Guide to Problem-Solving Through an Engineering Design Perspective

A Personal Handbook

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Introduction

This handbook is meant to serve as a guide for my future engineering design work. It is a document that outlines my engineering philosophy, details the framework through which I view engineering design, and discusses tools I have found helpful throughout this process. Further, it includes the projects I have taken part in, and the ways I have used these models thus far.

In the future, this will be a quick and concise reference to the comprehensive tools I have gathered in my first year in the Engineering Science program. To use this handbook as a reference, the tools, models, and frameworks, can quickly be referred to using the pros, cons, and future use sections. Further, the comprehensive list of questions for each stage of the engineering design process are quick checklists to guide one through the process of carrying out design work in the way that I do. The rest of the handbook details personal experiences which have led to the development of this process, and can be used to understand my biases and limitations when crafting this handbook.

Personal Position in Engineering

I see engineering as a means to provide me with the tools necessary to move forward in any field later on. I have never been sure of what I wanted to pursue as a career, and am still plagued by the uncertainty of what would suit me best. However, I have always believed that engineering equips one with the necessary problem-solving skills and tools to innovate effectively. No matter the context in which these skills are applied, they are immensely helpful in performing any task. That, is the essence of engineering design, to solve various problems in an effective manner in order to add value to the lives of others (referred to as stakeholders in this handbook).

Following this understanding that I don't view myself as an engineer, but rather as a problem-solver, I have equipped myself with a set of skills this past year that can be applied to anything I decide to pursue. This includes intentionality and purpose, an "engineering design process", and ensuring the effectiveness of a design. Intentionality means that I problem-solve with a goal in mind to ensure the final design will serve a meaningful purpose in the way I initially needed it to. The engineering design process is quoted, as it is not just applicable to engineering design work, but can be applied to any context of problem-solving. Ensuring the effectiveness of the design means continuously validating that the solution created to the problem genuinely addresses all aspects of the problem and is the best solution tailored to the stakeholders involved.

This has been the position I have had in regard to engineering design since the beginning of my engineering journey in 2021. However, I have further developed the process through which I problem-solve and have gathered the tools to carry out this process meaningfully. Thus, this handbook focuses on this engineering design process and the accompanying tools, in a way that is applicable to any situation where an innovative solution is required.

In this light, I acknowledge that I have certain biases. Mainly, I value the problem-solving aspects of engineering far beyond the more technical aspects of design. I often find myself in group situations pushing to diverge further to find the most innovative solution, while allotting less time and effort to creating the products and detailing the materials, specific mechanisms, and tools required.

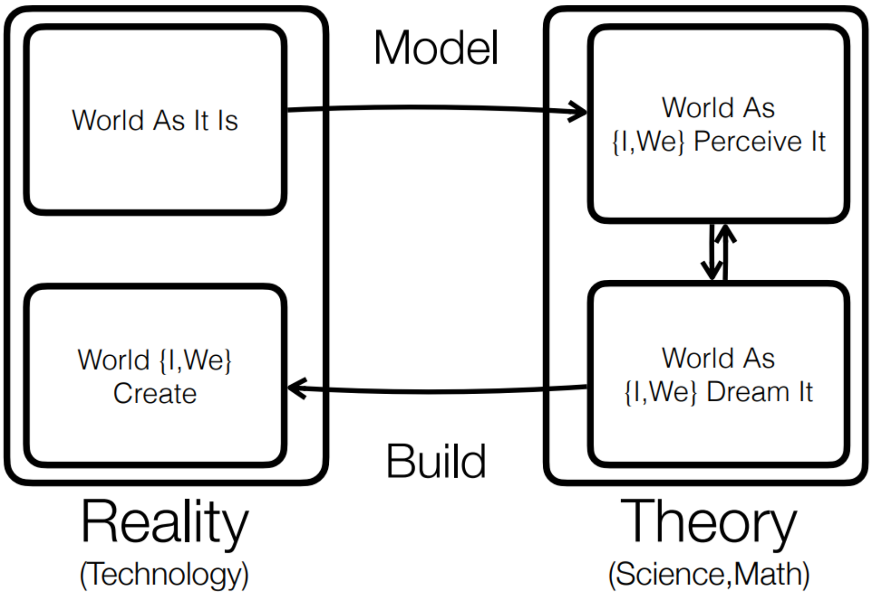
Further, I have the bias of sacrificing some requirements in return for more creative solutions to the problem at hand as set out by the stakeholder. However, I am actively working on this by setting realistic constraints and criteria in the requirements model to be able to refer back to with ideas.

Overall, the main evolution in my engineering design philosophy has been the development of a rigorous design process outlined below and as such, is the central theme of this handbook.

Personal Engineering Design Process

Although engineering design can be seen in a multitude of ways, I believe it boils down to one simple definition: a process. I see engineering design as a process that takes what humans do on a daily basis, problem-solving, and provides a systematic process through which to do so. Engineering design allows one to mold their way of thinking in a direction that uses requirements and arguments to implement change.

Under this umbrella definition, my design philosophy is the following iterative process: assessing the situation and stakeholders, interpreting what was perceived, assessing interpretations, and creating. This is based on the engineering model which bridges the gap between reality and theory.



Engineering Model as Defined in Praxis I

Within my design process, the bridge between the "world as it is" and the "world as we perceive it" is done by framing and scoping what I observe. This is where personal views and design values are introduced. The following is a comprehensive list of design values (DfX's), I have come to value the most:

- Safety

- Usability
- Effectiveness
- Accessibility

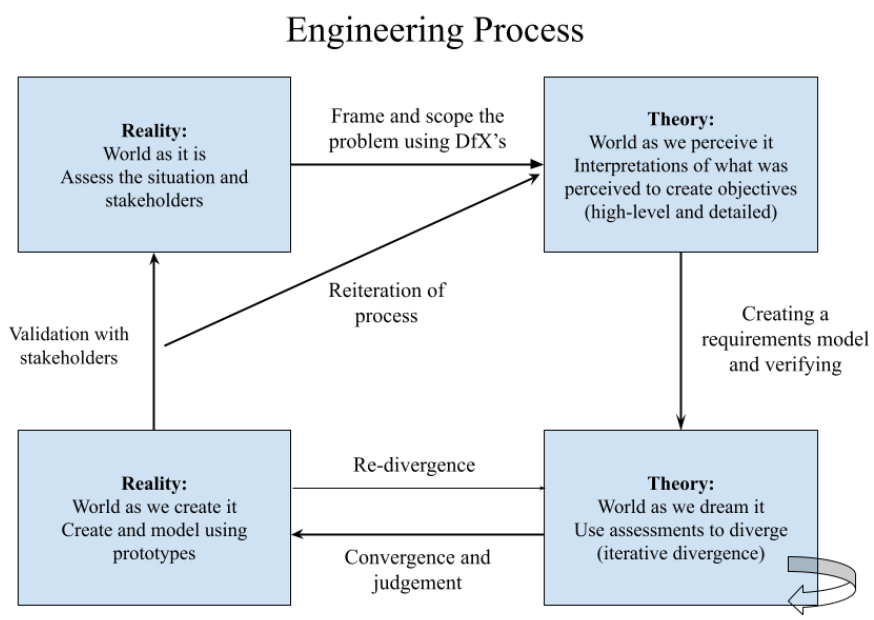
*Safety** ensures that the design can be used for the intended purpose without the user being hindered by designing out the hazard, including safety features and warnings or having special procedures in place. **Usability** allows understanding of how the design works in the world of the user and how it can be made to be more desirable and useful to the stakeholder. **Effectiveness** is insurance that the design resolves the original problem at hand, meeting the objectives laid out. Lastly, **accessibility** requires human interpretation to create a design that can equitably be used by all stakeholders and caters to their specific needs.

**I have included a definition of each DfX as a reference in the future since many of the terms can be misinterpreted or confused with one another*

The bridge between “world as we perceive it” and “world as we dream it”, is the creation of and use of a requirements model to diverge in the ‘dreaming’ stage. Using the DfX’s outlined above, as well as continual verification from the stakeholders, multiple diverging phases occur in this section.

After divergence, converging on ideas occurs using judgment and reference to the objectives previously laid out during the perception phase. Here, these ideas can then be modeled using a variety of prototypes and a final judgment call can be made.

The final bridge between the “world as we create it”, back to the “world as it is” must occur through validation with the stakeholders. Either this step loops the design process back to the perception phase to iterate further, or the design is introduced as the recommended solution to the original problem. This process is illustrated below.



First Stage: Assessing the Situation and Stakeholders

The first step is to identify what the issue is at its core. This means not only interacting with stakeholders to understand the problem, but also identifying what the base of the issue is that is directly causing the issue. This involves identifying a problem area, identifying key stakeholders, and identifying the root of the issue. This in itself may be iterative, as finding the root of the issue may create a new list of key stakeholders.

Comprehensive list of questions that may guide this stage:

- [ ] Who would directly be affected by the implementation of a solution to this problem?
- [ ] Of those directly affected, who could be negatively impacted depending on the solution?
- [ ] How do the stakeholders feel about the issue?
- [ ] How is the stakeholder interpretation of the problem differ from how you initially perceived the problem?
- [ ] What indirect stakeholders could be affected by a solution?

Second Stage: Interpreting What Was Perceived

The next stage is to pick an appropriate frame through which to interpret the situation. Picking the appropriate frame requires that the problem is understood comprehensively in order to pick a core objective and view the issue through that lens. Once this high-level objective is picked, the specific goals of the process can be picked and its accompanying constraints, criteria, and metrics can be chosen. In this way, the requirements model can be created.

Comprehensive list of questions that may guide this stage:

- [ ] If the problem could be described in one sentence, what would that be?
    - [ ] How can this key problem statement be transformed into a high-level objective to be addressed?
    - [ ] Would this high-level objective address the base issue identified in the previous stage?
- [ ] What sub-objectives can be extended from this main problem statement?
- [ ] Is there any aspect of the problem this frame excludes? If this aspect were missing, would the effectiveness of the solution be decreased?
- [ ] Do the objectives chosen focus on too many aspects of the problem? Could a narrower frame be chosen?

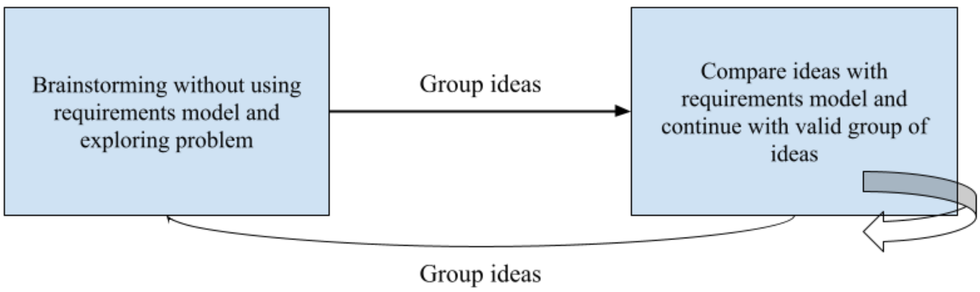
After the requirements model has been constructed:

- [ ] Do the constraints capture the bounds of the problem as laid out by the stakeholders or available resources?
- [ ] Are the metrics the most accurate way to address the objective?
- [ ] Do the constraints make it too difficult to diverge in a meaningful* way?

**In this case, meaningful means in a way that does not limit innovation and allows a multitude of solutions to be explored*

Third Stage: Assessing and Diverging

This stage requires that one is conscious of their own/their team's biases and assumptions, in order to diverge. At first, divergence can quickly be done by generating ideas and brainstorming conceptual designs. Here, the requirements model is not yet enacted, rather the bounds of the problem are being explored in a creative space. After this initial round of divergence, sets of ideas are grouped based on similarity and roughly compared based on the requirements model. Subsequent rounds of divergence move groups of ideas forward and more ideas are brainstormed. This is reiterated until all aspects of the problem are explored.



Comprehensive list of questions that may guide this stage:

- ☐ What are the aspects of the current solution (if existing) that can be improved upon?
- ☐ What components of the current solution (if any) work and can be carried through to a new design?
- ☐ How do the constraints limit the ideas that can be generated?
- ☐ How many ways can the objective be interpreted to create a new design space?
- ☐ How similar are the ideas generated to one another? Can they be combined?
- ☐ *(Should continuously consider)* Are there any biases that are hindering divergence?

Fourth Stage: Creating and Modeling

This step includes prototyping in various ways. Initially, prototypes are low fidelity and are simply proof of concept. However, as prototypes allow further converging, the design features that are crucial to understanding the functionality of the concept should be prototyped in more detail. In the final stages of the prototyping, the designs should be validated with the stakeholders to assess functionality in the space of the user.

Comprehensive list of questions that may guide this stage:

- ☐ What aspect of the design concept is least known and understood from research?

- ☐ Does the stakeholder interact with the product in the way initially intended?
- ☐ What are the limitations of the prototype created? Are these limitations crucial to the design concept as a whole or are they fine-tuning details?

Major Design Experiences and Skills Gained

Throughout the discussion of the tools, models, and frameworks I found helpful, I will make reference to the following projects:

<u>ESC101, Praxis I</u>

My group worked to understand and create a better system for the Eco2Go container drop-off and use at Chestnut Residence at the University of Toronto. We liaised with the dining hall manager to understand the motivations behind the current system as well as the kitchen staff to see where the system could be optimized. We also worked to create a more hygienic short-term storage solution for masks, creating a collapsible waterproof box.

Skills gained:

- As my first experience working in an engineering problem-solving setting, I learned how to objectively and more rigorously assess ideas using a set of objectives and metrics.
- Learned how to interact with stakeholders in a meaningful way, that is, to ask the correct questions which will allow an understanding of the issue at its core.

<u>ESC102, Praxis II</u>

My group worked to create a more accessible and adaptive hockey stick for level 3 power wheelchair hockey players who struggled with lower upper body strength. We created a spring-loaded assistive device that reduces the force of holding a hockey stick with a three-part hinge system. We worked with secondary stakeholders to understand the common disabilities of wheelchair hockey players and the motions they could perform.

Skills gained:

- Given the diverse group of designers we had, I truly understood the importance of getting everyone's opinion as distinct ways of understanding the problem allowed us to generate a large set of vastly differing ideas.
- Prototyping low-fidelity models allowed an understanding of the ways that systems interacted. I learned how to create prototypes that conveyed the specific aspects others had a hard time understanding while not focusing on other details irrelevant to these features.

Tools, Models, and Frameworks (TMFs) for Each Stage

In each stage of my engineering design process, there are applicable TMFs that can facilitate the design work. It is crucial to understand where each TMF is applicable and where it falls short. Specifically, I acknowledge that models are limited as they only provide simplification of various processes, creating a lens rather than an overview of the topic. Therefore, each limitation is acknowledged, and where the TMF can be used is discussed.

***I want to note that each TMF has been chosen as I have found it to be helpful in maximizing problem-solving and ingenuity in my design work.*

First Stage: Assessing the Situation and Stakeholders

Primary Research

This involves interacting with the stakeholder and doing testing in the field. Not only does this allow an initial understanding of the problem but also allows one to delve into the core of the issue since primary sources will often face the problem on a daily basis. Since all stakeholders are affected by the solutions recommended, it is critical that the interpretations made regarding their stakes be as meticulous and all-encompassing as possible which can mainly be done through primary research.

An example of the effective use of primary research was employed in Praxis I, where our group was initially having trouble understanding some of the motivations behind the Eco2Go system. Since the system directly affected me and other group members, since we ate at the dining hall every day, we were clouded by the inefficiencies in the system from our own perspective. However, correspondence with the dining hall manager allowed us to understand why some aspects of the system had to remain in place.

wondering if you could answer some of our questions? Any help would be greatly appreciated.

1) What made you choose the eco2go containers/system over other environmentally friendly container companies?
2) What are the standards, regulations and guidelines that are in place for the containers? What are the sanitation policies in place?
3) Why is the system set up the way it is (such as getting a card for your container and exchanging it)?
4) Are there any improvements you would make to the system now that it has been implemented?
5) How are the containers washed and cleaned? What is the process?

Questions asked to the dining hall manager to gain an understanding of various parts of Eco2Go Process

Pros:	Cons:	In the future:
- Verification with stakeholders which the solution will affect - Results in understanding issues	- It can be difficult to find stakeholders if they have not approached you - Primary stakeholders may not be able to	- Primary stakeholders should always be reached out to if possible when starting initial framing

from 'insider' perspective	pinpoint the root of the issue themselves	

Secondary Research - Articles and the Internet

The internet and scholarly articles found on the University of Toronto libraries resources is an accessible and informative method of learning more about stakeholders. As well, it is a great way of finding reference designs that can be used to base future designs on, especially if an on-the-market solution already exists. In further converging stages, this is the best way to find information about specific materials and mechanisms that can be implemented in a design.

During my Praxis II showcase project, my teammate was in charge of finding suitable materials that was durable enough to handle the large forces associated with playing hockey. Marlene was able to use known material properties found on the internet to make this decision, rather than using testing which would be time-consuming and unnecessary.

MECHANICAL PROPERTIES

	UNITS	ASTM TEST	
Tensile Strength	psi	D638	9,500
Tensile Modulus of Elasticity	psi	D638	345,000
Tensile Elongation	%	D638	135
Flexural Strength	psi	D790	13,500
Flexural Modulus of Elasticity	psi	D790	345,000
Compressive Strength	psi	D695	12,500
Hardness	scale as noted	D785, D2240	M70, R118, Shore D 80
Izod Impact	ft-lbs/in	D256	12.0 - 16.0

My teammate found multiple mechanical properties to pick the material of the hockey stick holder

Pros:	Cons:	In the future:
- Is easily accessible and expansive amount of information available - Able to find reference designs to guide initial diverging	- Difficult to assess the credibility of sources - Search results may not be applicable to specific situation	- Use to support insights gained from primary stakeholders

Second Stage: Interpreting What Was Perceived

The Requirements Model

Details the objectives and its accompanying metrics, criteria, and constraints as it relates to the high-level goal of the design. It sets bounds for a solution space in which the recommended design should fall. Using the requirements model allows the final design to be realistic for the stakeholder it looks to serve and also ensures that if followed, leads to a design that addresses the problem effectively.

During our Praxis II project of creating an accessible hockey stick, our team focused on diverging and forgot to refer back to the requirements model throughout the initial diverging process. While we thought that we had a promising design candidate, we realized upon referring to the requirements model, that the design did not abide by the rules aid out by the power wheelchair hockey association. Thus, it would not have served the community in any meaningful way.

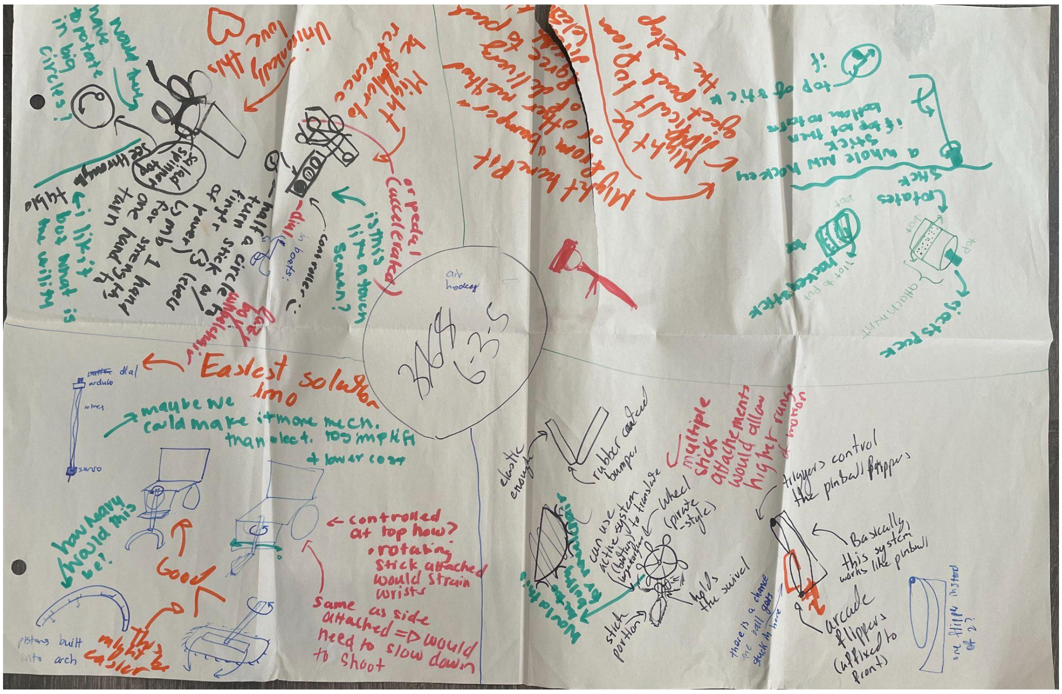
Pros:	Cons:	In the future:
- Allows all objectives to thoroughly be laid out as to not be missed - If there are multiple stakeholders, keeps track of individual stakeholder needs	- Since the designer (often) creates the model, it may be over or under constrained - “Weighs” all objectives equally, gives no way to emphasize key objectives	- Use to support keep track of the information gathered from stakeholders - Refer back to throughout the entire design process

Third Stage: Assessing and Diverging

6-3-5

In this brainstorming technique, teammates quietly draw their ideas and designs on a sector of chart paper and pass the design around. Other teammates have the opportunity to build on top of one another’s designs before it is explained to them. This allows for biases to be alleviated and encourages all members to share their ideas equally.

This brainstorming tool is more effective when used in the earlier stages of diverging as it allows initial ideas to be shared. However, as more diverging occurs, this tool becomes less effective as members begin to know what other members’ ideas are and bias can already exist. I have found this to be the most effective when a group has just begun exploring the problem. This was the first diverging tool my Praxis II team used and it allowed us to start off with a large range of ideas that were later combined to create our final design.



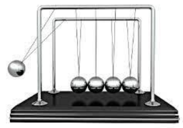
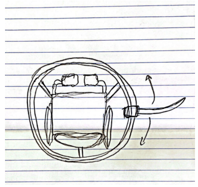
The group's different colored markers show the building of ideas atop one another, and the diversity of ideas is illustrated

Pros:	Cons:	In the future:
- *Encourages all members to freely express ideas which leads to a larger variety of ideas* - *Mitigates biases as verbal explanations are not given, only pictographic or text explanatory*	- *Designs may be misinterpreted and discarded if not later explained verbally*	- *Use as an initial brainstorming technique - aim to get ten ideas in ten minutes*

Morph Chart

The rows of the chart are the key features/aspects of the design and the columns are various ways that these aspects could be achieved. The various ways to achieve these aspects can be combined to create a diverse set of solutions. When a design combines several existing systems or tools, morph charts are helpful in finding the optimal combination of these systems. Further, it allows for a solution to be broken up into its aspects and built back up as a whole, which can be helpful when tackling larger systems or solutions.

When diverging in our Praxis II project, a morph chart was one of the final steps in combining the various aspects we wanted to include in the design. It allowed us to tackle the solution of the assistive hockey system piece by piece, as we realized it was combining several preexisting systems: hinges, springs, and clamps.

How to turn shaft	Pirate wheel 	Pneumatic (air) 	Hot wheels track 	Newton's cradle 
How to increase range of motion	Rail 	Pinball rotation 	Wedge pinball 	Paddle on track around wheelchair 
How to reduce upper body force	Mechanical arm	Air hockey ball	Mechanically advantageous pirate wheel	Lighter stick (carbon fiber material)

Pros: - Allows larger systems to be broken up into less overwhelming pieces - Allows optimization of each key feature	Cons: - Does not include how subsystems will fit together - a combination that is optimal may not be feasible to create	In the future: - Use if there is a large system that is difficult to tackle as a whole - Use if preexisting systems are being integrated into the solution

Pugh Chart

A table that has rows which represent the design criteria as laid out in the requirements model and columns which represent candidate designs to be judged. A separate pugh chart should be created where each of the candidate designs is set as the reference and other designs are compared as better or worse based on measurements from research and calculations.

In my Praxis I group, where we worked to create a short-term hygienic mask solution, we used the pugh chart to get a quick overview of the way other designs compared to our recommended design. Although we did not rely on the chart to make our decision, it aided as a quick visual in affirming that our recommended design would address the objectives well as compared to others.

Metric / Concept	Storage Box TPU-(Thermoplastic polyurethane) **REFERENCE**	Slap Band TPU-Thermoplastic polyurethane Stainless steel bistable spring bands	Cylindrical container (alcohol spray incorporate) PET- Polyethylene Terephthalate	Duo-tang Polypropylene
Time to store/retrieve mask (seconds) [20%]	**0**	-	-	**+/ 0***
Mass (grams) [15%]	**0**	+	-	+
Size (cm^2) [15%]	**0**	**- ****	-	**0**
The half-life of COVID on the material (time) [30%]	**0**	**0**	-	-
Degradation - shelf life of materials (years) (*correctly stored at room temperature) [5%]	**0**	**0**	-	**0**
Force to break the material (MPA) [5%]	**0**	+	+	-
Waterproofness (θ) [10%]	**0**	**0**	-	+

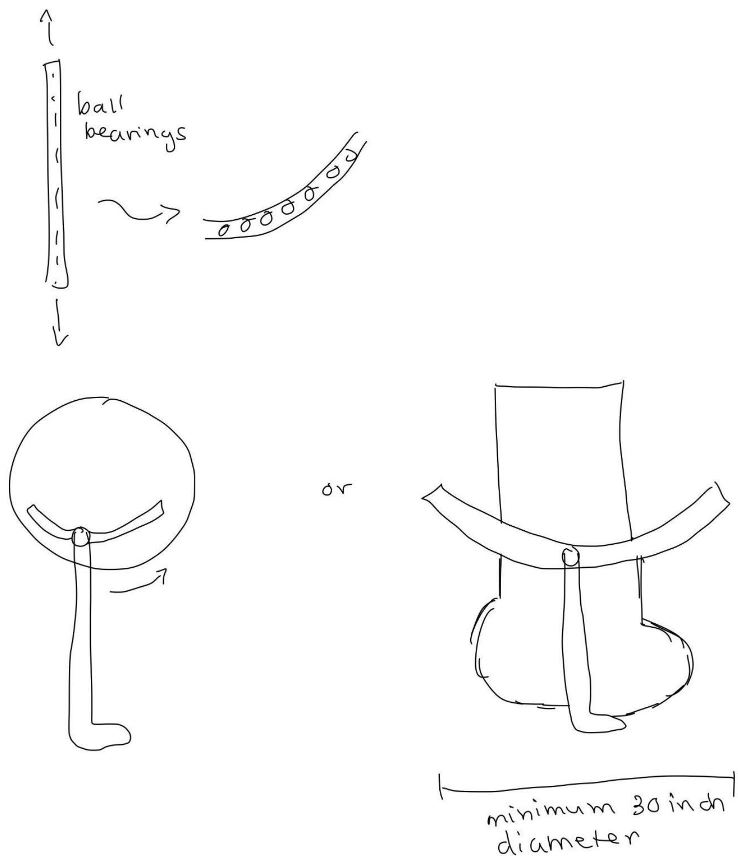
Pugh chart created to compare the main candidate design of a storage box to other ideas, showing that it ranked well in regards to various metrics

Pros:	Cons:	In the future:
- Compares designs based on individual criteria - uses requirements model - Serves as a quick visual reference for the viability of a specific reference design	- Could result in one “adding up” the positive and negatives to make a final decision which discludes personal judgment based on ‘use’ of the design	- Use as a quick guide to determining viability - Do not use to make a final decision as calculations do not encompass the design’s holistic features

Idea Advocate

This is a converging method where a group member picks a candidate design and presents a case in favor of the idea. The cases are discussed and a final decision is made by the group. This technique allows questioning and judgment of designs quickly and efficiently. It is helpful to use when designs are vastly different and minute details that require research will not be the deciding factor between them. This is more of a coarse method of deciding between candidates where the idea as a whole is being evaluated, rather than the finer details.

In my Praxis II group, in the initial converging stages where we had vastly different ideas, rough sketching and advocating of ideas from one member allowed quick disqualification of some candidates.



A simple sketch created by a group member, Satvick, as he advocated for a rail system design

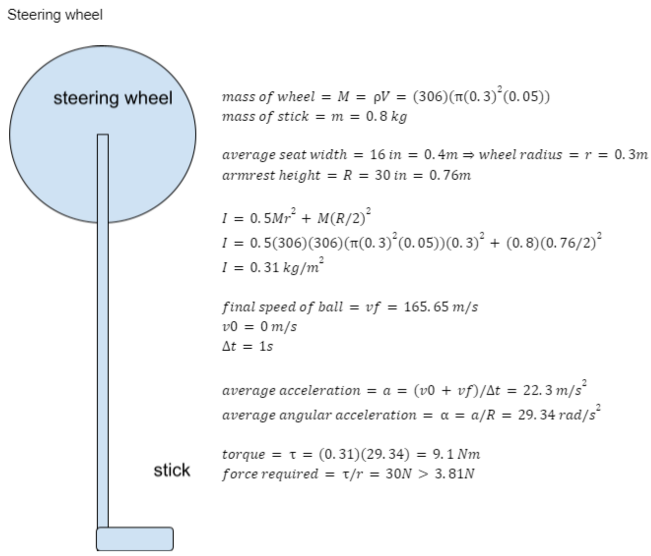
Pros:	Cons:	In the future:
- Is a quick and efficient method of converging - Results in elimination as a result of critical questioning of the viability of designs	- Could create bias as the advocate must stand behind their design - Does not focus on features or details of designs	- If there are a wide variety of ideas to choose from, use to quickly eliminate some options - Do not use if ideas are similar but vary in small features

Stage four: Creating and Verifying

Prototyping

There are a multitude of ways one can prototype but the ones I have found most helpful are calculation based prototypes, graphical drawings, and low fidelity functional prototypes.

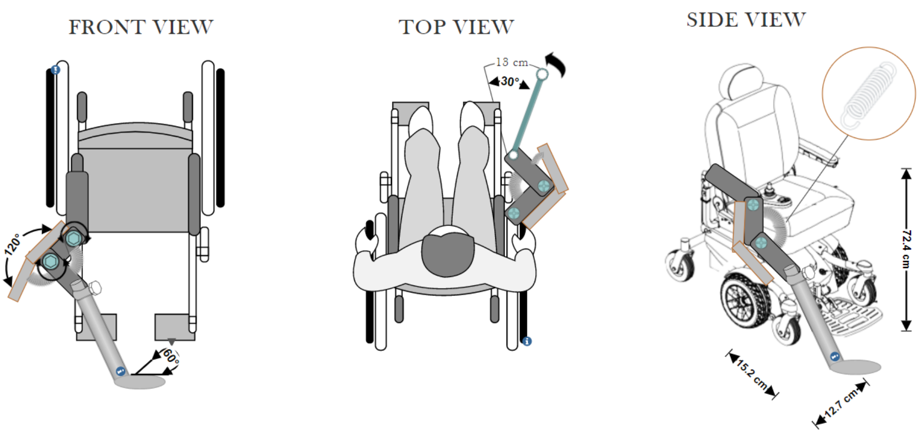
Mathematical prototypes:



Calculations performed by group member, Satvick in Praxis II, showed that it was physically not feasible for level 3 hockey players to lick the steering wheel

Pros:	Cons:	In the future:
- Allow understanding of the mechanisms of a design - If difficult to prototype, show the viability of the design	- Can be time-consuming - Assume ideal scenarios - Do not take into account the use of the design in the hands of the stakeholder	- Use as a means of showing the feasibility of designs in the early stages - Use when testing will not yield optimal results given low fidelity prototypes

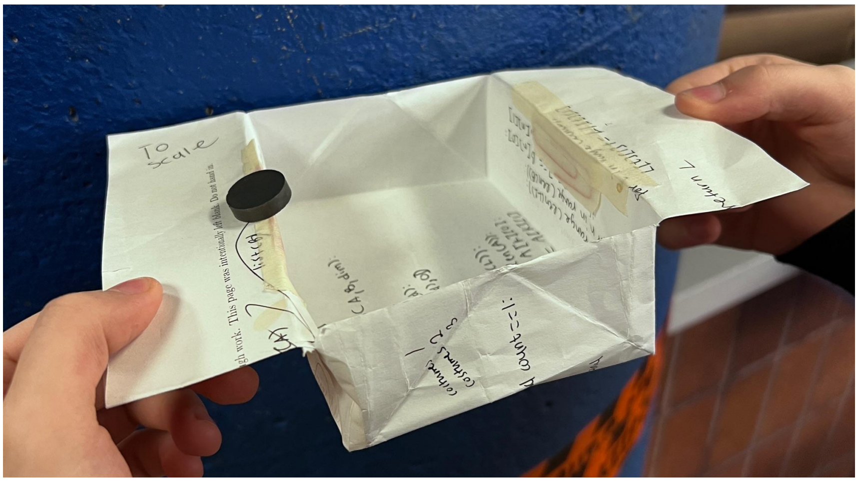
Graphical drawings:



I created graphical representations of the hockey stick, which showed spacially how it would interact with the wheelchair, and highlighted key aspects of the design

Pros: - Quick sketching can illustrate a design well and in a short period of time - More detailed drawings show dimensions and scale	Cons: - Difficult to convey how it will translate to "real-life" use - May not be refined enough to communicate ideas clearly if not accompanied by an explanation	In the future: - Use rough sketches to quickly show a message - Use to show dimensions and materials that may not be in a physical prototype

Low fidelity function prototypes:



The most unbelievable aspect of the collapsible storage box was how it would fold, which is what was prototyped with paper in Praxis I mask storage design project

Pros: - Demonstrates how various mechanisms combine to carry out an objective - Shows how subsystems interact	Cons: - Can be time-consuming or costly - Can become too focused on the fine details, and not on the key features, which is not the purpose of initial prototyping	In the future: - Use to convey how the design will work in the hands of the user - Focus on demonstrating the proof-of-concept rather than fixating on smaller details

Overall Key Takeaways

This section is a short list of lessons taken away from the engineering design work I have partaken in this year, especially things I would like to keep in mind for the future:

- [ ] Even though it may be difficult to reach out, contact stakeholders at every step of the design process to better serve their needs with the final design.
- [ ] It is more likely that a combination of existing systems will yield a better result than trying to create a completely innovative solution. Spend more time researching reference designs.
- [ ] Assess biases after each stage outlined above, especially anchoring bias when working with a group.
- [ ] Having a physical prototype is always more useful than elaborate sketches and calculations as it allows you to see how the design interacts with the user.
- [ ] Refer back to the requirements model more frequently to ensure your design is within the bounds outlined by the stakeholder.

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