benchmark. These benchmarks have been carefully chosen through research with the feasibility of achieving them in mind while not being insufficient to promote the best design. The evidence for each benchmark and an evaluation of how each design compares to its competitors for each criteria is included in appendix two.

Legend

++ Positive correlation
+ Positive correlation
- Negative correlation
-- Strong negative correlation

9 Strong relationship
3 Moderate relationship
1 Weak relationship



Rank customer requirements	Weighting out of 10	Percentage weighting		1.01 Components cost	1.02 Installation cost	1.03 Maintenance cost	2.01 Installation time	2.02 No. components	2.03 Length of wiring	3.01 User interaction	3.02 Automation %	4.01 Carbon footprint	4.02 Lifetime	4.03 Recyclability	5.01 Cost of power	5.02 Bulb efficiency	6.01 Colour contrast	6.02 Size per unit	7.01 Wire voltage	7.02 Heat from light
			Direction of improvement	↓	↓	↓	↓	↓	↓	↓	↑	↓	↑	↑	↓	↑	↓	↓	↓	↓
3	7.5	18.8	Cheap	9	9	9	3	3	1		3	3	3	3	3	3		1		
5	3	7.50	Simple	3	3	3	9	9	9	1	1			1				1		
2	9	22.5	User friendly					1		9	9		1		1	1		1		1
4	6	15.0	Environmental	3				1	1			9	9	9	3	3			1	
1	10	25.0	Efficient	3		1			1	1	3		3		9	9			1	
7	2	5.00	Unobtrusive	1	1	1	1	1	1		3						9	9		
6	2.5	6.25	Safe	1	1	1	1		3		1		1						9	9
			Weighting	323	203	227	135	169	150	235	363	191	295	199	349	349	45	94	96	79
			Percentage ranking	9.2	5.8	6.4	3.9	4.8	4.3	6.7	10.3	5.4	8.4	5.7	10.0	10.0	1.3	2.7	2.7	2.3
			Metric	$	$	$ / y	h	Int.	m	s/h	%	MJ/unit	y	%	$ / y	l/w	%	Cm^3	V	ºC
			Benchmark	3000	1000	200	3	50	10	10	95	4000	5	90	100	60	25	100	12	10

Figure 5: House of quality with benchmarks, metrics and direction of improvement.

Logic and Function

Understanding how a system works together is an important when considering changing it. A functional flow is used to model the existing system of turning a light on and off. It is a very linear process with few logical choices of yes/no if the system is working properly. The idea for automated networked house lighting has been modelled using a logical flow diagram to illustrate the software loop and decision making.

The existing system showing the flow of electric power is mapped for turning a light on and off. Power travels from its generation through wires to the on switch and then to the light. The process is ended by turning the light off. It is mapped as a functional flow as it is a very linear system if all parts of it work (figure 6). However, to work it relies on the user in two important stages: turning the light on and off. There is no redundancy for failure by the user for turning the light on or off and thus the system may never start or fail to end. This could occur if the user is unable to change the switch, for instance with their hands full or has simply forgotten. Hence the functional flow demonstrates that the current system would be more useable by removing the total reliance on the user. This improvement occurs in both of the sensor lighting control concepts from the concept classification tree. However, the LED light replacement option still follows precisely the same flow of logic as the original system except the light in step 4.0 where the light has been replaced with an LED. This is the most significant downside of the LED replacement lighting system that while it improves lighting efficiency its lack of automation leaves it vunerable to a total reliance on user interaction and thus conflicts with the customer requirement of useability.

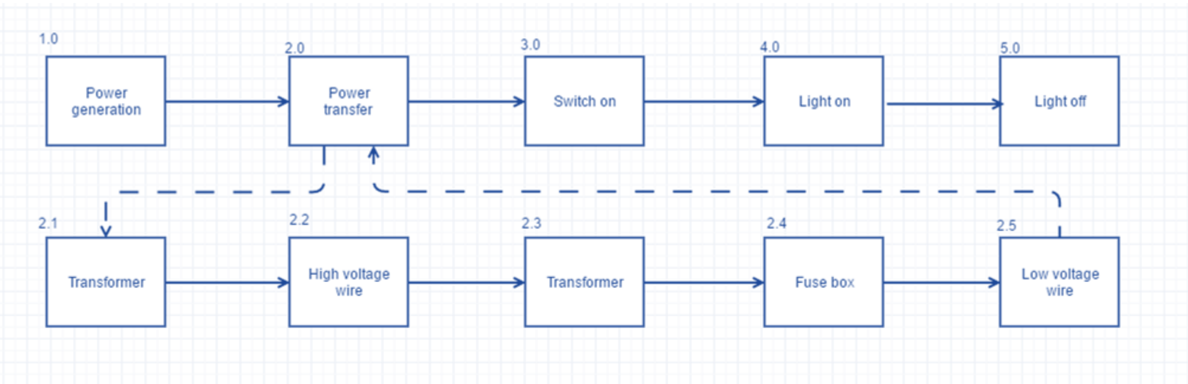


Figure 6: Existing system and using LEDs

The improved system is mapped as a logical flow including the process of how the software determines whether to turn the light on or off (figure 7). It is better than the existing system because the user is not required to do anything manually, thus can work for users of all abilities, including young children or even pets. Unlike the existing system there are many logical choices which determine the outcome, such as: does the house have power?, is the light already on?, is there sunshine through the window? or is there still movement in the room? Additionally to the autonomous control the user can also influence the light using a smartphone app through the Wi-Fi. The purple section refers to user control while the blue section to autonomous control. The green subsection shows the logic loop which repeats regularly every 15 seconds rechecking sunlight, preprogramed time settings, television use and room occupancy status. The program will only exit the loop if the room has been deemed to be unoccupied for a period and if this is the case the lights will turn off.

This logical analysis shows the capabilities of the system. With multiple sensors and input mechanisms it has great control over the lights and can adapt them according to the circumstances. The system can be further expanded and adapted according to the user's needs. For instance if the user wanted the capability of colour changing lights this could be added into the program and the colour and hence the atmosphere of the room could be altered depending on the settings. This system capability outperforms the other automated control concept of sensor light integrated unit system for each room. This system, while not totally relying on the user like the LED replacement proposal, is still limited for the lights are limited in capability to only be on with motion and room occupancy and off otherwise. There is no preprogramed setting or sunlight compensation control and while the system can be controlled manually by the user through a smartphone this necessity reduces the benefit of having an automated system. Further with reliance on a single sensor the lighting control is far more prone to erroneous switching on and off, wasting power and reducing light lifetime.

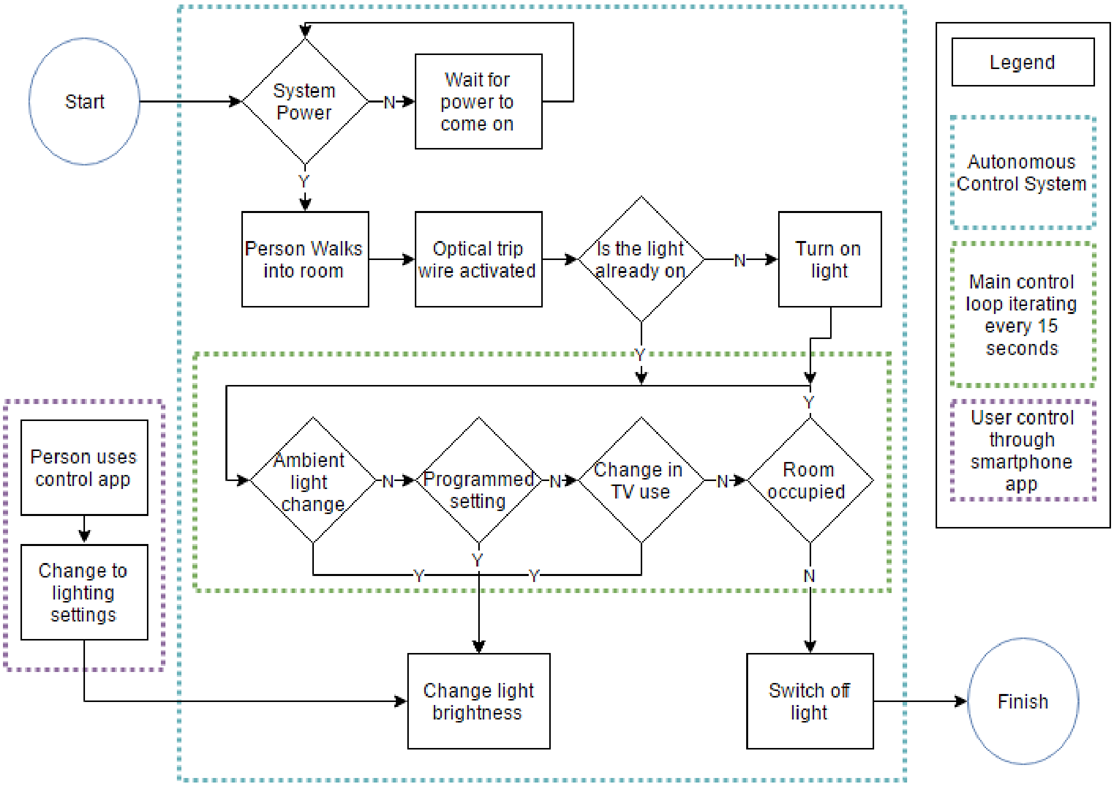


Figure 7: Logical flow in automated control system highlighting the main control logic loop

Subsystem Interfaces

Compared to the existing system architecture, the proposed computer controlled system is quite complex. The benefit of a simple system is that it is less likely to go wrong, however it is limited in what it can do. Instead of having only the user which turns the switch to regulate the flow of power to the light, now we have sensors for movement, heat and sunlight, preprogramed settings and smartphone control which can, through the software, control the flow of power to the lights (figure 8). The system has three main subsystems: the physical lights and wires, the computer and the sensors. Outside the system but interacting with it are the power source, smartphone, user and sunlight.

The importance of the Wi-Fi network is shown by the sheer number of components which interact through it. It is significant to consider the complexity of the design if every one of these interactions had to pass through physical wires. This diagram strongly reaffirms the earlier suggestion that a Wi-Fi connected network as opposed to a physical network is preferable. Additionally the feasibility of having additional user control through a smartphone is shown by the smartphone only having to interface with the main control unit which will then control individual lights. This is in contrast to having individual sensor light units where the smartphone would have to interface specifically with the individual light for every light needing to be changed. As a result of this it is clear that the most practical solution in terms useability is the networked home control system.

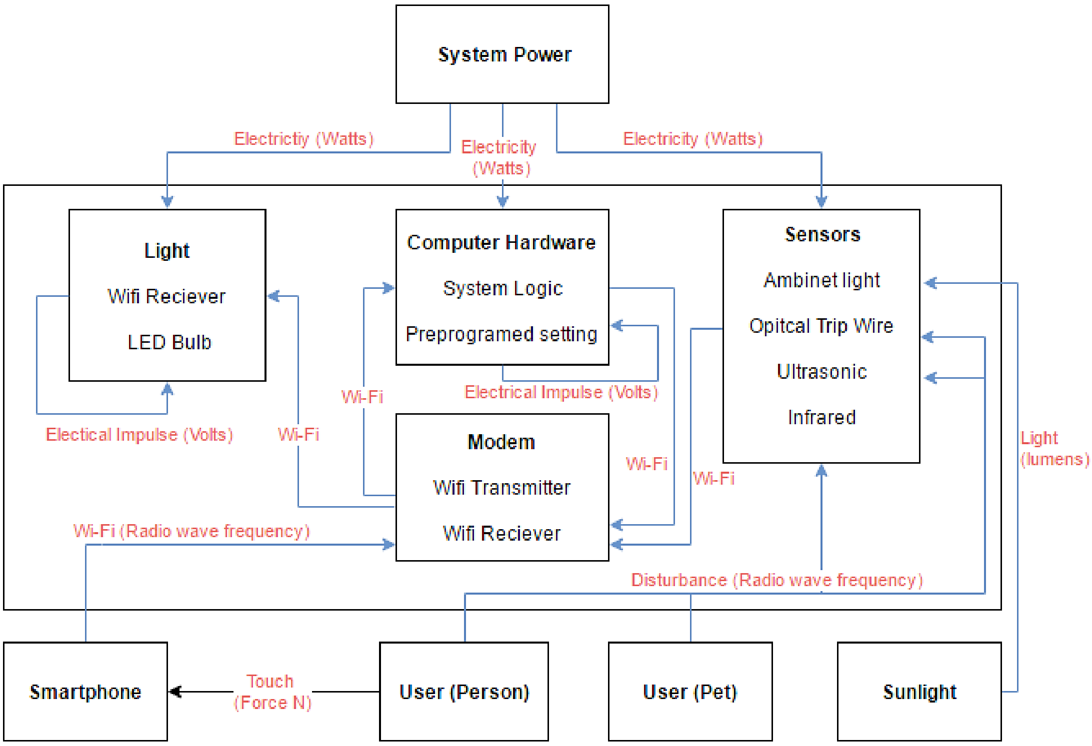


Figure 8: System architecture for computer controlled system

Evaluation

For the evaluation the current system was compared against three proposals (table 1). These proposals were determined in ideas generation: replace existing lights with small LED lights, have independent sensors in each room attached to the lights or have a computer controlled house lighting system with multiple sensors.

The three solutions and the existing system were evaluated through a weighted matrix using the percentage weightings of the design requirements determined by the House of Quality in requirements analysis. Each design is given a relative score out of 5 (5 being the best) depending on how well it meets the benchmarks provided in the House of Quality. The discussions relevant to specific evaluations are provided in appendix 2.

The conclusion that can be drawn from the evaluation is that the computer controlled system is the best, reaffirming the conclusion reached through the preceding discussion. (Tompros et al. 2009) LEDs will give a small improvement and independent sensors will give a slightly greater improvement. All solutions are better than the original system but care must be taken with the precise results and magnitude of the differences in score between the solutions, as small numerical changes in customer requirements could have a huge flow on effect through the House of Quality and into the evaluation matrix.

To check that the results are valid, approximate uncertainty in the matrix should be estimated. Due to the small scale of the scoring half an interval uncertainty means that there is a 10% uncertainty in each individual score. This coupled with similar uncertainty in the design requirements stemming from the scoring of the correlation between each customer requirement and design requirement as only a 0, 1, 3 or 9 means that there is at least an additional 10% uncertainty that needs to be propagated. However, the matrix results are not invalidated because due to a certain independence in the scoring of each proposal against the benchmarks it is highly improbable that a specific concept will have scored below on every single criteria making the total uncertainty of the total score less than the individual uncertainty of each mark against the criteria. Hence the minimum 5% differences between the proposal's final scores are sufficient to confirm the ranking is indeed valid against the given criteria.

Table 1: Weighted comparison of ideas against design requirements

Design Requirements	%	Existing		LED small lights		Independent sensors		Computer controlled	
		score		score		score		score	
1.01 Components cost	9.2	5	**46**	4	**37**	3	**28**	3	**28**
1.02 Installation cost	5.8	5	**29**	4	**23**	4	**23**	3	**17**
1.03 Maintenance cost	6.4	3	**19**	3	**19**	3	**19**	3	**19**
2.01 Installation time	3.9	5	**20**	4	**16**	3	**12**	3	**12**
2.02 No. components	4.8	3	**14**	4	**19**	3	**14**	2	**10**
2.03 Length of wiring	4.3	4	**17**	4	**17**	4	**17**	4	**17**
3.01 User interaction	6.7	2	**13**	2	**13**	3	**20**	4	**27**
3.02 Automation %	10.3	1	**10**	1	**10**	3	**31**	5	**52**
4.01 Carbon footprint	5.4	2	**11**	3	**16**	3	**16**	3	**16**
4.02 Lifetime	8.4	2	**17**	3	**25**	3	**25**	2	**17**
4.03 Recyclability	5.7	2	**11**	2	**11**	2	**11**	2	**11**
5.01 Cost of power	10.0	2	**20**	3	**30**	3	**30**	4	**40**
5.02 Bulb efficiency	10.0	2	**20**	4	**40**	4	**40**	4	**40**
6.01 Colour contrast	1.3	3	**4**	3	**4**	3	**4**	3	**4**
6.02 Size per unit	2.7	3	**8**	4	**11**	3	**8**	3	**8**
7.01 Wire voltage	2.7	2	**6**	2	**6**	2	**6**	2	**6**
7.02 Heat from light	2.3	2	**5**	4	**9**	4	**9**	4	**9**
Total	99.9		270		306		313		333

Legend for Scores				
1: No compliance with benchmark	2: Limited meeting of benchmark	3: Satisfactorily meets benchmark	4: Exceeds benchmark	5: Significantly above benchmark

Final Solution Recommendations

The sketch (figure 9) shows the automated lighting control design in operation in a living room. The sensors, lights and smartphone user switch are connected wirelessly. The occupancy of the room is determined by both an optical trip sensor at the door and an ultrasonic sensor in the ceiling. The ambient level of light is measured beside the window. This information is fed to the control system which dims or brightens individual LEDs in the ceiling. The system has been configured to the user's personal preference and can intelligently adjust lights, for instant dimming when the TV is on.

Design recommendation:

- **Networked home system**: multiple sensors and lights all controlled by a central program
- **Wi-Fi component interactions**: each light has Wi-Fi controlled switch, each sensor has Wi-Fi receiver and a smartphone can interact wirelessly with the control unit.
- **LED lights**: provide power efficient lighting with a large range of brightness control
- **Sensors**: Laser trip wire, passive ultrasonic, infrared, light intensity.

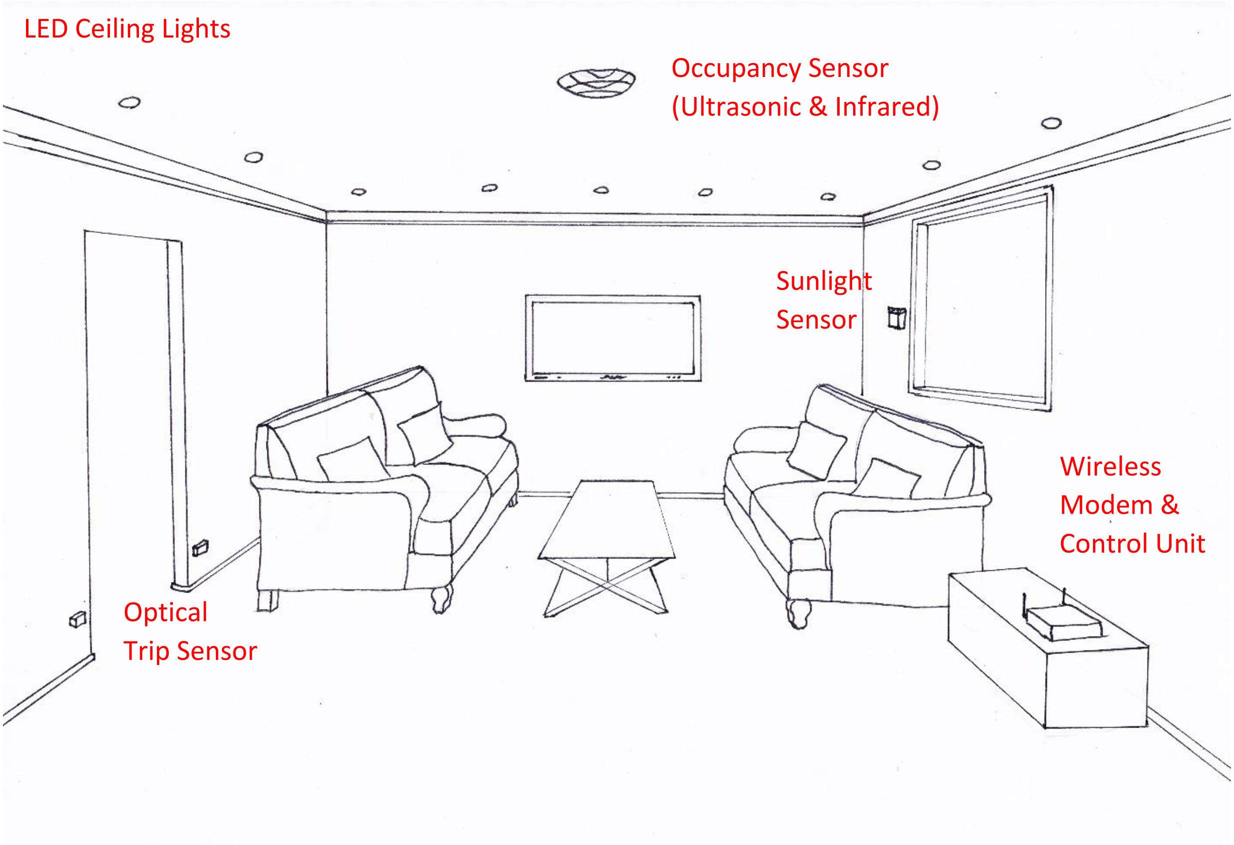


Figure 9: Final design proposal of home networked lighting control system

Conclusion

It is clear that the best option is Wi-Fi networked home system to control the lights. This provides an efficient system at an achievable cost that will suit users including adults, children and pets. The Wi-Fi component interaction allows for simple implementation improving the feasibility and the multiple sensors feeding into the control unit provide a robust highly automated system less prone to error. The other alternatives of sensor lights and replacing existing lights with LEDs would also be an improvement over the current system given the requirements of efficiency and useability. If the requirements were altered to focus on cost the best option may be to use LEDs and if automation performance was less significant sensor lights would be more appealing. Hence, for the typical Canberra family in this busy modern technological age and with the increasing significance of climate change making the effort to examine the various options available is a good decision. This paper has shown that for many, increased automation of lighting would improve time available for other activities as well as helping with the social responsibility we all share of reducing our impact on the planet and limiting our emissions to slow the acceleration of global warming.

Appendix 1: Pairwise comparison of customer requirements

Pairwise analysis	Cheap	Simple	Useable	Enviro	Efficient	Unobtrusive	Safe	Sum	Rank
Cheap		1	0	1	0	1	1	4	3
Simple	0		0	0	0	1	1	2	5
Useability	1	1		1	0	1	1	5	2
Environmental	0	1	0		0	1	1	3	4
Efficient	1	1	1	1		1	1	6	1
Unobtrusive	0	0	0	0	0		0	0	7
Safe	0	0	0	0	0	1		1	6

Appendix 2: Benchmarks

1.01: Component cost: $3000: This value was chosen after some research into both the cost of bulbs and the cost of sensor bulbs. Simple LEDs without any sensors would be somewhat cheaper and leaving the system as it is currently would incur no additional component cost. (Australian Government 2013)

1.02: Installation cost: $1000: This rough value was chosen given the high labour cost in Australia and the specialised expertise required to correctly install all the sensors (Homewyse 2016). Installation time is about the same between LEDs and Sensor LEDs as both just need to be fitted into the sockets. With the autonomous control unit extra time needs to be taken to put in extra sensors such as laser trip wires and to check that the system is functioning correctly.

1.03: Maintenance cost: $200: This value was chosen assuming that about 5 bulbs had to be replaced per year and is approximately the same for all alternatives with each wireless controlled bulb costing $40. (Amazon 2016) (Zaluzny 2015)

2.01: Installation time: 3 hours: This value was chosen because it is a reasonable time in which to install the sensors, a number of which can be fitted to the existing light sockets. Simple replacement of lights with LEDs is somewhat faster and making no change to the existing system requires no installation time.

2.02: Number of components: 50: There are about 20 lights in the house including several lamp lights plus sufficient sensors for all the doors and motion sensors and ambient light sensors. Thus the networked system would have the most components followed by the sensor light units.

2.03: Length of wiring: 10m: This value was chosen because an additional Wi-Fi router would need to be installed to cover the house. Also extra sensors might require cabling if they were not battery operated. As a result both sensor alternatives required additional wiring and while leaving the system as it is or replacing with LEDS did not require extra wiring, wiring was needed for easily accessible switches that would not be necessary with automation.

3.01: User interaction: 10s/h: This value was chosen to indicate that very little time had to be taken to control the lights, the user only having to change something in a special circumstance if the lights were not suitable (for instance, children playing a game where the lights had to be out). It is clear that both the existing system and the LEDs replacement requires far more time for the users to manually control the lights. The sensor controlled lights are somewhat better but require user intervention when they incorrectly sense the user activity. The home automated control system performs the best because it has the most sensors and logic and requires the least intervention.

3.02: Automation %: 95%: This value is chosen to reflect the purpose of time saving with the system working with very little user control. Clearly, both the LEDs and existing system fall short on this front as they have 0% automation. The sensor controlled lights are better but by no means perfect and the house network is the best, only rarely requiring user intervention.

4.01: Carbon footprint: 4000MJ/unit: This figure was arrived at after researching the amount of energy required in manufacturing a light and taking into consideration its functional lifetime. LEDs perform far better than existing lights, however the extra sensors have a higher initial energy cost but this is offset by the improved efficiency of the lighting. (US Department of Energy 2012)

4.02: Lifetime: 5 years: This value was chosen as a way of considering how often components would need to be replaced. LEDs last longer than typical bulbs (under average use approximately 3 years), however the increased possibility of a technical malfunction with the software meant that in comparison a home networked system did not fare as well as the other proposed alternatives. (Rácz, 2012)

4.03: Recyclability: 90%: LED lights are 95% recyclable and do not contain harmful components. However, sensors and electronic circuitry are not so easy to dispose of and as a result the alternatives do no better than the existing system in the recyclability criteria. (Thomas 2016)

5.01: Cost of power: $100: This value was chosen assuming a running cost of $5/year for each of 20 LED lights compared to several times as much for the existing system. The increase in efficiency brought about by increased automation was also taken into consideration and thus, as for all the new alternatives, the bulbs are the same, the networked home is the best, followed by sensor lights, followed by plain LEDs. (Victoria State Government 2016)

5.02: Bulb efficiency: 60 lumens/watts: For a typical LED bulb this value was set to be about 60 lumens of light produced for every watt of energy consumed. (Loe 2003) As all the LEDs have approximately similar values the three alternatives are equally ranked on this criteria and all the alternatives are far more efficient than the existing systems bulbs.

6.01: Colour Contrast: 25%: This value was chosen so that the fittings would be within 25% of the darkness range of the white surroundings. In other words the silvery metallic lights are within a quarter of the range of white to black and thus have less than 25% contrast. Due to none of the bulbs or fittings having vibrant obtrusive colours all alternatives ranked equally.

6.02: Size per unit: 100cm^3: This value was chosen to include both the size of the average LED lights and sensors for each light. (Tompros et al. 2009) The simple LED rated the best as it did not require sensors while the two other proposals fared equally with the current situation as the reduced size of the lights was offset with extra sensors.

7.01: Wire Voltage: 12V: While LEDs can operate at low voltages, sensors cannot necessarily operate at low voltages and existing lights still require high wire voltage. (Enscoe & Rubinstein 2010). As a result all alternatives and the existing system rated poorly on this criteria.

7.02: Heat from light: 10 degrees warmer 1cm from the light: LEDs produce hardly any heat compared to the alternatives and thus all three proposals rate higher than the current system. (Veitch & Newsham 2000).

Reflection

The process of completing the project changed my preconceptions about home automated lighting. Initially I thought it would require extremely complex implementation and require an experienced electrical engineer to understand. However, through the process of research, I discovered that the implementation could be broken into several clear sections. Further the logic of the circuit was quite clear and simply required a loop of conditional conditions. In this way I was able to get a grasp of how automation works and realised that the feasibility of implementation was higher than I had initially considered.

The peer review process was quite disappointing for I received a limited amount of constructive and helpful comments. While the reviewer told me what I had done, in many cases they did not provide many constructive comments about changes that could be made let alone how changes could be implemented. However the process of reviewing others work opened my eyes to problems with my own work and this was further emphasised in discussions with my peers of what they found problematic in portfolios they reviewed.

The most significant changes implemented from the peer review process were a more specific discussion of cost and a more encompassing expanded conclusion. The suggestion of discussing the cost of the system and more clearly defining the savings the new system would bring was defined through clear benchmarks that would allow a comparison between the alternatives in terms of implementation, maintenance and savings. I made the decision that using the benchmarks as opposed to simply mentioning the cost in passing in the text allowed for stronger and more rigorous comparison. The suggestion to expand the conclusion to include a mention of each of the alternatives considered and the step by step process of coming to the decision were two other suggestions. This made me reconsider the conclusion which at the time focused on the given solution and how it fitted into the context of climate change and fulfilled the client's requirements. I still wanted to keep the strong focus on the chosen solution but I did add a mention of the other alternatives considered. While summarising the process of reaching the decision linearly in a sequential manner would be the simplest and is what was suggested this would be somewhat cumbersome and inefficient. Instead the main realisations from each step were integrated into the conclusion allowing it to flow and show a deeper grasp of the systems approach to the solution.

Several of the suggestions from the peer review were not implemented for a variety of reasons. One suggestion was to have numbers for the references and then have a numbered reference list at the end. As Harvard referencing does not support the use of footnotes or endnotes I left my references in the author date system as specified in the ANU guidelines of engineering report writing. However, it is interesting that they made the suggestion that this would make the references easier to find so I changed the reference list to alphabetical ordering. Another suggestion was to make the stakeholder analysis into a tree diagram of the stakeholders. This option was not implemented as it would not show the interactions between the various stakeholders, simply list them. However, effort was made to make the diagram more clear for the reader and the importance of the user stakeholder as the most significant was re-emphasised. The suggestion to "further extend more arguments to support the final conclusion", was insufficiently specific to be particularly helpful not indicating what arguments or how to extend them. Nevertheless it made me reflect on the portfolio and I realised that I had been unconsciously focussing more on the techniques and not so much on how they helped me come to a solution. This change in attitude allowed me to go back through the portfolio with fresh eyes and focus the writing on strengthening the argument for the eventual outcome. This was achieved by more in-depth analysis, discussion and comparison of the alternative proposals throughout the whole process so that the reader comes to the same conclusion as the writer when they reached the recommendations and final conclusion.

During the process of reviewing others' work and in considering my own work, I thought of a number of changes to implement. In looking at others' work I realised it was necessary to more clearly define the client and their situation, to constrain the project and give a more clear direction and context. Further I realised that my evaluation matrix had to be more clearly justified in terms of why particular design proposals outscored others in specific design criteria. This justification along with the discussions of the benefits and drawbacks of each alternative throughout the process meant that the matrix was an appropriate summary of analysis throughout the process. However, it should still be emphasised that the evaluation was merely a way to formalise the relative ranking of the design proposals along with the existing design. This is due to the fact that the methodology used to create the matrix is not accurate enough to look at the precise percentage differences in ratings of the alternatives.

The systems approach used to tackle this problem worked well. My desire was to complete an analysis of approaches to improving lighting efficiency which, while it would satisfy the client's specific situation, the comparison would also be more broadly applicable to the typical Canberran family. The systems approach allowed for this with specific design requirements chosen to satisfy both the client and the typical family. With the regular work of the Threshold Concept homework (TCs) it allowed the possibility of having a rough draft of completing the design process. Then when writing the final portfolio I could go through the design process spiral once again. This system worked very well in creating a cohesive argument and helped build a strong understanding of the topic. Despite the time that having the additional work of the TCs take, they are well worth it in helping the use of the design process.

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