Assessing the feasibility of a circular economy for 3D printed tactile educational aids for visually impaired (VI) students in India

by

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Abstract

Access to higher STEM education is limited to students with disabilities globally. The issue is particularly prevalent in countries like India where students are frequently advised against pursuing higher STEM education due to insufficient devices and tools in schools. The unavailability of educational devices in the sciences along with insufficient pay and attention for instructors in public schools results in a massive under-representation in higher education. Even for those who are brave enough to pursue their dreams, the statistics are incredibly bleak. 6 out of 10 students fail graduate classes in the visually impaired (VI) community because their fundamentals have not been built up sufficiently [6]. The present system results in few VI students pursuing science and technology as their academic and professional future. This results in a skewed participation in higher education and technology professions which has a direct consequence of accessibility being treated as an afterthought in product design globally.

The extent of this problem is not apparent to sighted individuals as they do not face the same challenges as their differently-abled counterparts. Furthermore, there is a segregation of these students from standard schools; thus, the interaction between both groups of students is minimal. Having such a large problem space, the focus of this study has been on targeting the issue of a single-disability (VI) and a single-subject (geometry). The solution involves tactile devices that can be easily integrated into the curriculum, such as tactile tangrams puzzles and the Hexa-compass.

Focus areas of this study have been analyzing the current curriculum and determining integration of the devices into the same. Furthermore, stakeholder analysis was conducted based on the REAP framework along with determination of a technology strategy statement for the next five years from an ecosystem and technology perspective. This is a Blue Ocean Market analyzed using the Business Model Canvas, and a circular economy model has been piloted at Bengaluru and Chennai, India, in the past nine months. Finally, there is a recount of the challenges encountered, suggestions on future work, and a commentary on the more extensive socio-technical system.

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Contents

1 Introduction **15**

1.1 Context Setting 15

1.2 Project Aakaar 16

1.2.1 Prior Work and Progress 16

1.2.2 Planned Research and Undertaking 17

2 Background **19**

2.1 Present Situation in India 20

2.2 Goal and Approach 21

2.3 Scope 22

3 Literature Review **25**

3.1 Higher Education and Accessibility 25

3.2 Available Interventions 26

3.2.1 Non-Visual Desktop Access 27

3.2.2 BrailleNote Touch Plus 27

3.2.3 Seeing AI 28

3.2.4 Read Read 28

3.2.5 Kurzweil Education 29

3.2.6 Dancing Dots 30

3.2.7 BLITAB 30

3.2.8 Refreshable Braille Displays 31

3.3 Circular Economy Implementations 32

4 Stakeholder Analysis **35**

4.1 The REAP Framework 35

4.1.1 Application and Available Stakeholders 36

4.1.2 Strategy for Higher Engagement 37

4.2 The ARIES Framework 39

4.2.1 Application and Drivers For/Against 40

4.2.2 Stakeholder Saliency and Product Landscape 41

5 Technology Assessment **45**

5.1 Technology Readiness Level 46

5.2 Accelerating Technologies 47

5.3 Technology Strategy Map 49

6 Business Model Analysis **53**

6.1 What is a Blue Ocean? 54

6.2 Lean Metrics and Business Model Canvas 55

6.3 Net Present Value Analysis 58

7 Conclusion **63**

7.1 Major Takeaways 63

7.2 Challenges 64

7.3 Socio-Technical Complexity 65

8 Recommended Future Work **67**

A Artifacts **69**

A.1 Sample Stakeholder Interviews 69

A.1.1 Interview with Ms. Sushma 69

A.1.2 Interview with Mr. Prateek and Mr. Sharad 73

A.2 Train-The-Trainers (T3) Manual 76

A.2.1 Foreword 76

A.2.2 What are assistive technologies? 77

A.2.3 Accessibility in Design 79
A.2.4 Ideation to Digitization 80
A.2.5 Sightless Learning 80
A.2.6 Tactile Learning 81
A.2.7 Quality Assurance of Initial Designs 82
A.2.8 Slicing the CAD Files 83
A.2.9 Gathering Feedback from Potential End-Users 84
A.2.10 Construction of Second-Round Designs 85
A.2.11 Acknowledgements 86
A.3 Lesson Plan at SKEI 86
A.3.1 Sightless Learning 87
A.3.2 Tactile Learning 88
A.3.3 Empathetic Design 89
A.3.4 Digitization of Design 89
A.3.5 Design Validation 92
A.3.6 3D Printing 93
A.3.7 Quality Assurance 93
A.3.8 First Level Feedback 94

List of Figures

1-1 Customized Circular Economy Model 16

2-1 Refreshable Braille Display costing 6,495 USD [11] 21

2-2 Tangram Puzzles - Triangle Concepts [24] 22

2-3 Base Plate of Hexacompass [24] 22

2-4 Concept for the Taction Tablet [25] 23

3-1 Distribution of Differently Abled Students by Study Stream [13] . . . 26

3-2 BrailleNote Touch Plus (L) and Read Read (R) 29

3-3 BLITAB - First Ever Braille Tablet 30

3-4 Positive Effects of A Circular Economy [12] 34

4-1 Star Model of the REAP Framework [22] 36

4-2 Stakeholder Map for Project Aakaar - created by Prithvi Raj 38

4-3 The ARIES Framework, Nightingale and Rhodes, 2015 40

4-4 Product, Manufacturing and Distribution FFA 41

5-1 Object Process Model for In-Space Additive Manufacturing, Lee, Mandal and Moraguez 46

5-2 Technology Readiness Level [10] 47

5-3 Box Plate And Geometry Set [24] 49

5-4 Initial Design Structure Matrix for Aakaar 50

5-5 Revised Design Structure Matrix for Aakaar 51

5-6 Five Year Technology Strategy Map 51

6-1 Red vs. Blue Ocean Strategy [8] 54
6-2 Lean Impact Metrics - Project Aakaar 56
6-3 Business Model Canvas - Project Aakaar 57
6-4 Histogram Range based on Monte Carlo 61
6-5 Cumulative Distribution based on Monte Carlo 61
6-6 Flexible Strategy for Expansion As-Needed 62

8-1 Equality vs. Equity - A Comparison [17] 67

A-1 Types of Assistive Technologies 78
A-2 Accessibility in Web-design for Color Blindness [C] 79
A-3 Empathy Centric Design 81
A-4 Curved Edges or Fillets 83
A-5 Converting a CAD file to STL 84
A-6 Feedback Methodologies 85
A-7 Process of Iterative Development 86
A-8 Various Concepts of Triangles 87
A-9 Geometry Set of Original Aakaar Puzzles 89
A-10 Curved Edges or Fillets 91
A-11 Possible Theorem for Future Design 94

List of Tables

4.1 Stakeholder distinction for Project Aakaar 42

4.2 Envisioned Landscape of Future Enterprise 43

5.1 Figures of Merit for Fused Deposition Modeling, Lee, Mandal and Moraguez 48

6.1 Net Present Value using Atal Tinkering Labs 58

6.2 Net Present Value for Dedicated Makerspace 59

6.3 Net Present Value with Uncertainty - ATL Model 60

Chapter 1

Introduction

1.1 Context Setting

In countries like India, students with disabilities are systematically excluded from pursuing higher STEM education because of the unavailability of tools and proper training. The primary target group for this study is visually impaired (VI) school students in India, and as evident from conversations with VI students at Devnar School for the Blind in Hyderabad, India, these differently-abled students have great enthusiasm for science and technology as well. However, most of them cannot pursue it in higher studies because of the lack of resources to provide a solid conceptual understanding of STEM. Many of them are even encouraged by their parents and teachers to take up humanity fields like teaching and law, which are less technically demanding.

Notably, geometry, an essential topic for STEM, is particularly challenging due to the lack of visual perception in VI students. Conversations with teachers of VI students revealed that the education boards in India do recognize this issue and exempt students from answering geometry-related questions in the exam. While the problem is acknowledged, it is not being addressed and continues to be a prolonging issue. What seems like a relief for both student and the teacher soon becomes a hurdle at a higher education level because these exemptions also limit their ability to pursue higher STEM education. Further, the teachers focus less on the subject as it does not count towards exam preparations. These circumstances have a spiraling effect resulting in a geometry-deprived education for VI students.

1.2 Project Aakaar

1.2.1 Prior Work and Progress

Project Aakaar was conceived in 2019 when a group of 3 students from NIT Warangal - Sarthak Kapoor, Shantanu Landore, and Daksh Parmar attended a workshop at the L. V. Prasad Eye Institute conducted by Dr. Kyle Keane. Dr. Keane has been an advocate in the disability space for 2 decades and has established a global community of like-minded individuals who want to contribute to re-framing the narrative of "living with a disability or diagnosis" [1]. This community is called Humanistic, and their goal is to achieve equity for the differently-abled by including them in the design, development, and testing processes for accessibility inclined products [2].

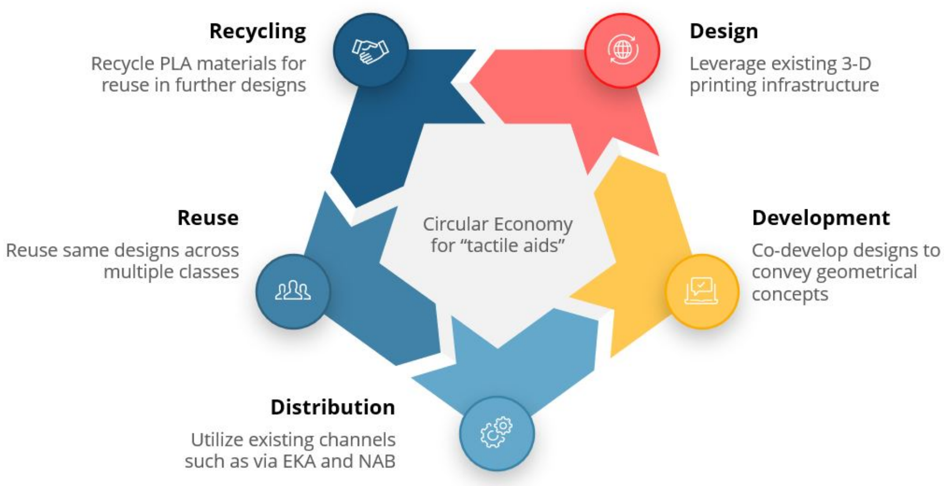

Figure 1-1: Customized Circular Economy Model

This project was conceived as a UG term project post the workshop mentioned above but lost traction as the students involved moved on to professional careers and graduate studies.

1.2.2 Planned Research and Undertaking

During Summer 2020, this thesis was undertaken under the guidance of Dr. Keane to pilot a customized circular economy model that would utilize existing infrastructure till capital funds are sourced to boost the project. The "Make in India" program has established 3D printing capabilities in over 6k schools in India, and these schools conduct regular workshops on additive manufacturing. While the students create aesthetically pleasing and fun products, they are usually discarded after the session, thus becoming non-utilitarian. By creating a Train-the-Trainers (T3) manual along with our publicly available 3D CAD designs, we were able to 1) leverage the existing infrastructure at Atal Tinkering Labs (ATL) and 2) facilitate co-design sessions between sighted and visually impaired kids for additional designs. The ATL program provides schools with a 3D printer and introduces instructors at schools to a nation wide community of facilitators and instructors who are working on additive manufacturing.

These devices are presently in circulation at the Shree Ramana Maharishi Academy for the Blind. While the circular economy can work, COVID19 presents a unique challenge as students are not present in schools, limiting collaboration and co-design capabilities. To maintain traction and ensure appropriate scaling, establishing a dedicated MakerSpace and activating a distribution network through the National Association for the Blind (NAB) are being explored.

Chapter 2

Background

According to the WHO, at least 2.2 billion people globally have a near or distance vision impairment. Young children with early-onset severe vision impairment can experience delayed motor, language, emotional, social, and cognitive development, with lifelong consequences. School-age children with vision impairment can also experience lower levels of educational achievement [20]. In countries like India, students with disabilities are systematically excluded from pursuing higher STEM education because of the unavailability of tools and proper training. The present system results in massive underrepresentation and accessibility being treated as an afterthought.

Most present statistics address the percentage of differently-abled individuals within current graduate populations instead of measuring the percentage transition within the community. Approximately 60 percent of students in the VI community compared to 25 percent in the entire student body fail graduate classes because their fundamentals have not been built up sufficiently. In 2010, almost 18.9 million children under 15 years of age were visually impaired globally [23], but the number of visually impaired students in higher studies, especially in STEM, is dismal (<1 percent). Furthermore, vision impairment poses an enormous global financial burden. For example, the annual global costs of productivity losses associated with vision impairment from uncorrected myopia and presbyopia alone were estimated to be 244 billion USD and 25.4 billion USD, respectively [19]. According to a 2011 report by WHO, there were a total of 253 million people affected by some form of blindness and visual impairment and over 1 billion individuals with some form of disability [26]. Scaling the figure while accounting for population increases and technological advances in the last decade, there is still a theoretical loss of multiple trillions of dollars on a yearly basis.

2.1 Present Situation in India

There are separate schools for visually impaired (VI) students in India, and they are usually segregated from sighted students. Students who come from affluent backgrounds have the financial capacity to buy the necessary tactile and Braille devices for integration into general education schools such as the one shown below. It is estimated that at least 200,000 to 300,000 children in India have severe visual impairment or blindness and approximately 15,000 are in schools for the blind who do not have the economic means to access these devices [21]. The minimal fraction of students attending school is dependent on the socio-cultural perception that there are minimal viable career paths for VI students. This is a direct consequence of inefficient education and potential futures for these students due to a systemic inadequacy on addressing the problem. Furthermore, there is a lack of training and severe underpay for the teachers (average salary approximately 4000 USD yearly), resulting in apathy for teaching complex concepts, especially in STEM disciplines.

Students are frequently advised against pursuing such dreams due to the systems' lack of adequate devices and tools in schools. This results in a systemic exclusion of differently-abled individuals from higher STEM education. Disabilities are not addressed in systems and product design as a precursor but rather as a band-aid to address any concerns. There is a need for higher inclusion, co-design, and a deeper understanding to create genuinely inclusive products and available.

This is a wicked problem, i.e., a social or cultural problem that is difficult or impossible to solve for as many as four reasons: incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden, and the interconnected nature of these problems with other problems [14] but that does not mean

Figure 2-1: Refreshable Braille Display costing 6,495 USD [11]

that it should be left unaddressed. Portions of this problem need to be incrementally tackled with greater involvement from all the stakeholders in the ecosystem.

2.2 Goal and Approach

Enabling equitable access to STEM education for VI students in the long term goal but attempting to address all of the problems in a single sweep is an attempt in futility. Project Aakaar initially targets a single disability (visual impairment) and a single subject (geometry) as a Proof-of-Concept before increasing the scope. They have already created cost-effective alternative educational aids such as 3D printed tactile tangram puzzles and the Hexacompass that enable visually impaired (VI) kids to touch, feel, and engage in learning Geometry concepts. The puzzles have been designed over two years of rigorous user interviews, ideation, user testing, iterations with the target audience, VI kids, and the extended community (teachers, schools).

This thesis elucidates the need for higher stakeholder engagement by utilizing the REAP and ARIES frameworks defined in the following sections. It establishes the Technology Readiness Level, introduces a Technology Strategy Map, and investigates a higher alignment with the current national curriculum being utilized in these schools. Finally, it addresses the Business Model Development using various method-

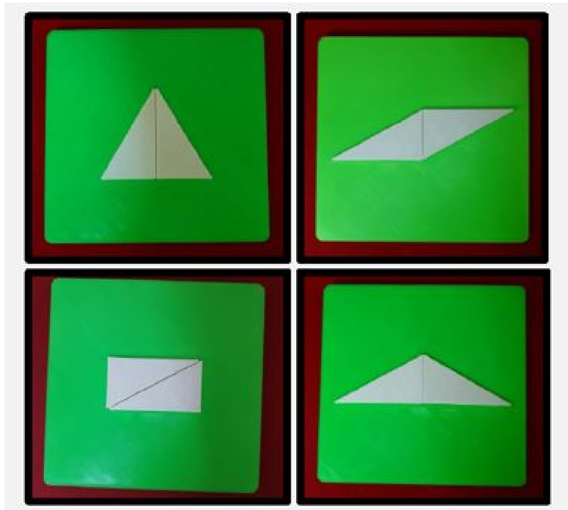

Figure 2-2: Tangram Puzzles - Triangle Concepts [24]

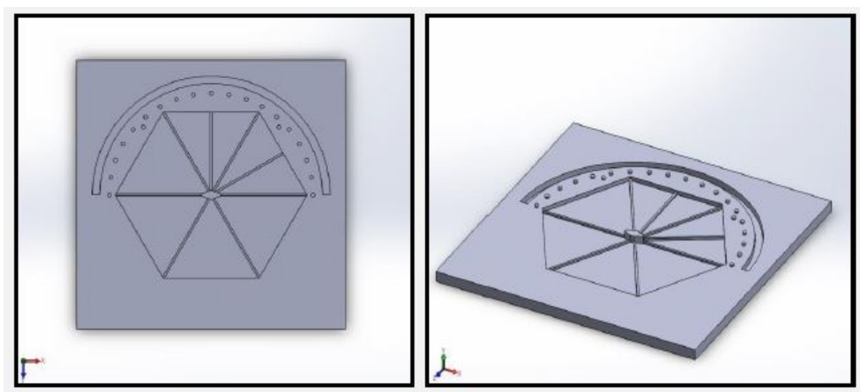

Figure 2-3: Base Plate of Hexacompass [24]

ologies such as Blue Ocean Strategy, Lean Impact Metrics, and Net Present Value (NPV) analysis.

2.3 Scope

The initial scope was to investigate a Refreshable Braille Display (RBD) that would cost a minimal fraction of the present commercially available devices (approximately 1/300th). The deliverables were a Train-The-Trainers manual and a financial sustainability plan.

However, COVID19 presented unique challenges which stalled the development of the product. This led to a pivot for the envisioned circular economy to Project

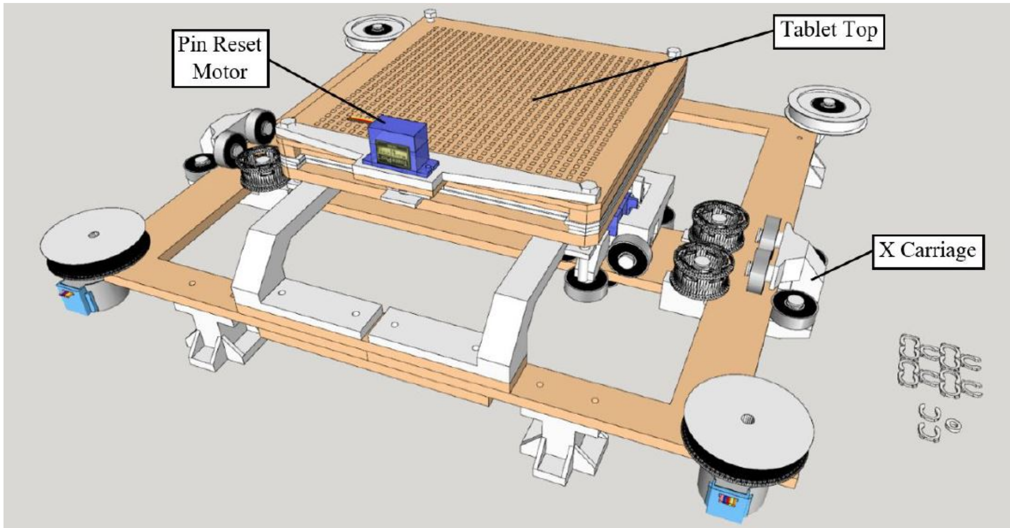

Figure 2-4: Concept for the Taction Tablet [25]

Aakaar, which was working on other tactile educational aids for greater STEM access. As this project was comparatively less complex in terms of its' technological components, different methodologies were used to assess the stakeholder network, technical feasibility, business model development, and future steps for successful deployment nationally.

Chapter 3

Literature Review

3.1 Higher Education and Accessibility

According to a study done by Syed Salma Jameel across 294 colleges in India and 1.6K students with disabilities, the least number of enrollments was in the sciences [13]. There are visual elements to higher education concepts in all of the sciences, physical, biological, chemical, or otherwise. Without efficient methods of conveying this visual information (tactile/audio), these individuals are not being exposed to the full extent of present available general and higher education.

In 1997, the US Congress passed amendments to the Individuals with Disabilities Education Act (IDEA), so that children with disabilities were to progress in the general education curriculum [3]. The ideal goal should be complete integration into the common student body but there is a continued segregation of VI students from the general student body in India because of a systemic structure. At present, there is a massive lack of cost-effective tools and devices, low pay and inadequate training of instructors that needs to be addressed. A no-cost manufacturing, limited cost distribution model is worth exploring given the edu-social benefits of the envisioned solution.

Mistry (2012) reported that students with disabilities did not have easy accessibility to classrooms, libraries, and academic and administrative buildings in their respective universities. They were also not provided with any learning resources,

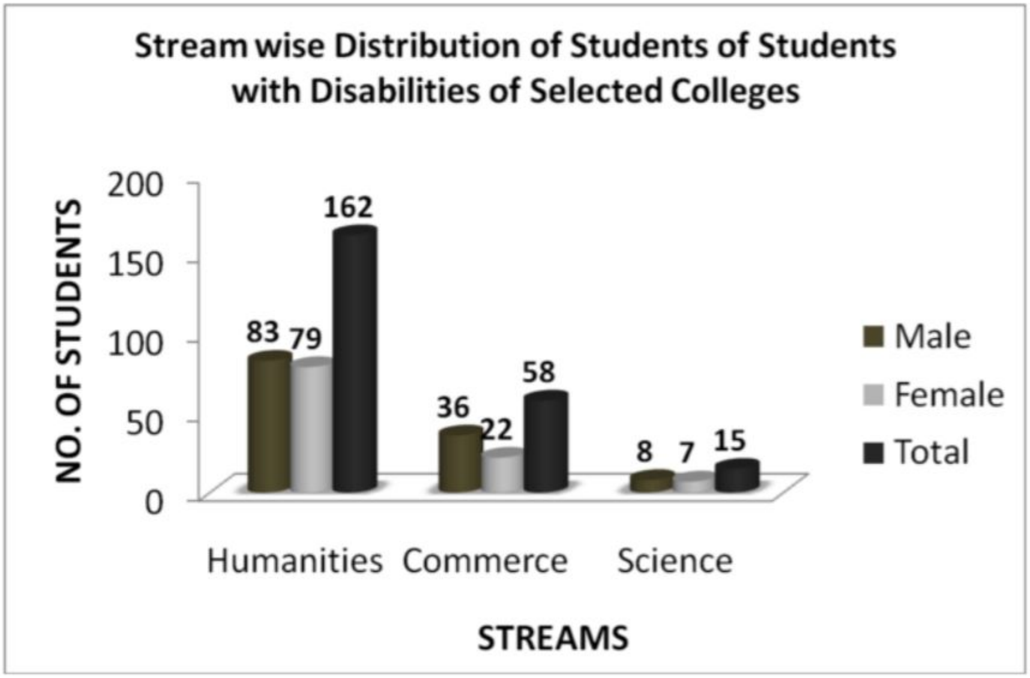

Figure 3-1: Distribution of Differently Abled Students by Study Stream [13]

including assistive technology. Though there were definite signs of progress in the provision of higher education to students with disability taking place within a demanding context, much more development is needed, and in particular, barriers to accessing the curriculum needs to be addressed [18]. Creating greater access to geometry for VI students through the use of tangrams and the Hexacompass is a presently small but potentially immensely meaningful step in the right direction.

3.2 Available Interventions

Global assistive technologies for the visually impaired market are expected to witness rapid growth over the coming decade due to increasing awareness and technological advancements. Additionally, there are growing cases of visual impairment and blindness, and more government initiatives to promote quality of life. Key players operating in this market include Cambium Learning, Access Ingenuity, VFO, Dolphin Computer Access Ltd., Amedia Corporation, HumanWare Group, Access Ingenuity, VisionCue, and TQM. In January 2018, VFO and Enhanced Vision announced a merger to create the world's largest assistive technology provider for the visually impaired. The product segment includes educational devices and software, mobility devices like canes, and low vision devices like spectacles. According to Fior Markets, the educational devices and software space is expected to grow with the highest CAGR of 10.09 percent from 2018 - 2025. A rise in demand for braille and leading machines and an increase in government awareness programs in developing economies are expected to fuel the segment's growth during the forecast period. These are major contributing factors to the segment's growth. Pre-pandemic, the Asia Pacific was the fastest-growing region due to the increasing disposable income of people in developing economies like China and India [15]. Some of the available device and software interventions in the market to enable greater educational access for VI students are mentioned in the section below.

3.2.1 Non-Visual Desktop Access

NVDA (Non-Visual Desktop Access) is an open-source screen reader for Microsoft Windows, enabling blind and vision-impaired people to use computers. A screen reader is a layer on the top of the operating system which intercepts every input and output and presents it to the user in a helpful way, either audio or braille format. It runs on both 32-bit and 64-bit editions of Microsoft Windows XP or later. NVDA has no additional hardware requirements beyond those operating systems and requires around 50 MB of disk space. The software is freely downloadable on their website [4].

3.2.2 BrailleNote Touch Plus

BrailleNote Touch Plus is one of the most powerful and up-to-date note-takers in the assistive technology industry. It is packed with educational tools for use in the classroom and beyond by both educators and students. It combines the simplicity and accessibility of a note taker with the power and efficiency of a modern smartphone or tablet and is supported by the Android Oreo platform. Modern tablets and notepads work on touch and require vision to access the multiple apps and features of the device, which are not powered by speech recognition. BrailleNote creates tablets with a built-in Braille keyboard, which makes them explicitly targeted at the visually challenged population to increase access to technology and incorporate them holistically into the digital world. The price per unit ranges from 4,995 to 7,095 USD based on the hardware specifications and category of the chosen device.

3.2.3 Seeing AI

Seeing AI is an artificial intelligence application developed by Microsoft for iOS. It uses the device camera to identify people and objects, and then the app audibly describes those objects for people with visual impairment. It describes short text, documents, products, people, currency, scenery, colors, handwriting, and light. Envision AI is a smartphone app that empowers blind and low vision users to be independent by speaking out the visual world around them. It is said to have the fastest and most accurate OCR (Object Character Recognition) and can recognize scripts of over 60 languages. As a non-blind person, it is difficult to understand the true extent of the issues faced by the visually challenged daily. Trouble identifying objects until they touch them, trouble reading signboards and other texts, trouble understanding images until it is described to them. In recent years, there have been apps that target each of those problems individually, such as TapTapSee for identifying objects. However, Seeing AI and Envision AI are among the first apps which integrated multiple needs such as text recognition, currency identification, bar code reading, and color identification. Seeing AI is freeware that can be downloaded from the App store, while Envision AI is priced at 4.99 USD per month after a 14-day trial period.

3.2.4 Read Read

The Read Read is an innovative, physical tool that allows the blind and visually impaired to independently practice reading braille and large print. It features a friendly, tactile interface with alphabetic and phonetic tiles, along with built-in, high quality audio supports. One of the major problems that is faced in government schools is that visually challenged and other disabled kids need much more attention than their abled counterparts, especially during their formative years. However, given the meagre pay and limited budgets, there is not enough time spent in the development of these children which results in them lagging in later years. There is a need for devices which can help these children to learn independently without the need for extra attention daily while ensuring that the quality of education is not lost. The cost is 645 USD per unit.

Figure 3-2: BrailleNote Touch Plus (L) and Read Read (R)

3.2.5 Kurzweil Education

Kurzweil Education offers assistive technology products and resources that transform struggling learners into successful, independent readers, writers, and test-takers. Kurzweil's assistive technology is an integrated solution for life for English language learners who live with dyslexia or are learning with a visual impairment. There are English and non-native English speakers in many school environments, or where literacy skills and abilities range from low to high achievers. The language breadth is a unique feature that is not available in many solutions. Additionally, Kurzweil 3000 tools are acceptable accommodations on high-stakes end-of-year tests. In Massachusetts, for example, when students with disabilities wrote end-of-year MCAS tests, electronic read-only versions of the test were made available on CD if they used the Kurzweil 3000 text-to-speech software. The cost is 700 USD for a single license versus 4K USD for an enterprise such as a school.

3.2.6 Dancing Dots

Dancing Dots offers technology, educational resources, and training to assist blind and low-vision individuals to read, write, and record their music. Their products and services foster inclusion, literacy, and independence for visually impaired musicians and audio producers engaged in educational, leisure, and professional pursuits. Education is not simply limited to text or objects and cannot be holistically covered by text-to-speech conversion software and vice versa or by Object Character Recognition (OCR) alone. The disciplines of art, music, and sports also need to be considered to target a holistic education and provide additional professional and recreational opportunities for the visually challenged population. It is pertinent to explore alternative solutions that can aid these individuals in creating arts, playing sports, and composing music. They have a wide range of products costing 400 USD onwards.

3.2.7 BLITAB

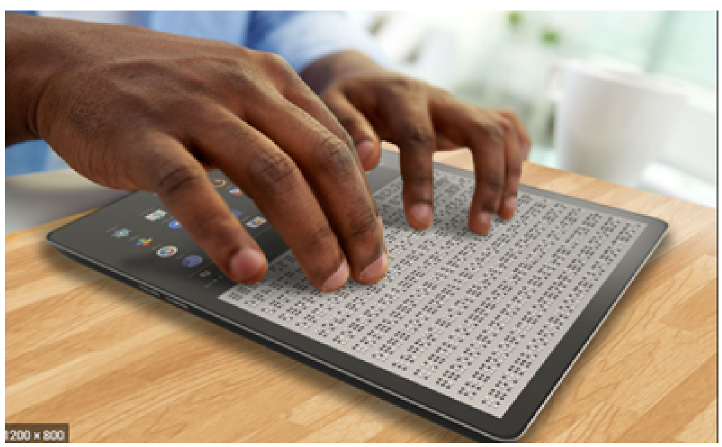

Figure 3-3: BLITAB - First Ever Braille Tablet

BLITAB is the first-ever Braille tablet using a disruptive actuating technology developed by a company of the same name to create tactile text and graphics in real-time. People call it “The tablet for the blind.” The novel invention is a cross-industry affordable technology (ICT and MTech/Health), which allows a whole page reading on a tactile screen. In the last few years, there has been a shift to cater to disabled populations and incorporate them holistically into the formal economy by providing greater access to technology and opportunities. However, a lot of the new assistive technologies are expensive and not affordable for the low-income demographics. This device is relatively inexpensive at 500 USD per unit.

3.2.8 Refreshable Braille Displays

Braille displays provide access to information on a computer screen by electronically raising and lowering different pins in braille cells. A braille display can show up to 80 characters from the screen and is refreshable. It changes continuously as the user moves the cursor around on the screen, using either the command keys, cursor routing keys, or Windows and screen reader commands. The braille display sits on the user's desk, often underneath the computer keyboard. The advantages of braille displays over synthetic speech are that it provides direct access to information; allows the user to check format, spacing, and spelling, and is quiet. Available market versions and their prices are listed below -

1) Actilino - 1,995 USD
2) Active Braille - 6,495 USD
3) ALVA BC680 - 2,995 (BC640) to 7,995 (BC680) USD
4) ALVA USB640 - 2,695 – 3,045 USD
5) Braille Star 80 - 9,995 USD
6) Brailliant B 80 - 7,985 USD
7) Brailliant BI 32 - 1,995 USD
8) Brailliant BI 40 - 2,995 USD
9) Easy Braille - 4,495 USD
10) Focus 14 Blue Braille Display - 1,295 USD
11) Focus 40 Blue Fifth Generation- 2,995 USD
12) Focus 80 Blue Braille Display - 7,656 - 7,995 USD
13) Orbit Reader 20 - 699 USD
14) Seika Braille Display - 2,495 USD

15) Vario 340 - 2,895 USD

16) Vario Ultra 20 - 2,395 USD

17) Vario Ultra 40 - 3,995 USD

18) VarioPro 80 Cells - 7,995 USD

It is clear that the present device interventions are expensive, and a large section of the population in India cannot afford the same. The software interventions are extremely helpful but require access to a PC, laptop, or smartphone to utilize its benefits. There is a clear need for low-cost solutions making Project Aakaar a worthwhile venture for research, development, and eventual incorporation.

3.3 Circular Economy Implementations

The term "circular economy" appeared for the first time in 1988 in "The Economics of Natural Resources" by Allen V. Kneese. The context of application was natural resources and their nature of renewability. It has been applied in various contexts and is a major agenda in China's long-term plan, and was included in both the 11th and the 12th 'Five Year Plan'. Alan Murray, Keith Skene, and Kathryn Haynes define the term as "an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being" [5]. According to Dr. Markus Laubscher and Dr. Thomas Marinelli, "A Circular Economy aims to decouple economic growth from the use of natural resources and ecosystems by using those resources more effectively. By definition, it is a driver for innovation in the areas of material-, component- and product reuse and new business models such as solutions and services. In a Circular Economy (CE), the more effective use of materials enables to create more value, both by cost savings and by developing new markets or growing existing ones..... The big difference in the CE approach is that the starting point is economic value creation with the improvement of the ecological aspects as a derivative and not the other way around." [16] These definitions align with the hypothesized CE model at Project Aakaar, as shown in Figure 1-1.

The Circular Economy as a concept has its antecedents in broader historical, economic, and ecological fields. Examination of these supports understanding of the subsequent application of the concept in practice. In the past decade there has been a big push towards sustainability and rightfully so. At Royal Philips, an organization committed to improving the lives of 3 billion people a year by 2025, key characteristics of this CE approach are -

1) Customer access over ownership, pay for performance e.g. pay per lux or pay per scan

2) Business model innovations, from transactions to relationships via service and solution models

3) Reverse cycles, including partners outside current value chains e.g. upstream-downstream integration and co-creation

4) Innovations for material-, component-, and product reuse, products designed for disassembly and serviceability [9].

While the terminology might be different, the approach is analogous to the 3R's - Reduce, Reuse and Recycle. At Project Aakaar, the goal is to reduce manufacturing costs and simultaneously PLA wastage at sighted schools by creating utilitarian prints distributed to VI schools. Each set of prints will be reused across sections as explained in Section 5-3 and integrated into the curriculum for long-term use. The PLA material being used for the end-prints is recyclable, but the intention would be to create quality prints that last at least 3-5 years. Frequently replaced materials such as office machinery, medical and optical equipment, and furniture have higher economic potential using the CE model.

The CE model is often critiqued for being oversimplistic and idealist in its' goals. Sometimes there are possible long-term unintended consequences that are not predicted or foreseen. As Alan Murray, Keith Skene, and Kathryn Haynes succinctly point out, "The three pillars of sustainability (economic, environmental and social) explicitly include the social dimension, in terms of human stakeholders, human well-being, and human rights. At times, these may stand in tension with environmental

Focus	***Value Flows*** *(Ellen MacArthur Foundation, 2013)*	***Primary Source of Revenue*** *(Lacy et al., 2014; Bakker et al., 2014b)*	***Economic Activities to Close Loops*** *(Stahel, 2013)*
Services	Cycling smaller – using less energy and fewer resources	Profit from increased utilisation rate of products, enabling shared use/access/ownership. Profit from selling access to a product for a specific period of time or 'uses', and retaining material ownership.	Reuse and remarket of manufactured goods
Manufactured products	Cycling for longer	Profit from providing maintenance services or sales of refurbished, remanufactured or repaired units Profit from repeated sales of consumables or services for a long-life product Profit from selling high quality products with a long lifespan at a high price	Product-life extension activities for goods
Materials	Cascaded uses Pure or regenerative cycles	Profit from recovering resources/energy out of disposed products or by-products from the same or other company, upcycling or recycling them. Profit from providing renewable energy, bio based- or fully recyclable materials to replace single-lifecycle inputs.	Material efficiency / recycling molecules

Figure 3-4: Positive Effects of A Circular Economy [12]

and economic pillars (Gray et al. 2014; Mathews 1995), but the social is explicit as a dimension. However, the Circular economy is virtually silent on the social dimension, concentrating on the redesign of manufacturing and service systems to benefit the biosphere. While ecological renewal and survival, and reduction of finite resource use benefit humankind, there is no explicit recognition of the social aspects inherent in other conceptualizations of sustainable development. It is unclear how the Circular economy concept will lead to greater social equality in terms of inter-and intra-generational equity, gender, racial and religious equality and other diversity, financial equality, or equality of social opportunity. These are important moral and ethical issues which are missing from the construct." [5]

Chapter 4

Stakeholder Analysis

Any venture or product's success or failure depends on successful interactions with a specific set of stakeholders. The "as-is" stakeholder network has to be analyzed, and the envisioned future "to-be" network needs to be tapped into to maximize the chances of success. Categorization of stakeholders helps in determining the appropriate points of integration and entry. In the following sub-sections, the stakeholder gap will be addressed based on the REAP framework and drivers for/against implementation and saliency of the involved stakeholders based on the ARIES framework.

4.1 The REAP Framework

The Regional Entrepreneurship Acceleration Program (or REAP) was started by Dr. Fiona Murray and Dr. Phil Budden to accelerate entrepreneurship-driven innovation ecosystems. The introduced framework reveals the presence or absence of five critical stakeholders, namely entrepreneurs, risk capital providers, universities, policymakers (government), and large corporations, as shown below. Based on learning from existing innovation ecosystems such as Silicon Valley, Boston/Cambridge, London, Israel, and Singapore, suggestions are provided for accelerating progress.

One of the critical features of the REAP methodology is distinguishing between Innovation Capacity (I-Cap) and Entrepreneurship Capacity (E-Cap).

Innovation Capacity (I-Cap) is the capacity of a place, a city, a region, or a nation

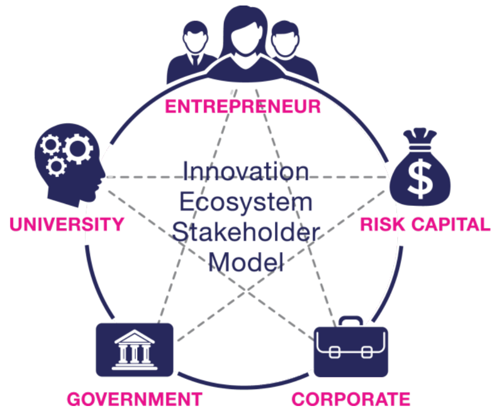

Figure 4-1: Star Model of the REAP Framework [22]

to develop creative (in sciences and arts) ideas and take them from 'inception to impact.' In other words, innovation capacity covers the development of basic science and research and the translation of their 'solutions' into valuable products, technologies, and services that genuinely solve problems. Government universities such as the Indian Institute of Technology (IIT) and the National Institute of Technology (NIT) have long been innovation centers. Private universities like Birla Institute of Technology (BITS) Pilani and Manipal Institute of Technology are also getting into the game. Entrepreneurship Capacity (E-Cap) refers to general entrepreneurial capability and conditions for forming enterprises. Traditional governmental policies support the formation of small-medium enterprises more than innovation-driven enterprises. The aspects of 'E-Cap' that are of most interest to innovation support the innovation-driven enterprises or IDEs in an entrepreneurship capacity, tailored to support the growth of innovation IDEs in a specific place, such as a city, region, or nation. Venture capital in India has been consistently rising in the past decade, especially in Bangalore and Mumbai. Additionally, private investors in cities such as Surat are actively contributing to the E-Cap of the nation as well [7].

4.1.1 Application and Available Stakeholders

Traditionally, the REAP framework analyzes a physical geographic location, but the same principles and methodologies can analyze a logical product and its ecosystem.

For Project Aakaar, the stakeholder availability was as follows -

University: The initial project was conceived by undergraduate students at NIT Warangal in 2019 and has been further refined in collaboration with graduate students from IIT Kanpur and MIT during the past two years. The UG students presently pursue graduate studies at RWTH Aachen and UC-Davis, providing access to a more extensive academic network.

Government: The "Make in India" program proposed by the central government promised to build 3D printing capabilities across 6000 sighted schools in India. Publicly accessible MakerSpaces such as Atal Tinkering Labs (ATL) were created under the program.

Entrepreneur - The original team consisted of 3 innovators from NIT Warangal (Sarthak Kapoor, Shantanu Landore, and Daksh Parmar) with a design engineer (Prithvi Raj) and outreach personnel (Radhika Manoharan) being added in 2020. However, there were no entrepreneurs on the team.

Risk Capital: The edu-social value of the solution, while seemingly apparent, has not been tracked and quantified, resulting in a lack of risk capital providers. Capital investors can be approached once the solution's effects are validated and have a sufficient coverage level of curriculum. This should be viable by Year 3 of the Technology Strategy Map shown in Section 5.3.

Corporate: For a social entrepreneurship idea like this, leveraging corporate social responsibility (CSR) funding is a viable direction. However, CSR funding is usually devoted to proven interventions instead of early-stage projects, which are still under development. There should be a long-term play to secure such funding by Year 5 of the Technology Strategy Map shown in Section 5.3.

4.1.2 Strategy for Higher Engagement

Project Aakaar while having a high I-Cap, had no E-Cap, and hence there was a dire need to address the same. During the past nine months, a long-time entrepreneur (Ankit Budhia) with over five years of experience in different sectors has been added to the team and a systems engineer (Indrayud Mandal) who has had practical and

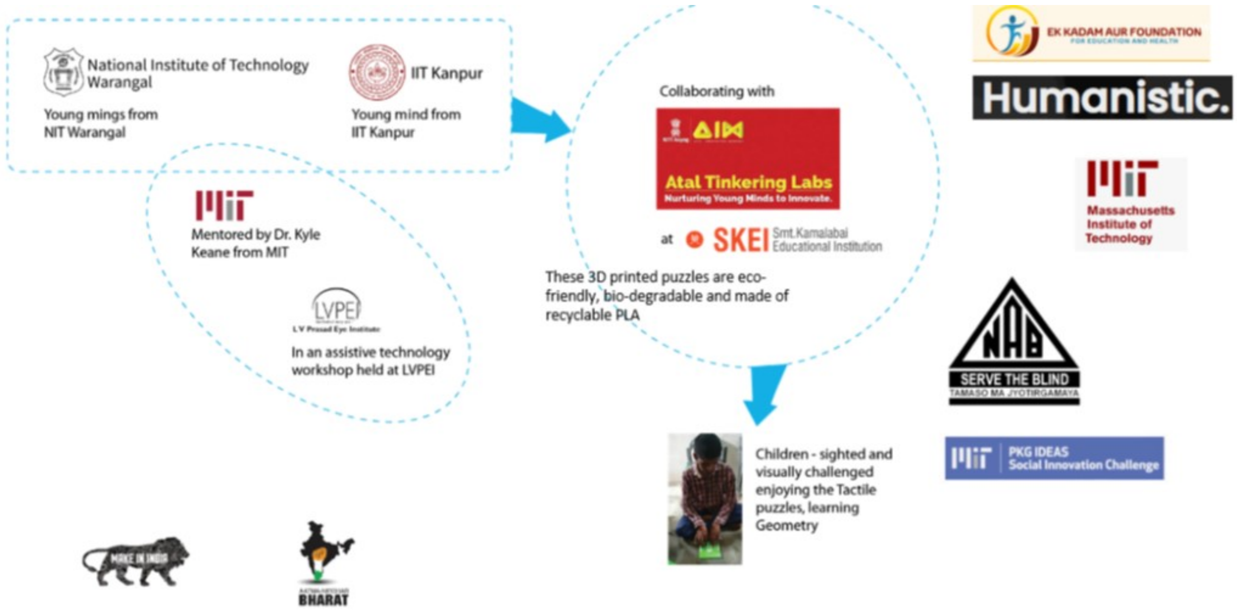

Figure 4-2: Stakeholder Map for Project Aakaar - created by Prithvi Raj

theoretical entrepreneurial experience at MIT.

Post-August 2021, there will be alumni affiliations with IIT-Kanpur and MIT and current affiliations with RWTH Aachen and UC-Davis. Twelve months ago, a customized circular economy model was piloted to leverage existing infrastructure to maximize impact with minimal finances by collaborating with ATL. Eventually, the goal is to integrate these devices into the national curriculum via collaborations with publishing houses such as NCERT and state and national educational boards. As mentioned above, access to risk capital and CSR will not be possible till the solution reached a certain coverage level of the current curriculum. Financial investment has been minimized as additional designs were collated by conducting workshops at Smt. Kamalabai Educational Institute (SKEI). ATL provided End-prints, but distribution costs needed to be financed. The National Association for the Blind (NAB) has agreed to support the distribution costs a reasonable number of sets (250 to 300) have been printed.

Universities and educational institutes are traditionally the sources of intellectual capital and academicians in the REAP framework. However, they can also be a source of financial support through grants and competitions. The project received financial support of 1K USD from the MIT SOCIAL IDEAS Innovation Challenge, which will be utilized to distribute a printed docket of the Train-the-Trainers material shown in Appendix A. It is also a part of the MIT SOLVE Challenge for "Equitable Classrooms" that can provide potential funding of up to 200K USD. The figure above shows the present stakeholders in the product ecosystem.

4.2 The ARIES Framework

The ARIES framework was developed by Dr. Donna H. Rhodes and Dr. Deborah J. Nightingale in 2015 and establishes a model for enterprise strategy. It has varied elements of strategy and software development life cycles (SDLC). The figure below shows the primary stages that lead to the establishment of an enterprise strategy. Establishing an enterprise strategy at this stage of product development is difficult, especially since there is no existing venture landscape. The approach would be different as it would involve establishing an enterprise along with core organizational values instead of analyzing an "as-is" enterprise and suggesting a strategy for a "to-be" enterprise. However, specific tools in the framework can apply to a product or an enterprise elaborated on in the next section.

Presently, Project Aakaar utilizes a holocracy model where each self-assigns responsibilities on tasks they believe they are best suited to address. There are weekly stand-up meetings to discuss progress during the last week, re-assign tasks and minimize overlap across practitioners. The team presently consists of 7 members, and this format enables the team to avoid hierarchical conflicts, maximize productivity and promote ownership of tasks. There will be an enterprise restructuring to a traditional organizational structure as there are plans for legal incorporation. While holocracy works in a small team, the same advantages provided by the model become disadvantages as the organization scales up. Discussions have already begun on the division of responsibilities such as operations, execution, repository maintenance, communications, CSR outreach, each with a primary and secondary owner.

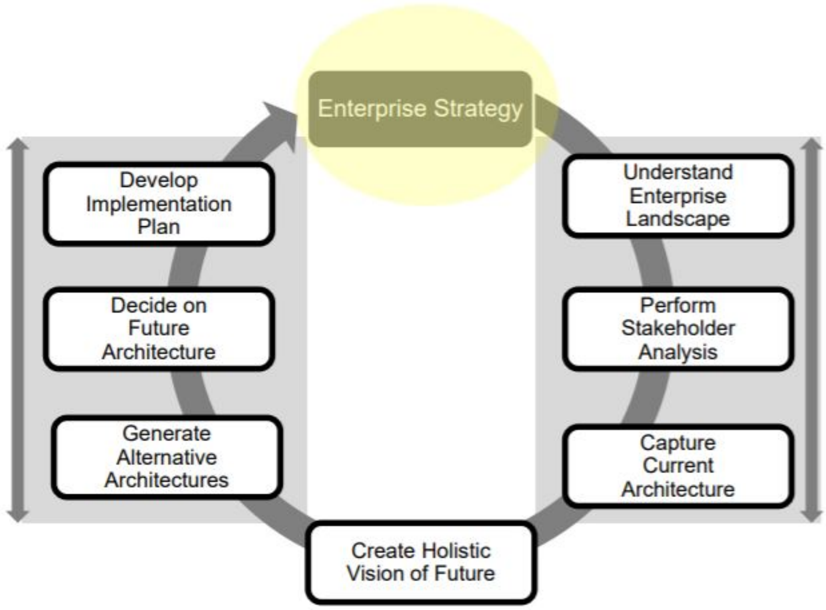

Figure 4-3: The ARIES Framework, Nightingale and Rhodes, 2015

4.2.1 Application and Drivers For/Against

Whenever an organization plans a restructuring or enterprise rearrangement, there are competing drivers for and against implementation. Similarly, when a new product is introduced in the market, there are drivers for and against implementation. This method is called Force Field Analysis (FFA), and the specifics related to Project Aakaar, its' current manufacturing and distribution strategy are shown in the figure below.

Key takeaways from the analysis in Figure 4-4 include the following -

1) Six of the seven drivers for implementation are related to higher educational and social value.

2) While the current manufacturing and distribution strategy has minimal costs, it results in lower limited operational time and a dependence on third parties.

3) The workshops create empathy at an early age which is essential in today's day and age but again creates a third party dependence.

4) Enabling equitable education for VI students is a noble cause, but covering the entire geometry curriculum would take time and might not be entirely

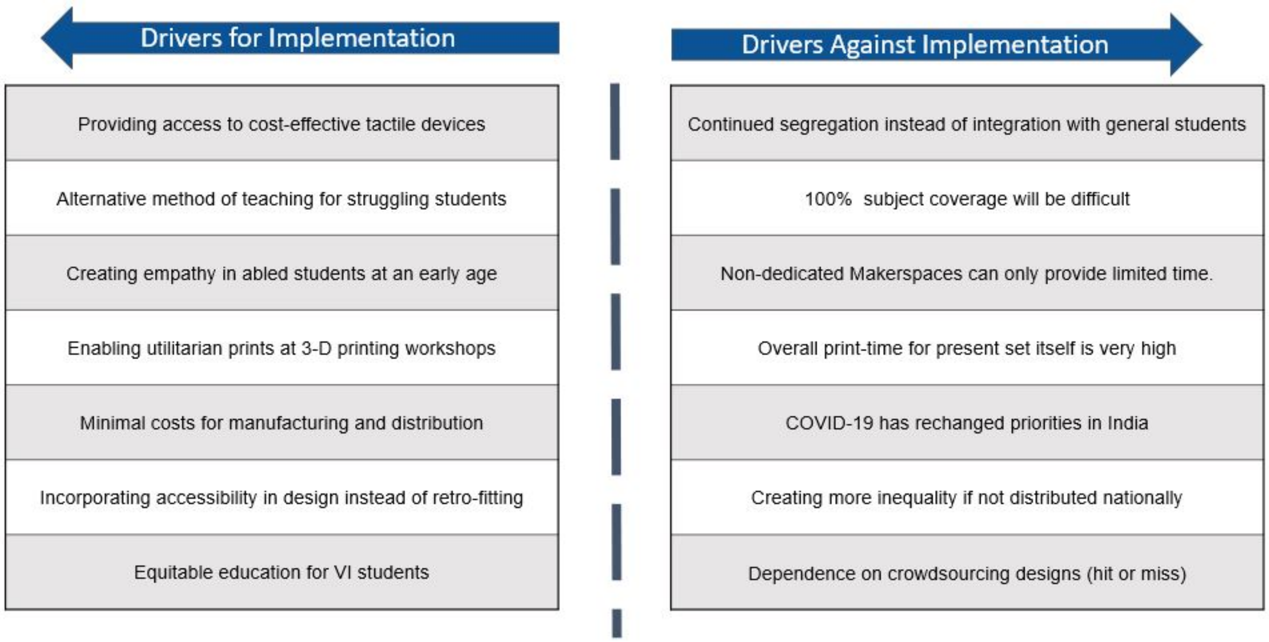

Figure 4-4: Product, Manufacturing and Distribution FFA

possible.

4.2.2 Stakeholder Saliency and Product Landscape

The Stakeholder Saliency model developed by Ronald Mitchell et al. in 1997 categorizes stakeholders based on three distinct characteristics -

1) Power - Ability to influence the product
2) Legitimacy - Legal, contractual, moral, or financial claim
3) Urgency - Has a claim for immediate attention

Table 4-1 shows a list of stakeholders in Project Aakaars' ecosystem based on this model. The list shows the categorization of stakeholders groups such as educational grants instead of individual stakeholder institutions such as MIT Solve. Key takeaways from this analysis are as follows -

1) The most important stakeholders are VI students and teachers at these schools, along with the design team, responsible for quality checks before repository expansion.
2) While government and regulatory bodies can affect final designs, there is

neither urgency nor a contractual obligation of any sort at present.

3) Funding and distribution partners such as private investors, VCs, national and grant agencies as well as social organizations such as NAB, need to be engaged with as soon as possible to ensure long-term success and maximum impact.

4) The repository expansion and design curation is highly dependent on sighted students beyond the core team. This creates a dependence, as highlighted in Figure 4-4, and makes them a dangerous stakeholder as defined by the Stakeholder Saliency framework.

Stakeholder Category	Attributes	Examples
Dormant	Power	Governmental and Regulatory agencies
Discretionary	Legitimacy	Parents of VI students
Demanding	Urgency	Potential investors, Social organizations, Educational grants
Dominant	Power, Legitimacy	Development team, Quality assurance, Standards organizations
Dependent	Urgency, Legitimacy	Instructors at sighted schools
Dangerous	Power, Urgency	Core team, Sighted students at 3-D workshops
Definitive	Power, Urgency, Legitimacy	Visually impaired students, Design team, Teachers at VI schools

Table 4.1: Stakeholder distinction for Project Aakaar

There are nine elements to an Enterprise Landscape as described in the ARIES framework. While defining an Enterprise Architecture (EA) at this phase of the product exploration is not feasible considering the small size of the team, it is useful to establish a vision of the future enterprise along these metrics to ease the scaling up process and transition into official incorporation.

Enterprise Element	For Project Aakaar
Strategy	Provide cost-effective educational aids for facilitating equitable education
Information	Expand design set in a curated and quality controlled open-source repository such as DIAGRAM
Infrastructure	Establish a dedicated Makerspace and acquire 3-D printers for higher print times
Product	Create a quality set of designs that effectively cover a large part of the curriculum
Services	Continue engagement with sighted schools via the Train-the-Trainers (T3) program
Process	Institute a quality check process for incorporation of crowdsourced designs into repository
Organization	Incorporate as a social innovation/entrepreneurship for-profit organization
Knowledge	Collaborate with academics, innovators and start-ups in the disability space

Table 4.2: Envisioned Landscape of Future Enterprise

Chapter 5

Technology Assessment

In this section, the underlying technology and the designed product will be elaborated on and assessed to determine the technical feasibility of the solution. There is a lack of large-scale enterprise funding for the product, which is why traditional manufacturing processes could not be utilized. As mentioned in the previous section, collaborations were done with Atal Tinkering Labs (ATL) to leverage existing 3D printing infrastructure to generate the end-prints for distribution to visually impaired students. ATL provides access to printers such as the Creality 3D Pro, which uses recyclable PLA materials to generate prints using a process called Fused Deposition Modeling (FDM). The diagram below shows an Object-Process-Model for additive manufacturing with a focus on In-Space Additive Manufacturing. The relationships and Figures of Merit (FOMs) for determining relative performance remain the same for all additive manufacturing processes.

Fused filament fabrication (FFF), also known as fused deposition modeling (with the trademarked acronym FDM), or called filament freeform fabrication, is a 3D printing process that uses a continuous filament of a thermoplastic material.[9] The filament is fed from a large spool through a moving, heated printer extruder head and is deposited on a flat plane. The print head is moved under computer control to define the printed shape and moves in two dimensions to deposit one horizontal plane, or layer, at a time. The print head is then moved vertically by a small amount to begin a new layer. As shown in Fig 2-1 and 2-2, the FDM process was used to

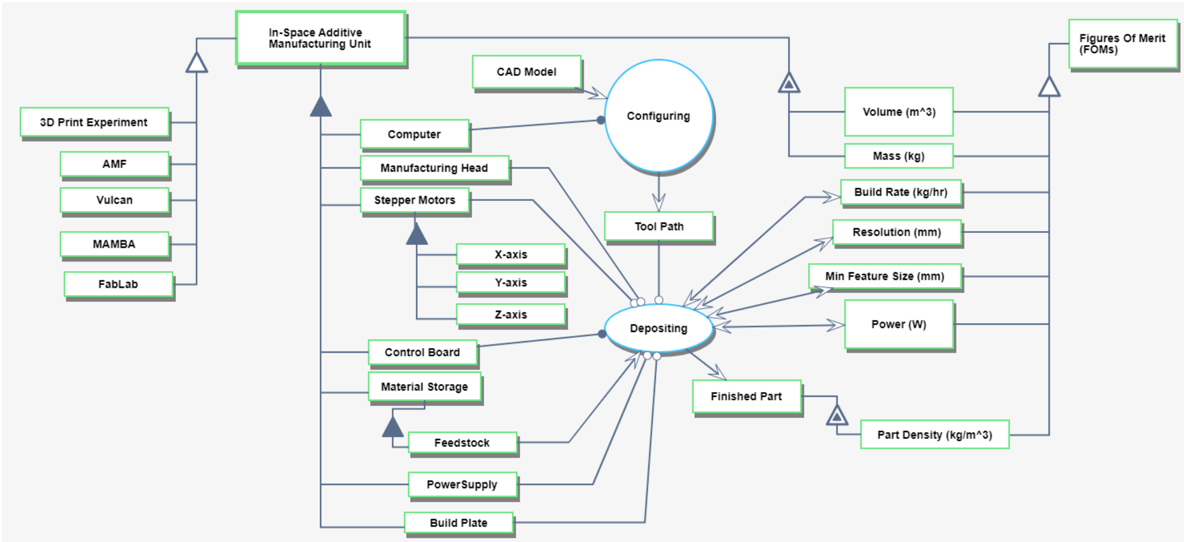

Figure 5-1: Object Process Model for In-Space Additive Manufacturing, Lee, Mandal and Moraguez

generate geometry themed prints such as the tactile tangrams and the Hexaxompass. In the following section, we will analyze the readiness level of both the underlying technology and the product as well.

5.1 Technology Readiness Level

Technology Readiness Level or TRL is a methodology that was established by NASA in the 1970s to establish the maturity of technologies. It is now an industry standard that is used to judge the technological maturity of products and solutions enabling a common and consistent form of evaluation. FFM or FDM is presently the most popular method (by number of machines) for 3D printing globally and is operating at TRL9. The solution is mature and has been tested in a variety of applications successfully.

Project Aakaar is at TRL7 presently as the technology has been co-designed and demonstrated at visually impaired (VI) schools and the circular economy prototype has also been piloted between Smt. Kamalabai Educational Institute (SKEI) and Shree Ramana Maharishi Academy for the Blind at Bengaluru (operational environment). The Technology Strategy Map in Section 5.3 shall elaborate on an action plan

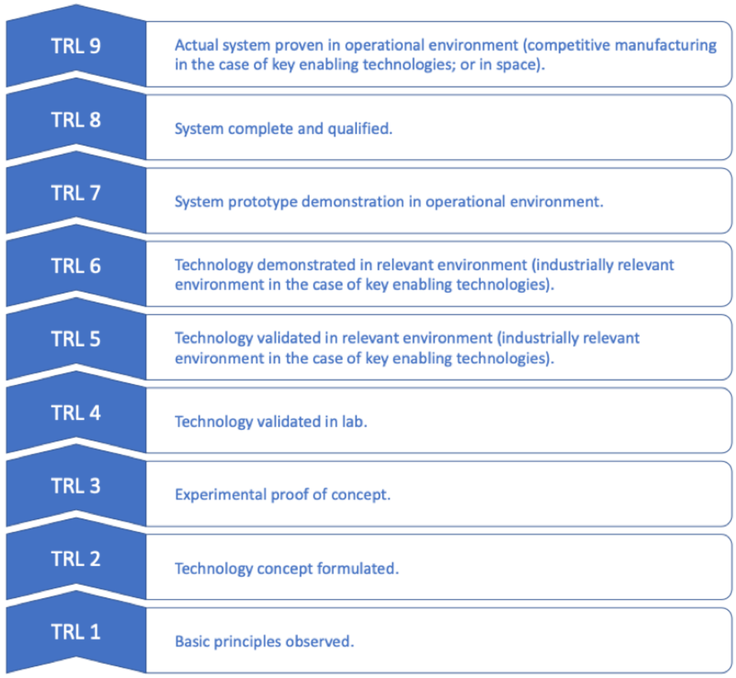

Figure 5-2: Technology Readiness Level [10]

which will help the technology reach TRL9 within the next 5 years.

5.2 Accelerating Technologies

Both of the involved technologies are at a high technology maturity level but there is a technical constraint with FDM and a technological gap between the present solution and the intended goal that need to be addressed. In the table below, FOMs are listed for FDM and the ones which are critical to this project are the Build Rate and the Mean Time Between Failure. The present set of designs at Project Aakaar takes approximately 200 hours to print including all of the base plates, shapes and box plates (shown in Figure 5-3). A higher build rate and mean time between failure would result in faster prints but there is a trade off between build rate and resolution resulting in physical and technical limitations.

The present solution consists of the following set of designs -

1) Geometry Set - Four puzzles consisting of four base plates with a rectangle,

FOM Name	Units	Description
Build Rate	[cm^3/hr]	Rate at which material can be deposited
Resolution	[μm]	Minimum feature size that can be fabricated
Build Volume / Equipment Volume	[unitless]	Packaging efficiency in terms of the ratio of the largest manufacturable component relative to the overall volume of the unit
Feedstock Mass / Equipment Mass	[unitless]	Mass efficiency in terms of the feedstock mass for printing relative to the overall mass of the unit
Peak Power	[W]	The maximum instantaneous power draw of the unit
Average Power	[W]	The average power draw of the unit
Part Density	[kg/m^3]	A measure of the material quality of the printed material, inversely related to the porosity.
Lead Time	[hr]	The time delay from identified need for part manufacturing to integration of completed product into the spacecraft system
Mean Time Between Failure	[hr]	The average time between failures of the manufacturing unit itself
Cost	[$]	The cost of the additive manufacturing unit, including recurring costs and amortized development costs.

Table 5.1: Figures of Merit for Fused Deposition Modeling, Lee, Mandal and Moraguez

an isosceles triangle, an equilateral triangle, and a parallelogram respectively. Two equal right-angled triangles need to be fit into the given base plate. For example, in the 'rectangle' puzzle, the triangles should be placed such that their hypotenuse touch. Shown in Fig 2-2.' 2) Monument Set - Four puzzles consisting of four base plates with tactile images of the Taj Mahal, Leaning Tower of Pisa, the Pyramids of Giza, and Eiffel Tower respectively (see Figure 5-3). These bring in a cultural aspect to the puzzles and also enable students to feel macro objects (larger than can be felt) and understand their structure. Furthermore, some of the pieces are interchangeable between structures showing the applicability of common design in different cultures and architectures.

The original repository needs to be expanded by conducting further workshops at sighted schools and curating designs. The team is already working towards the same. In the next section, we will analyze the present puzzles for greater value creation and integration into current curriculum.

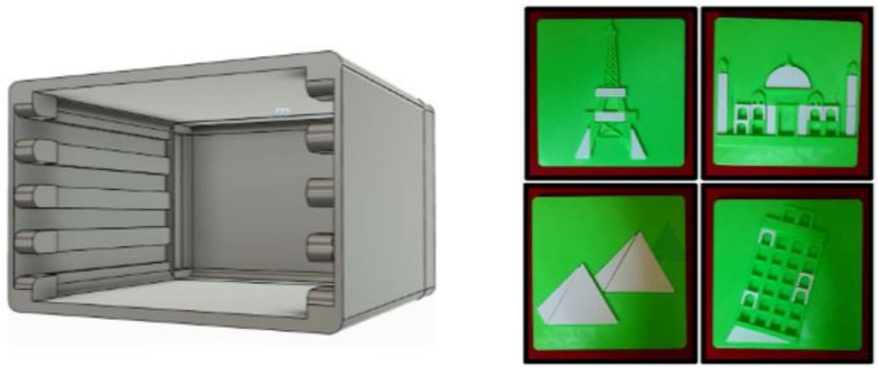

Figure 5-3: Box Plate And Geometry Set [24]

5.3 Technology Strategy Map

The build rate for 3D printers utilizing FDM is dependent on the present technological limitations of available stable energy sources, uniform application under differing voltages, trade offs between build rate and resolution amongst others. These are complex technical problems that this team does not have resources or expertise to address. The addressable problem is ensuring a wide coverage of concepts with minimal designs and to have a comprehensive set of designs for integration into the current curriculum. This would result in minimization of prints, maximization of utility and a systemic integration. A Design Structure Matrix (DSM) is a morphological matrix that enables representation of complex systems and clustering of commonalities from a product, organizational or process perspective. To create the initial DSM below, the present Mathematics curriculum at middle school (Classes 4 - 8) in the Central Board for Secondary Education (CBSE) was distributed into distinct concepts and listed on the columns. The present "as-is" solution pieces available under Project Aakaar were listed as rows and a mapping was done to check coverage across the middle school curriculum.

There are two things that stand-out from this analysis. Firstly, the present coverage is not sufficient for proposing this as a solution for middle school students. There is a need to modify present designs for incorporation of more concepts using the same

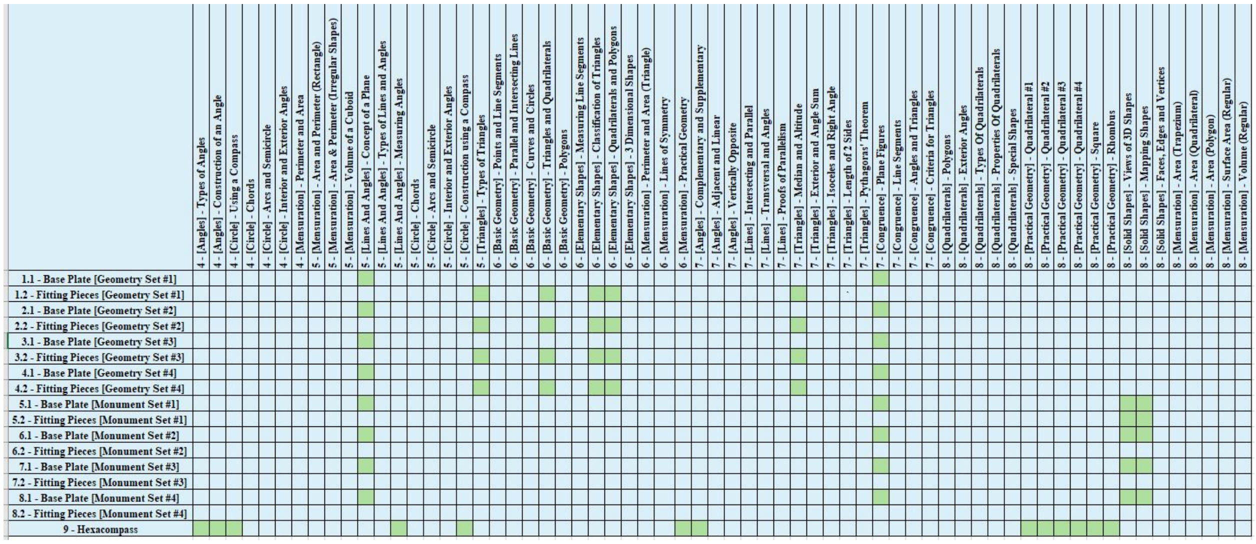

Figure 5-4: Initial Design Structure Matrix for Aakaar

end-prints and to design a new set of prints for concepts that cannot be covered even with alterations to the present set. Secondly, the Hexacompass covers the most number of topic areas presently and should be a focal point in the coming year. While a prototype has already been generated, end-user feedback needs to be gathered and further refinement to design is required.

A second DSM was created with the following updates -

1) Common subject areas across different classes were clustered together.

2) Additional concepts can be conveyed by the same prints with some adjustments. For example, the rectangle solution can also be used to convey concepts of parallel lines, alternating angles, perimeter, area and symmetry with additional Braille notations and use of embossments. These cells have been highlighted in orange.

This is the maximum coverage that can be obtained with alterations to the present designs but leaves 17 out of 65 topic areas unaddressed. For example, concepts of circles cannot be taught till we have dedicated prints for the same. The goal should be to maximize the concept coverage for these future "to-be" prints. A 3D cuboid with Braille notations and embossments can be used to convey multiple concepts such as projection of 3D shapes, measuring volume and surface area while a Hexagon can

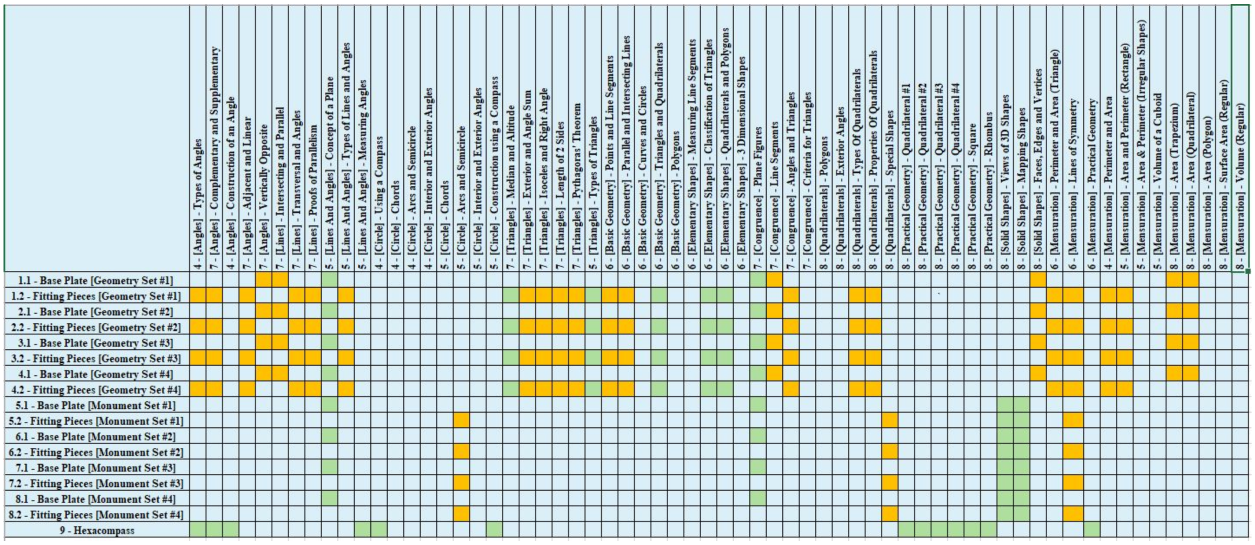

Figure 5-5: Revised Design Structure Matrix for Aakaar

be printed to address area of regular polygons, lines of symmetry and other polygon related features. The suggested 5 year Technology Strategy Map is shown below.

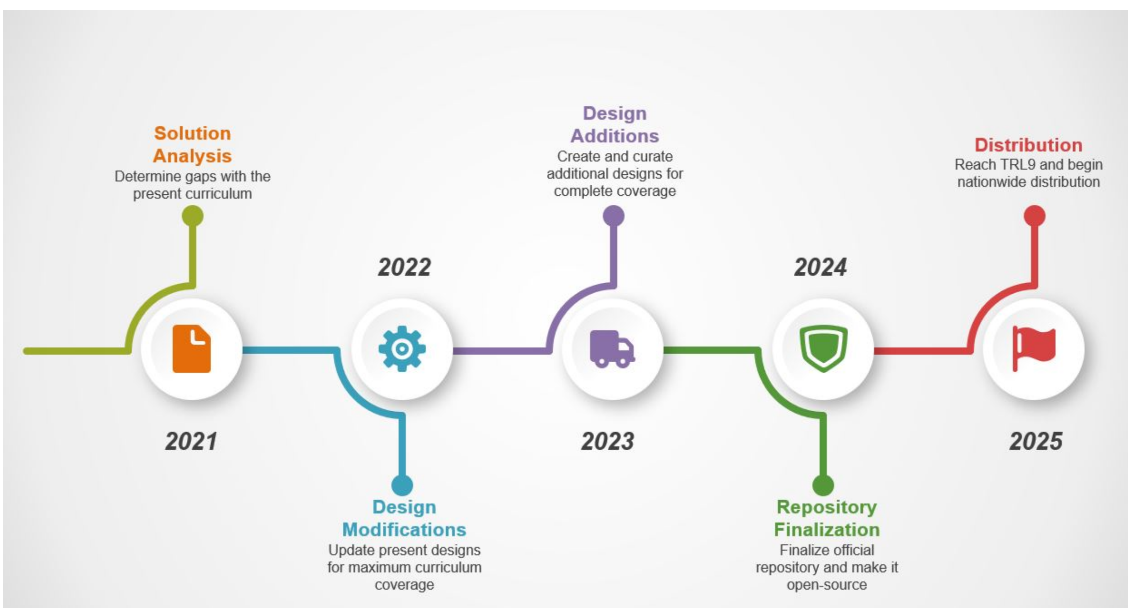

Figure 5-6: Five Year Technology Strategy Map

Chapter 6

Business Model Analysis

Defining the potential upside (and downside) is essential for any startup organization, and the goal at Project Aakaar is to incorporate it as a for-profit social innovation enterprise. The tangrams in the Geometry set have been distributed to VI students across different regions (India, Saudi Arabia, and the US) and have received positive feedback. The team is actively working on design curation and repository expansion, a crucial milestone in the implementation roadmap. The Train-the-Trainers (T3) manual was tested at Smt. Kamalabai Educational Institute as a trial run of the envisioned circular economy by coordinating with Shree Ramana Maharishi Academy for the Blind in Bengaluru. The initial prints were revised in coordination with VI students, and the utility of the final prints was validated. The empathy-based workshops were received well at the non-disabled schools, and the envisioned circular economy worked out with minimal distribution costs and overhead during the trial run. The model works on a small scale but does not work when scaling up, which is why dedicated MakerSpaces and sellable end-products are needed. The key financial drivers are assets (printers and materials for printing) followed by labor (maintenance and MakerSpace and coordination with distribution partners – NAB and EKA).

6.1 What is a Blue Ocean?

The term Blue Ocean Strategy was coined by authors Chan Kim and Renee Mauborgne in a book by the same name which was first published in 2005. It studied strategic moves by a multitude of enterprises over 100 years and across 30 industries. Since the strategy applies to a specific sort of market, blue ocean strategy is applicable to a blue ocean. In essence, a blue ocean refers to a completely new industry or establishment of an indusrtry in a region that is not yet contested. In blue oceans, demand is created rather than contested and there is ample opportunity for rapid financial and organizational growth.

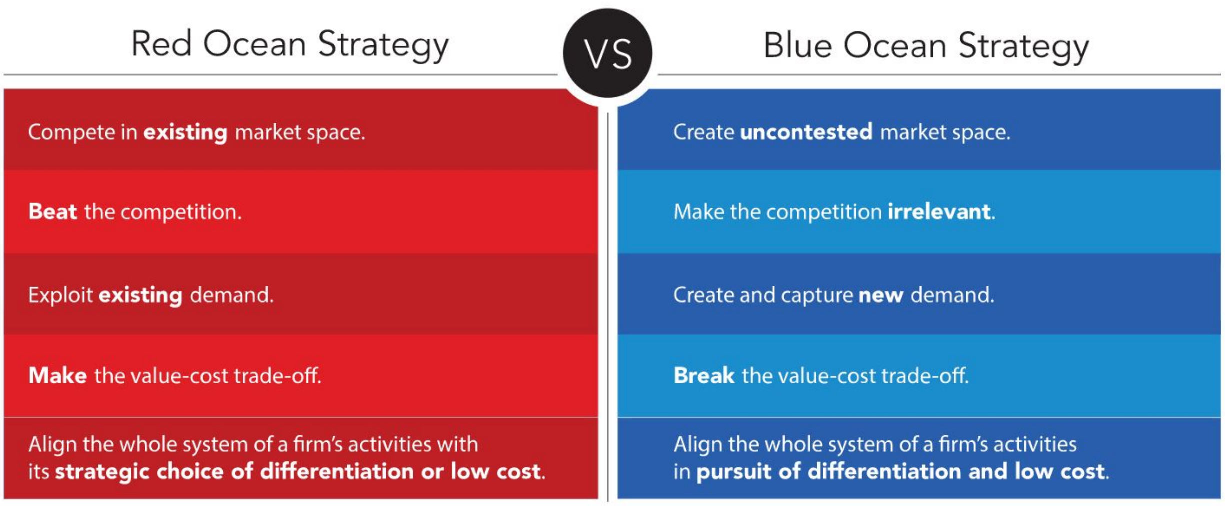

Figure 6-1: Red vs. Blue Ocean Strategy [8]

In contrast, red oceans are all industries today where boundaries are defined and accepted, with an established market presence. There is a ruthless competition, and companies are always trying to outperform rivals to gain a higher share of the market demand. With a higher number of competitors, there is reduced profits and growth. The figure above shows the major differences between a red and blue ocean as defined by the authors.

Education in India for visually impaired students is primarily audio-based, making it difficult to convey complex visual concepts in higher classes. At present, there are no cost-effective tactile devices in India that can teach a multitude of geometrical concepts to middle-school and high-school students. The standard pedagogy is to treat accessibility issues as a band-aid instead of designing for it from the beginning. While there are organizations such as the Fittle Project and LEGO Braille bricks working on creating 3D printed Braille puzzles for play, none explicitly work on VI educational aids. LEGO Braille also does not have a center in India.

Project Aakaar aims to develop creative, fun-filled ways to teach geometry to visually impaired students, which is an approach that has not been taken up by any organization in India so far. There is an eventual goal of integration into the current curriculum, recognizing that building intuition and geometry in visually impaired children will be a critical link in facilitating them in taking up STEM majors in the future. The lack of tools and techniques at present is the main thrust for the proposed solution.

6.2 Lean Metrics and Business Model Canvas

The most important activity is the technology development, design curation, and repository expansion for maximizing curriculum coverage. However, establishing a tentative business strategy early on will provide time for adjustments based on development and manufacturing progress. As mentioned in section 4.2, CSR and risk capital cannot be leveraged until sufficient coverage is achieved. To achieve this, measuring the impact of the solution via qualitative surveys and quantitative metrics is equally essential.

Lean Impact Measurement is a framework introduced by Ingo Michelfelder, a post-doctoral fellow at the MIT Sloan Sustainability Initiative, to measure value creation by social enterprises. It provides a framework and skills necessary to map ones' social venture's relationship between actions/activities and positive social change. Figure 6-2 shows the specifics for Project Aakaar. Key takeaways from the analysis are as follows -

1) The product adds long-term value to both visually impaired (VI) and sighted students.

2) If adequately implemented, parents and teachers of VI and sighted students would have a significant stake in the product as well.

3) Short-term impact can be measured against control groups, but the long-term impact would be challenging to measure.

4) The product is genuinely inclusive because it can be used by both VI and sighted students. It can be used as a supplementary tool to teach the same concepts to sighted students struggling with traditional geometry instruction methods.

Impact Area Title	Status Quo Solution	Differentiating Factor	Stakeholder	Change for Stakeholder	Indicator 1	Indicator 2
Providing low cost tactile educational aids for VI students	Availability of high cost aids not available to public schools and financially challenged families	Lost cost, eco-friendly material, circular economy	VI students and techers at VI schools	Students would be able to easier grasp concepts by using these tactile aids and teachers would have an easier time explaning the concepts as well.	Increase in scores in the geometrical concepts taught via the puzzles vs. those without	Demand for additional shapes and puzzles to convey concepts
Greater access to higher STEM education for VI students	In middle and high school, VI students are urged towards Arts and Humanities instead of the sciences due to the lack of availability of these types of commonly available aids.	We are facilitating the first set and hope to open the floodgates for more designs across more subjects and more disabilities	VI students, Parents of VI students, Universities	The systemic exclusion from higher STEM education that has been rampant in the past few decades would be addressed to some degree. There is a long way to go but this can be definitive start in the right direction.	Increase in number of students taking Science in high school	Increase in number of students signing up for STEM degrees
Empathy building in non-disabled children	Our team was not aware of the extent of the problem till in our mid-20s. It is likely that most of our non-disabled high schoolers are unaware of the issue either.	Building empathy at a young age for our differently abled friends	Non-disabled students and their teachers	If we are aware of these problems at a younger age, then we become empathetic to the cause early on. Students will start thinking of solutions earlier and look at their environment from different perspectives.	Increase in students working for disability related initiatives	Increase in collaborations between disabled and non-disabled students
Higher inclusion and diversity incorporating accessibility in design	Tradiitonally, design is done for the centre of the bell curve and then it is retro fitted for the fringes. Thus, accessibility is an after-though instead of a part of the design process.	Designing for the fringes and ensuring that the middle is not left out, thus, being truly inclusive,	Everyone	Accessibility becomes a focus area before the design process instead of an adjustment area after the same. This enables nearly all-inclusive designs.	Difficult to track direct correlation	

Figure 6-2: Lean Impact Metrics - Project Aakaar

As it is commonly known, Business Model Canvas, or BMC, was proposed by Alexander Osterwalder in 2005 and is a management strategy template. There are nine building blocks of this business model design template that address core elements such as value proposition, key partners, revenue streams, and customer segments, amongst others. Figure 6-2 illustrates the BMC developed by the team at Project Aakaar, and key takeaways from the discussion are as follows -

1) The stakeholder network is diverse and there are a multitude of partners to engage with. In-roads should be developed to create connections with the neces-

sary stakeholders such as an expansion of partner schools (both sighted and VI) for repository expansion and activation of the NAB connection for nationwide distribution.

2) Multiple revenue streams are possible such as direct product sales, remuneration for services provided during T3 programs and edu-social grants provided by academic, governmental and international organizations.

3) The proposed methodology has a distinctively unique value proposition because the early-stage empathy building in non-disabled students is unique and has not been employed before in the Indian context.

4) The distribution channels and the customer relationships are highly interlinked but that does not apply for the sales and marketing channels. The division between separate stakeholders is important for the business team to determine their go-to-market strategy.

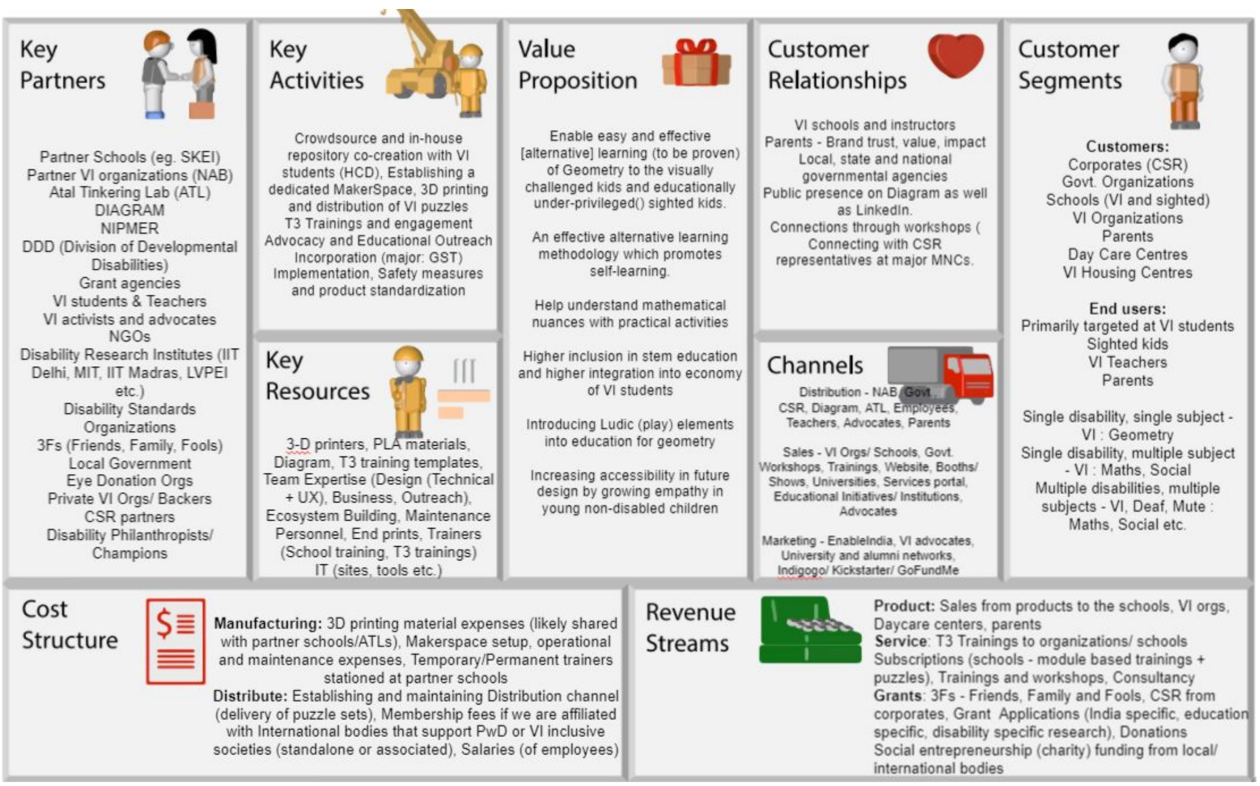

Figure 6-3: Business Model Canvas - Project Aakaar

6.3 Net Present Value Analysis

There are risks and uncertainties associated with new product introductions in any market, which will be analyzed in this section. Additionally, projected net present value (NPV) would be determined for the current strategy along with a proposed flexible strategy. In the following two tables, separate deterministic cases have been analyzed. The first case analyzes a model where we leverage MakerSpaces such as ATL to outsource the manufacturing but manage the distribution and other operations in-house. The second case analyzes a scenario with a dedicated MakerSpace with an initial capacity of 50 machines that doubles in Year 5 and triples in Year 10.

Year	0	1	2	3	4	5	6	7	8	9	10
Demand		400	400	400	440	484	533	587	646	711	783
Capacity	0	420	420	420	420	840	840	840	840	840	1260
Revenue	$0	$2,800	$2,800	$2,800	$2,940	$3,388	$3,731	$4,109	$4,522	$4,977	$5,481
Shipping and delivery costs		$200	$200	$200	$210	$242	$267	$294	$323	$356	$392
Operating costs	$0	$600	$600	$600	$630	$726	$800	$881	$969	$1,067	$1,175
Cashflow	$0	$2,000	$2,000	$2,000	$2,100	$2,420	$2,665	$2,935	$3,230	$3,555	$3,915
DCF		$1,786	$1,594	$1,424	$1,335	$1,373	$1,350	$1,328	$1,305	$1,282	$1,261
Present value of cashflow	$14,036										
Net present value in INR (India)	$1,025,771.13										

Table 6.1: Net Present Value using Atal Tinkering Labs

Common features across both models include the following -

1) Year 1 corresponds to Year 3 in the Technology Strategy Map while Year 3 corresponds to Year 5, respectively.

2) Considering a total of 250 working days in a year with 70 percent uptime and 200 hours required for each set, a single machine should be able to create 21 complete sets yearly.

3) Revenue per set is 7 USD per unit while operating and shipping costs have been modeled as 1.5 and 0.5 USD, respectively.

4) The analysis has been done over ten years with varying demands based on manufacturing capacities.

Significant takeaways from the analysis are as follows -

1) The ATL model provides a greater NPV over the ten years but extending the analysis over 20 years reverses the results. This is because capacity at ATL

is inflexible and cannot be increased on-demand.

2) The print-time per set is a crucial bottleneck as it allows a very limited number of completed sets per year. Alternative manufacturing methods should be explored, such as injection molding.

3) For the ATL model, 20 printers have been modeled for Year 0, which expands to 40 in Year 4 and 60 in Year 9. For the dedicated Makerspace, the project is purchasing 50 printers in Year 0 with an additional 50 in Year 4 and Year 9.

Year	0	1	2	3	4	5	6	7	8	9	10
Demand		1000	1000	1000	1200	1440	1728	2074	2489	2987	3585
Capacity	0	1050	1050	1050	1050	2100	2100	2100	2100	2100	3150
Revenue	$0	$7,000	$7,000	$7,000	$7,350	$10,080	$12,096	$14,518	$14,700	$14,700	$22,050
Cost of PLA		$2,500	$2,500	$2,500	$2,625	$3,600	$4,320	$5,185	$5,250	$5,250	$7,875
Shipping and delivery costs		$500	$500	$500	$525	$720	$864	$1,037	$1,050	$1,050	$1,575
Operating costs	$0	$1,500	$1,500	$1,500	$1,575	$2,160	$2,592	$3,111	$3,150	$3,150	$4,725
Land leasing and fixed costs	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Printer costs	$10,000	$0	$0	$0	$10,000	$0	$0	$0	$0	$10,000	$0
Cashflow	$0	$500	$500	$500	$625	$1,600	$2,320	$3,185	$3,250	$3,250	$5,875
DCF		$446	$399	$356	$397	$908	$1,175	$1,441	$1,313	$1,172	$1,892
Present value of cashflow	$9,498										
Net present value	$7,498										
Net present value in INR (India)	$547,976.47										

Table 6.2: Net Present Value for Dedicated Makerspace

The model above results in an NPV of INR 1,025,771 for the ATL strategy compared to an NPV of INR 547,976 for the dedicated MakerSpace model. The static deterministic cases reveal that the ATL strategy has a higher financial potential presently. In the next section, the following uncertainties were applied to the ATL model to examine possible upside and consequent downside -

1) In new product introductions, the demand projections are highly uncertain, especially in a blue ocean market. An uncertainty of 80 percent in demand has been baked into the model.

2) Traditional uncertainties such as operating and shipping costs have been set at 15 and 30 percent, respectively.

3) In traditional manufacturing, capacity is sure and consistent. However, since manufacturing is outsourced, a 30 percent uncertainty has been factored into the model for capacity. There might be weeks with higher or lower available capacity at the ATL centers.

Salient features from the analysis are as follows -

Year	0	1	2	3	4	5	6	7	8	9	10
Demand projection		433	769	1,079	1,363	1,625	1,867	2,089	2,293	2,481	2,654
Demand growth projection			78%	40%	26%	19%	15%	12%	10%	8%	7%
Realised demand growth			77%	34%	16%	21%	17%	15%	-5%	-2%	7%
Realised demand		542	767	1,034	1,251	1,645	1,898	2,148	1,985	2,246	2,646
Capacity	0	420	420	420	420	840	840	840	840	840	1260
Realized Capacity	0	578	651	643	698	1248	1404	1363	1298	662	1738
Revenue	$0	$3,794	$4,557	$4,501	$4,886	$8,736	$9,828	$9,541	$9,086	$4,634	$12,166
Shipping and delivery cost		$710	$847	$547	$804	$1,570	$955	$812	$1,545	$334	$1,974
Operating costs	$0	$1,185	$1,144	$1,310	$1,199	$2,688	$2,499	$3,119	$2,877	$1,375	$3,264
Cashflow	$0	$1,899	$2,566	$2,644	$2,883	$4,478	$6,374	$5,610	$4,664	$2,925	$6,928
DCF		$1,696	$2,046	$1,882	$1,832	$2,541	$3,229	$2,538	$1,884	$1,055	$2,231
Present value of cashflow	$20,932										
Net present value (in INR)	$1,529,732										

Table 6.3: Net Present Value with Uncertainty - ATL Model

1) Due to a dependence on third-party manufacturing, potential upside from growing demand is not being captured, resulting in lower revenue and NPV over ten years.

2) A Monte Carlo analysis of 2000 simulations was conducted to generate the histogram shown in Figure 6-4 and the cumulative distribution in Figure 6-5, respectively.

3) Average values with maximum probability lie in the 1.7M to 2.05M USD range. In the next section, a flexible strategy will be analyzed to maximize potential financial upside.

The potential upside needs to be leveraged when demand spikes so that market needs can be addressed appropriately. Burgeoning demand without supply results in negative feedback and creates a barrier for future success. In the flexible model shown below, an expansion rule has been factored in to purchase printers, PLA, and manufacturing space (land leasing costs) if the realized demand of the past year is 1.5 times the available capacity.

Once an expansion occurs, ongoing land leasing costs of 2K USD are factored in along with the purchase of ten 3D printers and PLA materials for 2K USD. The expansion results in a capacity increase of 210 additional sets on the year of expansion. This flexible approach results in the highest average NPV, which is in the range of INR 1,811,617, as shown above.

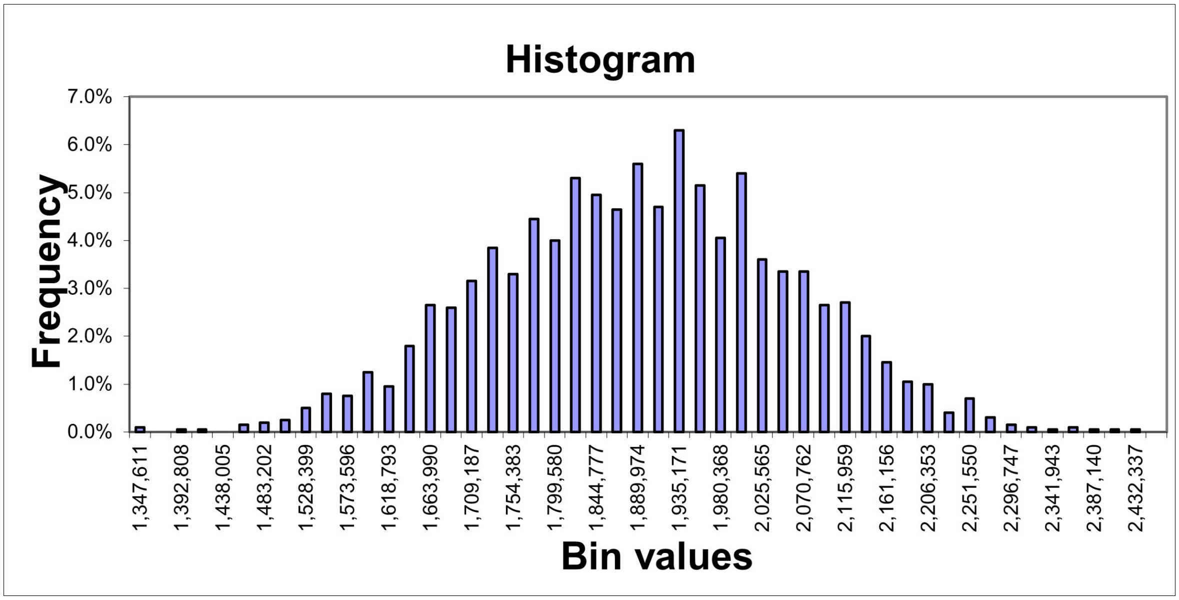

Figure 6-4: Histogram Range based on Monte Carlo

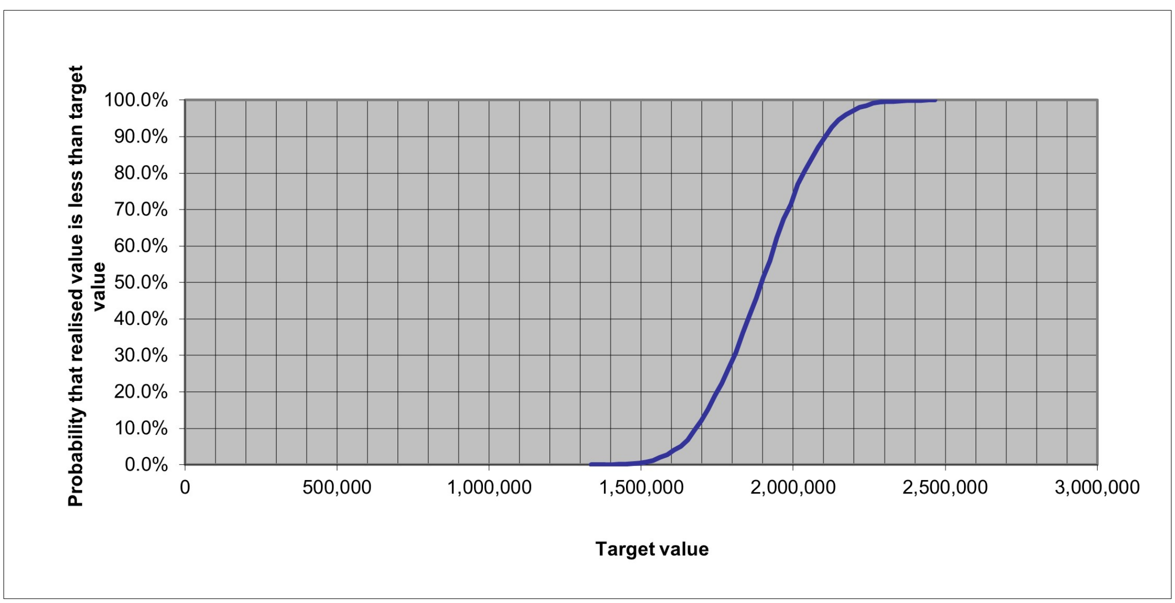

Figure 6-5: Cumulative Distribution based on Monte Carlo

Year	0	1	2	3	4	5	6	7	8	9	10
Demand projection		426	767	1,079	1,366	1,629	1,871	2,093	2,296	2,483	2,654
Demand growth projection			80%	41%	27%	19%	15%	12%	10%	8%	7%
Realised demand growth			89%	31%	41%	34%	20%	7%	-4%	14%	7%
Realised demand		457	805	1,005	1,519	1,827	1,953	1,993	2,019	2,628	2,644
Capacity	0	420	420	420	630	840	840	1050	1260	1470	1470
Realized Capacity	0	451	436	656	1047	624	950	1250	1988	1232	2357
Expand			no	yes	yes	no	yes	yes	yes	no	yes
Printer + PLA costs			$0	$0	$2,000	$2,000	$0	$2,000	$2,000	$2,000	$0
Land leasing costs			$0	$0	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Revenue	$0	$3,157	$3,052	$4,592	$7,329	$4,368	$6,650	$8,750	$13,916	$8,624	$16,499
Shipping and delivery cost		$226	$237	$249	$261	$274	$288	$302	$317	$333	$350
Operating costs	$0	$923	$765	$1,385	$2,337	$1,281	$2,059	$2,431	$4,255	$2,283	$4,312
Cashflow	$0	$2,009	$2,050	$2,958	$4,731	$2,813	$4,303	$6,017	$9,344	$6,008	$11,837
DCF		$1,793	$1,634	$2,106	$3,007	$1,596	$2,180	$2,722	$3,774	$2,166	$3,811
Present value of cashflow	$24,790										
Net present value (in INR)	$1,811,617										

Figure 6-6: Flexible Strategy for Expansion As-Needed

Chapter 7

Conclusion

7.1 Major Takeaways

Each section of analysis provided different insights into the potential future of Project Aakaar. In this section, we will be collating the lessons learned from the prior sections. The Literature Review revealed that there is massive underrepresentation of students with disabilities in the sciences. While there is an availability of tactile devices and software that enable higher access to STEM education, they are expensive and cannot be accessed by a vast majority of the population in India. There is also a dearth of educational toys in the space that utilize "ludic" or game elements to convey STEM concepts as an alternative method of instruction, making Aakaar a unique proposal. Two separate interventions are happening simultaneously – firstly, the introduction of tactile devices into the curriculum for VI students for learning geometry in middle school. Secondly, building empathy in non-disabled students at an early age by exposure to the problem so that Diversity, Equity, and Inclusion (DEI) principles are inculcated.

In traditional design, the target product is aimed at the middle of the bell curve or the maximum possible market (non-disabled). Then the product is retrofitted for accessibility and other requirements in the margins of the bell curve (disabled). This leaves out edge cases and makes most products unusable by specific demographics. At Project Aakaar, the product was designed targeting the visually impaired population (using Braille notations and embossments in the prints). However, the product can be used by sighted students as well. Some sighted students struggle with traditional learning methods, and the tangrams at Aakaar can be an alternative way of teaching geometry-related concepts to all students, making it a genuinely inclusive product.

The Stakeholder Analysis revealed a dire need for repository expansion and design curation before stakeholders such as Corporates and Risk Capital could be engaged. There is a need for constant and regular interactions with sighted students because of the present design dependence. The underlying technology is at TRL9, but the present print speed creates a technical barrier in terms of a possible reduction in overall print time. The current set of designs needs to be updated with number notations, embossments, and Braille to cover many topics, but that would still not cover the entire middle school syllabus. Additional designs would be required for 17 topics, including but not limited to circles and mensuration.

Finally, the business analysis established lean impact metrics that need to be measured to quantify the venture's short-term and long-term social impact. There are multiple possible revenue streams such as the end-prints (packaged as a product), the T3 programs (packaged as a service), and educational and government grants. The NPV analysis confirms that the customized circular economy model is financially better on a 10-year horizon. However, the team should be planning for a dedicated Makerspace within five years for timely expansion.

7.2 Challenges

COVID19 presented the most significant challenge during this thesis. It was challenging to line up interviews with stakeholders and gather data due to critical concerns, such as family members being hospitalized, resulting in limited availability. Schools for both sighted and visually impaired students were closed for most of the past year due to government-mandated restrictions that limited co-design, workshop conduction, repository expansion, and printing progress. A handful of sighted students who volunteered and had access to a PC/Laptop/Smartphone were available from Smt.

Kamalabai Educational Institute for the 3D printing workshops. Furthermore, prints had to be sent to individual VI students instead of at schools which constrained the feedback process to a limited number of students.

It is always a challenge to quantify social entrepreneurship organizations' impact and establish causality of the impact. For short-term impact, the control groups need to be defined carefully and measured by comparing pre and post-scores in geometry concepts being taught by the suggested tactile devices amongst VI students and sighted students struggling with traditional instruction methods. The two main long-term hypotheses are that introducing tactile devices for VI students will increase access to higher STEM education, and building empathy at an early age will result in greater accessibility in design. This is going to be much more challenging to keep track of, quantify and determine causality.

7.3 Socio-Technical Complexity

Providing greater equitable access to higher STEM education for students with disabilities (visual impairment for this study) is a highly complex problem that will require a combination of solutions to be addressed holistically. Research and development should continue to reduce costs for high-tech tactile devices such as the Refreshable Braille Displays. Simultaneously, cost-effective, low-tech alternatives such as Project Aakaar should be explored, which do not need a high level of expertise for use.

It is an unfortunate but grim truth that there is a massive lack of awareness about the problem. The individuals at Aakaar became aware of the extent of the problem in their mid and late 20s. Early introduction to the problem could result in higher engagement of non-disabled students in schools and universities to address the root cause by pursuing projects. The government already has multiple projects to address disabilities in higher education, but there is a lack of information and inefficient execution, resulting in continued disparity.

The lack of infrastructure to support disabilities in technological jobs is also a prohibiting factor for parents to support education in STEM. This is a systemic problem that will take time to solve. However, there is a need to start addressing portions of the problem and informing parents and teachers about the available interventions that can be leveraged for making learning easier for these students.

Along with assistive technology, there is a need for a social change in attitude towards disability. For example, a person who can see receives most of their sensory inputs through sight. If they are doing quality checks by looking at a part, there are chances that their eyes might deceive them due to corrective action. However, if a blind individual touches them to feel for quality, they could theoretically be better suited to the job than a sighted individual. According to McKinsey, gender inequity is a 12T USD "lost economy," imagine the lost economy for all disabilities.

Chapter 8

Recommended Future Work

As touched upon in Section 6.1, this is a Blue Ocean Market and deserves attention because of the potential socio-economic value of the solution. Sighted individuals and visually impaired (VI) individuals with access to aids such as spectacles and lenses are minimally aware or unaware of the extent of the problem due to the segregation of schooling and eventual professional opportunities. The following research could help achieve educational equity in India, which is the long term goal of Project Aakaar -

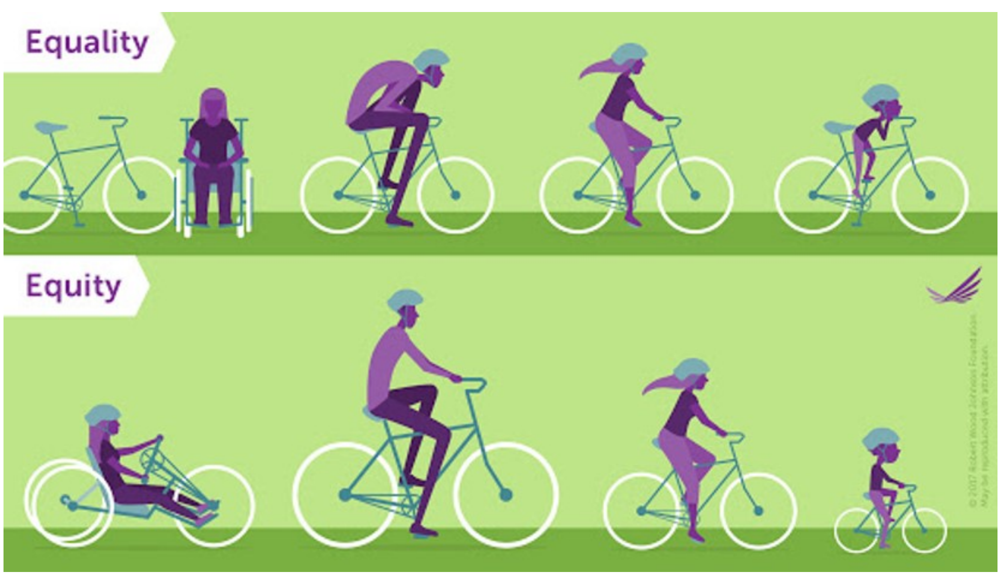

Figure 8-1: Equality vs. Equity - A Comparison [17]

1) Repository Expansion - The team is exploring a set of designs that can ideally cover the middle school CBSE curriculum in India. However, there could be various

better designs that are not in our purview. The repository will be open source, and curation of publicly submitted designs could be as essential as generating the same in-house.

2) Subject Coverage - The goal for this project was a single-subject and single-disability to have a manageable scope. This is an immense space with many possible solutions and should be extended to other STEM subjects with complex visual theories such as Biological and Physical Sciences.

3) Curriculum Integration - Solutions fail due to a lack of integration with the present system. There is a need to integrate proposed solutions with the existing curriculum to maximize impact in a standardized manner nationally. All envisioned solutions should be evaluated for maximal coverage and adjusted based on the evolving curriculum in VI schools (public and private).

4) General Education Integration - VI students are presently segregated from the general educational (GE) and professional services system. While this solution addresses a significant problem, it still segregates. There is a need to integrate VI students into traditional public schools, which can be facilitated by addressing the point above.

Appendix A

Artifacts

A.1 Sample Stakeholder Interviews

A.1.1 Interview with Ms. Sushma

[Indrayud] - Hi, Ms. Sushma. It is great to meet you. I am a graduate student at MIT and am working on addressing educational challenges for visually impaired students. We would love to know what you are currently doing - can you talk about your educational background and your current job?

[Sushma] - I am currently an employee at the Indian Railways in Saharanpur (a city in Uttar Pradesh, India). I am married and have kids. I finished my schooling at the National Institute for the Visually Handicapped (now called NIEPVD), and for graduation, I attended Miranda House at Delhi University. As a born blind, I started using a computer from grade 2, so by the time I went to college, I was very comfortable using a laptop for taking notes. I do not use a special keyboard (she felt very proud!).

[Indrayud] - That is truly awesome!! Was the computer provided at your school, or did you have one at home or both? If you had one at home, what was your average daily exposure to and usage of the same?

[Sushma] - I have been fortunate to have very understanding teachers, even in college. I used to sit in front of the class to ensure that I could hear the instructor properly. I did not face any challenges with the material or classroom teaching, but I faced problems in navigating my way through the college campus. Remembering my initial days in college, I felt lost on the college campus due to the lack of proper tactile pavements. I would reach the classroom for the lecture, but it would take me several minutes to figure out if I was standing outside the correct classroom. It took me about 10-15 days to get a sense of the college campus, after which I became comfortable with the routes.

[Indrayud] - In the short term, this seems to be a job for smart canes but I would be cautious to suggest the same. Even with sight, I had a tough time getting used to and getting my way around MIT because of the huge campus and the number of interconnected buildings to navigate. There should be projects in universities to map their premises efficiently but it isn't done and is a larger problem in general.

[Sushma] - A friend has told me about an application that could detect classroom numbers but it would take so long to recognize the numbers and give me feedback, I just found it easier to ask someone instead. At my workplace, I do not face any challenges. I live very close to my office, so it is only a three to four minute walk for me. My superiors and colleagues all help me out if I ever need any guidance.

[Indrayud] - Have you heard about Be My Eyes? I explained to her what the app does and how it can help her.

[Sushma] - While this sounds helpful, my immediate concern is that of talking to some on the phone in a crowd. I depend a lot on my hearing ability to stay present in a crowd, and if I use earphones or a similar headset to talk to someone on the app, I will be very distracted and will end up feeling uncomfortable. I can see how this app will be useful for me when I am by myself or in a closed room, but I will feel uncomfortable using such an application in a crowd where my sense of hearing is my savior. Using a headset will hinder my ability to sense directions and the source of sound.

[Indrayud] - Be My Eyes can be used in private setting such as when cooking dinner or when at home. For navigation, haptics based devices make more sense to not take away from the other senses. For public environments where discretion is required such as when reading ATM balances, or during professional meetings or even in class during lectures, devices such as HaptiRead and the Tactile Reader make more sense. Would you agree? What kind of applications do you use on a daily basis? Are you using any color identification or AI-enabled apps to help you navigate through your day?

[Sushma] - I have heard a lot about color identification apps but I have never used them personally. I mostly use text identification apps at work to go through paperwork and compile reports. All I need to do is click a picture of the document and the software converts the text to speech (I could not catch the name of the app, I will ask her the next time we talk). For communication, Android has a talkback software pre-installed on its devices that reads out everything on the screen. Using that, I am able to hear the messages I receive and I can type in my responses accordingly. If I ever come across any issues, my colleagues help me out. I wish to decrease my dependency on my colleagues for such tasks. I find myself struggling with the photographs that are shared with me because I am not able to understand what is in them. It would be helpful to have an app or software that helps me understand images as well. I primarily use Google Pay and PhonePe (digital wallet) to pay my bills and it has made me independent.

[Indrayud] - This is a commonly occuring theme across interviews for resolving but it is a NP hard problem espacially given the number of metrics to be analyzed to give an accurate representation of a picture. Color and object recognition is already pretty efficient and sentiment analysis is getting there but exact translation of picture to text will still require leaps in computational analysis. If a picture s presented, what are the essential details you would like to derive from the same in order of importance? I know this is a difficult question because each picture is different and that is what makes the solution incredibly complicated as well. What would you say is your biggest challenge?

[Sushma] - My biggest challenge is traveling. I have become increasingly comfortable traveling for work, however, I still face difficulties when I go shop for groceries. The area that I live in is still developing, so not all shops accept online payments. I have to depend on the people around me for directions, but people can only help me to an extent. I want to be able to do these things on my own.

[Indrayud] - Do you go to shop for groceries with the shop name or the address? Have the local stores retained ownership and names regularly over time? In certain regions, these specifics change regularly such as restuarants in the Powai region in Mumbai. Address mapping might be easier to accomplish. Have you tried using a money identifier app?

[Sushma] - I have heard about them but I have never used them. I am willing to give it a go.

[Indrayud] - How do you presently distinguish between notes. Are they differentiated enough in texture based on touch or any other sense which makes them distinguishable to you?

[Sushma] - They are very difficult to distinguish and I usually need someone to help me. Digital platforms are more easier to use.

[Indrayud] - Do you think you can talk a little about the things that have been the most helpful for you?

[Sushma] - Tactile paving is the most useful tool for the blind. The challenges I face while traveling will be minimized if proper tactile paving is present in public places. I am also blessed to have parents who helped me out every step of the way. From an early age, they taught me how to recognize objects and sensations through touch. I remember learning the difference between hot and cold beverages! I am the person I am today because of the support of my parents and my teachers. Note: the need for training programs for the VI is becoming more apparent to me!

[Indrayud] - Tactile paving is definitely a solution for the future but a humongous task to take on for all possible pathways for our project scope. Can a haptics based device such as Wayband or Guidesense be a viable short-term solution till universal tactile paving is achieved?

[Sushma] - Maybe. But it is difficult to say how effective they will be till they are used by people who need it instead of people who are designing it.

A.1.2 Interview with Mr. Prateek and Mr. Sharad

[Indrayud] – We are exploring assistive technologies which can be used by visually challenged demographics for improving educational access as well as quality of life. We want to understand the technologies which have helped you till now and understand the gaps which still exist in incorporating this demographic holistically into the education and work sectors. Quick Question - How do you perceive images and color in your mind?

[Prateek] – There is a very wide spectrum in the visually challenged demographic. Some individuals are born blind while others have sudden accidents or deteriorating sight over time. Based on the origin of their challenge, individuals perceive colors in different ways and there is no regular standard for the same. I have been using assistive technologies since 2002/03. Some of the apps that I have used over time have been –

- Cash Reader: Bill identifier on the App store. Recognizing currency by touch is difficult, especially in recent years with a move towards standardization of bills with respect to size, paper texture and so on. This app helps the visually challenged to identify notes via nudges. So, for example, Rs. 10 bills would trigger a single vibration while Rs. 20 bills would trigger two vibrations and so on.
- Microsoft Apps – AI Written | Seeing AI: Written AI uses Optical Character Recognition (OCR) and other features for efficient text to speech conversion. The color identification feature is useful when finding the correct shirt or clothes to wear as well as identification of cables when identifying the correct slots for assembling a system. These apps are already there but the challenge lies in making them daily-use.
- Be My Eyes: A free app that connects blind and low-vision people with sighted volunteers and company representatives for visual assistance through a live video call. Really useful and a great add-on for the visually challenged but labor-intensive on the service side.

NOTE – Object recognition in the present scenario is extremely pertinent and greater data sets which would fuel the ML algorithms in the space would be welcome to the entire community.

Existing Challenges -

[Sharad] – On WhatsApp groups, there are reports, visuals and infographics etc. which are shared that are easily discernible to individuals who can visually interpret them but are extremely limited in the same translation for the visually challenged. In government positions in India, equal opportunity is not provided for the visually challenged to perform at the same level as their visually adept counterparts.

Problem Statement –

[Prateek] - While infographics can be read out using text to speech translation apps, there is a bigger problem with plain pictures and their interpretation. You can get basic details such as age of a person, basic emotions and so on but what the entire picture depicts or is supposed to depict is difficult to discern using present apps.

[Sharad] – In every age group there are different challenges for the visually challenged demographic. During formative years there are unique challenges versus those which occur during education, transition to industry, parenting and so on... Furthermore, there are different challenges in different professions. Prateek coming from software background vs. me in the governmental sector, we have separate and unique challenges. During my experience, I faced a lack of equal opportunity in the playground as well as equitable access to classroom materials. Since Prateek has his own organization and he understands the problems faced by this group of individuals, he can provide greater access and be more empathetic to the situational problems that are being faced but that does not apply to the governmental sector that I am involved in.

[Prateek] – There are a lot of applications which exist in this space, but they are not holistically integrated into the entire Play Store ecosystem. For example, there are a lot of apps which are not easily accessible for visually challenged populations. PayTM has to be used with a Screen Reader App and cannot be used directly. There are challenges like this because of which these individuals have to take extra steps to use the apps instead of them being integrated. A Screen Reader App (especially one which can also do graphics translation or interpretation) integrated into WhatsApp would be a big help because it would reduce the steps required to achieve the same level of understanding and would also enable standalone app development instead of manual integration. OCR is helping in a big way, but major improvements are still required. Affordability is another major issue. JAWS costs close to 800 USD which is not affordable to a large section of the Indian blind population. Non-Visual Desktop Access (NVDA) is free and open source but are not easily accessible unless one has the appropriate devices. Additionally, required hardware is awfully expensive.

Long Term Challenges -

[Sharad] – In rural villages across the country, the medium of information is still Radio and there is minimal support from State governments in terms of finances and facilities. Alongside, there also exists the unfortunate reality of immense discrimination in such areas from both families and societies towards blind and disabled children as compared to able ones.

[Prateek] – Other than being born blind, there are various causes of blindness in our country. Some people lose their eyesight due to malnutrition or insufficient treatment of cataracts or industrial/playground accidents (such as during Gulli-Danda). Interventions are required at these intersections as well.

[Sharad] – There needs to be better education about the available technologies instead of just exploration of new ones. A lot of applicable technologies already exist – what is important is how to make the public educated and how to make them easily accessible and financially feasible. The visually challenged demographic need to be appropriately trained and educated instead of the same methods as used for the visually adept. One learns technology by hit-and-trial, and while mentoring is helpful, access is critical.

NOTE – There should be a dedicated focus on how these ideas can be practically used, propagated, and implemented in villages and low-income economic zones.

A.2 Train-The-Trainers (T3) Manual

Mentoring in Empathy, Design, 3D Printing and Assistive Technologies

Project Aakaar

Educational Aids for Visually Impaired students to Learn Geometry Effectively

In collaboration with SKEI, ATL and EKA

Prepared by Prithvi, Indrayud, Dr. Kyle Keane

Massachusetts Institute of Technology, Boston, MA

Contents:

Foreword 3

What are Assistive Technologies? 4

Accessibility in Design 5

Ideation to Digitization 6

Quality Assurance of First-Round Designs 8

Slicing the CAD Files 9

Gathering Feedback from Users 10

Construction of Second-Round Designs 11

Acknowledgements 12

About the Authors 12

A.2.1 Foreword

According to the World Health Organization (WHO), it is estimated that at least 2.2 billion people globally have a vision impairment or blindness. At least 1 billion of them have a vision impairment that could have been prevented or has yet to be addressed. These 1 billion people include those with moderate or severe distance vision impairment or blindness due to unaddressed refractive error (123.7 million), cataract (65.2 million), glaucoma (6.9 million), corneal opacities (4.2 million), diabetic retinopathy (3 million), and trachoma (2 million), as well as near vision impairment caused by unaddressed presbyopia (826 million). (Cieza, 2019).

Vision is the most dominant among all our senses. According to an article, up to eighty percent of our perception and learning has some link with vision. Vision plays an important role in self-learning as we grow up and observe the environment. Much of this self-learning forms the basis of understanding the subjects we encounter in schools. For example, as students with typical sight, we were not explicitly told that a cylindrical pillar appears like a rectangle when seen from a certain distance, or that the projection of a spherical ball is nothing but a circle, something that we understood intrinsically. On the other hand, for children with visual impairment, this natural perception that is triggered by the visual system becomes a luxury they do not have. As a result, many of them need more time and effort to understand concepts like geometry, where just chalk-and-talk pedagogy is inadequate.

The team at Project Aakaar realized that there is a need for easy-to-procure educational aids which can help visually impaired students understand relationships among/between geometric shapes and the environment and have the potential to be used for practicing geometry. They utilized their learnings to create cheaply produced 3D prints in 3 separate categories which will be elaborated on later in the manual.

The purpose of the Train-the-Trainer Manual is to provide instructors/facilitators with competencies that will enable them to effectively mentor students in the principles of empathetic design, translation of digital designs to 3D prints, garnering user feedback and incorporation of feedback for further design iterations.

As mentors you will work with students and guide them on the path from ideation to actualization. More than likely, as a new mentor/trainer you will be assigned to teach others, and in this capacity you will serve in the role of a teacher, leader, guide, sponsor, and role model for others.

A.2.2 What are assistive technologies?

Assistive technology is any device, software, or equipment that helps people work around challenges so they can learn, communicate, and function better. A wheelchair is an example of AT. So is software that reads aloud text from a computer. Or a keyboard for someone struggling with handwriting. These tools can help people work around their challenges, while also playing to their strengths. This is especially important for kids who struggle with learning—whether in reading, writing, math, or another subject. AT can help these kids thrive in school and in life. And that can help grow their confidence and independence. There lots of myths about AT. Some wrongly believe that using AT is “cheating.” Others worry that kids who use AT may become too reliant on it. One of the biggest myths is that using AT will prevent kids from learning academic skills. That is simply not true. For instance, experts agree that listening to audiobooks does not keep kids from learning to read. While AT has many benefits, keep in mind that it cannot “cure” things like dyslexia or ADHD. It cannot replace good teaching and instruction, either. Despite the word “technology,” not all AT tools are high-tech. AT includes many simple adaptive tools, like highlighters and organizers. A great example of low-tech AT is a pencil grip for students with messy handwriting. Nowadays there are more sophisticated tools, specifically in software and prosthetics. Fig. C-1 below shows generalized categories of ATs and this workshop deals with the Study Skills/Aids sub-category for visually challenged students.

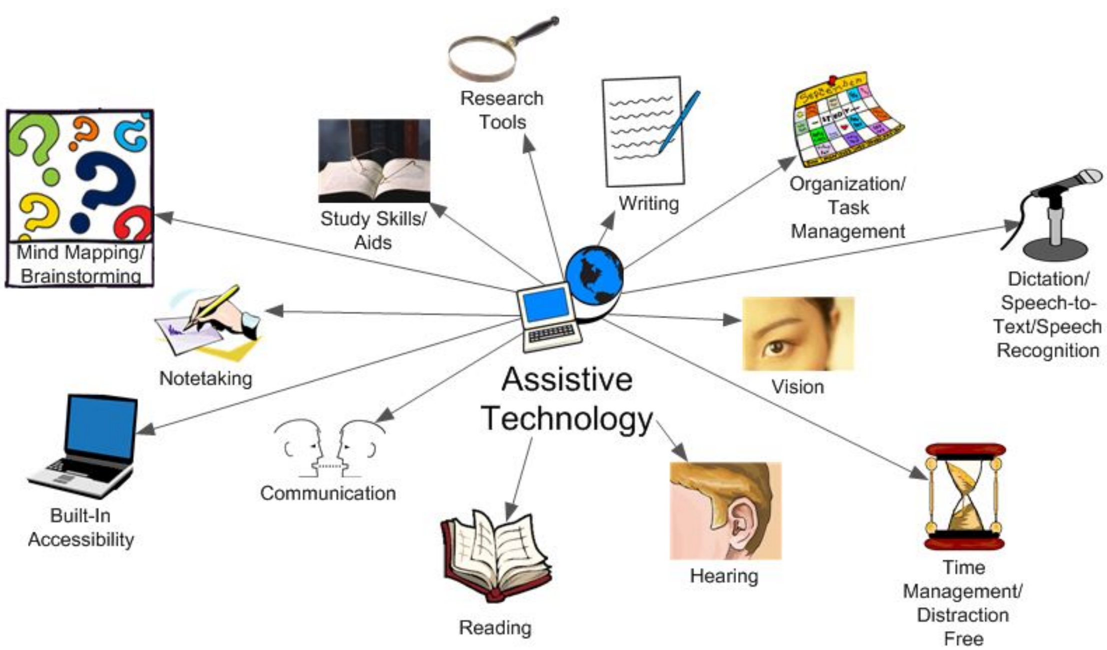

Figure A-1: Types of Assistive Technologies

A.2.3 Accessibility in Design

When it comes to digital experiences, every one of us can recount a frustrating interaction with a website or app. To improve customer experiences and ensure equal access for all users, more businesses are adopting a human-centered, inclusive approach to design. But building a culture of accessibility can be a daunting task. While most businesses agree accessibility is important, getting internal buy-in can be a bumpy process. There is a misconception that inaccessible products only affect a small portion of end users. However, 1 billion people, or 15 percent of the world's population, experience some form of disability, and we must include them when designing products.

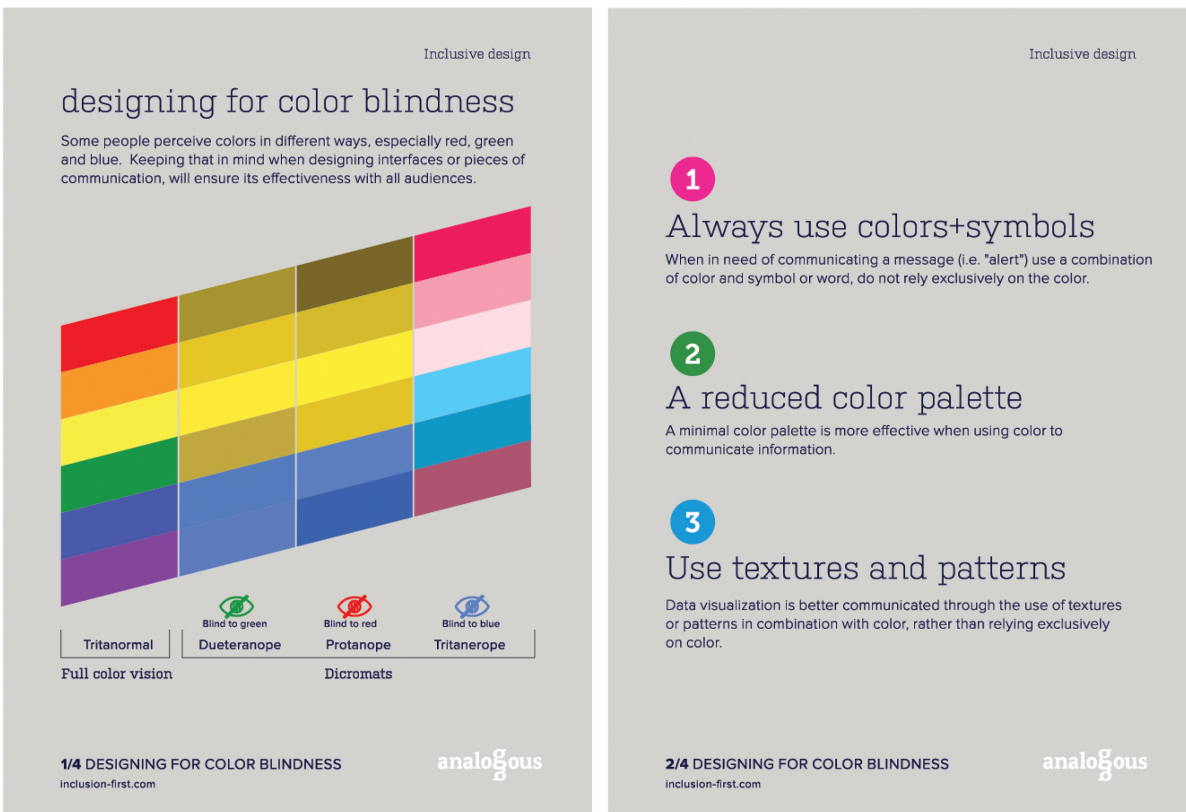

Figure A-2: Accessibility in Web-design for Color Blindness [C]

Additionally, the following points can help champion an accessibility program: 1. Accessible products benefit everyone no matter their physical or cognitive ability because accessible products represent an ideal user experience that is clear and

intuitive. For example, many people tend to be power users of keyboard shortcuts. The ability to tab through inputs or use the enter key to submit a form makes all users more productive, not just those who rely on a keyboard instead of a mouse. Similarly, applications with proper focus management and strong color contrast have better navigation, while also empowering those with low vision to perceive changes.
2. Accessibility is an investment in your customers and employees and future economic growth. Measuring the business value of accessibility can be tricky. One way to frame it is to think about the ripple effects of inaccessible products. Not only are you preventing users with disabilities from using your product, but you're also limiting the people who can work at your company and develop your product. That impact is further extended for B2B companies—you are limiting who your customers can engage with and sell to, as well. While measuring the success of an accessible product is not always easy, it's clear that inaccessible products can create unanticipated and cascading business and legal problems.

A.2.4 Ideation to Digitization

Students should be made to quickly recall the "sightless" and "tactile" learning exercises to remind them of the challenges that they might not personally face daily.

A.2.5 Sightless Learning

Do they remember the Learning Objectives?
1) Understand the importance of sight in interpreting geometrical concepts.
2) Re-learn concepts related to triangles while blindfolded.
3) Observe the difficulty in teaching these concepts to VI students.

Activity – Ask students to remember the effect of the blindfold. Request them to think of and suggest improvements to the verbal cues provided that might have helped them in determining the answer.

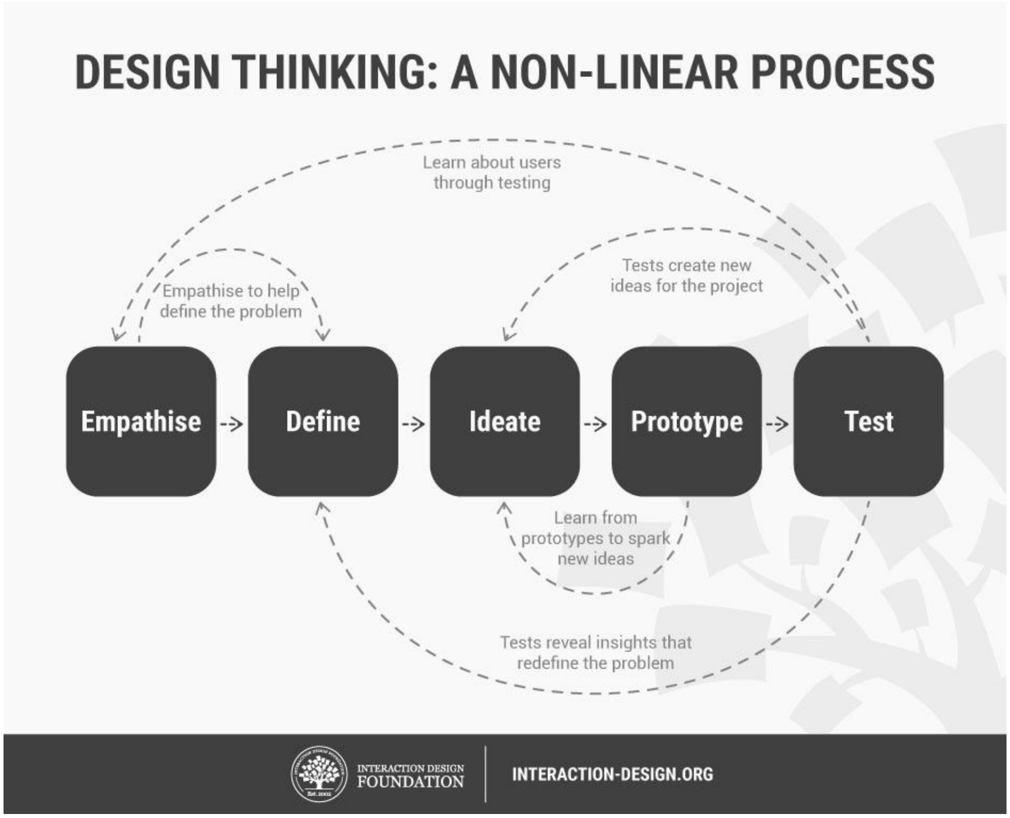

Figure A-3: Empathy Centric Design

A.2.6 Tactile Learning

Do they remember the Learning Objectives?

A) Understand the importance of tactile information for VI students.

B) Verify the effectiveness of the tangrams in conveying concepts related to triangles.

C) Provide feedback on the present set of designs including possible improvements.

Activity – The students will still be blind-folded, and some of the concepts will be re-taught using the distributed tangrams. Students will be provided with two isosceles triangles and four base plates. All four puzzles can be solved with the same 2 pieces and they convey the following concepts – use of 2 right angled triangles to create an equilateral triangle, parallelogram, rectangle, and an isosceles triangle. The third puzzle can also be used to illustrate why area of a triangle is (1/2 * base * height).

The next step is to guide students in exploring geometrical concepts that can add the most value via tactile inputs. For example, the triangles can have embossments to improve design and convey concepts of lines, angles, perimeter and area as well.

Tactile Solution – Print a base plate with an embedded circle. Additionally, print a right-angled triangle with the 90-degree side having a length equal to the diameter of the circle. Fitting the triangle into the circle would convey the message of the theorem. One could print a trio of right-angled triangles on the same radius but different sides to convey the information efficiently.

One can construct a 3D structure from the ground up using traditional software such as CAD, online hosted software such as TinkerCAD, or cutting-edge ones such as Blender, SketchUp, Hexagon and Fusion 360. Each of them has a different set of operational commands and interface instructions but the basic steps are mostly common including superposition of shapes, creation of line and curve alignments and so on.

A.2.7 Quality Assurance of Initial Designs

Once the 3D designs are created, they need to be validated for quality assurance to ensure that we have "clean" prints during the printing process, thus minimizing rework. Suggestions from the Project Aakaar team to ensure smooth 3D printing, a durable structure (as it is to be used by children), and above all, to make sure that all the features are legible and useful to VI students include -

1. Base plates must have a thickness >= 5mm for ease of handling and structural integrity.

2. Designs should have minimal use of support structures during desktop 3D printing. Since our tools are touch-based, we wanted to avoid the risk of unwanted surface roughness resulting from the removal of support structures after printing.

3. Smaller the dimension, the higher the tolerance for good fitting. In our puzzles, the scale factor of a piece was approximately from 0.87 to 0.98 times the dimension of its groove.

4. To feel a certain feature properly, all its dimensions should be at least equal to 2.5mm. We understood this the hard way. Some features were too detailed/small

for the VI students to interpret. We did not anticipate this during the design phase and could only be known after printing. Thereafter, we estimated a threshold for the dimensions beyond which they are interpretable.

5. Include fillets wherever possible (see Figure below).

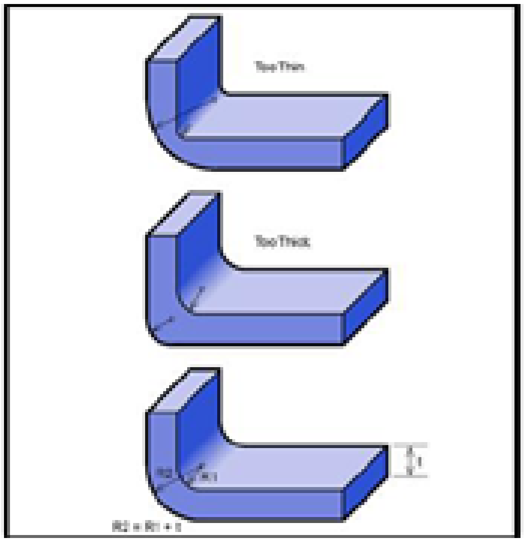

Figure A-4: Curved Edges or Fillets

This serves two purposes:

a. It reduces the stress concentration at the given edges, thereby increasing the strength and life of the component.

b. It reduces the possibility of a sharp edge possibly hurting the user.

Following link might be helpful for introduction to OpenSCAD code for Braille dots: https://github.com/KitWallace/openscad/blob/master/braille.scad

A.2.8 Slicing the CAD Files

Once the 3D designs have been virtually generated, they need to be processed by a slicer to create a set of horizontal prints. Each 3D printer will have its' own specific software which either comes pre-loaded on the SD card or had to be downloaded from a licensed site. The figure below shows the steps that the Creality software uses: Load the CAD file -> Slice into Gcode -> Save on the TF card. Once the processed code has been transferred to the TF card, insert it into the appropriate slot in the

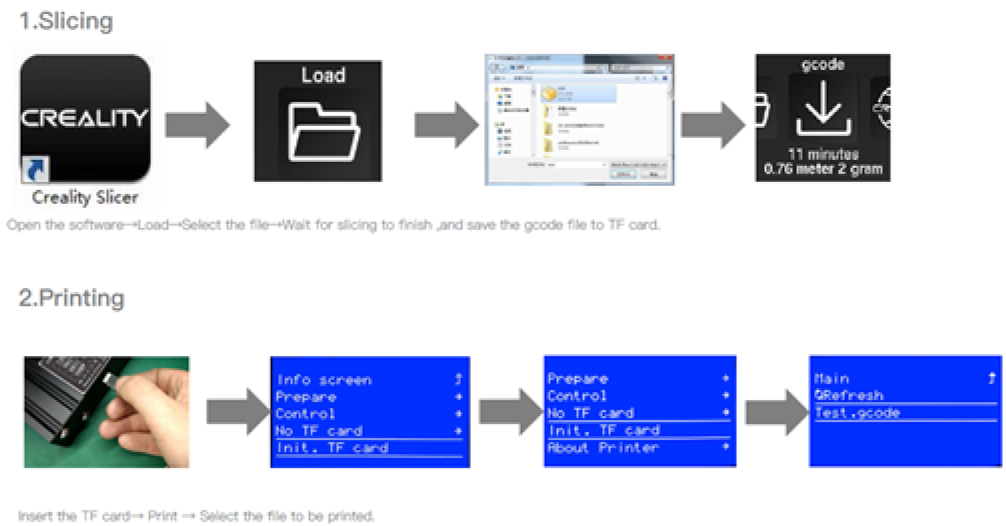

Figure A-5: Converting a CAD file to STL

3D printer. Initiate the TF card -> Select the file to print -> Initiate the print and observe the estimated time to print.

The printing process itself is very time-intensive and does not need much manual intervention. Depending on the complexity of the print, it can take anywhere from 30 mins to over 12 hours. During the daytime, smaller prints should be done so that the baseplate can be reset at the required intervals once prints complete. Longer prints (over 6 hours) which do not require manual intervention should be processed overnight.

A.2.9 Gathering Feedback from Potential End-Users

Once the first-level designs have been printed, they need to be distributed to visually impaired students for gathering feedback. The team at Project Aakaar will take care of these distributions. Present affiliations include Ek Kadam Aur Foundation, Ramana Missionary School for the Blind and National Association for the Blind. Garnering feedback is essential to understand improvements required to the designs and issues faced by the users. The suggestions given above were only understood after the original "triangle" prints were used by students and further improvements are bound to rise as we explore additional concepts and more prints.

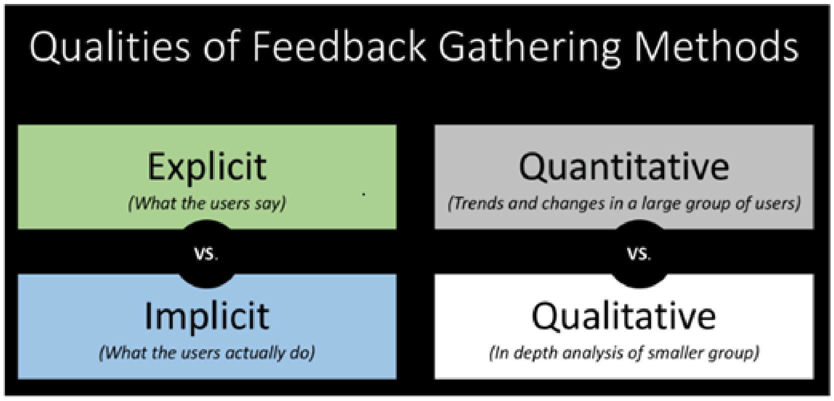

Figure A-6: Feedback Methodologies

We will be asking the VI students to provide explicit and qualitative feedback on the delivered prints. Considering the print time, it might be difficult to have a separate set of prints for each VI student. Instead, we will be sending a command on set of prints for each school which should be shared by the students. Each student will be asked to provide their feedback on each print, their feedback will be collated and shared with the trainers. The most heat-seeking issues should be identified in collaboration with Project Aakaar and the lessons learned should be conveyed to the students in the 3D printing workshop.

A.2.10 Construction of Second-Round Designs

Project Aakaar was conceived with an intention of conveying geometrical concepts to VI students and is presently in the ideation and prototyping phase for new concepts. Concepts related to triangles in specific have been tested already and feedback has been garnered which has resulted in the present state of the project. However, much is left to be done as there are hundreds of geometrical concepts to be covered and the principle itself can be extended to other STEM disciplines such as biology, chemistry, or physics. Once the feedback has been prioritized, trainers will work with students on incorporating the suggestions into the 3D designs. Based on the level of engagement, the partnering organization can choose to go for another additional round of prints or upload the updated 3D designs to a common repository. Conducting these 3D printing workshops, gathering feedback, reiterating on the designs and creating a

Figure A-7: Process of Iterative Development

common repository would help us generate a reusable library of designs that can be utilized by VI students globally to understand STEM concepts.

As the number of workshops and users increases, we will be able to gather implicit and quantitative data which will feed into the designs as well. The aim is to rapidly prototype, learn from feedback and to constantly improve the design and amount of tactile information being conveyed by these prints.

A.2.11 Acknowledgements

We would like to extend our thanks to the following organizations and their representatives for making this work-product a reality. • Smt. Kamalabai Educational Institution (SKEI) • Ek Kadam Aur Foundation (EKA) • Ramana Missionary School for the Blind • National Association for the Blind (NAB)

A.3 Lesson Plan at SKEI

Smt. Kamalabai Educational Institution; Edward Road, Bengaluru
September to October 2020-21
Lesson plan prepared by Indrayud Biswas Mandal and R. Prithvi Raj
Class: VI to X

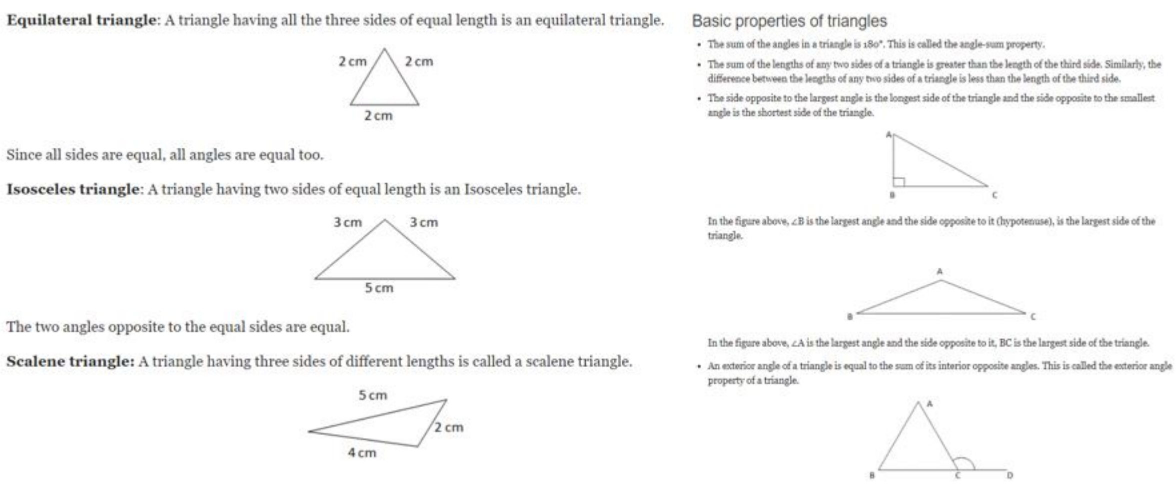

Figure A-8: Various Concepts of Triangles

Subject: Aakaar Tactile Puzzles @ Atal Tinkering Labs

Topic: Aakaar Tactile Puzzles

Estimated Time: 16 hours

Materials Required: PCs or Laptops, Access to 3D Printer, Sample 3D Prints, PLA Material for Printing, Notebooks and Sketching Material, Objects to Feel, Blindfold Cloth, Image Capture Scanner

A.3.1 Sightless Learning

Learning Objectives: The students will be able to

1) Understand the importance of sight in interpreting geometrical concepts.

2) Re-learn concepts related to triangles while blindfolded.

3) Observe the difficulty in teaching these concepts to VI students.

Activity – The students will be blind-folded and specific concepts related to triangles will be taught to them by the instructors using verbal inputs only. Concepts can include – types and properties of triangles, combination of triangles to create various types of quadrilaterals, using 2 triangles to show why area of a triangle is (1/2 * base * height).

Questions – Based on the concepts taught above, the students should be asked to answer certain questions while still being blindfolded:

A) Can you draw an equilateral, isosceles and right-angled triangle?
B) How will you divide a rectangle into 4 isosceles triangles? Draw and show.
C) Describe a scalene triangle using only words so that someone else can draw it based on the given verbal instructions.
D) With a drawing, can you show why the area of a triangle is (1/2 * base * height)?

A.3.2 Tactile Learning

Learning Objectives: The students will be able to
1) Understand the importance of tactile information for VI students.
2) Verify the effectiveness of the tangrams in conveying concepts related to triangles.
3) Provide feedback on the present set of designs including possible improvements.

Activity – The students will still be blind-folded, and some of the concepts will be re-taught using the distributed tangrams. Students will be provided with two isosceles triangles and four base plates. All four puzzles can be solved with the same 2 pieces and they convey the following concepts – use of 2 right angled triangles to create an equilateral triangle, parallelogram, rectangle, and an isosceles triangle. The third puzzle can also be used to illustrate why area of a triangle is (1/2 * base * height).

Questions –
A) Was it easier to understand the concepts using the tangrams? If not, what difficulty did you face?
B) Which of the concepts in the earlier exercise would be easier to understand with similar designs? What kind of prints would help to explain those concepts?
C) Do you have any feedback or design improvement suggestions for the prints which we provided to you?
D) Is the importance of tactile feedback for VI students clear to you?

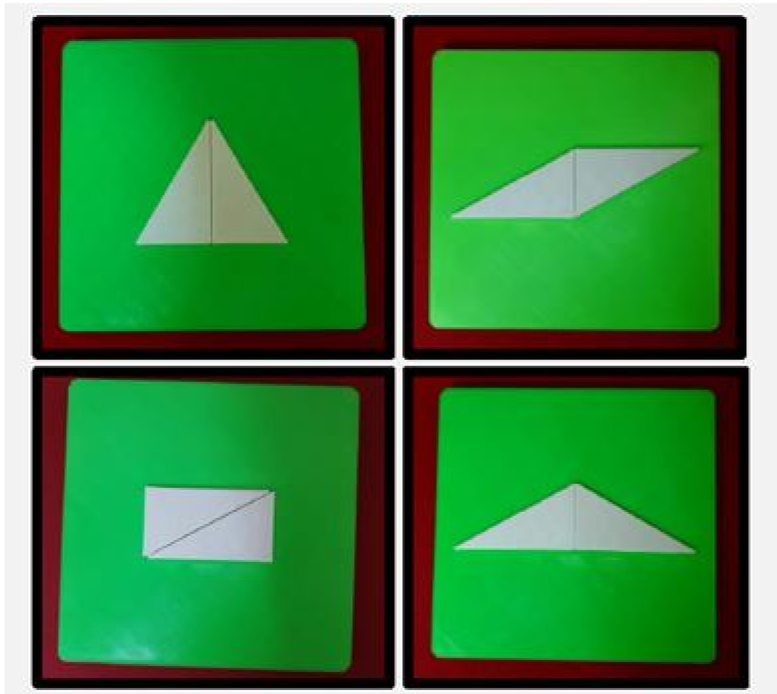

Figure A-9: Geometry Set of Original Aakaar Puzzles

A.3.3 Empathetic Design

Learning Objectives: The students will be able to

1) Recall the issues that they observed during the "Engage and Empathize" and "Explore" activities conducted during the first week.

2) Utilize the lessons learned in the "Sightless" and "Tactile" learning exercises.

3) Recognize the importance of empathy in Design Thinking.

Activity –Ask students to list 2-3 lessons from their experience in the first weeks' workshop. They should also note down the feedback that they have on the tangrams for incorporation into their designs. Finally, the instructors should go over the "Empathy Centred Design" process which is shown below.

A.3.4 Digitization of Design

Learning Objectives: The students will be able to

1) Use principles of "Empathy Centered Design" when creating sketches or preliminary designs for VI students.

2) Convert hand-drawn sketches to digital designs and manipulation of STL files using TinkerCAD.

3) Actualization of design by 3D printing of the STL files.

Activity – This is the final activity to be conducted on this day of the workshop. Students will be guided through the Sketch, CAD, and Print process. They will also get hands-on experience in TinkerCAD as we will provide the original STL files for the Aakaar geometry puzzles into which their suggestions can be incorporated.

Sketch: The next step would be to sketch either improvements to the existing tangram designs or additional designs which could be helpful in teaching geometrical concepts related to triangles to students. Please note that these should not simply be 2-D prints of 3D objects. The designs and prints should convey a core concept which is taught such as a theorem or integration into complex combinatorial shapes.

CAD: Original STL files for the tangrams are attached below and will be shared with the students during this portion of the exercise. They can either incorporate their suggestions to the existing tangram designs or create ground-up designs (that teach a theorem) based on their familiarity with TinkerCAD. Students can also print Braille messages on the print for the VI students to read.

Suggestions from the Project Aakaar team to ensure smooth 3D printing, a durable structure (as it is to be used by children), and above all, to make sure that all the features are legible and useful to VI students include -

1. Base plates must have a thickness >= 5mm for ease of handling and structural integrity.

2. Designs should have minimal use of support structures during desktop 3D printing. Since our tools are touch-based, we wanted to avoid the risk of unwanted surface roughness resulting from the removal of support structures after printing.

3. Smaller the dimension, the higher the tolerance for good fitting. In our puzzles, the scale factor of a piece was approximately from 0.87 to 0.98 times the dimension of its groove.

4. To feel a certain feature properly, all its dimensions should be at least equal to 2.5mm. We understood this the hard way. Some features were too detailed/small

for the VI students to interpret. We did not anticipate this during the design phase and could only be known after printing. Thereafter, we estimated a threshold for the dimensions beyond which they are interpret able.

5. Include fillets wherever possible (see Figure below). This serves two purposes:

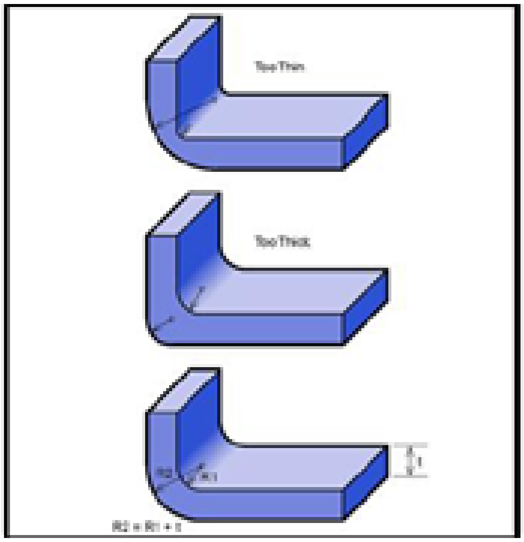

Figure A-10: Curved Edges or Fillets

a. It reduces the stress concentration at the given edges, thereby increasing the strength and life of the component.

b. It reduces the possibility of a sharp edge possibly hurting the user.

Print: The new or updated STL files should be uploaded at a common location – Google drive or Dropbox so that it can be accessed by the facilitators at SKEI and Prithvi for actualization and printing of the virtual designs.

This is an extension of the first workshop and hence there are some common elements which require reiteration for the sake of continuity while maintaining modularity. Instructors and workshop facilitators will guide the attendees in creating the virtual designs, quality test the end prints and garner feedback from VI students for future iterations.

Activity – The students will be provided with the digital tactile tangram designs from Project Aakaar on the first half of the second day. The file is available on the Humanistic site at https://www.humanistic.app/project.php?id=21. Students are supposed to analyze the base designs and add on personal messages in Braille such as Greetings from Ashwin, Love from Nuzhat, Best wishes Payal and so on.

The following link for Braille dots in OpenSCAD might be useful:
https://github.com/KitWallace/openscad/blob/master/braille.scad

NOTE – Printing Braille on a horizontal plane has lesser fidelity than vertical prints. So, a 3D print of the same pattern of tactile inputs on a X-Z plane is more accurate and sensitive than on the X-Y plane. Please keep that in note when accentuating the present designs in the set.

Questions –

A) Are you comfortable with the software being used?

B) If yes, what is working for you? If not, what improvements or alternatives do you suggest?

C) Would embossments be useful? If so, in which instances?

A.3.5 Design Validation

Learning Objectives: The students will be able to

1) Ascertain QA (Quality Assurance) for digital designs by instructors and/or workshop facilitators.

2 Validate incorporation of the print suggestions mentioned below.

Activity – Suggestions from the Project Aakaar team to ensure smooth 3D printing, a durable structure (as it is to be used by children), and above all, to make sure that all the features are legible and useful to VI students include -

6. Base plates must have a thickness >= 5mm for ease of handling and structural integrity.

7. Designs should have minimal use of support structures during desktop 3D printing. Since our tools are touch-based, we wanted to avoid the risk of unwanted surface roughness resulting from the removal of support structures after printing.

8. Smaller the dimension, the higher the tolerance for good fitting. In our puzzles, the scale factor of a piece was approximately from 0.87 to 0.98 times the dimension of its groove.

9. To feel a certain feature properly, all its dimensions should be at least equal to 2.5mm. We understood this the hard way. Some features were too detailed/small for the VI students to interpret. We did not anticipate this during the design phase and could only be known after printing. Thereafter, we estimated a threshold for the dimensions beyond which they are interpretable.

10. Include fillets wherever possible (see Figure below). This serves two purposes:
a. It reduces the stress concentration at the given edges, thereby increasing the strength and life of the component.
b. It reduces the possibility of a sharp edge possibly hurting the user.

Questions –

A) Why were the Braille messages done on a vertical base? If not, why?

B) How were embossments used, if at all? If not, how can they be efficiently used for future prints?

A.3.6 3D Printing

Learning Objectives: The students will be able to

1) Observe the actualization of design by 3D printing of the digital STL files.

Activity – The "sliced" gcode files will be processed and printed by instructors/facilitators to generate the envisioned design. There is minimal participant involvement during this phase owing to the extensive printing times of these devices for complicated designs. New example shown below –

Questions –

A) Conceptualization -> Digitization. What was your biggest obstacle for this translation from a mental concept to a virtual design?

B) Were there any issue(s) during printing? If so, what was it and how can we help?

A.3.7 Quality Assurance

Learning Objectives: The students will be able to

1) Observe the actualization of their envisioned prints

Theorem #1 - Thales's theorem states that if A, B, and C are distinct points on a circle where the line AC is a diameter, the angle ABC is a right angle.

Tactile Solution – Print a base plate with an embedded circle. Additionally, print a right-angled triangle with the 90-degree side having a length equal to the diameter of the circle. Fitting the triangle into the circle would convey the message of the theorem.

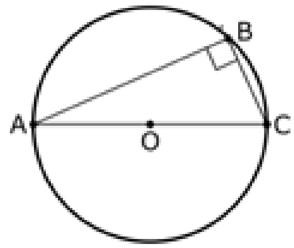

Figure A-11: Possible Theorem for Future Design

2) Get their "prints" verified and validated by the instructors

Activity – Verification and Validation (VI&V) are essential stages of a new system. The diagram below shows a commonly accepted Venn Diagram about the same. During this stage facilitators and event conductors will evaluate the end prints to check the fidelity and accuracy of the physical prints compared to the digital files.

Questions –

A) Were there any common discrepancies across the prints designed by the students?

B) Given the time that it takes to print one of these designs, does it make more sense to promote cottage industries on a larger scale?

A.3.8 First Level Feedback

Learning Objectives: The students will be able to

1) Observe their "prints" being used by VI students.

2) Garner feedback on possible improvements in future iterations.

Activity – This is an ongoing activity which will continue to the next stage. At this point we will distribute the collective "prints" to an associated VI school (to be finalized) and garner their feedback. There will be greater detail on this stage on the next "Lesson Plan" based on the generated associations.

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