Making Cochlear Implants Affordable for those in Developing Countries

Hugh Johnson

u5569847

Abstract

Introduction

The cochlear implant is a hallmark of neural prosthetic engineering as it allows individuals who have no or little hearing ability to hear again. However, the cochlear implant is expensive and as such it is unaffordable to those in the developing world.

Methods

This portfolio aims to use systems techniques to find ways to reduce the cost of cochlear implants.

Results

It was found that reducing the number of electrodes in the electrode array was an effective way to reduce cost, while maintaining adequate performance. Using a generic digital signal processor was also an effective method of reducing costs. It was also established that the design of the implant should be similar to previously approved implants to avoid a lengthy regulation process.

Conclusions

An alternative design of a cochlear implant is proposed which has fewer electrodes than current models, a simplified signal processor and standard batteries. It is anticipated that this design will be 8000 USD cheaper than current models manufactured by Cochlear and Advanced Bionics. Further work should look at implementing insurance programs and using humanitarian aid visits to reduce patent medical costs.

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1   Introduction

1.1   The need for cochlear implants

Cochlear implants have the ability to provide people who are otherwise deaf with the ability to hear again. Generally cochlear implants provide enough information for someone to perceive environmental sounds, have a conversation, or even listen to music. This can have a huge effect on the quality of one's life (Wilson & Dorman 2008). It has been established in many developed countries that cochlear implants are cost effective, and have many social and economic benefits (Bond et al. 2009; McKinnon 2014; Wyatt et al. 1995). However, in developing countries, where wages are lower, the cost-benefit of cochlear implants are less clear.

1.2   Why are cochlear implants so expensive?

Cochlear implants are one of the most successful yet expensive medical implants available, with the cost of the implant alone often exceeding 25,000 USD (Nadège et al. 2011). Part of the reason why these implants are costly is that manufacturers often have little incentive to make their implants affordable. In developed countries, where cochlear implant manufacturers sell most of their products (Cochlear 2015a), cochlear implants are generally covered by government health insurance (Tucker 2012), so implants do not need to be cheap for companies to access potential customers. In contrast, developing countries often do not have expansive public health insurance, making cochlear implants unavailable for most. People in developing countries typically have annual household incomes which are a small fraction of the cost of a cochlear implant and as such a cochlear implant is financially not feasible.

1.3   How does a cochlear implant work?

A cochlear implant replaces the function of a damaged inner ear by electrically stimulating the cochlea. Figure 1 explains the basic function of the cochlear implant.

① Sounds are picked up by the *microphone*.

② A *digital signal processor (DSP)* codes the signals into a pattern of electrical pulses.

③ The pulses are sent from the *external coil* and transmitted across the skin to the *internal coil.*

④ The *stimulator* sends a pattern of electrical impulses to the *electrode array* in the cochlea.

⑤ The auditory nerve picks up these signals and sends them to the brain
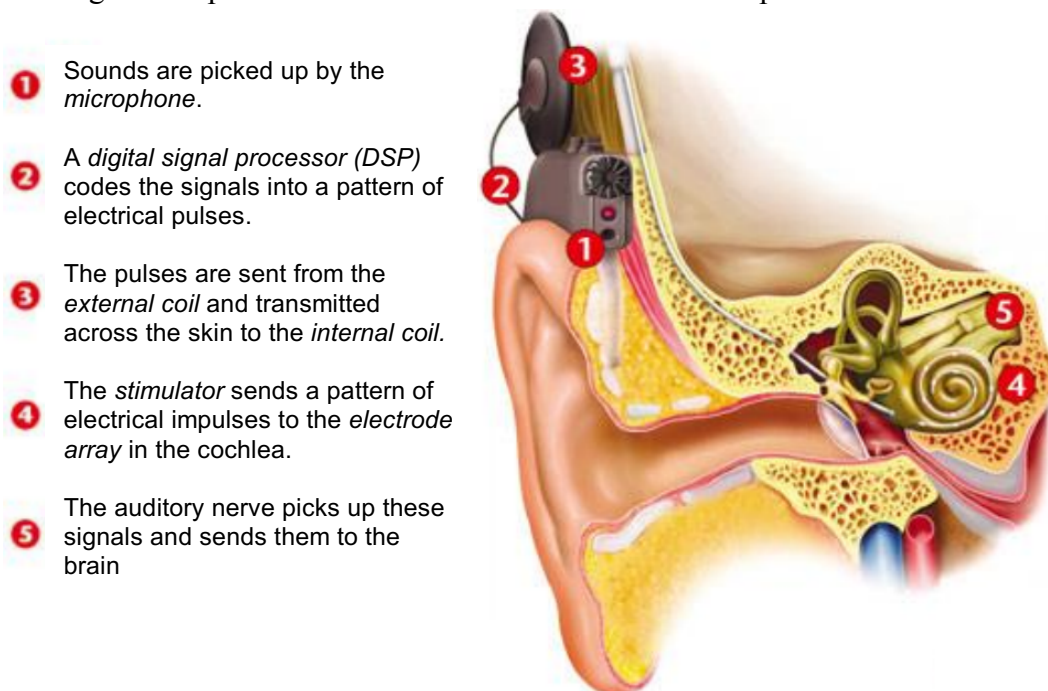
Figure 1: Operation of cochlear implant (Northwestern Medicine 2014).

1.4   Estimation of cost of a cochlear implant

In Table 1, the cost of the components of a cochlear implant was estimated. Further explanation of the method used to estimate the cost is detailed in the appendix. Notice how the components here are the same as those described in Figure 1.

Component	Cost (USD)	
Digital Signal Processor	9900±3800	(Harrison 2015; Ok Medical 2016a)
External Coil	165±9	(Cochlear 2016; Ok Medical 2016b)
Rechargeable Battery	250±10	(Connevans 2016; Ok Medical 2016c)
Internal coil, stimulator and electrode array	15400±7600	(Nadège et al. 2011)
Total	25700±6500	(Nadège et al. 2011)

Table 1: Cost breakdown of cochlear implant.

It is clear that the digital signal processor and the implantable unit are the most expensive parts of the device, so these areas should be targeted for cost reduction. It is acknowledged that that there is much error in these costs, and as such the estimate errors are also detailed in Table 1.

2   Design Process

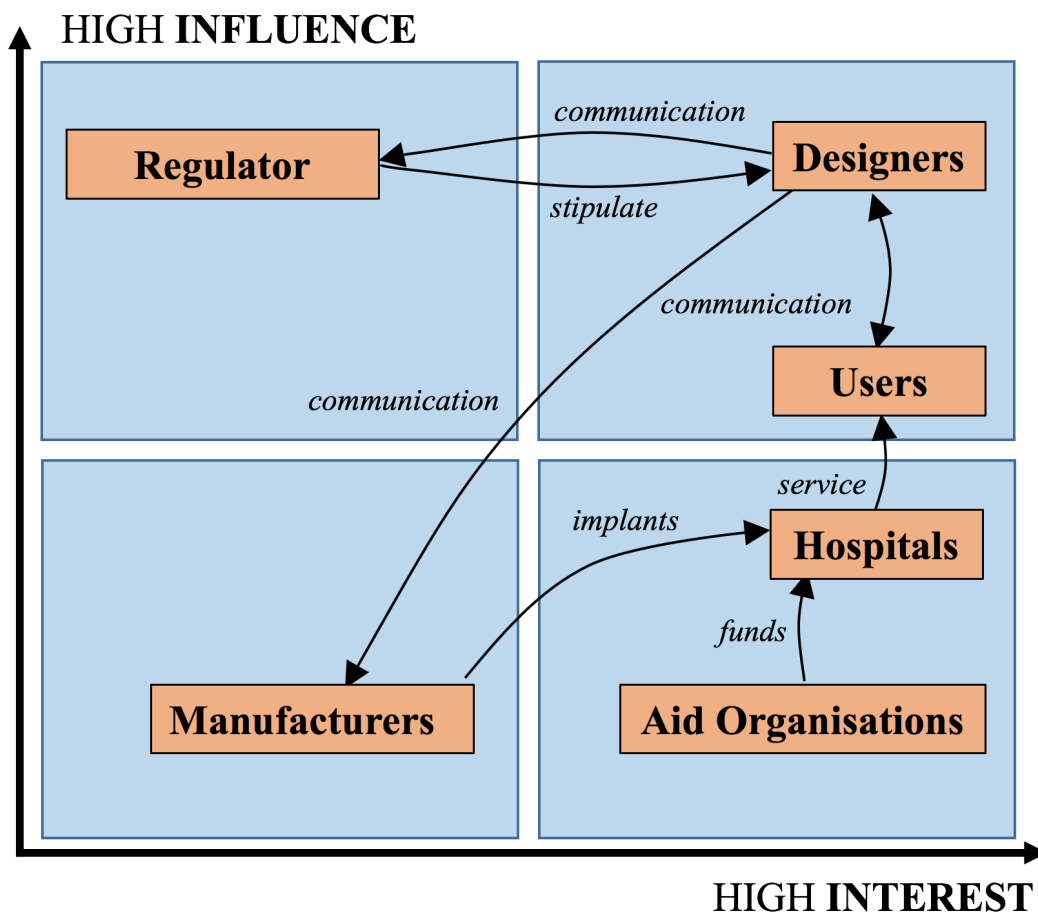### 2.1   Stakeholder map when marketing a cochlear implant

Figure 2: Stakeholder map when marketing a cochlear implant.

From Figure 2, it is apparent that the designers are the most important group. The designers could be a company such as Cochlear or Advanced Bionics who also manufacture the devices. There are several other groups that should be pointed out. Regulatory organisations, such as the US Food and Drug Administration (FDA) have a great deal of influence, as these organisations decide whether the implant is allowed to be sold. If a cochlear implant is marketed in an overseas country, then regulatory approval is needed from both the home country and the overseas country. This means that the process of marketing a cochlear implant overseas will be significantly longer.

2.2 Regulatory Process for Cochlear implants

From the stakeholder map, it was determined that regulation is one of the most important aspects of the process of marketing a cochlear implant. In Figure 3, a logical flow diagram was constructed to show the process of obtaining regulatory approval for a cochlear implant in a developing country. For this example, China was chosen because it is one of the largest developing countries, and has a historic higher than average rate of hearing loss due to the overuse of ototoxic drugs (drugs that cause damage to hearing and balance) in the 1970s and 1980s (Gerber 2000). The GDP per capita of China is 7590 USD (The World Bank 2014), so from this it can be seen that most of the population would not be able to afford the minimum of 20,000 USD (Papsin & Gordan 2007) to purchase a conventional cochlear implant.
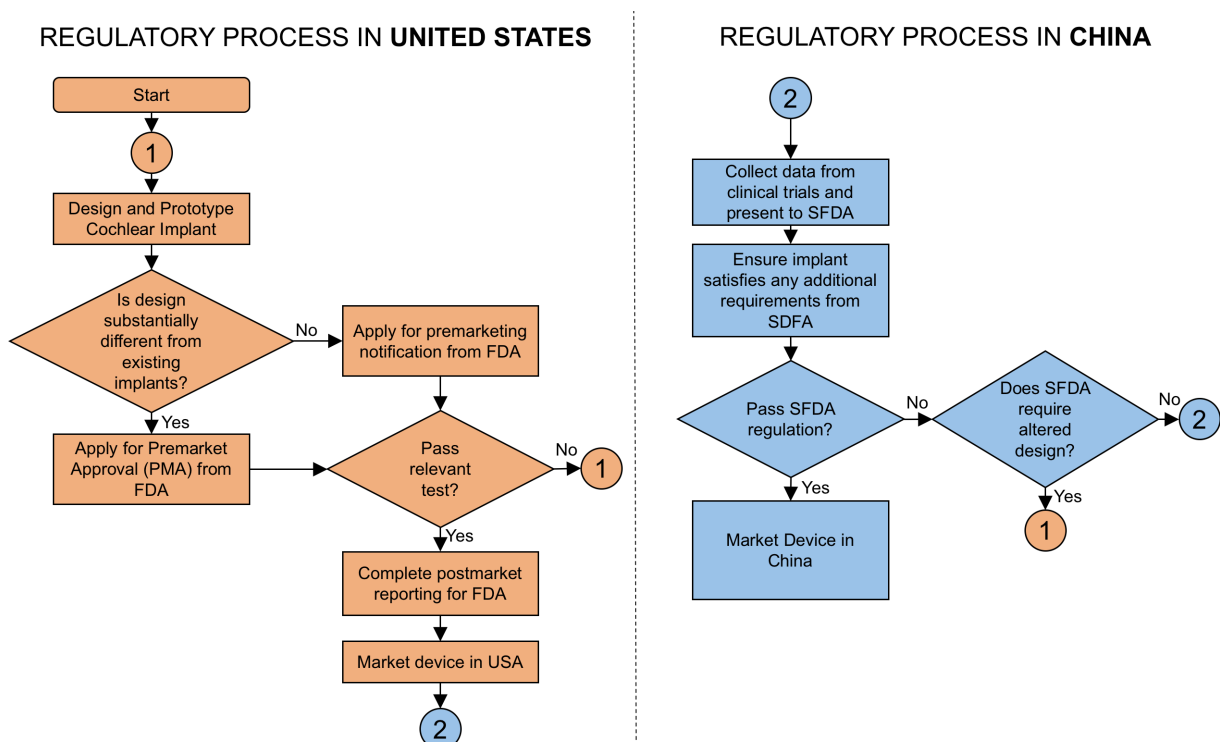

Figure 3: Regulatory process for obtaining regulatory approval for a cochlear implant in China. Notice that regulatory approval from both American and Chinese authorities is required. SFDA is the State Food and Drug Administration, the Chinese equivalent of FDA.

Chinese Law mandates that medical devices that are first produced overseas have to be approved in their country of origin (Tuv Sud 2016). This means that approval from the United States Food and Drug Administration is essential to getting devices approved in China and other developing countries. The FDA categorises cochlear implants as Class III devices since they are implanted inside the human body. This means that cochlear implants must undergo clinical trials and be shown scientifically, to be effective and safe (Sauberman 1983).

From Figure 3, it can be seen that to obtain approval for an implant in the United States, Premarket Approval or Premarketing notification is obtained. The latter is a more desirable option, as it faster, less stringent and does not necessarily require data from clinical trials. Therefore, if possible, for the developing country scenario, an existing approved design should not be greatly changed so that the manufacturer does not have to go through the expensive and time-consuming process of obtaining Premarket Approval.

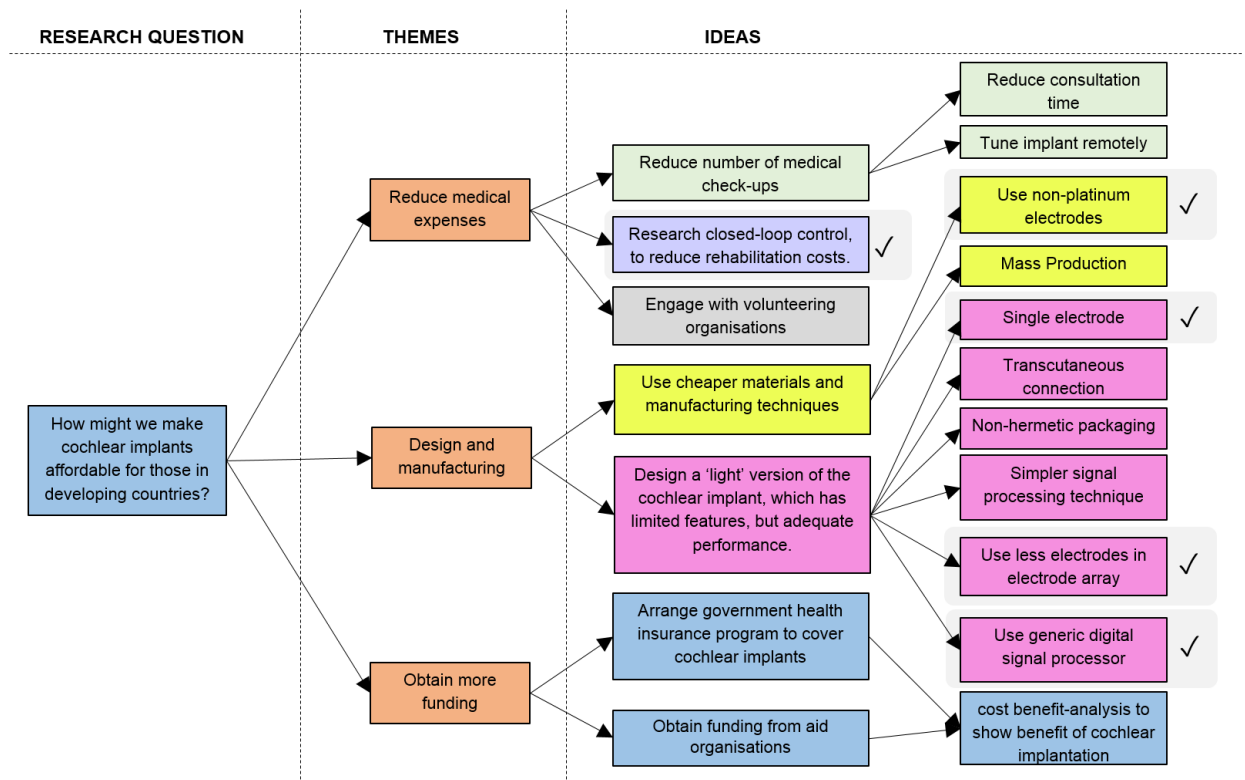## 2.3   Idea Generation

Figure 4: Structured Brainstorming chart

It is clear that there are many possible approaches to addressing this problem. Notice that the selected ideas revolve around four major themes: Closed loop control, a light cochlear implant, aid organisations and volunteers. The usefulness of each of these approaches will be examined further in Idea Selection (section 2.4).

The use of a transcutaneous connection is a promising area to reduce cost, but this has many disadvantages. This involves using a wire to connect the external components to the internal components, so the external and internal coils are removed. One risk of this approach is there is an increased chance of infection. Further, previous attempts using the transcutaneous coil have not been successful, such as a single electrode model developed by Peking University, in which most devices had to be removed due to infection (Zeng 1995).
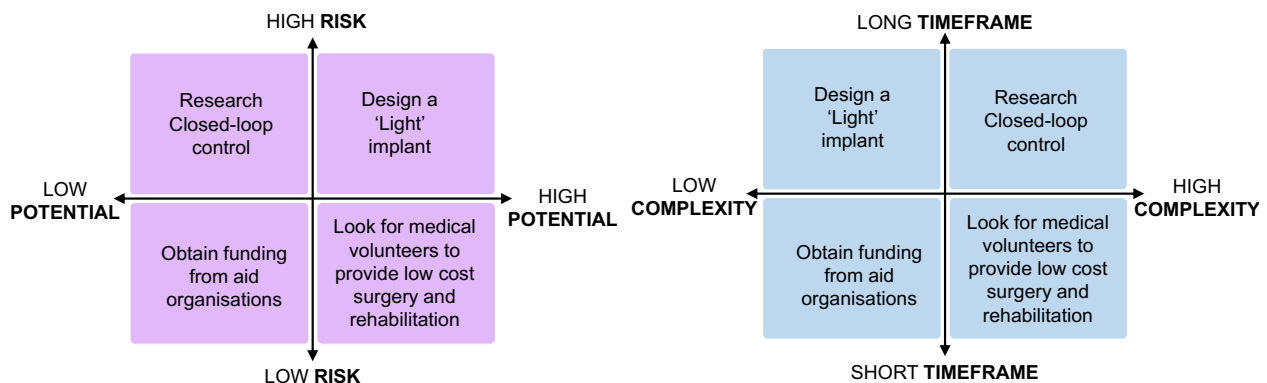
2.4   Idea Selection

Figure 5 (a), (b): Scenario Planning Chart

Obtaining funding from aid organisations is an interesting suggestion, however the main issue with this idea is that a great deal of funding is required as the cost of purchasing a cochlear implant is around 25,000 USD (Nadège et al. 2011). From a marketing perspective, this is concerning. For a comparison, the Fred Hollows Foundation (2015) advertises that a donation of just $25 can restore someone's sight. However, it is unlikely that donors would be willing to pay $40,000 to restore someone's hearing. Further, if a utilitarian position is taken, where the greatest good for the greatest number is maximised (Vardy 2013), spending a large amount of money on a cochlear implant is not justified, when there are more effective ways to spend aid money. Therefore obtaining additional funding alone is not a good solution.

In Figure 5, the ideas are initially evaluated using the scenario planning. Notice that closed-loop control is in the undesirable quadrant in both Figure 5 (a) and (b). It was previously suggested by Johnson (2015) that if closed-loop control were implemented, it would reduce the cost of post-operative rehabilitation due to the implant requiring less tuning. However, since this idea has not been implemented yet, there is a large risk that the idea will not work. Also, many years of complex research will be required and it is unlikely to reduce the cost of the device itself.

From Figure 5, it can be deduced that designing a 'light' version of the cochlear implant and looking for medical professionals to volunteer are promising ideas. It was found that over 90% of America cochlear implant surgeons would perform a cochlear implant in a developing country and that several physicians have already implanted cochlear implants on trips abroad (Saunders & Barrs 2011), so this is a promising area to reduce cost. However, this project will focus on the design of the cochlear implant, so this idea will be considered for future research.

2.5   Customer Requirements

As there is not an individual client, statistical information for the group of clients has been provided instead. In 2014, the average annual disposable income in rural China was 1,700 USD and in urban areas this was 4,700 USD (Wanli 2015). Despite more than six million Chinese being totally deaf, only approximately 10,000 cochlear implants have been implanted, so there is much opportunity for expansion. Around 30,000 children are born every year with hearing problems but currently, the Chinese government has only committed to providing cochlear implants for 4,000 children every year, which is a small fraction of those children who need cochlear implants. Also, it is unclear as to whether future funding will be available for adults who require cochlear implants (Liang & Mason 2013).

It is clear from the information above that most of the Chinese population, particularly those in rural areas, would not be able to afford a cochlear implant. Most of the customers would not have access to government funding, so a key customer requirement is affordability.

From a pairwise analysis, the customer requirements and rankings were determined to be:
- 1: Safe
- 2: Enables them to understand speech adequately
- 3: Reliable
- 4: Affordable

It is interesting to note that although affordability is main aim of this project, it has a low importance compared to the other categories. This is because the cochlear implant must be safe, reliable and must work (i.e. the user understands speech), before it is affordable. It is also noted that without the top three requirements, the device will not obtain regulatory approval.

2.6   Requirements Mapping

The house of quality was used to gauge the effects of changing various parts of the cochlear implant, such as the those selected in idea generation. This is so it can be determined what components can be made cheaper, without reducing the quality significantly. The function and cost of the various components of the cochlear are explained in section 1.3.

Legend
1 weak relationship
3 medium relationship
9 strong relationship

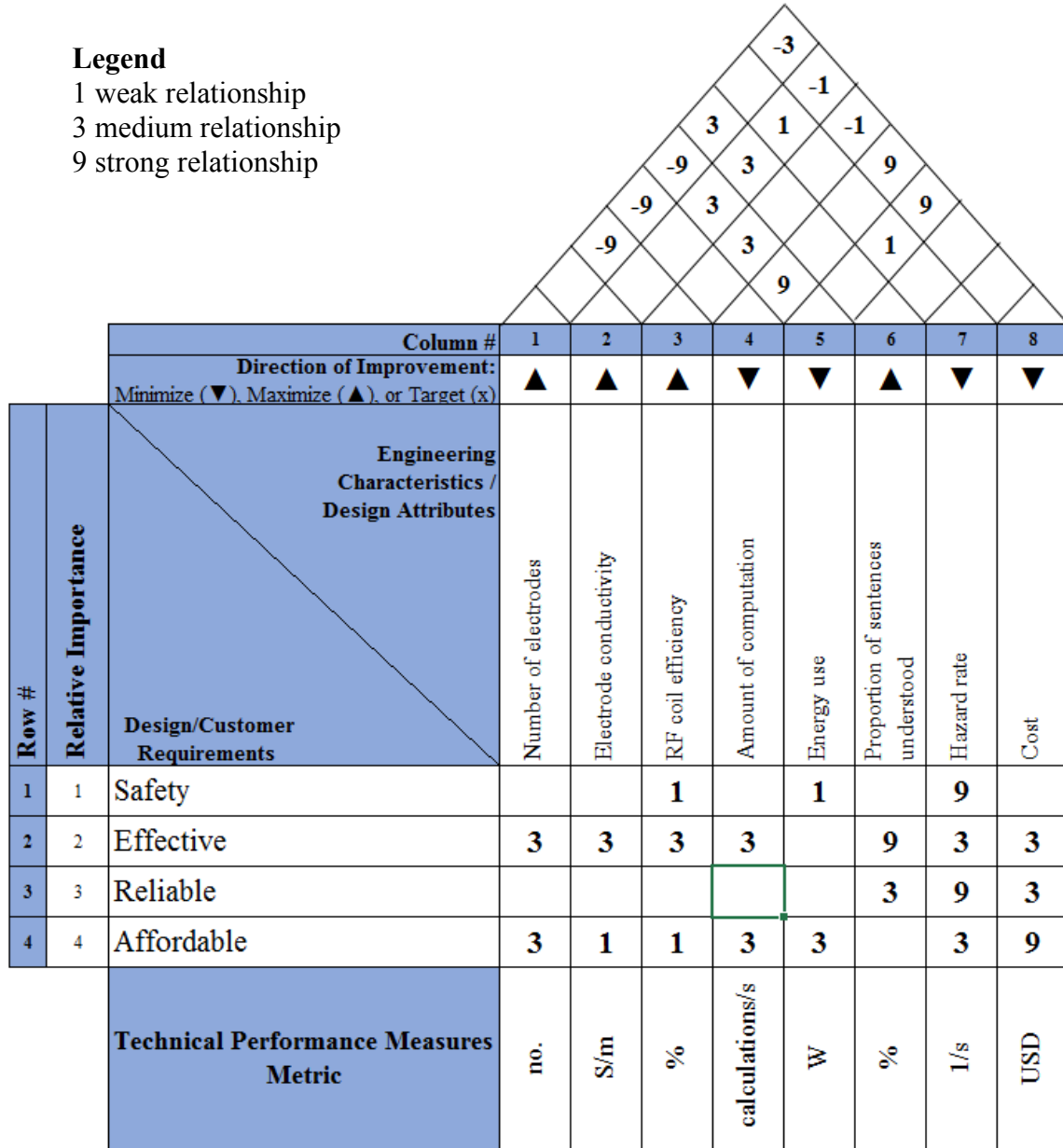| Column #	1	2	3	4	5	6	7	8
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	▼	▼	▲	▼	▼
Engineering Characteristics / Design Attributes → Design/Customer Requirements	Number of electrodes	Electrode conductivity	RF coil efficiency	Amount of computation	Energy use	Proportion of sentences understood	Hazard rate	Cost
1 / 1 Safety			1		1		9	
2 / 2 Effective	3	3	3	3		9	3	3
3 / 3 Reliable						3	9	3
4 / 4 Affordable	3	1	1	3	3		3	9
Technical Performance Measures Metric	no.	S/m	%	calculations/s	W	%	1/s	USD

Figure 6: House of Quality

Notice that the RF coil efficiency should be maximised. A larger coil implies greater energy efficiency (Flynn & Fotopoulou 2013), however, due to limited space in the head, particularly in children (Waltzman & Noel 1998), minimising the size of the coil is ideal. Therefore there is a trade-off here in balancing competing imperatives of energy efficiency and optimal size.

The amount of computation should be minimised, as excess computational power is an unneeded strain on energy and space. Electrode conductivity is also parameter that should be maximised, as this reduces the amount of heat dissipated in the body, which reduces energy losses. Since as many of the flagship models use platinum electrodes (Cochlear 2012), this makes using highly conductive electrodes expensive. However, the raw cost of the platinum is

small so using another material apart from platinum would not be a very effective way to reduce cost.

From analysing Figure 6, it can be seen that reducing the number of electrodes will have positive effects on all other parameters, except proportion of sentences understood. Therefore it would be useful to see if the number of electrodes in the electrode array can be decreased without significantly reducing performance. Fishman et al. (1997) showed that after a certain point, the number of electrodes used in the electrode array does not increase the performance. Notice that in Figure 7, after around 7 electrodes the performance plateaus. This is because there is a limit in the spatial selectivity of the electrodes which means that there are at most 4-8 independent stimulation sites (Wilson & Dorman 2008). Similar results were confirmed by Friesen et al. (2001). Wei et al. (2004) confirmed the relationship for Mandarin speakers. Therefore the number of electrodes can be reduced safely without greatly effecting the performance and 4-7 electrodes is adequate to provide a reasonable understanding of speech.
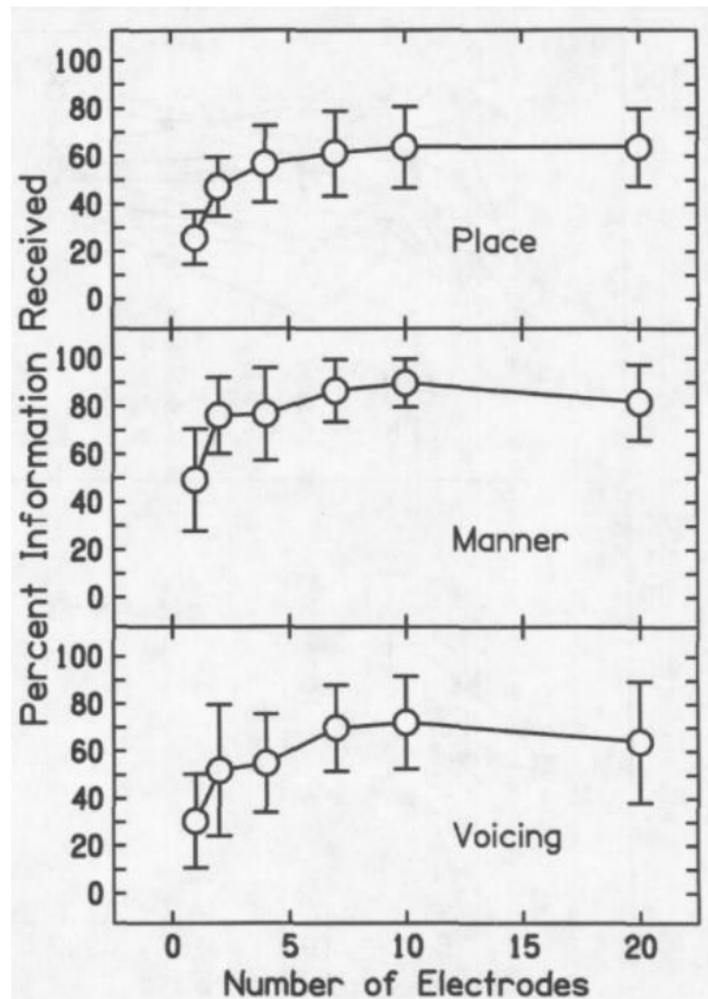

Figure 7: Implant performance as a function of electrodes (Fishman et al. 1997).

2.7   COTS vs Custom

The COTS vs Custom tool was used to compare customer-off-the-shelf items (COTS) with their custom counterparts. As many items used to build a cochlear implant are not available off-the-shelf, a looser definition of COTS has been applied to make a comparison between existing approved components and new designs.

Subsystems	COTS	Modified COTS	Custom
Electrode array	Existing electrode array from previously approved implant		New electrode array design
RF coils (internal & external)	Existing RF coil designs from previous implant		New design of RF coil for the proposed implant
Processor	Standard programmable digital signal processor		Custom digital signal processor
Battery	Standard removable disposable/rechargeable battery	Non-removable battery	Custom battery design

Table 2: Existing vs Custom components

From Table 2, it can be seen that there are several existing components available. It is recommended that components from existing implants be used where possible, as it will be easier to gain regulatory approval. This is particularly true of the electrode array. Therefore, the specific design for the electrode should be very similar, if not exactly the same as a previously approved model.

It is recommended that a standard removable battery be used, such as AAA, as they are easily and cheaply replaced.

A standard DSP (digital signal processor) should be used as this is significantly cheaper than their custom counterparts. As a custom cochlear implant DSP costs approximately 9,900 USD (Barton et al 2003; Harrison 2015; Ok Medical 2016a), there is much opportunity here to reduce cost. A commercial DSP is cheaper than customised DSP, however it uses more power (An et al. 2007). Also, if the number of electrodes is reduced as recommended in section 2.6, then less processing power will be required at the DSP.

2.8   Subsystem Interface of Proposed Design

In Figure 8, the subsystem interface of a conventional cochlear implant is shown, the Cochlear Nucleus 5 (Cochlear 2009).
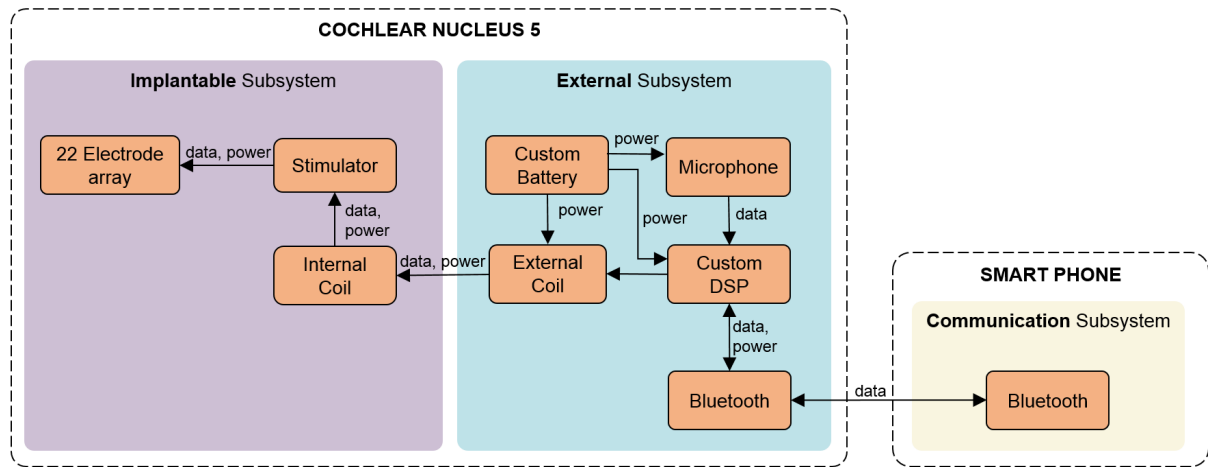

Figure 8: Subsystem interface of conventional cochlear implant: Nucleus 5 (Cochlear 2009).

In Figure 9, the proposed design is shown. The main change is that the number of electrodes has been reduced from 22 to 5, based on the discussion in the House of Quality (section 2.6). Generic batteries and generic DSP, have been used. The proposed design removed the Bluetooth function as this is largely an unnecessary luxury. Furthermore, it is possible that many of the clients would not be able to afford smartphones, which use the wireless technology of Bluetooth.
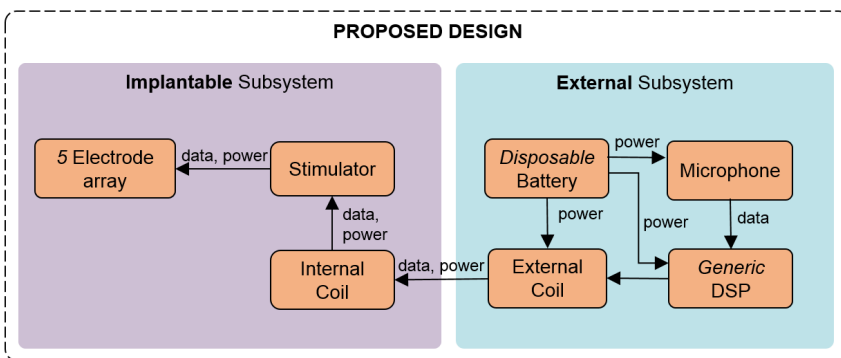
Figure 9: Subsystem interface of proposed design

Both Figure 8 and 9 both have the same basic structure in terms of the connection between components. This is because the structure of the cochlear implant has been refined over the past few decades. It is not wise to make drastic changes to this structure as a subsequent design would be far more difficult to obtain FDA approval, as explained previously in section 2.2. A largely different cochlear implant design would require expansive clinical trials and would likely be subject to the Premarket Approval process, which is much longer and more expensive. It is hoped that the proposed design is similar enough to similar cochlear implants to avoid Premarket Approval, and instead apply for premarketing notification.

2.9   Cost of Design

Table 3 shows the estimated cost of the proposed design. When comparing this to Table 1, notice that all components except the external coil have been changed. A Generic DSP costs approximately 80 USD (Arrow Electronics 2016). The external casing is expected to cost no more than that of a smartphone. Therefore, it is estimated that the total processing unit will cost 500±200.

The changes made to the electrode array were estimated to reduce the cost of the internal coil, stimulator and electrode array by a modest 15-25%. This is because the only changes is to the electrode array, so the internal coil, casing and stimulator will remain similar to previous models. The uncertainty in this is shown in Table 3.

Component	Cost (USD)	Source
Generic Digital Signal Processor	500±200	(Arrow Electronics 2016)
External Coil	165±9	(Cochlear 2016; Ok Medical 2016b)
Rechargeable Battery	36±10	(Kogan 2016; Officeworks 2016)
Internal coil, stimulator and electrode array	15402±6379	(Nadège et al. 2011)
Total	16104±6382	(Nadège et al. 2011)

Table 3: Cost of the proposed design

The total cost is around $16,000 USD, which is approximately 2/3 of the price shown in Table 1 and cheaper than any of the models quoted in Table 5 (Section 9, Appendix). It is acknowledged that this cost still too high and there is still much work to be done.

3   Evaluation

In the following section an evaluation matrix was constructed where the benchmark technique was utilised. This is shown in Table 3. The benchmark technique is appropriate since as discussed in the Customer Requirements (section 2.5), although some requirements are more important than others, all of these requirements need to be above a certain level for an acceptable cochlear implant. For example, if just one of these requirements have a poor performance rating, then the implant will not be acceptable to the client.

Customer Requirements	Importance	Benchmark	Nucleus 5		Proposed design	
			Score	Rating	Score	Rating
Safe	5	3+	4	1	4	1
Effective	4	3+	5	1	4	1
Reliable	3	3+	5	1	5	1
Affordable	2	3+	1	0	3	1
		Total		3		4

Table 4: Evaluation Matrix (meets a benchmark) comparing Cochlear Nucleus 5 and the proposed design.

Below is an explanation on why the scores were chosen for the Nucleus 5 and the proposed design:

Safety:
The most dangerous safety concern is infection, particularly Pneumococcal Meningitis. From 1988-2008, around 0.2% of people who received cochlear implants were infected with Pneumococcal Meningitis (Wei et al. 2008). The changes described in Figure 9 are unlikely to affect safety, since the specifications of the implant are being changed, rather than the structure of the implant itself. Therefore, both implants were listed with a safety score of 4.

Effectiveness
The Nucleus 5 is the one of the newer models from cochlear, the world's largest cochlear implant producer. Therefore, the performance is one of the highest available, and as such the score was set to 5. The proposed design will have a slightly lower performance due to the reduced number of electrodes. Based on research by Fishman et al. (1997), reducing the number of electrodes to five will have approximately 15-25% reduction of the percentage of information received. See Figure 7 for further information. For this reason, the score for effectiveness of the proposed design was set to 4.

Reliability
Cochlear implants are some of the most reliable classes of biomedical implants. For example only 1% of Cochlear's CI24RE Coutour Advance model have failed after 10 years (Cochlear 2015b). The nucleus 5 is a newer model, so there is limited data on its reliability over a long period of time, but it can be assumed that it is equally as reliable as older Cochlear products. It is assumed that the proposed design will have a comparable failure rate to conventional implants as the parts that generally cause failure have not been changed. For example, according to Brown et al. (2009) the most common cause of failure was due to the loss of a hermetic seal or cracked case. Since the case has remained unchanged in this design, it is not expected that reliability will be a major difference between the designs.

Affordability
A standard cochlear implant costs around 25,000 USD (Nadège et al. 2003), so the conventional model is most likely unaffordable to the client. As the proposed design was estimated to cost 16,000 USD, the score for the cost was set to 3.

It is acknowledged that the above reasoning is largely estimated. Therefore it would not be a valid form of evidence to gain regulatory approval and is certainly not publishable. The only way to definitely test the effectiveness and reliability of a cochlear implant is to conduct a clinical trial, but these are time-consuming, expensive and out of the scope of this project.

However, from Table 3, it can be seen that the proposed design is better for the client based on the benchmark methodology. This is mainly because the Nucleus 5 does not satisfy the cost benchmark.
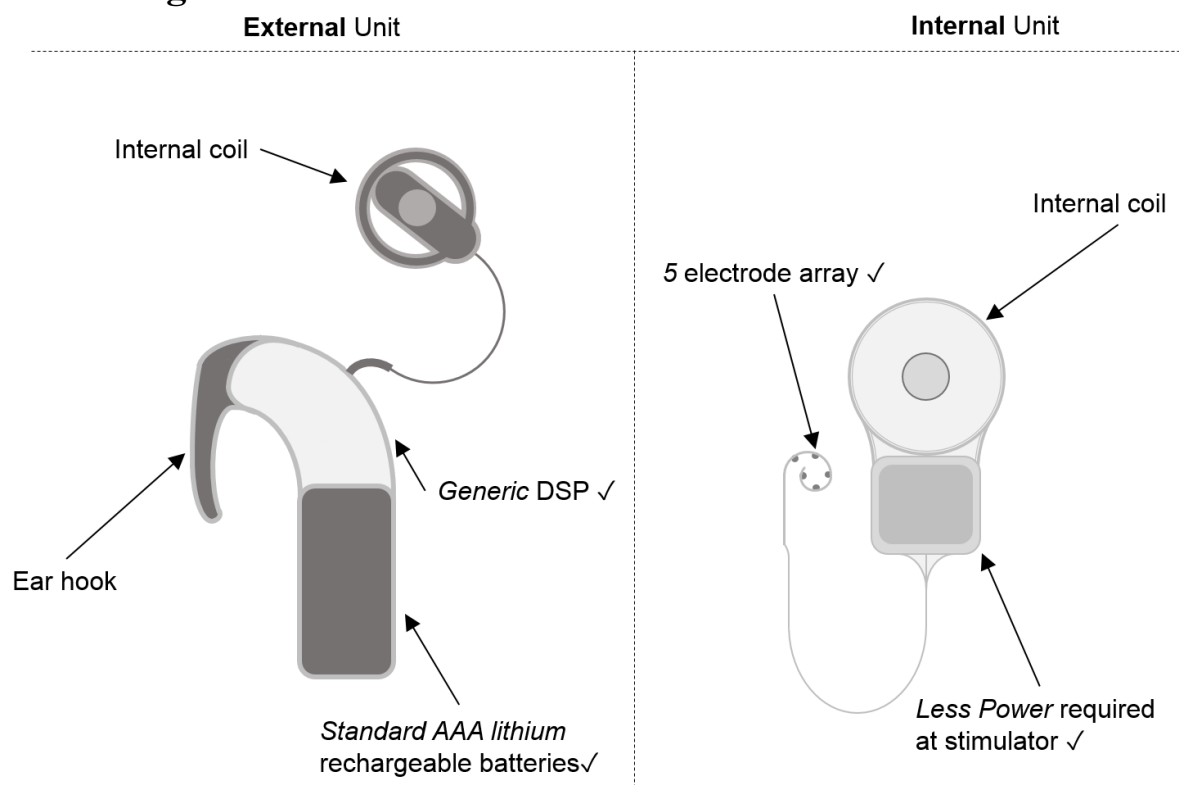
4   Design Communication

Internal coil

Internal coil

5 electrode array ✓

Generic DSP ✓

Ear hook

Standard AAA lithium
rechargeable batteries✓

Less Power required
at stimulator ✓

Figure 10: Diagram of design

In Figure 10, a diagram of the proposed design is shown. The general structure of the design is based off the cochlear Nucleus 5. The main changes are the use of a 5 electrode array, a generic DSP and standard AAA batteries. The structure has been kept the same as conventional cochlear implants to avoid a difficult regulation process.

5   Recommendations

5.1   Use a Generic Signal Processor

From analysis in COTS vs custom, it was found that using a standard DSP compare to a custom DSP will reduce the cost by 5000-8000 USD. Although the standard DSP will use more power, its effect on performance will be minimal.

5.2   Use a smaller number of electrodes in the electrode array

Based on research done by Fishman et al. (1997), it was determined that the number of electrodes in the electrode array could be decreased to five without affecting performance greatly. From the requirements mapping it was determined that this would have positive effects on the rest of the system, such as reducing the amount of power required, and reducing computation. It was estimated that this would reduce the cost of the implantable component by 15-25%.

5.3   Use generic rechargeable batteries

From the COTS vs Custom, it was determined that using generic batteries would be cheaper, and more widely available to the clients. It was estimated that this would reduce the cost by 150-200 USD.

6   Further research

6.1   Undertake a cost-benefit study in developing countries

Although the cost-benefit of cochlear implants in developed countries has been well established, it is unclear whether the same benefit is present in developing countries where wages are lower. If the cost-benefit can be shown, then it will give governments further incentives to fund cochlear implant procedures.

6.2   Investigate use of humanitarian medical visits to reduce surgery costs

It was shown in Idea Generation that volunteers may be useful to reduce medical and surgical costs. This should be researched in the future to assess the effectively and validity of this claim.

7   Conclusion

From the journey through the design process, a cochlear implant design with fewer electrodes, a generic digital signal processor and standard batteries has been proposed. The cost of this device is expected to be around $16,000 USD. Further research should look at reducing the device cost further, and looking for ways to reduce surgical and rehabilitation expenses.

8   Reflection

From completing this portfolio I have gained a greater understanding of how to use systems engineering techniques to solve a problem. I also learnt that the systems design process is much more fluid than I first expected. I originally thought it was a relatively linear process of finding a problem, using the systems tools and then presenting solution. Now I know it is not as easy as this. In my portfolio I have gone around the design circle many times and my final solution involves somewhat of a mismatch combination of various techniques in an unconventional order. It has required me to think expansively and laterally about problems, where some intuition and imagination has been a factor in my consideration of the complex issues.

As I have also studied systems engineering analysis, I think the comparison between the design and analysis approach is interesting. Although the ANU degree structure somewhat separates these two subjects, I would use the tools from each course in conjunction to solve a problem. I think that although some problems lend themselves more to analysis or design, there is certainly cross-over between the two areas. Therefore, if I was solving a similar problem in the future I would use a combination of design and analysis techniques.

I would have liked to do some experimental work for this project. If I had more money and time, I think it would be great if I could replicate the graph shown in Figure 7. I think it is also

unfortunate that I was unable to determine a precise cost for my design. Since cochlear implants manufacturers keep this kind of information secret, this was not possible for me to achieve. However, if I had access to accurate costings of cochlear implant components, I would really like to do further research on this area.

I found the peer review process useful. From reading the peer reviews I found that I should restructure the report to make more logical. In my original report, it separated into the different design tools, in the original order that they appeared when presented in lectures. This meant that my report was disjoint and difficult to follow. In the final report I reordered my report so it was more fluid and changed the section title from undescriptive names of design tools to more specific descriptions. For example, a logical flow diagram was used to show the regulatory process for cochlear implants. Instead of labelling this section 'Logical Flow', I called it 'Regulatory Process for Cochlear Implants', which is much more meaningful.

Some of the peer reviews were brief and it looked like they had not read the report in depth. As such they missed some important details. Based on this, I restructured my report so that the important information was emphasised more so that the main points of my report can be gathered by someone who has little time to read it.

A common comment in my peer reviews was that I had not included a picture of my design or of the cochlear implant. I agree that this was a large problem. To improve this, I included a picture of how the cochlear implant interacts with the ear in the introduction. I think it is really important to include this as many readers would not know the function of a cochlear implant, so providing them with this context is important. As I have spent a lot of time studying this topic, I have found it easy to forget what a general audience will understand. Therefore, I made a special effort to ensure that everything is explained adequately.

I found that going through the design process opened my mind to other ways to approach this problem. Before I started the project, I had relatively narrow and simplistic ideas of how make an affordable cochlear implant. However, now I have a broader view of how to solve this problem, and the cost issues surrounding cochlear implants in general.

9   Appendix: Detailed cost breakdown of cochlear implant

Total Cost of Cochlear implant
To determine a range of costs for cochlear implantation the cost of several different cochlear implants were determined. The currency was converted from Euro to USD using XE (2016), and the inflation was adjusted for using data from The World Bank (2016). The mean and standard deviation for this set of prices was calculated.

Year of implantation	Cost (Euro)	Cost in 2016 (USD)
2006	32754	44061
2006	16405	22068
2006	22338	30049
2006	21987	29577
2007	21931	29502
2007	16465	22149
	Mean	29567
	Standard deviation	7321

Table 5: Cost of implant for various implants sold in Europe from 2006-7 (Nadège et al. 2011).

Cost of Digital Signal Processor

Year	Cost	Cost in 2016 (USD)	Source
2015	8000 AUD	6038	(Harrison 2015)
2016	9500 GBP	13775	(Ok Medical 2016a)
	Mean	9907	
	Standard deviation	3868	

Table 6: Estimation of cost of Cochlear Nucleus Digital Signal Processor. Currency conversions were calculated using data from XE (2016) and inflation was adjusted using data from The World Bank (2016).

Cost of External Coil

Year	Cost	Cost in 2016 (USD)	Source
2016	235 USD	174	(Cochlear 2016)
2016	108 GBP	157	(Ok Medical 2016b)
	Mean	165	
	Standard deviation	9	

Table 7: Estimation of cost of Cochlear Nucleus External Coil. Currency conversions were calculated using data from XE (2016) and inflation was adjusted using data from The World Bank (2016).

Cost of Rechargeable Battery

Year	Cost	Cost in 2016 (USD)	Source
2016	180	261	(Ok Medical 2016c)
2016	164	238	(Connevans 2016)
	Mean	250	
	Standard deviation	12	

Table 9: Estimation of cost of Cochlear Nucleus Rechargeable Battery. Currency conversions were calculated using data from XE (2016) and inflation was adjusted using data from The World Bank (2016).

Internal coil, stimulator and electrode array pricing estimate

As these components cannot be purchased individually the cost of these components were calculated by subtracting all the other components from the cochlear implant cost price. The error in this estimate was determined using standard error propagation.

	Cost of internal components
Mean	19246
Standard deviation	8280

Table 10: Estimation of cost of internal component of cochlear implant.

10   Bibliography

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