Integrated Product Design graduation assignment
Faculty of Industrial Design Engineering

3D printing for Frugal Innovation in Kenya: the design of a hand grip tool

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While writing this thesis, I received a great deal of support, encouragement, and input for which I must express gratitude and praise.

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This thesis is concerned with exploring just how to develop products in line with this frugal methodology through the case study of a hand exerciser. This main research question for this design project asks to what extent can FDM 3D printing be applied to assist Kenyan occupational therapists in the provision of therapy to individuals with hand dexterity and strength challenges.

This self-initiated graduation project is being completed in collaboration with Kijenzi (www.kijenzi.com) - a design and manufacturing company based in Kenya. Kijenzi is using additive manufacturing technology to produce products locally using low-cost FDM 3D printers.

Research into the context of occupational therapy, additive manufacturing, and the context of Kenya revealed the following key insights:

- Professionals in Kenya do not have access to suitable tools because of their high associated cost and the challenges involved in importing the products and distributing them into rural locations.
- Traditional hand exercisers can have drawbacks that hinder patient recoveries.
- 3D printing is a laborious process and partially digitizing the process could lower production costs.
- Occupational therapists require products in a large range of sizes and strengths to suit the individual needs of their patients. This could be achieved in a product customising system.

The synthesis of the insights gained in the research activity created an envisioned scenario which involved a product/service/system scope. In this scenario, patients can exercise their hands safely in a purposeful way with a meaningful outcome. Healthcare professionals would be empowered to order customised products from the manufacturing company by means of an online product customiser. The manufacturer would then be able to produce these customised goods in a way that minimises the cost of doing so. A list of requirements, design drivers, and design challenges were prepared as support to design activity.

The HandBand product, service, system (PSS) concept is a holistic structure which affords the provision of patient-specific hand therapy. Through the use of the 3D-printed therapy device, an online configurator, and a production system, the concept’s full design articulation is achieved in a low-cost and feasible manner. The three-part proposition aims to provide impact for key stakeholders in both the Kenyan healthcare picture and the Kijenzi context.

Six levels of the European Space Agency's Technology Readiness Level were followed to embody these design proposals. The ultimate validation in this involved a test of the 3D-printed product in a clinical setting in Kenya.

The outcome of this evaluation for the product was clear and decisive: the occupational therapist confirmed that the HandBand had made a significant contribution to the recoveries of multiple patients. The hand exerciser was a marked improvement to the current equipment and tools available in the hospital.

Conclusions were derived from the feedback in the final chapter. Finally, recommendations were prepared for the development of the design proposal in future.
1. INTRODUCTION

This chapter outlines the background of the assignment and provides insight on the methodology applied. The initial project requirements providing approximate scope at the beginning of the thesis are outlined. Finally, a guide to reading and understanding the document is provided.
Kenya is a coastal, east-African country, with a population of 52 million. Nearly half of this (46%) sit below the poverty line (WHO, 2017) and Kenya is regarded as a lower-middle-income country (LMIC). With nearly one fifth of the government’s annual expenditure funnelled into healthcare - Kenya has made remarkable progress in improving healthcare access for its population in order to attain “the highest possible standard of health in a manner responsive to the needs of the population.” (Pharmaccess Group, 2020).

1.1. Introduction

Frugal Innovation concerns the application of new, low-cost manufacturing technologies to societal challenges in developing nations, with benefits for their people and the planet. Healthcare is a great benefactor of Frugal Innovation, rewarding greater access to higher quality healthcare at a lower cost. This thesis aims to investigate the convergence of Design for Healthcare and Frugal Innovation in a case study of the development of a therapeutic hand-held exerciser. There exist marked challenges in accessing quality healthcare in Kenya juxtaposed with the nation’s determination to improve the system. As such, Kenya is a capable proving ground for new innovations that can improve healthcare in a low-cost manner.

This self-initiated graduation project is being completed in collaboration with Kijenzi (www.kijenzi.com) - a design and manufacturing company based in Kenya whose mission is to put “localized, distributed manufacturing to work for institutions who do the public good”. Producing low-cost goods in their additive manufacturing hub, Kijenzi can tailor-make and mass-produce products for the healthcare system in Kenya. Kijenzi have identified a need based on collaboration with individuals in the Kenyan primary healthcare sector for low-cost and locally-produced therapeutic devices to assist in the administration of physiotherapy and occupational therapy.

Within Kenya’s primary healthcare system exists a path of therapy known as occupational therapy. This clinical practice is concerned with reintegrating patients into their daily life after an illness or an injury. Alongside the promotion of natural healing, product interventions can help to improve patient recovery by allowing patients to complete a specific exercise movement in a safe manner to rebuild mobility and strength. In this manner, patients can rehabilitate on their own time without the presence of an OT, shortening rehabilitation durations, costs and hospital stays (Fionnula Fahey, personal communication 30th November 2020). Furthermore, these products can provide an assistive functionality to help patients complete activities of daily living (ADL), like brushing teeth.

Kijenzi is using additive manufacturing technology to produce products locally using low-cost FDM 3D printers, where the broken links in supply chains and the complicated logistics of healthcare can be surmounted. This thesis is concerned with exploring just how to develop products in line with this frugal methodology through the case study of a hand exerciser. The desire is for these frugal equipment and devices to allow for higher quality, personalized healthcare to be administered - all the while significantly reducing the cost of doing so.

Additive manufacturing is a means to produce physical part geometry based on a digital model through the deposition of polymer material in a layer-by-layer fashion. This technology is gaining widespread acceptance as a means to mass-produce end-user products, and this context is no different. Furthermore, these products are made and sold at a fraction of the price of market alternatives thanks to additive manufacturing.

In conclusion, there exists an exiting opportunity to blend additive manufacturing with human-centered design principles for the context of Kenya.
1.2 Problem definition

Despite the progress that the Kenyan healthcare system has made, Kijenzi’s market research has uncovered that healthcare workers in Kenya are still without the adequate means to conduct effective therapy (Ben Savonen, personal communication, 15th October 2020). While there are many accepted and widely used tools available to developed nations, professionals in Kenya do not have access to suitable tools by reason of their high associated cost and the challenges involved in importing the products and distributing them into rural locations (Boaz Angienda, personal communication, 8th December 2020). The therapists resort to using whatever arbitrary materials they can source locally, including lumps of clay and commissioned objects produced by carpenters to treat and rehabilitate patients with dexterity and strength challenges.

The therapy administered to patients in occupational therapy is patient-specific, and can vary greatly in method and medium. For example, while two patients may present with the same injury or illness, the treatment will explore their lifestyle and motivations to tailor a recovery plan to suit them best (Lizanne van Paassen, 6th January 2021).

A young, active patient may be told to simply play and exercise as a therapy method for a hand injury, whereas an elderly and frail patient may be supplied with splinting, and assistive devices to overcome the same injury. Product interventions are case-specific, and creating product interventions that are meaningful, durable, and low-cost is challenging and resource-intensive (Elise Audier, personal communication, 20th January 2021). While the 3D printing solution offered by Kijenzi can be seen as an enabler of custom-fitting solutions, and a solution to the supply chain challenges in the Kenyan context (see chapter 2.1) there is a link broken in the chain that connects patients to their products (David Okia, personal communication, 7th December 2020). This link refers to the ability for healthcare professionals to translate patient requirements into the digital files necessary for 3D printing. Therapists must first possess the computer literacy, the computing infrastructure, and the awareness of 3D printing to do so.

Thus, the ultimate evaluation of the hand exerciser made in this design should ask whether:

- The needs of the patient can be met in a product intervention (desirability).
- The product intervention is commercially and practically viable for production using FDM 3D printing (viability).
- The link between 3D printing and the occupational therapists can be bridged to enable customized products (feasibility).
1.3 Assignment and project scope

This main research question for this design project asks to what extent can FDM 3D printing be applied to assist Kenyan occupational therapists in the provision of therapy to individuals with hand dexterity and strength challenges.

Kijenzi presents a unique advantage to traditional manufacturing methods and the importing of healthcare equipment by means of additive manufacturing. This graduation assignment will explore on this advantage, carried in a practical assignment of the design and development of a new low-cost, 3D-printed device. This product will support therapists in administering hand therapy to individuals with hand dexterity and strength challenges.

Within the 20 week project, the considerations of desirability, feasibility, and viability should be thoroughly considered in respect of the human centered design principles. To achieve this, the project will investigate the user, the patient journey, the context, and the technology, in primary and desktop research methods.

Client requirements:
The design should consider the following requirements as outlined by the client:

- Parametrisable/customizable design, production parameters, or feature so as to suit different users & hands.
- The device must be manufactured at less than 20USD cost.
- The device must principally be manufactured using FDM 3D printing with minimal post-processing and assembly.
- The solution should be simple and robust, with minimal moving or extraneous parts.
- The solution should minimize the 3D printing duration and associated production cost.
- The design process should consult healthcare professionals and users, incorporating their needs and feedback.
- The solution must provide treatment in line with the relevant accepted medical procedures and practices.

Desirability

The design should consider the following trifecta in accordance with human-centered principles:

When assessing desirability, the device should offer the patient a safe, enjoyable, and effective means to exercise their hands and rehabilitate from illness or injury. In consideration of viability, the design process and eventual solution should also consider the local contextual factors present, such as climate, geography and history, and the cultural preferences and practices present in Kenya. In order to create real value for the local economy and lasting impact for the population, the device should consider and fit within the abilities and expectations of both parties across its entire life cycle. It must also be sufficiently low-priced in accordance with the project requirements, so as to be profitable for Kijenzi and affordable for patients.

With respect to feasibility, the concept should also integrate Kijenzi’s research into the production of user-specific, parametrisable (customisable) devices and the development of the system to enable and support this using FDM 3D printers.

The challenge in this project is to design a product intended to ensure effective and safe treatment in line with standard healthcare practices, while also meeting the contextual and technical requirements of local production with fused deposition material (FDM) 3D printing to produce a device that can be manufactured and sold by the firm.

As detailed further in section 1.4, the project’s resolution will be an evaluation and further recommendations of the product intervention and the generated knowledge.

Figure 3: IDEO’s design thinking lens (IDEO, 2021)
1.4 Approach and methodology

This thesis is structured to bring the reader through the timeline of the project from this main research question, to final design proposal and recommendations. This topic will outline each chapter’s contribution to the document, and detail the overarching project planning methodology.

The project is projected to split into four main stages, namely research, analysis & synthesis, development, and reporting/presenting. The traditional double-diamond design process popularized by the British Design Council (2021) is serving as an overarching model on which the project is modeled.

A full description of the planning is given in appendices item 17.

Chapter 5
Pages 18 - 129

Chapter 5 of this report documents the analysis and synthesis of the research performed in chapters 2-4. Applying such methods as Vision in Product Design (VIP) (Hekkert, & van Dijk, 2016) will help to assimilate the information gathered in chapters 2-4, to reformulate a problem statement and worldview of the specific context. From this the following can be derived: a product design specification, design drivers, and design challenges relating to the domain. These will serve as the basis for the design activity in chapter 6.

Chapter 6
Pages 130 - 197

Chapter 6 documents the second diamond of the Design Council’s model, where the product intervention is developed. In this 11 week period the TRL methodology (European Space Agency, 2021) is applied to guide and direct the design activity while providing
regular opportunities to test and evaluate the design against the performance requirements synthesised in chapter 5. Six levels from ten of the TRL method are selected to ensure that the project scope can be satisfied in the time frame, while allowing for sufficient depth to each stage to satisfy the desirability, feasibility and viability criteria. Level six employs product testing in the relevant context, and was agreed as a satisfactory activity to resolve the project in discussion with the client during the project kick-off meeting.

1.5 Navigating the document

Glossary

FDM: fused deposition material
SLA: stereolithography
3DP: 3D printing
AM: additive manufacturing
ADL: activities of daily living
ViP: vision in Product Design
SME: subject matter expert
CAD: computer aided design
PSS: product, service, system
MVP: minimum viable product
CRM: customer relations management
ERP: enterprise resource program
API: application program interface
OEM: original equipment manufacture
IT: information technology
LMIC: lower-middle income country
BoP: base of the pyramid
ToP: top of the pyramid
MCP: metacarpophalangeal
CSA: cross-sectional area

Legend

Follow how the list of requirements was formulated by referencing the supporting research insight:

LoR: List of Requirements
LoRX: Section X
LoR-Y: Requirement Y
Example: LOR.2.3: List of Requirements, section 2, requirement 3.

SME Interview

Follow the aim, method and appendices item reference for a subject matter expert interview in these special pages with a brown background.
2. Frugal Innovation

How can Frugal Innovation best be applied to the Kenyan context?

The first part of chapter 2 in this project aims to gather a deep understanding of the Base of the Pyramid (BOP) (OECD, 2012) and the methodology of Frugal Innovation (Zeschky, M., et al, 2011), and explore just how Kijenzi are applying this methodology to the context of Kenya. This desktop research was conducted using online publications, by conducting interviews with SMEs, and analysing scientific and government papers. The output of this research takes the form of main takeaways, insights and conclusions that form the basis for the synthesis in chapter 5.
2.1 Base of the Pyramid and Frugal Innovation

Countries around the globe are undergoing monumental changes in their population, and the rate of this growth is only increasing every year. The Base of the Pyramid is a representation for how to classify these populations with respect to the developed world. One such method is to arrange the world’s wealth, and the power for people to purchase a basic basket of goods and services, into a pyramid structure (OECD, 2012). The world economic pyramid is divided into four tiers. The top of the pyramid (ToP) consists of 75-100 million affluent consumers, earning more than US$20,000 per annum. Tier 2 & 3 constitutes the Middle of the Pyramid (MoP) and consist of 1,500-1,700 million consumers with annual per capita income in between $1,500-20,000. MoP consists of rising middle class in developing countries and poor consumers from developed countries. Approximately four billion people live in BOP countries, in which the population’s subsistence on a minimum wage income identifies these nations as low-income markets (Pralahad, 2012). Although Africa is growing its share of the wealthy elite, including the new middle-class, the growth has not trickled to the base of the pyramid, and poverty has not decreased from the level a decade ago (Kristofer Hamel, 2021). Sub-Saharan Africa, which in 1981 counted 205 million inhabitants living in extreme poverty (less than 1.25 US-dollar per day), in 2010 counted 414 million inhabitants according to the World Bank. Conversely, the middle class in Kenya is growing rapidly (Kingombe, 2014). Calculated as those people earning more than US$2 a day and less than US$10, the size of the African middle class has increased to 310 million in the past 30 years (African Development Bank, 2011). Accompanying this educated majority is a drive in democracy, a race for employment (Cheeseman, 2015). In recent years, spending power in Kenya has increased for the majority of its population, and with it comes an increase in demand for entertainment, consumer goods and healthcare. This new demand ushers in a ground-breaking way to innovate and to produce goods differently, known as Frugal Innovation.

Frugal Innovation

To employ the design theory of Frugal Innovation that this project is centrally concerned with, it is important to gain a fundamental understanding of it. This topic will explore the methodology’s raison d’être, how it integrates to the BoP, and two lenses of the technologies with examples. Frugal Innovation is a relatively new methodology to solving problems in the developing world, and is defined by (Zeschky, M. et al, 2011) as: “a scarcity-induced or minimalist approach to innovation”, in essence: doing more with less. It is an all-encapsulating theory that seeks to explore the intersection of society, emerging technologies and the societal impact of innovation. Environments in which Frugal Innovations emerge are characterized by low and irregular incomes, limited education, inadequate infrastructure and fragmented distribution (Nari Kahle & Dubiel, 2013). Frugal Innovations are seen as low-priced, yet valuable products that can drive profits through volume and meet the needs of resource-constrained customers, by stripping out “luxury” features. Value, affordability and simplicity are prioritized to create products that can be produced for the financially marginalized. A dual model of Frugal Innovation is proposed by (Maric, Rodhain, & Barlette, 2016) who classify the term with respect to additive manufacturing in two domains. The first views Frugal Innovation in the lens of the production of low-cost 3D printers and manufacturing equipment for use in low resource settings. In this manner, innovation occurs thanks to frugal inventions. Taking the first lens into consideration, Frugal Innovation can create opportunities for developing nations in four key domains: education, infrastructure and distribution, and income and security. This bottom-up initiative can be seen as an economic enabler. The cost of importing specialist technology and tooling to establish a production facility, and the challenge of maintaining regular supply of raw materials is a significant challenge in Kenya (See chapter 2).
One such company to overcome these importation challenges is AB3D (www.ab3d.co.ke), who began locally producing printers with waste electronics material.

Karl Heinz, engineer, and founder of AB3D was interviewed to investigate the context of manufacturing in Kenya, and how 3D-printed parts, and 3D printers are consumed in this market. Furthermore, the interview looked to probe more into the aforementioned logistical challenges in Kenya. For the full interview transcript see appendices item 11.

By establishing a ground-up movement to produce and maintain low-cost 3D printers using local knowledge and waste materials, AB3D operates sustainably in the Kenyan market. This is both in terms of profit, and through ensuring continuous passing on of the required knowledge and skills to operate the printers. The indirect effects include improvements to education, with schools being a top consumer of the sold printers. Furthermore, a steady supply of goods and services can be provided to the surrounding community.

However, the ability to design in 3D and prepare parts for 3D printing was reserved for only a select few, mostly students at large universities. A critical step in the chain was broken that connected the public to 3D printing.

The 3D printing movement in Kenya grew too big for its boots, whereby the capacity and capability to produce en masse existed, however the general public were not fully aware of this capability. Without fully understanding how the technology worked, the healthcare industry would not change their procedures to incorporate it.
If a country is not adequately endowed to manufacture goods and services by means of inadequate workforce skill set, climate factors, or barriers to capital resources, the alternative means to access these goods and services is by importing them. Importing goods and services may provide a short-term solution to pressing issues such as hunger or drought, however it can come at a significantly higher price (Field Ready, 2020).

Furthermore, in the long run it does not establish the knowledge, contribute to infrastructure development, or create the wealth to produce domestically. Importing, distributing and transporting goods and services into and across a country can be challenged by bureaucratic factors including port customs, laws, and regulations (Karl Heinz, personal communication, 16th December 2020). These constant supply lines can be interrupted, and with it the steady flow of life for their users. 3D printing on-demand has the advantage of always being operational, and ready to print anything. Rather than establishing one supply line for each required part or product into a country, one supply line is organized for the 3D printing facility to supply it with 3D printer filament that is capable of producing multitudes of products. 3D printing also makes use of a digital supply chain to transfer the digital files needed to print parts, which instantly can bypass any road, port or sea straight to the 3D printer bed - meaning that the time to deliver a product is only as long as it takes to print it.

Humanitarian organisation Field Ready claims to cut costs by 50% in disaster relief settings through local-production of parts (Field Ready, 2020).
Main findings

The BoP maintains a significant global presence where equality, quality of life, and access to healthcare face challenges. Local production of goods and services with Frugal Innovations can overcome importation challenges and reap benefits for local societies and the people living in them. This project will explore the application of 3D printing to produce low-cost goods and services with a digital supply chain, to maximise product value for customers at the BoP. Value, affordability and simplicity are prioritized to create products that can be produced for the financially marginalized. Frugal Innovations strip out the “luxury” features to deliver value to their customers.

Positive changes

Currently, there are two competing narratives on Africa. One is a story of modernisation, growth and global integration (Kingombe, 2014). In Kenya, this has produced three wholly positive effects. Literacy rates in Kenya peaked to 84% in 2015 (The World Bank, 2020). Kenya’s economy grew by 5.7% in 2019 and remains one of the fastest growing in Africa (The World Bank, 2020). Thanks to improvements in healthcare and food production, the rate of stunted children stands alone in 5. This is a reduction from one in three in 2005 (The World Bank, 2020).

Challenges

The second narrative of Africa is less positive. Although Africa is growing its share of the wealthy elite, including the new middle-class, the growth has not trickled to the base of the pyramid, and poverty has not decreased. Sub-Saharan Africa, which in 1981 counted 205 million inhabitants living in extreme poverty (less than 1.25 US-dollar per day), in 2010 counted 414 million inhabitants according to the World Bank (2020). This inequality is both parts societal as it is geographic. Although Kenya is now regarded as a lower-middle income country, approximately 75% of its population are rural based and face markedly greater challenges to life. Kenyans...
living in different regions face totally different realities and lifestyles. Individuals in Nairobi have 15.2 times more access to secondary education than individuals in Turkana (Netherlands Enterprise Agency, 2016). Children in Turkana are 7 times less likely to have access to a secondary education than the average Kenyan (Kenya National Bureau of Statistics, 2013). When considering resources, urban areas have 10 times higher electricity coverage (51%) than rural areas (5%).

Agriculture is key to Kenya’s economy, contributing 26 per cent of the Gross Domestic Product (GDP) and another 27 per cent of GDP indirectly through linkages with other sectors. The sector employs more than 40% of the total population and more than 70% of Kenya’s rural people (NPR, 2020).

Poverty incidence in Kenya is amongst the lowest in East Africa and is lower than the Sub-Saharan African regional average, at 35.6% (2015/16) (The World Bank, 2020). This figure represents the number of Kenyans who are not able to afford a minimum basic needs basket of goods and services. Although this number is dropping each year, it is unlikely that poverty will be eliminated from Kenya before 2030 (The World Bank, 2020).

A clear picture of Kenya has been painted, and it is one of hope and a bright future if the statistics are to be believed. Although there are marked problems in the country that face its population arising from inequality and poverty, Kenyan people are determined, strong and optimistic. The desire to face these problems and restore the ‘Kenyan Dream’ (NPR, 2020) will require a totally new approach to innovation and working. The outlined reduced spending power in Kenya, with the shooting roots of innovation and drive for reduction in poverty has created the perfect opportunity to implement Frugal Innovation and business models capable of enabling the BoP populations to consume goods and services. Kenya is a promising proving ground for manufacturing firm Kijenzi and Frugal Innovation.
To understand how the context of Kenya impresses on the design process, an interview with Kijenzi design engineer Magdalia Campobasso was conducted. A full transcript of the interview is given in appendices item 9.

The design processes pertaining to the Frugal Innovation methodology are unique for the following reasons:

- Part performance, and the associated design embodiment considerations for 3D printing production are different to traditional manufacturing for the following reasons:
  - The environment of use in Kenya is different to western climates.
  - Low-resource settings might prioritise different product characteristics to western society.
  - The design of components to be 3D printed must consider their printability (ease of printing). Print failure results in waste of material and operator time, and must be minimised (LoR 9.4).

It can take up to 6 months for spare parts for medical equipment to be imported to Kenya. Often, the manufacturers do not keep stock of these spare parts, meaning that fixing broken equipment by conventional means is not possible.

Concurrent engineering is performed with the printer operator. The two-way communications typically concern fit, tolerance and production capacity.

The parts are then passed on to the print farm operator who prepare files for 3D printing.

3D-printed products must use non-specific spare or extraneous parts that can achieve the same purpose as others (LoR 4.1 - 4.4).

There is a different design process followed for if the part is a once-off design, or for mass-manufacturing (see chapter 2.4).
The final research topic in chapter 2 is posed with conducting an analysis of the client company Kijenzi. This hopes to explore such relevant aspects as their mission statement, their clientele, and their product offerings.

The insights gathered from this probe aim to provide strategic directions at the outset of the design project that will allow the best possible integration of the project into the company practices, and the product into the market in which Kijenzi operates.

The analysis will also hope to unearth contextual clues about Kenya and its culture which can be used to aid the project. The output of this research takes the form of main takeaways, insights and conclusions that form the basis for the synthesis in chapter 2.

This analysis was conducted through the review of online publications including the Kijenzi website, social media, and news articles. Semi-formal interviews were conducted with company SMEs to probe deeper, and to pose more specific questions pertaining to the research question.

Kijenzi is a design and manufacturing company based in Kisumu, Kenya. The east-African firm produces specialist goods in an on-demand nature for local customers.

Kijenzi is a social business, meaning that all profits are directly re-invested into the business. To date, Kijenzi has produced 3,587 discrete parts for 39 customers, and can boast to have achieved 73 unique product offerings thanks to its revolutionary approach to manufacturing (Kijenzi, 2021).

The firm offers a bespoke design and manufacturing service to the Kenyan market. Their unique solution is in creating "a network of manufacturing hubs tied together with centralized engineering" (Kijenzi, 2021)

where teams of engineers located in the United States assist engineers based in Kisumu to develop and test products for Kenyan clients. Kijenzi has responded to the symptoms of a worldwide ailment (Macioszek1, 2017) by addressing the high cost of last-mile delivery (Netherlands Enterprise Agency, 2016), and a lucrative opportunity to overcome these challenges in developing nations. The firm leverages a digital supply chain to allow for products to be designed remotely and produced locally, offering a price and time advantage to current alternatives.

The development of the Kisumu manufacturing hub hopes to pave the way for an archetypal manufacturing hub which can be rolled out globally. The manufacturing performed in Kisumu should be seen in the bigger picture as a pilot trial for such a solution, and Kijenzi have made clear their intention to scale up in the near future (Simon Lipsky, personal communication, 11th December 2020).
**Business model**

Kijenzi have two main sources of revenue, detailed in a business model canvas (appendices item 1):

- The first is by means of design consultancy for the development of products. In this method, Kijenzi sells the expertise and experience of their engineering teams to develop and realize products using local manufacturing.

- The second source of income is through the sale of parts in their product catalogue.

**Triple bottom-line**

Their benefits for the triple bottom line of people, planet and profit employ three main articulations:

1. Firstly, a key priority of Kijenzi is the production of goods in a low-cost manner, achieved through the application of local additive manufacturing. This has the effect of overcoming the costs associated with shipping, logistics, and production startup. This access to low-cost goods in a timely manner has positive benefits for local economic activity including fostering innovation and improving the quality of education.

2. Secondly, Kijenzi addresses people. Local manufacturing also requires local employment, and the 3D printing farm in Kisumu offers just that to 3 skilled engineers. The introduction of cutting-edge technology to a developing nation can boost workforce skills and competence. Likewise, the knock-on effect to local education services and universities bears potential for skills growth, training and employment opportunities for graduates and students.

3. Thirdly, AM poses benefits for the planet when compared to the process waste produced in traditional manufacturing, and the CO2 emissions generated by traditional international shipping and logistics.

These commodity parts have been developed by Kijenzi as spare or replacements for otherwise expensive or hard to source alternatives, including for example door hinges for hospital equipment and facial visors for healthcare workers (Kijenzi 2021).

Figure 4: The Kijenzi printing farm

Figure 5: Farm manager David Okia inspects a 3D print
Clientele

The most prominent of Kijenzi’s customer base involves the Kenyan primary healthcare sector. Kijenzi produces spare and custom parts for the reported 40% of healthcare equipment that is non-functioning in the developing world (Perry & Malkin, 2011). This includes for example, spare hinges for centrifuge doors, finger clamps for a pulse oximeter, and nebulizer connectors (Kijenzi, 2021). Kijenzi also produces consumable medical equipment for the rural healthcare facilities that bear a reported 23% of the equipment they require in stock (Perry & Malkin, 2011).

Corporations running the private healthcare sector and insurance providers are incorporated into the base of stakeholders. In this pool, the desire for the highest quality of healthcare is juxtaposed to the need for the most economic of healthcare equipment - and Kijenzi serves as an important mediator between the two.

The second stakeholder is the therapeutic healthcare market. Consisting of 215 physiotherapists (KSoP, 2021) and over 900 occupational therapists (KOTA, 2021), this market has seen huge growth in recent years. The increase in Kenyan disposable income (see chapter 2.2) allows for spending on non-essential healthcare has seen a surge in the demand for therapeutic tools such as writing aids, hand grippers, and shape tools. The high cost of purchasing and importing traditional tools has seen therapists turn to the more cost effective offerings of Kijenzi. As these devices are non-invasive to the human body, the certification requirements are less stringent and 3D printed tools can be widely implemented.

Design process

The life cycle of a 3D-printed product begins with an outreach activity where influential members within a hospital’s ranks will be contacted and shown just how Kijenzi can improve the situation (Elvis Ogweno, personal communication, 9th December 2020). Most often, it comes as a total surprise to these officials that the technology can be applied to fix broken equipment or produce consumable parts.

The engineer will then make contact with the biomedical engineers working there to capture their needs, and perform an analysis on the broken equipment.

Those parts most suitable for replacement by 3D printing are noted. The engineer will then take measurements to fit a replacement, and translate these into a 3D model using Fusion360 CAD software. Care will be taken to note just how the original part broke and strengthen the replacement to ensure that it is not repeated.

2.4 Main findings

In response to the research question for this chapter set out in Chapter 1: How can Frugal Innovation best be applied to the Kenyan context?

Frugal Innovation can best be applied to the Kenyan context by providing locally-manufactured, low-cost goods to the primary healthcare sector. The traditional method of importing goods for the healthcare industry has had a detrimental effect on the quality and access to healthcare in the country.

Kijenzi operates a functional, viable, and feasible means to produce and sell goods for the healthcare industry. However in order to truly meet their mission statement, the healthcare industry must develop a greater awareness of 3D printing and its capability to impact the healthcare industry. To achieve this, the gaps between 3D design, 3D production, and the healthcare workers must be bridged.

Kijenzi is developing new corporate procedures and practices that aim to integrate a more professional and effective means to operate. This includes areas such as internal communications, customer relations management, design testing, and quality control documentation. This thesis should explore this topic to allow the firm to minimize product cost, and improve their production output (Simon Lipsky, personal communication, 11th December 2020).
3.

THE HAND & THERAPY

What pathologies of the hand exist, and how is therapy performed?

This project seeks to design and embody a low-cost product for providing therapy to patients with afflictions of the hand. To understand the domain of therapy, the requirements for a device in this domain, and the operating practices of therapists, it is necessary to conduct primary research in the domain. This research for this topic makes use of SME interviews to deepen and broaden the information gained from online publications and anatomical literature. The output of this chapter takes the form of main takeaways, insights and conclusions that form the basis for the synthesis in chapter 5.
Furthermore, our hands are intimately correlated with our brains, both in the evolution of the species and in the development of the individual - to a certain degree we “think” and “feel” with our hands, and, in turn, our hands contribute to the mental processes of thought and feeling (Taylor, C. L., 2020). Sensory areas in the hand are some of the largest in the body, allowing advanced functions such as stereognosis (the ability to recognize the shape of an object simply by holding it in the hand). This tactile sensitivity of the hand is a reward from the considerable supply of sense organs in the hand surface itself. The threshold for touch in the finger tip is 2 gm. per sq. mm., as compared to 33 and 26 for the forearm and abdomen respectively (Best, C. H. 1937).

Like any modern smart mechanism or product, the functional capability includes both structural characteristics and the sensory control system. This research topic will examine both the sensory and mechanical features making up this fascinating part of the body, exploring its biological building blocks, to the executive control system of nerves that runs it, and the movements that this system allows.

Functioning hands and fingers are essential to even the most basic of ADL. Thanks to having two mirrored hands with opposable thumbs on each, the hands are capable of a vast range of motions, prehensions, and degrees of movement that allow us to interact with and manipulate the world around us.

The hand is an appendage of the human body located at the end of the arm, which consists of tissues, bones and nerves. An incredibly complex and capable part of humankind’s evolution, the hand is powerful enough to allow climbers to scale mountains, and also sufficiently precise enough to handle complex actions like writing.

3.1 Anatomy of the hand

Each hand consists of 19 bones, and there are three types of bone in each hand. The palm region includes five metacarpals, and phalanges are found in the fingers, in groups of three.

Each finger except the thumb contains one proximal phalanx, one middle phalanx, and one distal phalanx. The thumb doesn’t have a middle phalanx (Moran, 1989). Carpal bones create the wrist, with a total of 8, arranged in two rows.

Each bone is connected by a series of ligaments. Ligaments are strong, fibrous tissues that fix and bind joints in the hand. Ligaments appear as criss cross bands that attach bone to bone and help stabilize joints (Healthline, 2021), with over 100 individual ligaments helping to allow one hand to function.

Cartilage is a shiny and smooth layer intersecting two moving bones which allows two bones to move about each other without causing pain or discomfort. Cartilage is also responsible for absorbing impacts and force between bones, for example during weight-bearing activity like walking (Moran, 1989).

- Metacarpal bones
- Distal phalanges
- Proximal phalanges
- Carpal bones

Figure 6: The bones of the hand
Muscles

A network of over 34 muscles, ligaments, tendons and sheaths work in tandem to operate the hand’s movement (TeachMeAnatomy, 2021). Muscles are structures that contract and elongate under the direction of electrical impulses from the brain, applying tension forces on to tendons and bones, which allows the body to move. Within the hand, muscles can be broken into two main sub-groups: the extrinsic and the intrinsic.

Extrinsic muscles are long flexors and extensors that originate in the forearm, and are responsible for crude movement and producing a strong grip. Put simply, these muscles open and close the hand. Straddling the fingers on both the top and bottom are long flexors tendons which allow for the actual bending of the fingers (closing the hand), and two long extensor tendons which are responsible for straightening out fingers (opening the hand). These strong tendons secure muscles in the forearm to bones in the fingers. These tissues run through routing tubular structures called sheaths that surround parts of the fingers and the wrist. This anatomical feature allows for various parts of the hand to move independent of each other and complete fine motor movement of different fingers (Moran, 1989).

The intrinsic muscles are located in the hand itself, and are responsible for fine movement. Thenar muscles are a group of muscle tissues located at the base of the thumb and are responsible for movements of the thumb. The interossei muscles are located between the metacarpals, and assist in finger abduction (away from the middle finger) and adduction (towards the middle finger) (Gray, H., 2005).

Neurovascular system

The neurovascular system includes arteries, veins and nerves which are responsible for providing blood flow and sensation to the hands and fingers. Nerves are responsible for carrying signals back and forth from the brain to muscles in our body, enabling movement and sensation such as touch, pain, and hot or cold (TeachMeAnatomy, 2021). The three most important nerves in the wrist and hand are the median, ulnar and radial nerves.

The fingers have some of the densest areas of nerve endings in the body. The area in the brain devoted to controlling the hands, approximately equals the total area devoted to arms, trunk, and legs (Best, C. H. 1937). This ensures great ability for coordinated movement and for learning new activities (Taylor, C. L., 2020), and suggests why the hands are a key part of activities of daily living (ADL).
Hands have the greatest positioning capability in the body, which makes it possible to complete everything from ADL to competing in extreme sports. To understand how this is possible, this topic will explore each of the hand’s articulations from gross to fine.

In a gross sense, the hand can move in flexion, extension, abduction and adduction about the wrist. The range of radial deviation (inwards) is only 15°, whereas ulnar deviation (outwards) has a freedom of approximately 45°. This freedom is maximised when the wrist is held in the neutral position between flexion and extension. Flexion (downwards) and extension (upwards) both have a range of 85°, with the wrist in the neutral. Using muscles in the upper arm and forearm, the hand can rotate to a state of pronation (palm down), and supination (palm up) (Oatis, 2009).

Moving from the wrist to the fingers, the metacarpophalangeal (MCP) joint of each of the second to fifth fingers is a ‘ball-and-socket’ joint. The possible movements are up to 90° of flexion, and extension sometimes to 90° as well as abduction and adduction. The index finger has the greatest mobility of the hand. The rotatory movements of the fingers are not clinically important, or common in ADL (Oatis, 2009).

The interphalangeal joints (located in the mid-finger) are hinges that allow flexion without extension. In the proximal interphalangeal joints, the range of flexion is more than 90° and increases from the index to the little finger in which flexion can be 135°, which allows a ‘fist’ to be made (see figure 11) (Oatis, 2009).

The three major types of movement described by Stetson and McDill (1923) are achievable with the hand, thus allowing for a broad range of ADL activities. These movements include:

- Fixation movement: In all the basic prehension movements in figure 12, the hand assumes one position. If the object that is being prehended (held) is fixed, solid and immobile, then reaction to the flexion (holding forces) are afforded by the prehended object. If the prehended object is fragile, or the hand empty, then the position is maintained by cocontractions of the opposing muscle groups. For example: holding on to a glass.

- Slow and rapid movements: in motions or movements of the hand that range from slow to fast, which have direction control, intensity and rate. For example: scrolling on a mobile phone.

- Ballistic movements: these are rapid, repetitive motions, in which active muscular contractions begin the movement, but stop or reduce their activity throughout the later part of the motion. For example, rapidly tapping on a mouse button.

Prehension pattern is a key human characteristic, and a major differentiator between our species and animals. Humans with the ability to oppose the thumb with respect to the fingers demonstrate a wide variety of grasping movements that are normally identified by the position of the fingers and the area of contact between the fingers, thumb, and the object grasped.

Napier (2009) offers the classic description of prehensile patterns. Prehension is identified as either pinch or grasp. Pinch is a prehensile movement that involves the thumb and the distal (further) aspects...
of the index and/or middle finger (see figure 12). It is used primarily for precision and fine manipulation. In contrast, grasp typically involves all of the hand, including the digits and the palm (see figure 12).

A full grip however can be distinguished from a pinch by several factors. Grasp uses the volar (palm) area of the hand, all of the digits, and thus produces a more forceful prehension. Another characteristic of a strong grip is the position of the thumb, where it flexes over the fingers and moves towards the smallest 5th digit (Napier, 2009).

Powerful gripping/grasping actions require the efforts of most of the muscles of the wrist and hand. The extrinsic finger flexors produce Interphalangeal flexion (figure 7). The interossei and lumbrical muscles assist in flexion of the MCP joints and increase the force MCP joints (figure 7). The hypothenar muscles form the volar arch for added force, and the dedicated wrist muscles stabilize the wrist in the appropriate position (figure 7) (Oatis, 2009).

3.2 Hand therapy and pathology

This project seeks to design and embody a low-cost device to enable healthcare professionals to administer therapy to patients with afflictions of the hand. To understand the domain of therapy, the requirements for a device in this domain, and the operating practices of therapists it is necessary to conduct a study into therapy and the practices of healthcare therapists.

In the manner of acting as the individual who purchases this device from Kijenzi, and successively administers therapy to a patient by means of the patient using this device, the occupational therapists can be seen as intermediate users. In this way, the device must consider both the acute needs of a user with a disability, injury or affliction - and the needs and procedures of a therapist who works in a healthcare system both national and private.

Although the device does not have to fit the ergonomic needs of a therapist, it must consider such factors as their resources, their regulations, and their cultures as professionals.
The field of occupational therapy is a holistic healing service that assists patients to reintegrate fully into daily life after an injury or illness. Occupational therapy is any activity, mental, or physical, medically prescribed and professionally guided to aid a patient (client) in recovery from disease or injury. (Crabtree, J., 2000). Defined by Söderback (2016) “A patient of occupational therapy is diagnosed with medical conditions causing functional limitations and restrictions in activities of daily living, such as self-care, and in home, work, and leisure activities”.

There are three perspectives of occupational therapy professionals (OTs) as defined by Soderback (2016).

The first is the healer, who works directly with patients to prevent, treat, and restore bodily function and movement.

The second, the teacher is responsible for helping patients to regain control and autonomy in their day-to-day life and complete activities of daily living (ADL).

The third level regards ergonomics in the home, and assists patients in adapting the home, work, and school environments to increase bodily function and prevent injuries.

Occupational therapy seeks to employ a four-factor method to provide assistance for patients, namely, adaptive interventions, recovery activities, interventions using the teaching–learning process, and measures of health promotion and risk assessment.

For example Soderback, (2016) describes the case of a patient with a femur fracture who undergoes the post-operative rehabilitation process:

• Firstly, an anecdotal activity would be determined for this patient as an incentive to share about occupational therapy, while doing something meaningful for the patient. This activity is to make a teddy bear for the patient’s granddaughter.

• Secondly, the therapy would next employ an individualized learning process to improve the patient’s ability to ambulate (move about indoors, such as light housework tasks).

• Thirdly as an environmental adaptation, the OT can prescribe an assistive device such as a crutch.

• Finally, to promote health and recovery, a home visit aimed at preventing further accidental falls, and injuries seeks to ensure the effectiveness of this therapy. In other words, purposeful and meaningful activities are used in occupational therapy (Stein, 2000) to restore people’s functioning and to prevent disability.

ADL activities can include:

- Cooking
- Grooming
- Caring for pets
- Driving
- Writing
- Getting dressed
- Doing laundry
- Using a mobile phone
- Using a computer
- Accessing public transport
### Hand pathology

<table>
<thead>
<tr>
<th>Osteoarthritis</th>
<th>Osteoporosis</th>
<th>Bodily deconditioning</th>
<th>Stroke</th>
<th>Cerebral Palsy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common ailments of the body and hand, for which a Kenyan OT will provide therapy and support (Boaz Angienda, personal communication 8th December 2020).</td>
<td></td>
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</tr>
</tbody>
</table>

#### Description
- **Worsening degradation of the cartilage lubricating joints**
- **Reduction in bone density and strength**
- **A reduction in bodily strength and motor function**
- **Death of cells in the brain as a result of oxygen cut-off**
- **A group of disorders that affect a person's ability to move**

#### Causes
- Wear and tear on joints
- Ageing
- Overuse
- Illness
- Extended stays in hospital care facilities
- Hypertension
- Diabetes
- Cardiovascular disease
- Abnormal brain development
- Brain damage caused by illness

#### Symptoms
- Pain
- Stiffness
- Mobility reduction
- Increased risk of bone fracture
- Reduction in mobility
- Low dexterity & strength
- Low motivation
- Inability to ambulate
- Trouble speaking
- Numbness in arms & legs
- Sight issues
- Movement challenges
- Poor posture
- Sight or hearing loss

#### Direct treatment
- Cortisol injections
- Anti-inflammatories
- Joint replacement/fusion
- Medication
- Nutrition support
- Assisted exercise
- Medication
- Thrombectomy
- Medicine
- Surgical procedures

#### Therapeutic intervention
- Thermal therapy
- Light resistive training
- Stretching
- Exercise
- Physical activity
- Physical exercises
- Play
- Neuroplasticity exercises
- Physical exercise
- Bracing
- Physical therapy
- Speech therapy

#### Product intervention
- Assistive devices to reduce loading and work on joints
- Exercise balls
- Exercise equipment
- Therapy bands
- Resitive squeeze balls
- Hand exercises
- Therapy bands
- Arts and crafts materials
- Peg boards
- Coins, toys
- Gym equipment
- Braces
- Exercise equipment
- Toys and games
In the domain of hand therapy, occupational therapists will make use of a number of key devices & materials that can assist patients to develop and heal hand mobility and strength. A comprehensive study and review was performed with professional therapists, where 8 of these commonly found products were explored and evaluated.

All of these devices make use of a resistance exercise to develop muscles in the hand and forearm. The resistance force is achieved through either interaction with an elastic component, namely a metal spring or a rubber band, or by means of the elastic nature of the material. For example, the finger adductor employs an elastomer band which is stretched by the fingers against its original shape. The resistance is useful for when one tool is to be shared between multiple patients, or by one patient throughout a recovery journey (Fionnula Fahey, personal communication 30th November 2020).

What varies between all of the products is the movement that they afford, and the muscle groups that are trained as a result. Each trainer employs slightly different muscle groups, movements, and forces which constitute a different movement. Likewise, as they are a fixed size, the devices will sit differently in the hands of two users and will thus employ slightly different muscle groups, movements, and forces. OTs should be aware of this effect, and make decisions to use equipment on a case-by-case basis.
# Hand tools for strength and mobility

<table>
<thead>
<tr>
<th>Hand tools</th>
<th>Opposite band</th>
<th>Hand grip trainer</th>
<th>Finger trainer</th>
<th>Stress ball</th>
<th>Grip ring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Build: Multi-finger strength</td>
<td>Build: Hand grip strength</td>
<td>Build: Multi-finger strength</td>
<td>Build: Multi-finger strength</td>
<td>Build: Multi-finger strength</td>
</tr>
<tr>
<td></td>
<td>Increase: Force adjustment</td>
<td>Increase: force adjustment</td>
<td>Increase: Grip strength</td>
<td>Increase: Finger strength</td>
<td>Increase: Grip strength</td>
</tr>
<tr>
<td></td>
<td>Increase: Ambidextrous use</td>
<td>Increase: Comfortable rear handle</td>
<td>Increase: Durable</td>
<td>Increase: Easily cleaned</td>
<td>Increase: Durable</td>
</tr>
<tr>
<td></td>
<td>Increase: Non-slip coating</td>
<td>Increase: No choking hazard</td>
<td>Increase: Low cost</td>
<td>Increase: No choking hazard</td>
<td>Increase: Multiples needed for larger hands</td>
</tr>
<tr>
<td><strong>Exercises</strong></td>
<td>Opposite of all fingers</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole-hand squeeze</td>
</tr>
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<td></td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
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<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
<td>Whole hand grip maximum grasp repetition</td>
</tr>
<tr>
<td><strong>Steps</strong></td>
<td>Hold in hand, squeeze to full extension</td>
<td>Hold in hand, squeeze as hard as possible, repeat</td>
<td>Hold in hand, squeeze as hard as possible, repeat</td>
<td>Hold in hand, squeeze as hard as possible, repeat</td>
<td>Hold in hand, squeeze as hard as possible, repeat</td>
</tr>
<tr>
<td></td>
<td>Squeeze to max. X times</td>
<td>Slow contraction release</td>
<td>Finger opposition</td>
<td>Finger opposition</td>
<td>Finger opposition</td>
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<tr>
<td><strong>Rating</strong></td>
<td>Multiple strengths</td>
<td>Size &amp; force can be adjusted</td>
<td>Ambidextrous</td>
<td>Durable</td>
<td>Durable</td>
</tr>
<tr>
<td></td>
<td>Cleanable</td>
<td>Ambidextrous use</td>
<td>Comfortable rear handle</td>
<td>Low-cost</td>
<td>Low cost</td>
</tr>
<tr>
<td></td>
<td>Ambidextrous use</td>
<td>Non-slip coating</td>
<td>Durable</td>
<td>Easily cleaned</td>
<td>Easily cleaned</td>
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<tr>
<td></td>
<td>No choking hazard</td>
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<td>No choking hazard</td>
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<td></td>
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<tr>
<td><strong>Pros</strong></td>
<td>Picks up dirt and dust</td>
<td>With force adjustment comes a change in the size of the device</td>
<td>Force can not be adjusted</td>
<td>Slips with sweat</td>
<td>Multiples needed for larger hands</td>
</tr>
<tr>
<td></td>
<td>Slow fitting for larger hands</td>
<td>Uncomfortable rear handle</td>
<td>Plastic is slippery on single finger use</td>
<td>Force only applied with middle digits</td>
<td>Slips in sweat</td>
</tr>
<tr>
<td></td>
<td>Non-medical colour</td>
<td></td>
<td>Single fingers do not move straight &amp; controlled</td>
<td>No force identification</td>
<td>No force identification</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clicking and catching of the independent parts</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Squeaky plastic</td>
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<td></td>
<td></td>
<td></td>
<td>Choking hazard</td>
<td></td>
<td></td>
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<tr>
<td><strong>Cons</strong></td>
<td></td>
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</table>
### Details

**Elise Audier**  
Revalidation therapist at Basalt Revalidation Clinic, Netherlands

**18th January 2021**  
In-person interview

### Description

Occupational therapy is also applied in revalidation centres to assist patients in recovering from debilitating illness or hospital stays. An interview was conducted with revalidation therapist Elise Audier to assess how the body as a holistic unit is treated, which exercises are used, and how products fit into this picture.

A full transcript of the interview is given in appendices item 13.

### Findings

It is important to be able to identify the strength of a resistive exerciser, and to have various strengths available when treating patients.

The size of a patient’s hand influences how well they can use hand exercisers. Different hand sizes perform different movements.

Passive exercise devices and exercises do not constitute a purposeful or meaningful activity and are not commonly applied or prescribed in her practice.

Select OTs have experience with 3D printing, however producing patient-specific products is too time-consuming and expensive.

Children are recommended to complete activities such as crafting, making and playing in place of exercise and exercise devices.

<table>
<thead>
<tr>
<th>Details</th>
<th>Description</th>
<th>Findings</th>
</tr>
</thead>
</table>
| Increase:  
- Increase grip strength  
- Single finger strength |  
- Increase grip strength  
- Increase single finger strength |  
- To build fine and gross hand strength  
- To develop dexterity |
| - Whole hand grip maximum grasp repetition  
- Single finger squeeze |  
- Whole hand/single finger grip maximum grasp repetition  
- Single finger maximum squeeze |  
- Single finger maximum squeeze |
|  
- Squeeze as far as possible, repeat |  
- Squeeze as far as possible, repeat |  
- Squeeze as far as possible, repeat |
|  
- Comfortable to use  
- Durable  
- Use of simple spare parts |  
- Forced ergonomics suggests use cue |  
- Cost effective  
- Varied strengths  
- Patient can keep it  
- Versatile treatment |
|  
- Does not fit all hand sizes  
- Strength limited by band strength  
- Stiction in sliding parts  
- No use cue for orientation  
- Hooks are too small for larger bands |  
- Forced ergonomics doesn’t maintain at full extension  
- Resistance force is too low  
- Force depends on slicing conditions and material  
- Shear force across printing planes  
- Small contact area on build plate on coil |  
- Non-hygienic |
Based on the gathered information, a representative patient journey map was synthesised for a patient undergoing hospitalization for COVID complications, and receiving therapy for de-conditioning as a result.

COVID-19 has had a significant global impact, and at the time of writing there have been over 148,999,876 confirmed cases, and 3,140,115 deaths (WHO, 2021). The effects of this virus on the body are also a prevalent development for OTs (Boaz Angienda, personal communication 8th December 2020). It has been selected as a case-study for this patient journey map due to its relevance at the time of this thesis. Furthermore, the impact of long-COVID on a person’s health can have detrimental effect on hand mobility and strength (Elise Audier, personal communication, 20th January 2020). Patients diagnosed with long-COVID must undergo therapy to revitalise and rebuild their hands through strength and mobility training.
Kijenzi currently sells a 3D-printed hand exerciser to OTs in the Kenyan market. This device was developed with members of the Kenyan Occupational Therapy Association. Kijenzi notes that there are some shortcomings in the design of the device (Magdalia Campobasso, personal communication, 10th December 2020). An explorative study of the device, including SME consultations, and bench-top testing was performed to explore the performance of a device designed for Kenya.

‘Geen nut’

The nature of a single-movement hand exerciser such as that pictured left is ‘too simple’. Without a meaningful, purposeful, or enjoyable application the device does not align itself with the nature of occupational therapy (Elise Audier, personal communication, 20th January 2021).

Different hands, different movements

The slider has a limited range of motion (32.8mm) and does not allow a patient to create a full fist using the MCP joint. Users with smaller hands do not engage the MCP Joint. The intrinsic muscle training is important to improve hand function.

Unnatural prehension

Hand grip closure is a full rotation, yet this holds fingers flat in one place and the device inclines during use. Linear movement is not aligned with MCP movement. In the proximal interphalangeal joints, the range of flexion is more than 90° and increases to 135°, allowing a ‘fist’ to be made.

Size challenges

The interior handle of the hand gripper is too small to fit four digits in comfortably. A comparison of the product with DINED (2021) data shows the sizing challenge for both average Kenyan and Dutch bodies. Should the device aim to provide care for the most people, it need be sized appropriately.
Introduction and hypothesis

An investigation was conducted into the resistive behaviour of the currently-sold Kijenzi hand exerciser. The exerciser makes use of rubber bands to provide a resistive force. These bands are cheap and plentifully available, meaning that they could be employed as a resistive feature in the design concept.

Hypothesis 1: Not all rubber bands are the same - and different bands will bear different resistance forces.

Hypothesis 2: It is challenging to predict the increase in resistive strength arising from creating more loops in the band.

Method

Using a digital spring balance, the resistance force of rubber bands attached to the hand exerciser were measured. Three force values were recorded for each band, and the mean of the three was calculated and applied. A loop refers to the amount of times that a band is hooked and twisted on itself, to tighten the bind and increase the resistive force.

Firstly, a single band was loaded to investigate the consistency in performance/resistance between bands. In total, three bands were evaluated. Each band was tested with a single loop, a double loop, and a triple loop. The testing hypothesis posed that no two rubber bands are alike, and achieving repeatable performance with two bands is not possible.

Secondly, the force required to operate the hand exerciser using multiple bands was evaluated. The hypothesis posed that determining the resistance strength of the device could not be accurately guessed.

Results

Hypothesis 1: One band folded three times could require 7N more to use than others (+21% force) (figure 16)

Hypothesis 2: There is a variable slope in the elongation/stress curve of the elastic bands. Resistance forces in bands become progressively (stronger as they elongate (figure 17).

Conclusions

Hypothesis 1: OTs need to be aware of inconsistencies in band strength and the risk for patients.

Hypothesis 2: Users must be aware that adding more loops adds a progressively stronger resistance, and it is difficult to guess the resistance strength accordingly.

The study revealed negative aspects relating to their performance that offer concern for application in professional healthcare.
The application of 3D printing to the production of OT devices can offer both benefits and drawbacks for these tools. Traditional manufacturing of OT devices make use of injection molds, which are expensive and time-consuming to make. Changing the shape, size, or material of a product is an expensive and lengthy process. The ability for 3D printers to produce unique items means that in a production system the output can be changed with little to no extra cost or time. Applied to this project, devices that fit an individual patient's body or purposes in their lives can be enabled with 3DP.

Where high resistance forces are applied, strong supporting structures are required to ensure safe use. 3D printed components are by nature weaker than their moulded counterparts. This effect is significant in directions perpendicular to the layer orientation (see chapter 4.1). The solution to this is to employ exotic materials, and densely-filled prints which incurs a hefty price penalty. While flexible materials such as Ninjaflex TPU (thermoplastic polyurethane), Nylon-based TPU, and TPE (thermoplastic elastomer) exist in the 3DP material portfolio, none achieve the truly elastic performance of those achieved with traditional manufacturing. It is simply too difficult to force a truly elastic filament through a 3D printer’s extruder, so slightly stiffer compounds are used. The material properties exhibited in these parts are that of a semi-rigid material and do not exhibit the soft touch, elongation, or fully compressible qualities of standard OT tools.

Ultimately, the healthcare industry has to provide the highest level of care for the lowest price. Expensive, experimental, and time-consuming methods rarely see real-world adoption. Furthermore 3DP requires a very specific set of skills, knowledge, and machinery to make functional products that are more than a proof-of-concept print, and the availability of these skills and training in the healthcare industry is rare in both Kenya and the Netherlands (Karl Heinz, personal communication, 16th December 2020). Often the challenges of high cost and skills gap are inhibiting the true potential for 3DP to be applied to this OT context.
An introduction to OT in Kenya

The Kenya Occupational Therapists’ Association (KOTA) is the national professional association established in 1974, to represent the interests and concerns of occupational therapy practitioners and students and improve the quality of occupational therapy services (KOTA 2021). Currently, the organization represents over 900 individuals in the country.

Designing occupational therapy tools for the Kenyan OT sector must take into account a number of key factors of functionality, desirability, and the healthcare context.

Occupational therapists work in a fluid discipline, creating very different requirements for product functionality when compared to traditional healthcare. OT is by its nature adaptive, resourceful, and open. Likewise, the tools and devices used by the therapists embody the same characteristics. OT seeks to create an environment of therapy where activities that are meaningful, and patient-specific are used as a tool, rather than employing a tool that is used to a specific activity, movement or treatment.

A study by Spicher (2020) determined that there are three main factors of design desirability when creating new products for professional occupational therapists in Kenya:

- **Portability**
  - Allowing patients to take therapy tools home allows them to continue treatment outside of the clinics and recover faster. Transportation is expensive, and individuals have to take the time off work or school to make appointments. Portable assistive devices accelerate the quality and speed of a patient’s recovery at home.

- **Customizability**
  - Kenyan OTs are eager to work with designers to create unique and personalized treatment solutions that meet patient needs. These devices can be patient-specific, or as a commonly used tool in a clinic/office based on requirements of the OT.

- **Cost**
  - Occupational therapy departments in Kenyan hospitals do not receive as much budget as other departments with which to order supplies as it is seen as ‘less critical’. Tools made for these therapists should be low-cost, to allow them to expand the services that they can provide and improve patient care at a hospital.

Boaz Angienda
Occupational therapist at Kisumu County Hospital

Details
10th December 2020
Zoom interview

Description
Boaz Angienda is a Kenyan occupational therapist, working at the Kisumu County General Hospital. He is an informal ambassador for Kijenzi, assisting with new product development. Boaz will also act as a prominent source of information for this thesis, providing formative information on the context, the practice and serving as an extension of his patients. Boaz is also a prominent individual in the Kenyan Occupational Therapist’s Association (KOTA). This interview seeks to understand how he works with and rehabilitates patients, and which product interventions are applicable to his practice. It also seeks to understand his relationship with 3D printing and how a Frugal Innovation could best be designed for his context.

A full transcript of the interview is given in appendices item 6.

Findings
OTs in Kisumu have to order equipment from Nairobi, which is difficult and slow. Consequently, they are eager to work with designers to locally manufacture appropriate, customized products that meet their patients needs.

Boaz makes use of therapy practice activities related to normal life in order to rebuild hand mobility and strength. These activities include the use of taps, electric switches, and many other activities commonly present in our environment.

Boaz owns a range of custom-made 3D-printed tools including a hand goniometer, ADL board, peg board, fidgeting tool, number puzzles, word puzzles.

There are currently no OT tools available for children in his practice, but homemade solutions suffice.

Boaz finds visiting the printing farm a rewarding experience. Seeing 3D printing applied to other solutions in this environment allows him to in turn come up with new ideas himself.
The effect of the Coronavirus pandemic on the Kenyan healthcare system has significantly reduced the access to healthcare. Boaz has had to ask predisposed patients not to come to the hospitals, and is not permitted to visit them at home for treatment.

Patients in Kenya cannot afford the costs of transportation to a hospital for regular therapy. Boaz will provide therapy equipment to patients in certain circumstances, depending on whether it is easy to use at home, and where they are from. Instructions are provided with a request for safe-keeping of the equipment.

Hand trainers prove useful in his practice to build hand strength as a basis on which to train other functional activities. They are not useful in cases like a tendon tear, where excessive force can cause further injury. There is a difference between patients who experience bodily repairs, such as broken bones, tendon tears and those who experience strokes or traumatic brain injuries. Grip strength may not be safe for all patients.

Therapeutic products must come in varied resistance strength. Therapy will consider the type of injury, the amount of strength that is available for that particular work, (which is also in relationship with the age of the patient). For a child or elderly patient the OT will not use a higher resistance force for hand exercises.

3.4 The role of grip strength training

So far in this thesis, the term hand exerciser has been used interchangeably with such terms as ‘grip device’, ‘grip trainer’ and ‘hand trainer’, but to fully understand this concept, it is necessary to reflect on the purpose of these devices, and the purpose of building hand strength and mobility.

Hand and finger strength is important as it is required for many everyday activities such as doing up buttons and zips, climbing monkey bars or cutting up a piece of steak at mealtimes. It also helps to develop the endurance to complete activities such as writing a full page. (Rivati, et al 2017) reported that hand strength is affected by various factors, including aging, nutrition, muscle strength, mobility and overall health. Certain health conditions including rheumatoid arthritis, coronary heart disease, chronic obstructive pulmonary disease and diabetes can all affect an individual’s grip strength.

By training a grip prehension, all of the key working parts of the hands, fingers and forearms are applied. By squeezing the hand into a full fist, all MCP joints undergo full flexion, the thumb is fully flexed, and the interphalangeal joints are fully flexed. It has already been mentioned by both the orthopaedic surgeon and OT how early mobility exercise is a key factor in the recovery of a patient.

Should a resistive force be applied to this, the muscles responsible for flexing and extending the hand and fingers are strengthened. The physiological adaptations to resistance training include changes to muscle size and strength (Kraemer, Deschenes & Fleck, 1988), cardiovascular response, and release of neuroendocrine cells. In short, resistive training promotes positive bodily function.

Grip strength isn’t just important for daily tasks, it is a key biometric marker. (Leong et al., 2015) propose that grip strength can be a predictor of overall mortality. People with decreased grip...
To contribute to the established knowledge concerning hand pathology and therapy, a revalidation therapist was consulted. The consultation hoped to identify why resistance exercises were used in hand therapy, to bring to the surface how products could be applied to improve patient recovery, and what the relevant procedures are for specifying and applying these products. The therapist was asked in this session to deconstruct, analyse, and review common hand therapy devices, and how the Kijenzi 3D-printed device compared to these.

A full transcript of the interview is given in appendices item 14.

Lizanne van Paassen
Occupational therapist Direct Ergotherapie, Netherlands

6th January 2021
In-person interview

A strong grip prehension is necessary for even the most basic of ADL. Rebuilding the ability to hold, squeeze and manipulate objects after illness or injury begins first by restoring the mobility in the hand, and then building up strength.

Mobility is more important than strength. First build mobility, then strength later. A patient can have mobility without strength, but they cannot have strength without mobility.

Milestones and goals are an essential part of recovery. Having a target pertaining to strength or mobility which a patient can work towards is beneficial for therapy. Incorporating a ‘progress’ feature that demonstrates increased hand flexion or grip strength could be used for building morale and to promote habitual use.

The viability of hand exerisher devices for the purpose of building strength is questionable, as by the stage that it becomes time for their application, patients are using their hands again in ADL, which is preferred by OTs.

Every treatment is different. Even though there are two patients with the same injury, you have to look at the person and tailor treatment to suit their lifestyle and body.

strength were found to be at higher risk of all-cause death, cardiovascular-related deaths and cardiovascular disease in general.

However the key benefit of stronger muscles and greater mobility in the hand is the effect on an individual’s self-sufficient ability to navigate the challenges of life. From basic tasks such as grooming, getting dressed in the morning, and preparing a meal, to carrying shopping, opening a car door, or using a handrail.

Grip strength is not the be-all and end-all of bodily function, but it is a good place to start when improving the lives of patients and their ability to complete ADL.

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Hand grip strength

Hand rehabilitation implies that there is a progression towards a desired ability or level. To see this progression in a measurable sense is important to also consider the capability of the hand to apply force in addition to the theoretical operation of how the forces are applied.

Hand grip force is a commonly used metric with which to assess the functional performance of a hand. Grip strength isn’t just important for daily tasks. According to a study published by Leong et al. (2015), grip strength can be a predictor of overall mortality. People with decreased grip strength were found to be at higher risk of all-cause death, cardiovascular-related deaths and cardiovascular disease in general.

When measuring grip strength, the peak force applied in a whole-hand grip is measured by an instrument such as a hand dynamometer. Also known as hand dynamometry, is a relevant consideration for a hand exercise device.

A study by Rice, Leonard & Carter (1998) documents hand grip strength in healthy adults, and evaluates the premise that stronger hand grip results in a stronger pinch grip needed to open household containers.

The average maximum grip strength in this study are between 333N and 139N. According to this study, a commonly adhered to operating principle in occupational therapy clinics is that a person must exhibit 20 lb of grip strength before his or her hand is considered “functional.” This study examined the relationship between hand and finger grip performances with the forces required to open common household containers.

However, further supporting information on this claim is weak, and there must be more research into this with OTs to define a framework for strength progression and goals.

3.5 Main takeaways

In response to the question: what pathologies of the hand exist, and how is therapy performed?

The hand is an intricate and powerful appendage, constituted by bones, ligaments, muscles and tendons.

Hand strength and mobility training can assist the prevention of and recovery from illnesses such as arthritis, stroke, osteoporosis, and deconditioning.

The key benefit of stronger muscles and greater mobility in the hand is the effect on an individual’s self-sufficient ability to navigate the challenges of life.

By training a grip prehension, all of the key working parts of the hands, fingers and forearms are applied. Grasp typically involves all of the hand, including the digits and the palm. Powerful gripping/grasping actions require the efforts of most of the muscles of the wrist and hand.

Active movement in the hand post-surgery and injury is essential to stop scar-tissue build-up and the inhibition of hand function. Using high resistance forces in therapy straight after surgery or injury is dangerous, and risks re-injuring the hand.

Hand trainers are designed for building hand strength as a basis on which to train other functional activities, however passive exercise devices and exercises do not constitute a purposeful or meaningful activity and are not commonly applied or prescribed. Purposeful and meaningful activities are used in occupational therapy to restore people’s functioning and to prevent disability.

OTs in Kisumu have to order equipment from Nairobi, which is difficult and slow. Consequently, they are eager to work with designers to create appropriate, customized products that exactly meet their patients needs. Kenyan OTs prioritize portability, customizability, and low cost above all other considerations.

Patient-specific interventions are key to successful rehabilitations, and therapy programs must consider the patient’s lifestyle and body when determining a treatment plan.
This chapter explores the field of additive manufacturing - ranging from the fundamental workings of a 3D printer, to cutting-edge advances in the field. In response to the requirements and needs relating Kijenzi and the patient that were identified in chapter 2 and 3 respectively, new technology prospects are surveyed and evaluated for their application to this thesis and context. The output of this research includes main takeaways, and conclusions.

How can advances in AM be applied to this project?
4.1 Technology

Intro to AM

The paradigm of design, manufacturing, and consumption as we know it is undergoing a total revolution thanks to the development of additive manufacturing. No longer a futuristic fantasy akin to 'The Replicator' featured in Star Trek: The Next Generation (1987), current practice is seeing real world application of the technology to manufacture end-user products. This shift allows for on-demand production across a broad spectrum of industries, including for example in the production of structural aerospace components, organ replacement (Melchels et al., 2012), and in the emerging mass-personalization and bespoke manufacturing movement.

Additive manufacturing, or 3D printing, is a collective term for the production of parts through deposition of material in a layer-by-layer fashion. The technology translates a digital model of an object into a part by slicing it into multiple 2D layers and depositing successive layers of raw-material on top of each other to create a 3D object. This additive fashion contrasts it to traditional subtractive methods such as milling and sawing, where a material is removed to form it into the desired shape.

Three common methods of 3D printing are used to additively manufacture goods. These include Selective Laser Sintering (SLS), Stereolithography (SLA), and Fused Deposition Modeling (FDM, also known as FFF). FDM and SLS make use of solid material to create geometry, whereas SLA employs a laser to harden liquid resin into geometry. The solid type of printing is divided into two subcategories: extrusion, and powder bed fusion.

A brief history of FDM

The concept of 3D printing was first explored in the 1970s, with the first demonstrations in 1981 by Dr Kodama (3Dsourced, 2021). This experiment was an early proof of the polymerization of UV-light sensitive resin, and formed the basis for SLA technology we know today. This early technology was patented in 1986 by Charles Hull, and in 1988 he released the first commercial SLA 3D printer. Meanwhile in the same year, the technology of SLS manufacturing was first awarded a patent under the name of Carl Deckard at the University of Texas. The final nail was put in the coffin for equal innovation in the technology in 1992. US industry giant Stratasys registered a patent on FDM extrusion, cementing their sole right to produce the printers.
It wasn’t until 2004 that 3D printing began to gain traction around the world with the establishment of the RepRap movement. This open-source project sought to develop a self-replicating 3D printer that could be used to produce parts to make another printer, allowing makers and everyday people to use the technology. Up to this point, mass-industry was strongly deterred from selling any application of the technology due to the existing patents.

The most important year for FDM 3D printing was 2009, when the patents held by Stratasys fell into the public domain, opening the gates for the world to run wild with the technology. Thanks to low-cost players such as Makerbot and Ultimaker, the technology spread to all corners of the globe (and further). In 2014 NASA announced that their astronauts had printed a tool on the International Space Station. Distributed manufacturing was now a real force to be reckoned with. Fused deposition material saw huge diversification in applications and materials over the last 11 years, from making 3D printed houses, to living tissue, to boats (3D Sourced, 2020).

Arguably the most important development in FDM did not come from landmark one-off prints, but from the refinement of the technology to produce the basics reliably and meet the needs of the many in a low-cost and accessible manner. While manufacturers such as Ultimaker and Makerbot have shifted their attention to large-scale industry, players such as PRUSA research and Creality have entered the game of producing low-cost, reliable and functional printers that are coming close to the limits of what is achievable with FDM extrusion. Creality currently offer a €149,94 printer [Creality 2021], and PRUSA research operate a nearly 600-strong printer fleet of their €769 i3 printer in 24/7 production (PRUSA research, 2021). As these printers become smarter, more accurate and faster, companies like Kijenzi have leveraged this to enable such positive movements as Frugal Innovation to the world (see chapter 2.1).

The largest challenge for the technology in the context of Kenya still remains the challenge for the population and the healthcare industry to produce the digital models used to make the prints.
Fordism vs. Additive

To understand how 3DP claims to shift the paradigm, it is useful to know what paradigm exists in the first place. Global mass-manufacturing and consumption traditionally applies the Fordist methodology. Originating over a century ago in Henry Ford’s Detroit Ford Motor Company a new era of unprecedented manufacturing efficiency was ushered in (D’Aveni, 2021). Economies of scale were employed to produce cars so cheap that even the blue-collar workers building them could afford to purchase one. Standardization of components ensured production continuity, and that a steady supply of Model-Ts rolled off the assembly lines.

The high productivity of this system resulted in the finished goods being pushed onto the customer or dealer, regardless of their desire for the inventory. In the case of Henry Ford’s enterprise, if a dealer did not agree to take on the amount supplied, their contract with Ford would be cancelled. This overproduction causes problems associated with saturation of the market, with automobiles leading to aggressive and dishonest sales tactics - but more importantly, it causes large amounts of waste - be it unused inventory, or premature end of life for sound automobiles on the road.

The end of World War 1 in Europe saw the adoption of Fordism in Europe (De Grazia, 2005) and an acceptance of “Technical Rationality”. This rationality built the produced world that we live in today, and birthed the process of formative manufacturing (injection-molding) where expensive production systems were established to reduce cycle times to mere seconds. Through producing such a high volume of products, their costs-per-unit become low. The success of this technical rationality is undeniable, but challenges of over-production of plastics are now becoming a significant global disaster.

Additive manufacturing is remarkably different. Unlike injection molding, the cost-per-unit doesn’t change wildly if 1 unit, or 1 million units are produced. The raw-materials necessary to produce products are simpler, and require only one supply line of printing filament to feed a factory. Finally, if the production output were to change from producing hand exercisers one day to replacement centrifuge components the next, the only thing to change is the Gcode file on the SD Card. While additive manufacturing still has yet to reach the output volumes and surface quality of formative or subtractive manufacturing, this new paradigm passes the tests with flying colours for producers in the developing world.
The capability of a 3D printer

Traditionally employed in rapid-prototyping and low-volume production applications, the technology has seen a number of breakthrough improvements that have paved the way for its entrance to mid and mass-volume production to make it more cost-effective, more environmentally friendly, and more efficient than ever. With the trifecta of people, planet, and profit in mind, let’s reflect on three applications that demonstrate how FDM 3DP can prove its capability.

Field Ready - People

Field Ready is a humanitarian organization, pioneering 3DP in disaster relief. By establishing local FDM production facilities in disaster zones, they can reduce the price of essential products by up to 50% (Field Ready, 2020) when compared to ‘pushing it along’ traditional supply networks. Producing not only critical supplies and spare parts, they also put heavy emphasis on working in partnership and passing on skills to others. The body works with other initiatives, such as Refugee Open Ware and World Vision, to create innovation labs and other activities to respond to humanitarian needs and offering impact for the People aspect of this trifecta.

Refil3D - Planet

Refil3D is a Dutch material manufacturer who have pioneered the production of 3D printer filament using 100% recycled material. Shredding ABS car dashboards, PET plastic bottles, and PLA food containers, their model successfully integrates large-scale plastic recycling into a quality filament for similar cost to market competition (30euro/kg) (Refil3D, 2021). 3D printers offer the opportunity to help combat plastic waste, employing this valuable resource to produce other goods and services in a more planet-friendly way.

Kijenzi - Profit

The potential for a 3D printer to create economic activity and improve the financial prosperity of communities is also significant, and we need look no further than Kijenzi for proof of this. Local manufacturing also requires local employment, and the 3D printing farm in Kisumu offers just that to 3 skilled engineers. The introduction of cutting-edge technology to a developing nation can boost workforce skills and competence. Likewise, the knock-on effect to local education services and universities bears potential for skills growth, training and employment opportunities for graduates and students alike.

The capability of a 3D printer
The operation of a 3D printer

Extruder:
The heart of the machine, the extruder, is a moving assembly responsible for melting and extruding the plastic material. An extruder contains an extruder motor, a melt chamber, and a nozzle. A heater cartridge, a temperature sensor, and a cooling fan are responsible for maintaining temperatures, commonly around 200°C-225°C.

There are two main extruder designs found on desktop printers; bowden and direct-drive. The main difference is that bowden extruders have the extrusion motor fixed to the printer frame, while direct-drive incorporates the motor onto the moving head. On common 3D printers, the extruder can move in both X and Z axes only (PRUSA, Creality), but may also move on a gantry in the X, Y axes (Ultimaker).

The build plate:
The build plate, or bed as it is commonly referred to, is the surface onto which molten plastic will be extruded. This part can be mobile, or fixed. The print bed is heated to promote bonding of the material to the surface, and depending on the material this temperature can range from 45°C-100°C. Exotic materials such as PEI and Kapton can also be applied to promote bonding and overcome the common print failure where material detaches from the bed.

The frame:
There are a number of common frame types used in desktop 3D printers. These include Cartesian, Delta, and Polar. The role of the frame is to orient and secure the moving parts of the printer, providing a stable platform for operation of the axes at high speeds. The type employed by the Prusa i3 printers used by Kijenzi is Cartesian style.

The control system:
A 3D printer is run by a control board, which translates GCODE files into printer movements and temperatures. A control board can be either proprietary (Einsy, RAMBo) or generic (Arduino, RasPi).

A GCode file is a text file containing determined commands and coordinates which when executed in sequence print a part. For example, M106 is the command to turn on the print fan.
3D printing begins first with the creation of a digital model using computer aided design (CAD) programs, such as SolidWorks, Fusion360, or OpenSCAD. This native file must then be saved as an STL, OBJ, or 3MF file for use in a slicing program. This file type contains only surface information, with a mesh of tessellating polygons.

The file is opened in a slicing environment which translates the part’s geometry and printing settings into a tool-path file that the printer can use to extrude plastic to build up the part. In this Gcode file, such parameters as the wall thickness, the infill density, the extruder temperature and the printer speed are specified.

The file is transferred to the 3D printer, where the print is started. Pre-requirements may include inserting the correct material, preheating the build plate and extruder, and levelling the bed. The finished part is removed from the build plate, and any support material is removed.

**How is it performed**

With respect to the benefits of AM for the production of occupational therapy equipment, please see chapter 3.3 - ‘3D printing applied to OT tools’.

**Benefits of the technology**

The advantages of additive manufacturing technologies include:

- The possibility to realize geometries with almost arbitrary shape complexity, with no incurred cost penalty.
- The preprocessing efforts to manufacture products shrinks when compared to conventional manufacturing, leading to faster development cycles and reduced costs. For example, injection molds production.
- On-demand manufacturing. As soon as the 3D model of the part is created, manufacturing can begin. Should this model change, a new production run can be immediately started with minimum incurred costs.
- The manufacturing costs involved with the production of small numbers of pieces are relatively low.

**Drawbacks of the technology**

With respect to the benefits of AM for the production of occupational therapy equipment, please see chapter 3.3 - ‘3D printing applied to OT tools’.

**Support material**

Support material is used in additive manufacturing to physically support bridges, overhangs and excessive inclines that would otherwise cause detrimental effects on the printed parts’ quality or dimensional stability. Because gravity is a key factor in 3D printing, parts not attached to the print bed, or sufficiently affixed to the preceding layer must be physically connected to the bed by means of a deposited mesh.

The use of support material carries positive and negative traits. Using support material can increase the surface quality of parts, ensure tighter dimensional tolerances and can reduce the risk of print failures and nozzle collisions. Conversely, the use of support material can increase the overall cost of production through extended cycle times, increased use of material, further required processing after printing and increased wear on machinery (LoR 9.5).

The requirement for support material can be reduced in the design phases of components by ensuring that any overhangs or bridges are supported. Likewise, the orientation of the part on the print bed can ensure that the use of support material is minimized.

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**Anisotropic strength**

The layer-on-layer technique used by the majority of additive manufacturing technologies can have adverse effects on the mechanical properties of the part especially when resistance to dynamic loading is required.

For example, a simple part printed using FDM technology may be greatly resistant to a compressive force applied perpendicular to the orientation of the layers as they were printed on the bed, yet may catastrophically fail when a tensile strength is applied in the same direction. As the material is extruded at close to melting point, each layer can be assumed to be made of a solid or continuous flow. As the layer cools and the following layer of plastic is applied, both layers may not re-melt and mechanically bond, but rather the layers will adhere to each other.

This anisotropic strength can cause disbonding between layers as the constricting stresses of later layers cool, or when external forces are applied to the artefact. In many cases, 3D printed parts are not printed with a solid infill, but rather in layers of multiple perimeter lines with a 3D matrix infill. This further affects a part’s ability to resist strain in a reliable and homogeneous manner.
Surface quality

The surface quality in 3D printed artefacts varies greatly due to a number of factors, and can be assumed to be of a lesser quality than alternative manufacturing methods such as injection molding and CNC machining.

First and foremost, the height of each layer plays a key role in the visual quality of the part. It is assumed in the majority of printing technologies that the lower the layer height (higher resolution) used, the greater the surface quality of the part. This comes at the price of cycle time - where a 100% increase in resolution causes a 100% increase in printing duration.

Stratification is also seen in FDM printing, where any planar Z surface (parallel to print bed) is made by applying an infill of parallel lines. Furthermore, the surface quality of an object can be significantly affected if support material is not used (see above). These detrimental factors affect how customers perceive the product.

Surface imperfections can be hotspots for dirt build-up and bacteria growth. In some high-standard instances such as healthcare settings, these factors will make a 3D-printed product unsuitable (LoR 11.1 - 11.3).

David Okia
Kijenzi Kisumu Hub Manager, Kenya

Details
7th December 2020
Zoom interview

Description
This research topic investigates the logistical challenges involved with, and engineering skills required to operate a fleet of 3D printers at the Kijenzi farm. The day-to-day operations of a print farm are also explored.

A full transcript of the interview is given in appendices item 8.

Findings
The key ability in running a successful frugal farm lies in interfacing with clients to bring their latent needs to the surface and maximise value for them with the technology of 3DP. Healthcare customers are not currently aware of or cannot distinguish between the effect of printing parameters or materials on part performance and price. This is left to the discretion of the 3D printer operator.

Kijenzi is seeking to expand on their capability for single-material 3D printers. David would like to see multi-material, and stereolithography 3D printing make its way into the Kijenzi production portfolio with benefits for part complexity and speed.
4.2 Analysis of the Kijenzi Print farm

Strategy and goals

The goal of the Kijenzi 3D printing farm is to produce low-cost products for institutions that do the public good.

3D printers

In total, 20 FDM desktop 3D printers are employed at the farm (LoR 9.1, 10.1). Their makeup includes:

- 16 Prusa i3 Mk3s printers
- 2 Makerbot printers
- 2 Monoprice printers

Planning

The print farm is managed by individuals both on-site in Kenya, and remotely in the U.S. AirTable is an online database used to record order management and material stock, and store production information.

Raw materials

The print farm makes use of 3D printing filament as its primary raw material. This material is ordered from manufacturers including PRUSA Research, or sellers such as Amazon, and is delivered by logistics companies such as FEDEX & DHL. The filament constitutes multiple materials including PLA, PETG, TPU, and ABS, in various colours (LoR 9.2, 12.2)

The material is stored in air-tight containers on the premises and is protected from UV exposure for the following reasons (Mombasa 2021):

- Due to its proximity on the equator, Kenya experiences 2990 hours of sunlight p/a (LoR 2.1)
- Summer temperatures can reach up to 26C
- 69.0% humidity average

Quality

A self-developed program is used in conjunction with COIBO toolbox to record printer information and failure stats. With this program, preventative maintenance can be planned to ensure that printers are running at their optimum to maximise production efficiency and quality. Parts are inspected by design engineers before being packaged for shipping.

Kijenzi is striving to implement more effective, more stringent and better documented quality control with 3D printed parts.

Waste

3D printing production employs filament which is rolled onto spools. Once used, the spools constitute waste. Manufacturers do not currently offer a take-back service for these rolls, and they end up in landfill. A valuable solution would be to up-cycle these into new products.

The printer operator is responsible for performing preventative maintenance on the fleet of printers. The farm operator must also prepare the printed parts for shipping, which includes removing support material and packaging the parts.

Labour tasks

A design engineer works in conjunction with a printer operator to produce the CAD files necessary for printing. The design engineer is also responsible for interfacing with clients to translate their needs into production requirements. A printer operator is tasked with preparing the CAD components for 3D printing, and operating the printers.

Software

Fusion 360 is employed as the current CAD software. Print files (Gcode) are prepared in the Prusa Slicer software.
4.3 Emerging technologies

To satisfy the company goals identified in chapter 2, the patient requirements identified in chapter 3, and to elevate this thesis’ understanding and capability with the manufacturing method, a survey of existing and new technologies was performed.

This exploration sought to investigate such topics as the following, and evaluate their application to the project:
- Advanced printing techniques
- New printer technology
- Printing fleet management
- Innovative business models

Key opportunities and challenges facing this thesis are identified so far are summarized below. The associated user needs are extrapolated which provide the rationale for the application of the surveyed technologies.

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Challenge</th>
<th>Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTs in Kenya are eager to work with designers to create appropriate, customized products that exactly meet their patients needs.</td>
<td>There is low computer literacy and 3D skill set present in the workforce in Kenya, and the computer/software infrastructure needed to do so is low in supply.</td>
<td>The ability for customers to create custom solutions without the need for design software and associated skills, increases the accessibility of 3D printing for all, and lowers the cost of patient-specific products.</td>
</tr>
<tr>
<td>Kijenzi have outlined their desire to develop a scalable hub that can be implemented into many contexts, while still ensuring that their products can be produced for the lowest possible cost.</td>
<td>Operating a 3D printing farm is a complicated and laborious process. For each stage from order to preparation for shipping, a person is needed to complete a task which reduces output and increased costs. (Lot 9.5).</td>
<td>The benefits offered by partially digitizing the farm management could assist Kijenzi in overcoming the problems faced by rapidly expanding production systems, and produce and sell goods at a lower cost.</td>
</tr>
</tbody>
</table>

Figure 22: Kijenzi production workflow
4.3.2

Kijenzi have outlined their desire to scale operations both in terms of OEM part production and custom device design. Traditional parametric 3D modeling software is optimized for traditional subtractive manufacturing or plastic injection molding. The workflow can be clumsy and inefficient when multiple file types and software packages are combined. Developing a system to streamline and integrate the many processes required to manage a printing facility could assist Kijenzi in scaling their printer operations, while reducing the effort and cost needed to produce parts.

Devices that fit an individual patient’s body or purposes in their lives improve recoveries and assist with ADL. Recreating complex geometry and reverse engineering objects in CAD requires prolonged effort and refined skills. New data-capture technology could help to create products which fit comfortably in the hand in a quick and cost-effective manner.

Method

The research topics were divided into four distinct categories, namely: 3D printing software, 3D printing hardware, end user & customer interface, and 3D printing materials. Online publications including news articles, company websites, and corporate white-papers were consulted. For a number of potential solutions, live demonstrations or trials were observed to gain a deeper understanding. To gather a sense for how an industry 4.0 manufacturing facility is operated, an individual within Philips’ state-of-the-art lighting production facility was consulted.

An interview with Kijenzi process engineer Simon Lipsky detailed how critical it is for new technology to be field-proven in addition to being low cost for use at Kijenzi. The surveyed technologies were then plotted on a Cost vs Technology Readiness graph (see figure 23).

For application to the scope of this thesis, technologies were selected should they meet the requirements of high readiness and availability, and their low-cost.

Figure 23: Technology readiness graph
Simon Lipsky
Kijenzi process operations engineer, USA

**Details**

11th December 2020
Zoom interview

**Description**

Having established that Kijenzi is on the lookout for new technologies to bring their business forward, an interview with process operation engineer Simon Lipsky was organized. This research hoped to identify the rationale for Kijenzi identifying new and upcoming printing technologies that could be applicable, and which criteria made them a desirable and feasible opportunity in the near future. The interview also sought to create a snapshot of the current systems in place to manage their enterprise, and how new technology systems would integrate into it.

A full transcript of the interview is given in appendices item 7.

**Findings**

Kijenzi are at present researching and evaluating software solutions which will allow them to expand and grow their business. Currently, a medley of cloud databases, local documents, and software packages are intertwined to run the Kijenzi sales, business planning and manufacturing systems. Operating and populating these programs with data is a manual affair, and is directly inhibiting expansion from one manufacturing hub to multiple. An integrated and interconnected enterprise resource program (ERP) could allow Kijenzi to manage such aspects of their business as sales, CRM, manufacturing and maintenance, sales, finances, and accounting.

The high functionality of these software packages is mirrored by their high price, and at present they lie out of reach of the Kijenzi wallet. Likewise, building a tailored software solution from the ground-up requires an advanced set of skills, and carries a heavy cost. The firm needs to find not only a viable solution, but a feasibly low-priced one if they are to survive and grow.

As Kijenzi expand their product portfolio and attract new customers, they realise that FDM can’t meet all of their needs. FDM was the perfect technology with which to launch the business minimum viable product (MVP). The printing flavour offers benefits for low-startup cost, wide adaptability and ease of use, however it is not precise enough for application to the medical industry. Stereolithography (SLA) is being trialled as the next significant expansion for the firm, to overcome the shortcomings of FDM. This move is just the beginning, and in the future Kijenzi envisions to offer many different manufacturing methods.

The current strategy for Kijenzi’s is not just simply to produce goods, but also to figure out how to apply new technologies and adapt them to maximise their efficiency and integration into the business. For example, the pilot of SLA printing technology seeks to streamline the piloting process. Consequently in future the firm can procure new forefront production technologies, test and standardise them, and be the first in the market to translate this new consumer technology into products in the hands of people.

Huge strides will be made in the next decade allowing low-cost 3D printing to incorporate new materials and processes, including metal, glass and concrete. All of which exist now in research, and have existed in research for the last decade, but the technology is reserved for elitist manufacturing in the transportation and aviation industry. Kijenzi position themselves not on the first wave of technological development, but in successive, where the tech can trickle down to consumer level.

First generation iterations of multi-material, multi-extruder, and multi-tool printers exist in the consumer market, but they are escaping consideration for use in Kijenzi as the technologies are not consistent or reliable enough to enable mass-production. Should their efficacy improve, the firm may look to incorporate them.
1. Online product configuration

**Description:**
An online product configurator is a visual environment in which a customer can alter a number of characteristics of a product to build their own order. A product configurator is different from a standard webshop item due to both the quantity of factors that can be changed, with real-time visual feedback of the changes provided. The desired product can then be purchased like any normal online product. It is a low-cost, an accessible, and suitable capable method for Kenyan OTs to configure and order personalized products.

**Problem it solves:**
Customizability is a key factor of design desirability for Kenyan occupational therapists. However, this thesis research shows that one-off product interventions are priced out of the purchasing power of both Kenyan and Dutch OTs. Put simply, the price of a 3D-printed component is a combination of the time required for a designer to model and slice the component, plus the printing time and material fees incurred. Due to the design effort and time required to produce one-off parts, the price of a personalized or customized product in this nature is high, meaning that it is unsuitable for application to LMI contexts where low-cost is the key determination of product viability.

**Features:**
- Show products with all their variations and logic
- Integrate them in e-commerce platforms
- Share parametric files with partners and clients
- Send clear customer needs to a design engineer directly

**Cost:**
Online product configurators can make use of free-plugins for common package websites such as Shopify and WooCommerce. The annual cost of running a WooCommerce business store is approximately $110USD (WooCommerce, 2021).

**Readiness:**
Such software programs are in plentiful supply and see stable operation. As testament to this, WooCommerce is used by 7.4% of all websites globally (Galov, 2021). These sites are accessible and usable on mobile devices.
2. Connected production systems

Benefits:

- Reduces the time necessary for translating customer requirements into design requirements
- This system is scalable
- Patient-specific parts can be made low-cost
- The opportunity for miscommunication in customer orders is eliminated

Application to project:

A means to easily configure the product’s size and shape could be employed to allow patients to choose goods that suit personal factors such as their age, size, tastes, hand strength, and pathology.

Description:

A connected production system is a link between an online e-commerce site/product configurator and a manufacturing facility. For example, the Philips MyCreate is a production management system developed by Philips, Eindhoven, which is responsible for translating customer orders into 3D-printed products without human intervention. Mediating between online ordering application programming interface (API) and finished goods, the server system is developed to automatically process stages in the factory production system ranging from gcode creation, 3D printer operation, and stock management.

Problem it solves:

Operating a 3D printing farm is a complicated and laborious process. For each stage from order to preparation for shipping, a person is needed to complete a task. Likewise, a 3D printer will sit idle until a person unloads a finished print and starts a new print. Downtime is this regard significant. Even partially digitizing a factory operation maximises the benefits of 3D printing, allowing for production of personalized goods without the human effort needed to do so, machine downtime as a result of tool changing, and the costs incurred with operating and managing a printer farm.

Cost:

Both self-developed systems (Philips MyCreate), and OEM systems (Materialize Streamics) exist, but their high cost prices them past frugal applications. Open-source connected systems that link 3D printers to an online server are free to use. A network of four 3D printers can be fitted with a single micro-controller such as Raspberry Pi, but the cost of these computers is low (approximately 40Euro).

Readiness:

With respect to additive manufacturing, the system offers stable and supported functionality however the part slicing performance is not yet on par with Prusa Slicer. For a full comparison see chapter 8.3. AutoDesk have made their intentions to release improved versions in the near future.
3. Closed-loop CAD design & 3D printing

Description:
A new horizon of manufacturing requires a new horizon of 3D modeling, and a new way of thinking when it comes to part creation. Software companies are beginning to develop integrated design solutions for additive manufacturing where engineers and designers work in a single design environment without the need to move data from one software product to another.

Problem it solves:
Traditional parametric 3D modeling software is optimized for traditional subtractive manufacturing or plastic injection molding, and the workflow can be clumsy and inefficient when multiple file types and software packages are combined. When 3D printing a part, the part must be first 3D modeled, then saved as a readable file, opened in a slicing software, prepared for printing, saved to a removable drive and inserted into the printer or sent over WiFi, and the printer must be manually started. Furthermore, it can be difficult to use traditional CAD software to design components made with graded materials, create lattice structures or model porosity.

Cost:
Integrated modeling software such as Fusion360 is available for an annual fee of 495USD (Autodesk, 2021). This software is already in use by Kijenzi, so there is no extra cost incurred for adaptation of the method.

Readiness:
With respect to additive manufacturing, the system offers stable and supported functionality however the part slicing performance is not yet on par with Prusa Slicer. For a full comparison see chapter 8.3. AutoDesk have made their intentions to release improved versions in the near future.
4. 3D-Scanning

Description:
3D scanning is a revolutionary new technology, where a digital representation is created using an array of scanners to collect data on an object or an environment. There are many articulations of 3D scanning, including photogrammetry. By measuring a point on a surface's distance in relation to the scanner’s ‘eye’ and inputting this into a cloud mesh, a 3D picture of an object can be made.

Problem it solves:
Recreating complex geometry and reverse engineering objects has been the Achilles heel of CAD for years due to the complexity of measuring geometry accurately, and the effort and skills required to translate these into a digital model. Furthermore where organic shapes or body parts are involved, the task becomes impossible altogether. 3D scanning is a suitable solution to this.

Cost:
Desktop 3D scanners can be purchased for as low as 768€ (Matter and Form, 2021). The cost of this investment can be offset by a reduction in design engineering hours needed to recreate complex geometry.

Readiness:
Desktop 3D scanners are offered in a stable, supported and readily available supply. The technology incorporated into desktop devices is relatively new however, so care should be taken to assess the long-term effect of these new products.

Benefits
- Accurate capturing of organic forms
- Faster modeling of organic & complex forms
- Better fit and function of products for the body

Application to project:
Developing a system to streamline and integrate the many processes required to manage a printing facility could assist Kijenzi in scaling their printer operations, while reducing the effort and cost needed to produce parts. Likewise, the ease of creating parametric instances of parts for 3DP could be increased, with a significant reduction in the amount of digital file copies created for these parts and their movement between machines and software.

Benefits
- Shortened product development cycles
- Reduced cost to develop and manufacture 3D printed goods
- Increased production output
- Enhanced factory efficiency
The potential for a 3D printer to create economic activity and improve the financial prosperity of communities is significant. 3DP offers the opportunity to help combat plastic waste. Establishing local FDM production facilities in disaster zones can reduce the price of essential products by up to 50%.

The surface quality in 3D-printed products can be assumed to be of a lesser quality than alternative manufacturing methods. FDM 3D-printed parts bear anisotropic strength, and are prone to failure when a force is applied in a perpendicular direction to layer orientation.

The use of support material can increase the overall cost of production through extended cycle times, increased use of material, further required processing.

The key ability in running a successful frugal farm lies in interfacing with clients to bring their latent needs to the surface and maximise value for them with the technology.

3D printed parts

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Kijenzi’s future

As Kijenzi expand their product portfolio and attract new customers, they realise that FDM can’t meet all of their needs. Kijenzi have outlined their desire to develop a scalable hub that can be implemented into many contexts. Scaling an AM facility from one-off to mass-manufacturing is an IT infrastructure challenge rather than a hardware challenge. Operating a 3D printing farm is a complicated and laborious process, with high associated production costs.

(Partially) digitizing a factory operation maximises the benefits of 3D printing. The benefits offered by automated farm management could assist Kijenzi in overcoming the problems faced by rapidly expanding production systems, and produce and sell goods at a lower cost. Furthermore, digitization could enable the production of personalized goods without the extended human effort needed to do so.

The firm needs to find not only a viable solution to their challenges, but a feasibly low-priced one. It is critical for new technology to be field-proven in addition to being low cost for use at Kijenzi.

This project

The Key technologies for application to this project include: Online product configuration, connected production systems, closed-loop CAD, and 3D scanning.

Application to project:

3D scanning could be applied to this project to capture the form of products which fit comfortably in the hand. Traditionally, these forms are complex, and require significant CAD skill and effort. Likewise, fitting products to anthropometric data could be made more efficient and more feasible in the application of this technology.

4.4 Main Takeaways

The potential for a 3D printer to create economic activity and improve the financial prosperity of communities is significant. 3DP offers the opportunity to help combat plastic waste. Establishing local FDM production facilities in disaster zones can reduce the price of essential products by up to 50%.

The surface quality in 3D-printed products can be assumed to be of a lesser quality than alternative manufacturing methods. FDM 3D-printed parts bear anisotropic strength, and are prone to failure when a force is applied in a perpendicular direction to layer orientation.

The use of support material can increase the overall cost of production through extended cycle times, increased use of material, further required processing.

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This project

The Key technologies for application to this project include: Online product configuration, connected production systems, closed-loop CAD, and 3D scanning.
The research activity for this project has delivered rich insights and takeaways regarding the fields of occupational therapy, AM and the context of Kenya. However, this information alone is not enough to extract the core used needs, challenges to overcome, and to provide guiding directions for the redesign activity. This chapter will conduct a synthesis and analysis of the insights gathered in chapters 2-4 that form the current scenario description.
5.1 Introduction

This synthesis will employ a number of key methods, discussed in greater depth below, contributing to the creation of a program of requirements, design challenges, and design drivers. These will assist in designing for and moving towards the envisioned scenario. By evaluating the real-world performance and impact of the envisioned scenario, we can begin in answering the research question "to what extent can FDM 3D printing be applied to assist Kenyan occupational therapists in the provision of therapy to individuals with hand dexterity and strength challenges?".

Problem statement
goals can be achieved by:

Design Challenges ....................., to keep feet on the ground
Design Drivers .........................., to inspire divergent thinking
List of requirements ....................., to give structure & goals
ViP Statement .........................., to design things that matter
to help patients recover.

Current scenario

The domain of therapeutic products for the occupational therapy market in Kenya is currently experiencing several key obstacles which inhibit access to quality healthcare. Chapter 4 proposes that a hand exerciser product should consider the holistic product-service-system in which the device exists. To assess the current scenario in its totality, it is useful to address the scenarios of the main stakeholders individually. Personas are prepared below to accompany the stakeholder scenarios.

Emmanuel Chitundu
Tea distributor
Rimais, Kenya 43
Primary school

- Emmanuel is a recent graduate from the University of Nairobi, currently working as a teacher at a local primary school. He has a degree in Business Administration and is interested in entrepreneurship.
- Emmanuel finds it challenging to balance his teaching duties with his daily responsibilities. He seeks solutions to help him remain healthy and active.
- As a single parent, Emmanuel values his time with his children, and hence, he prioritizes healthy living practices.

Patient

Rebuilding hand mobility and strength after an injury or illness is essential to re-integrating into daily life, and a fundamental practice in occupational therapy. Product interventions can help improve this by allowing patients to complete a specific movement in a safe manner, and to rehabilitate on their own time without the presence of an OT, shortening rehabilitation durations.

Isolated hand exerisers are an inadequate solution for rehabilitating hand mobility and strength in an occupational therapy context, as their afforded use/exercise does not constitute a purposeful or meaningful activity. Furthermore, these general-issue products are not created to meet the specific needs of a patient undergoing a rehabilitation journey. Regular, safe or satisfied usage of these devices as prescribed by therapists is not guaranteed.
The therapy administered to patients in occupational therapy is patient-specific, and can vary greatly in method and medium. Product interventions are case-specific, and creating product interventions that are meaningful, durable, and low-cost is challenging and resource-intensive. OTs in Kisumu have to order equipment from Nairobi, which is difficult and slow. Consequently, they are eager to work with designers to create appropriate, customized products that exactly meet their patients’ needs. 3D printing can enable Kenyan OTs to produce product interventions that are patient specific and ADL focused - however the ability for OTs to meet these outcomes is hindered by scarce 3D design ability and capability. Furthermore, the potential and capability of 3D printing to achieve these needs is promoted amongst Kenyan OTs to achieve market penetration.

Currently, design engineers communicate with customers to accept and handle orders via email or telephone. The design engineer may make a visit to the customer in person to capture measurements and design requirements. Customer requests are translated into 3D models either through the creation of an entirely new product, or through alteration to an existing archetype. The 3D files are then passed between design software programs, and transferred manually to the printers for printing. The farm operator is required to manually transcribe and record printer information and manage these statistics into usable insights. Operating a 3D printing farm is a complicated and laborious process. For each stage from order to preparation for shipping, a person is needed to complete a task. This drives up production costs.
5.2 Envisioned scenario

This redesign project hopes to enable the following outcomes for each of the stakeholders so as to improve the context of 3D printing for Frugal Innovation in Kenya.

Patient

First and foremost, patients can exercise and strengthen their hand through a "meaningful" activity of daily living or task instead of through isolated exercise.

Secondly through the use of a hand exerciser, I want patients to see themselves as powerful instead of broken and needing to be fixed. This can be enacted by differentiating between making and doing, and making do. By enabling new opportunities and possibilities in making and doing, patients can be reminded of their potential, instead of focusing on their disability (please see chapter 5.4 ViP for more on this goal).

Finally, this hand exerciser should embody emotional intelligence in the product and its use case, knowing that therapy settings can be emotionally loaded environments. The concept should view the use of the product in the context of a recovery journey rather than in an isolated use case.
**Practitioner**

In this envisioned scenario, Kijenzi’s power to provide personalized product solutions is linked to occupational therapists, empowering them to provide higher quality therapy to their patients. The recognition and understanding of the capability of 3D printing amongst Kenyan OTs is present, and procuring custom solutions is accessible, simple and low-cost.

**Producer**

Kijenzi can overcome the problems faced by rapidly expanding production systems, scaling their business to meet the increased demand of their new therapist customers. In this scenario, their low-cost offerings, and high-quality standards are upheld. Likewise, by reducing the human activity and steps involved in the production process, Kijenzi can increase their output, and produce and sell goods at a lower cost.
5.3 List of Requirements

To give the redesign activity scope, guidance, and a means of evaluation, a List of Requirements (LoR) is prepared. This table outlines the requirements for the performance of the concept and its effect without specifying how that effect will look or exist. For each requirement, a supporting rationale is provided, and a reference to the chapter of the thesis where the rationale originates and is discussed in further detail.

A selection of 13 key requirements are provided here. For the full LoR, please see the appendices item 16.

The LoR will be employed as a steering force throughout the development part of the thesis. In the concept evaluation performed during TRL #3, the LoR will be consulted to assist in selecting the most suitable concept. In the final evaluation of TRL #6, the LoR will form the basis of the testing sessions and attempt to satisfy the evaluations in as much as possible.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Production</th>
<th>Ergonomics</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The device should allow a minimum ceiling of 88.97N of resistive force.</td>
<td>• The device should be produced for less than 20,000 USD (16,49 Euro, 2,203,00 Kenyan Shilling).</td>
<td>• The device should allow the fingers digits to flex in various degrees, increasing from the index finger to the pinky finger.</td>
<td>• The device should withstand temperatures of 80°C with no structural deterioration or change in appearance.</td>
</tr>
<tr>
<td>• The device should allow the user to form a fist against a resistive force, employing the hand’s extensors and flexors to flex the fingers, the intrinsic muscles to contract the fingers at the MCP joint, and the Flexor pollicis brevis muscle to flex the thumb.</td>
<td>• The device must consider print failure in its embodiment to protect the printing machinery from crashes, and ensure production continuity.</td>
<td>• The device should include a cognitive ergonomic affordance to suggest the correct use orientation.</td>
<td>• The device must withstand UV degradation and colouring.</td>
</tr>
<tr>
<td>• The device should achieve grip strength training through a “meaningful” activity of daily living.</td>
<td>• The device or its components should not exceed a volume of 250mm x 210mm x 210mm.</td>
<td>• The device should consider the anthropometry of the target users and the design/manufacturing method should allow personalization of the device fit these people.</td>
<td>• The device should be packaged to ensure safe transport from the production facility to the health centre or patient’s home, considering the environment (high heat, humidity, dust) and rough transport.</td>
</tr>
</tbody>
</table>
5.4 Design Drivers

Assisting the development process in addition to the LoR are design drivers. A problem such as those posed in the context of this thesis can also be reformulated as an opportunity for a solution, or ‘driver’. The goal of a driver is to inspire more divergent thinking in the hope of landing on something truly innovative, unique, or novel.

As Kijenzi are expanding, they realize that FDM cannot meet all of their needs. Likewise, their current processes are too manual to operate multiple hubs. Emerging technologies and software solutions could hold the key to elevating Kijenzi into a market leader.

5.5 Design Challenges

Analysis of the context of Kenya, hand therapy, and additive manufacturing highlighted three key challenges which must be addressed.

01

Look to the future, but make with the now

As Kijenzi are expanding, they realize that FDM cannot meet all of their needs. Likewise, their current processes are too manual to operate multiple hubs. Emerging technologies and software solutions could hold the key to elevating Kijenzi into a market leader. See TechMap for more information.

02

Challenge COVID-19

In 2020, the COVID-19 pandemic stopped the world in its tracks. While there is widespread optimism for Europe’s return to normality, the effects of the virus will linger in Kenya for a long time. New protocols for tele-health and equipment issuance are helping to combat disease transmission in hospitals.

Totally new solutions are required to help OTs treat the emergence long-Covid that affects 10% of patients.

03

Made for me.

There is no golden standard for therapy, and interventions must be patient-specific and based on their individual context and needs. Fitting a one-size-fits-all solution into this adaptive and personalized service is doomed to fail.

Instead, product solutions should empathize with the user, fitting into their personal rehabilitation journey.

01

Deciphering the true value of 3D printing for Kenyan OTs

Designing this solution for the best interests of key stakeholders does not guarantee that it will be accepted or appreciated. There is a significant investment and change in the status quo, procedures, by changing to 3D printing - not just by OTs, but by hospital coordinators too.

Bringing the key value of the solution for the stakeholders to the forefront must unearth answers to such questions as how do you create the want/need for OTs to implement, use and upkeep 3D printing in their workflow?

02

Overcoming the 3D skills gap

The buck for designing and realizing custom solutions does not stop with Kijenzi. For an OT even to embrace the mindset that products can be tailored and manufactured to fit patients requires the ability to think in 3D. There is a significant hurdle to overcome when designing in 3D for Kenyan OTs. Solutions that enable product personalization must consider this limitation and offer a simple and accessible alternative.

03

Performance limitations of 3D-printed parts

FDM 3D-printed parts are susceptible to a range of performance-inhibiting characteristics, including for example layer adhesion and extrusion inconsistency. Awareness of these factors is key during embodiment stages to minimizing and overcoming their effects. Likewise, the performance of a part with respect to the printing process must be considered to ensure efficient manufacturing processes.
5.6 Vision in Product Design

Vision in Product design is a design methodology created by Paul Hekkert & Paul van Dijk (2016) at TU Delft. The tool forces you to examine the ideas underlying your design in great detail, before coming to a manifestation: What exactly is it that you want people to understand, experience or do? (TU Delft, 2021).

This thesis applies the methodology for two purposes. The VIP exercise applied in this thesis will see only the preparation phase of the methodology applied for the analysis and synthesis chapter. The design phase will not apply stages 5-8 as it conflicts with the TRL methodology scope and planning. In order to ensure that this thesis can be tested in the environment of use, the TRL design process will be followed.

The COVID-19 pandemic had a significant impact on this thesis, inhibiting a field study from taking place, limiting access to the healthcare sector, and forbidding in-person user research and evaluation from taking place. As such, extra care was taken to ensure that the patient’s perspective and experience could be sufficiently explored despite the challenges. VIP is a suitable method to collect, reflect on, and formulate insights regarding the patient experience and journey. It is hoped that this extra attention and reflection can result in a meaningful and suitable product for these patients.

Products that fundamentally change the way people interact with products can only emerge if the designer wants to change the meaning of a product-user-relationship (Hekkert & van Dijk, 2016). To explore if this thesis can have impacts that lie past only improving the patient’s recovery or incrementally improving the MK1 hand exerciser, it is necessary to see the recovery in a greater context through the lens offered by VIP.

To design for a future context or outcome, it is necessary to set the bar for the world at present. In total, 120 factors were employed for this analysis, and can be seen as building blocks of the current scenario which underlies the design.

Making do is trying to fit square pegs into round holes. No two patients are the same, and giving them the same hand exerciser will not improve patient recovery. Embracing our uniqueness and identities in rehabilitation is the key to seeing yourself as powerful, instead of needing to be fixed because the doctor says so.

Statement

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Statement

I want patients to see themselves as powerful instead of broken and needing to be fixed by enabling new opportunities and possibilities in making and doing.
**Worldview:**
Making do is trying to fit square pegs into round holes. Embracing our uniqueness and identities is the key to seeing yourself as powerful, instead of needing to be fixed because the doctor says so.

**Statement**
I want patients to see themselves as powerful instead of broken and needing to be fixed by enabling new opportunities and possibilities in making and doing.
5.7 Techmap

To visualise the conclusions from the research in chapters 2-4, the surveyed technologies were plotted on a TechMap. A techmap is a structured, visual representation of a strategy - in this case for translating user needs into a product. The TechMap illustrates the technologies involved in a product's launch, and the market into which to launch the product.

In this visual, the next 5 years of the hand exerciser product line are considered, detailing the synthesised user needs, forecast markets for Kijenzi, and forefront technologies that can play a part in helping satisfy these. The Techmap demonstrates four clear product generations, from the currently sold hand exerciser (MK0) to the third (MK3) device. Technologies that were deemed too expensive, or not yet field-proven were assigned to later generations so that the technology has time to mature. Technologies that could help to meet the needs outlined in Chapter 2 & 3, which were sufficiently low-cost and field proven were applied for consideration for this thesis concept (MK1).
5.8 Goals

While meeting the criteria for a low-cost, 3D-printed device that meets contextual factors, the goals of this design activity are:

01. To link Kijenzi’s power to provide personalized product solutions to OTs, empowering them to provide higher quality healthcare by meeting the varying needs of their patients.

02. To achieve hand mobility and strength therapy through meaningful and purposeful activities.

03. To embody emotional intelligence, and consider the personal values of a user throughout a difficult rehabilitation journey.

04. To further the recognition and understanding of the capability of 3D printing amongst Kenyan OTs.
As yet, this thesis has sought to outline the problems and dilemmas facing this context. It has also unearthed the clues that might help to challenge or overcome them, and posed how to assess if the solutions have succeeded. This chapter documents how these clues have been systematically applied in a design process to create the concept detailed in chapter 7.
6.1 The TRL methodology

To realize a hand exerciser concept which could be evaluated to answer the research question, the Technology Readiness Level (TRL) methodology (Tzinis, 2021) was employed.

This methodology is an assessment tool to measure the maturity of a technology or product. The TRL outlines gated stages with which to progress through the development cycle of a product, from first ideas to market launch. In total, there are 9 stages, where 9 is the highest, and 1 is the lowest. While the TRL does not specify which design tools or methods to apply, it does offer a means to plan, to document, and to evaluate if the outcome of these tools and methods have created a successful product.

At the beginning of each TRL stage, a goals establishment session was performed. In this activity, the end goal for each stage was broken down into more achievable steps and tasks. A testing plan was determined, and evaluation criteria were detailed. Where possible, user evaluations were applied to test the product. At key stages throughout the design process, SMEs were consulted to validate or demonstrate the PSS.

For example, to achieve the TRL level 3 of “experimental proof of concept of critical function(s) and/or characteristic(s),” the desired goals were specified. At the end of this phase, the product concept must take one central form using durable materials to be able to perform testing with. The purposeful and meaningful activity should also be incorporated and considered through the patient’s recovery. The device should be comfortable, and also start to explore hand sizes and comfort, and chart the design space for an exerciser.

During the TRL #3 evaluation, the product could be assessed as to whether it met these criteria in a studio-setting. Because the selected concept did meet these, TRL #3 was awarded. Now, the project could progress to begin achieving TRL #4.

6.2 TRL Scope

During TRL #1, attention was given to identify the potential ‘tracks’ that subdivided the scope of the development process along the TRL methodology, and determine the extent of the TRL development. These tracks included: product, design process, and service system, and were derived from grouping the applicable technologies from chapter 5.

As each facet of the solution scope maintains its own identity and target users, independent evaluations of each are necessary to uphold legitimacy and clarity in the TRL process.

Next, the desired level of completion for each TRL track was then determined. At the outset of the development cycle, a target of TRL #6 was chosen for each. This means that all constituent parts of the design solution could be demonstrated in the context of Kenya.
The rationale for selecting this level includes:

1. A product demonstrated in the target context, with the target users, and the target technologies is a suitable means to complete an evaluation on the main research question of this thesis.

2. Kijenzi’s proven digital supply chain, their helpful staff, and online communications could serve as the medium to coordinate this validation, despite the lack of a field study.

3. Without knowing the specific functionality of the product, service or system, it was difficult to predict challenges that would inhibit a level #6 validation.

As the project progressed, the TRL target was adjusted based on how the determined solutions could be realised given time and budget constraints, and practical reasons. For example, to progress from a level #4 TRL validation for the online customization system, over 300 Euro would have to be invested to allow for the system to be accessed in Kenya. Budget for this did not exist, and so a higher TRL validation level was not deemed necessary for this thesis. The final TRL resolution is as follows:

![Figure 25: The TRL goals for each project sub-division](image)
TRL #1

**ESA Definition**

TRL definition: Potential applications are identified (e.g. by context analysis, literature research) and ideas generated following basic observations but concept not yet formulated (ESA, 2021).

**Goals**

This stage served as an opportunity to assimilate and reflect on how to translate the chapter 5 conclusions into a design, and to plan the development stages for the future weeks. The ESA’s defined criteria for TRL #1 incorporates the research and synthesis from chapters 2-5 of this thesis, and so a less stringent application of the stage was completed.

**Method**

Each TRL track was then subdivided once more to give more structure to the development and validation cycles (See figure 25). The very basic working principles of a hand exerciser were identified to be form, fit, and function from analysis of other products (see chapter 3), and were applied once more to this design challenge. The identified applicable technologies in chapter 4 were then included in this subdivision, and a survey was performed to identify providers of the technologies.

**Survey**

<table>
<thead>
<tr>
<th>Type</th>
<th>Provider</th>
<th>Link</th>
</tr>
</thead>
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<tr>
<td>Online Product configuration</td>
<td>Twikit</td>
<td><a href="http://www.twikit.com">www.twikit.com</a></td>
</tr>
<tr>
<td></td>
<td>ShapeDiver</td>
<td><a href="http://www.shapediver.com">www.shapediver.com</a></td>
</tr>
<tr>
<td>Connected production system</td>
<td>PrusaConnect (unreleased)</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>OctoFarm</td>
<td><a href="http://https://octofarm.net/">https://octofarm.net/</a></td>
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<tr>
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<td>Solidworks</td>
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</tr>
<tr>
<td>3D Scanning</td>
<td>Matter and Form</td>
<td><a href="http://https://matterandform.net/">https://matterandform.net/</a></td>
</tr>
</tbody>
</table>
Goals

This TRL activity looked to generate a large range of ideas for achieving hand exercise in a meaningful and purposeful way. The stage also set out to have a minimum of three unique concepts with articulate prototypes to explore their functionality.

Freehand sketching

This idea generation technique was used to create and visualise ideas for the embodiment and interaction with a hand exerciser. The sketches are shown overleaf.

To stimulate thought and idea generation, four questions were posed to guide the idea generation:

- Which meaningful activities can be used to exercise a patient’s hand?
- How can play be used to allow a patient to exercise their hand?
- What can be achieved with the various grip prehensions?
- Can a common mundane task be used to exercise a hand?

Morphological ideation

In an effort to create ideas faster and overcome the time-consuming nature of design sketching, a morphological exercise was conducted. This activity paired random hand prehension images with a common ADL task or product. The exercise then looked to envision a product link between the two images.

The ideas and sketches were reviewed and assessed. A simple evaluation criteria was formulated (see page 150) from the list of requirements and listed 7 key product consideration. Concepts which met more than four of these criteria were selected for further development in TRL #3. In total, 9 concepts were selected to advance to TRL #3. These concepts are annotated on the pictured sketching pages.

Validation

Without a prototype or working model of an idea to test, the full LoR could not be evaluated against the idea. Thus, it was deemed allowable to use a simplified version of the LoR, bearing requirements that could be tested.

ESA Definition

Exploration and formulation of potential applications and preliminary concept. ESA, 2021.)
Which meaningful activities can be used to exercise a patient’s hand?
How can play be used to allow a patient to exercise their hand?
What can be achieved with the various grip prehensions?
Can a common mundane task be used to exercise a hand?
Activity richness

The device should achieve grip strength training through a "meaningful" activity of daily living. The device should incorporate a means to identify and improve progress by means of degree of mobility or resistive strength.

Grip function

The device should allow the user to form a fist against a resistive force, in a manner that employs the hand's extensors and flexors. The user should also be able to flex the fingers, the intrinsic muscles to contract the fingers at the MCP joint, and the Flexor pollicis brevis to flex the thumb.

Durability

Does the product contain any loose or protruding parts which can be lost or damaged during transport? Can the device withstand vibration and impacts arising from driving on uneven road surfaces? Should allow a minimum of 89N of resistance.

Simplicity

The device should be easily repairable with basic skills and mechanical knowledge. Use of the device should be simple, with minimum risk of user error. The device should not employ complicated assemblies or mechanisms.

Use of AM

The device should prioritize the use of FDM 3D printing as a production method. The device should allow for the customer to easily select/configure design characteristics without the need for advanced 3D design software or CAD skills.

Productivity

The device must consider print failure in its embodiment to protect the printing machinery from crashes, and ensure production continuity. The cost to print (volume) should be as low as possible to improve the economic viability of the device.

Other costs

The device should be produced for less than 20,00 USD (16.49 Euro, 2,203.00 Kenyan Shilling).

Software provider selection

Fusion360 (F360) was chosen as the design software to develop the integrated method with the following reasons:

- The software was already in use by Kijenzi employees, and there was no extra cost incurred for its adoption.
- F360 has a dedicated 3D print preparation workspace.
- The software allows the use of plugin components to enhance functionality.

Integrated approach

Online customizer

Two online customiser softwares were trialled in this stage, namely Twikit, and a WooCommerce plugin.

Twikit, although highly refined and functional was expensive, and priced past the frugal nature of this project. Likewise, it required technical knowledge to operate and thus does not suit this context.

The WooCommerce plugin was chosen, as it is free and open source. Kijenzi already make use of a WordPress website, onto which WooCommerce can be connected. Thus, the option is a simple to use, and low-cost solution.
**TRL #3**

**ESA Definition**

Element concept is elaborated and expected performance is demonstrated through a feasibility test, providing a proof of concept (ESA, 2021).

**Goals**

TRL #3 desired first to bring the sketch concepts forward into low-fidelity prototypes which demonstrated the concept’s working principle.

The stage next sought to take the sketch ideas from TRL #2, and build prototypes representing them. A thorough evaluation of the prototypes was performed in order to select the most suitable concept.

Subsequently the selected product concept was refined to reflect one central form using ‘durable’ materials (E.G. could demonstrate the functionality in repeated bench-top trials).

The purposeful and meaningful activity embodied in the concept was also considered in the context of a patient’s recovery.

**Rapid prototyping**

Quick, low-fidelity models of the 5 concepts were made to explore the idea’s functionality, and to simulate the interaction. The prototypes were also a means to inspire further idea generation and vessels with which to simulate discussion with others.
To evaluate the performance of the concepts, and to select the most promising for further exploration, a first evaluation was performed. In this evaluation, a simplified LoR matrix (see page 150) was employed, yet this time the concepts were awarded a rank out of 8, and a weighted score was given to each rank.

The weighted scoring system was representative of the relative importance of each of the simplified LoR criteria. This importance was extracted from the project goals, challenges and drivers in chapter 5. The scores for each concept were tallied, and concept #3 was deemed the most promising in this evaluation.

Based on the promising results from evaluation #1, three further concepts were envisioned and prototyped.

Concept 6 employed a series of orifices into which objects could be held. Squeezing against the resistance force would allow for objects to be inserted, thus allowing the user to manipulate such items as a pen, bottle, or tool.

Concept 7 looked to achieve hand strength and mobility training through a simple, enjoyable activity. A rubber-band shooting mechanism was integrated, whereby squeezing the device would loose a band.

Concept 8 featured a moving window, and squeezing the device would reveal an obscured surface or orifice. Inserting an image or coins here could be an interesting exercise for children.

When the prototyping activity had concluded, two concept presentations and reviews were performed with the Kijenzi employees, and then with a Kenyan OT. This review sought to evaluate the early concepts with respect to contextual suitability, clinical viability, and manufacturing feasibility.

Two sessions were performed using online video calls and a presentation of photos, sketch illustrations and diagrams were shown. Here, the concepts and the interaction could be demonstrated and discussed. The participants were asked to provide feedback on the concepts, and then to rank the concepts in order of their determination of the most successful.

Interestingly, the answers from both parties were totally juxtaposed. The OT saw the value in the larger devices (concept 2, 7, 8) and expressed interest in trying them with his patients. The Kijenzi staff however voiced their concern for the difficulty in printing such a large object, and favoured concepts 1, 5, and 7.

The most valuable piece of feedback was on the weighted evaluation criteria. The Kijenzi staff were conflicted, wanting to nominate two opposing concepts as their favourite in two different perspectives - namely the perspective of the user, and the perspective of the producer. Because both parties bear such strongly different values, it is challenging to decide the most suitable concept. It is unlikely for example that a patient would care if the part is going to fail on a print bed.
A final TRL #3 evaluation was performed to assess and select the most suitable concept. In this evaluation, three methods were used to critique and score the concepts. An initial cost analysis was also performed to assist in this evaluation.

In a weighted decision matrix, concept 1 prevails as the most suitable when considering both the user, and the manufacturer in different lenses.

In this study, the concepts were evaluated from the lens of the user, and the lens of the manufacturer under a group of 6 criteria. Both perspectives could be independently assessed to create a more in-depth evaluation. As of yet, both were assumed to be of equal importance. Each criteria was given a different weight of importance, based on the perspective taken.

These criteria included for example simplicity which scored each concept based on the number of parts it has, external components required, the moving mechanisms, and the ease of use. These scores were then multiplied by the relevant weight, and the winner could be determined.

<table>
<thead>
<tr>
<th>RANKED</th>
<th>Activity richness</th>
<th>Grip function</th>
<th>Durability</th>
<th>Simplicity</th>
<th>Use of AM</th>
<th>Productivity</th>
<th>Total</th>
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<tr>
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<tr>
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<td>3</td>
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<td>227.5</td>
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<td>3.25</td>
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<td>3</td>
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<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>88</td>
</tr>
</tbody>
</table>

Figure 26. A) Manufacturer perspective - weighted decision matrix evaluation

Figure 27. B) User perspective - weighted decision matrix evaluation
Participants from the client company, and the Kenyan OT were asked to rank their top three most desirable concepts. The question posed was to which they deemed the most viable and successful product. A regular decision matrix was calculated by counting the votes. Achieving a rank of first awarded three points. The second rank was awarded two points, and the third rank was awarded one point. In first place was concept 7, followed by concept 8, and finally concept 6.

As a follow up exercise, the participants were asked to provide a qualification and explanation for their choice.

The final evaluation determined that Concept 1 is the most suitable concept when assessed against the key design characteristics of desirability identified for Kenyan OTs. In a study completed by a Kijenzi employee, the key characteristics prioritized by OTs operating in Kisumu county were portability, customizability, and cost.

Concepts that met the low cost of less than 10USD were awarded 3 points. 2 points were awarded for concepts priced between 10USD and 20USD. 1 point was awarded for concepts priced between 20USD and 30USD. Concepts were awarded points for the criteria of customizability and portability respectively based on a subjective assessment of their relative viability or ease.
The final adjusted tally/score determined concept 1 to be the leader in each evaluation. A scoring system was implemented where the concepts were awarded points based on their position in each study, with first place receiving 8 points, and last place receiving 1 point. The scores the previously detailed numeric evaluations A-D were tallied.

Concept 1 was then evaluated against the LoR. Based on the current prototype, all bar four requirements were met, or partially met. Four requirements stood out as requiring further investigation, and were earmarked for further investigation in TRL #4.

These include:

- The device must be structurally stable to afford a maximum resistance strength of X Newtons.
- The device should allow a minimum ceiling of 88.97N of resistive force.
- The device should allow a user to make as close to a full fist as possible during gripping prehension.
- The device should afford 25,550 use cycles (50 daily cycles).
Using Kijenzi’s own pricing structure spreadsheet (confidential), the cost to produce, and associated sales price were calculated for the 8 concepts. At the outset of project, the production price for the concept was determined by the client to be 20USD. A successful concept is then one that excels in the evaluations 1-3, and can be produced to meet this price.

Two of the concepts at present are priced below the 20USD target outlined in the project requirements, based on the associated 3D print duration and material cost.

Concept one is thus determined to be both a functionally suitable concept from evaluation methods A-D, and viable in an economic sense. The concept will be selected for further exploration in development in TRL stage #4, pending validation with a SME in the relevant field.

Cost evaluation

Concept vs. cost

USD

0 10 20 30 40 50 60 70

Scissor grip Maze Rotation grip Ball game Grip reader Manipulator Rubber band gun Hidden Surprise

Concept
**TRL #4**

**Goals**

TRL #4 aimed to take the fundamental idea of ‘a hand exerciser with meaning’ (concept #1), and elevate this to a lab-validated concept. The stage would see both explorative development and design refinement to bring the concept to a point at which one defined form/functionality/interaction exists. This form and functionality development considers the sizing and resistance force factors. A consultation with an occupational therapist is specified as the manner of validating the concept and user interaction. Benchtop material testing is used to determine a suitable material for the 3D printing production method.

**ESA Definition**

Component and/or breadboard functional verification in laboratory environment (ESA, 2021).

**Idea generation**

To begin, the concept of a ‘meaningful exerciser’ achieved with an attachable spring was further explored. A range of common hand tools and meaningful activities were observed, and a ‘spring’ object was designed to create the resistance for these tools and activities.

**Concept validation**

The conclusions and validations from this discussion included:

- Most of the prepared prototypes were too dependant on use with one specific tool, and interchangeability was poor. Concept #1 however lent itself to the most variety of tools brought for testing.
- Furthermore it was discovered that the band could also be used on its own without an accompanying tool, as a means to exercise single fingers or a whole hand grip in early rehab stages.

The most promising of these concepts were brought to life with rapid prototyping. The idea generation sketching for this activity is included overleaf.
This 3D-printed TPU band employs flexible material to provide a springy resistance force. This device can be attached to a hand-tool, like scissors or pliers. The concept makes squeezing the tool require more force by doing so, an activity where these tools are employed becomes an opportunity to exercise hands. These activities can be derived from meaningful purposes to meet LoR 1.3.

For these reasons, the principle of concept #1 was selected.

**Concept #1**

This 3D-printed TPU band was non-invasive on the function of the hand, or the operation of the tool during use. As a result, a natural gripping prehension could be formed, enabling the desired biomechanical movements (LoR 1.4).

Establishing size requirements

The LoR established in chapter 5 outline that hand strength and mobility training should be carried out through a meaningful and purposeful activity. A suitable manner for this involves fitting a resistance band to a common hand tool which can be used in an anecdotal activity determined by the OT.

Suitable common hand tools in this application refer to those that employ a full grip prehension (see chapter 3.2), and include but are not limited to scissors, shears, pliers, tongs, cable snips, and wrenches.

What is not specified by these requirements is which hand tool to use with the resistance band. Because there is a near endless variance in the size, shape and function of these tools, it is challenging to design one part to fit them all.

The factors that differ between common hand tools include:

- Inter-handle width
- Handle thickness
- Handle width
- Shape of the handle
- Handle cross-section shape

To address this challenge, a suite of product sizes were envisioned. In conjunction with an online product configurator (see chapter 7.2), the customer can select from three sizes of resistance band. With this product range, the customer can choose a product to suit a tool, or to achieve a particular task. For example, a pliers has a large inter-handle width, thus a size large is suitable.

A representative sample of three tools were selected as a case study for which to base the sizes on.
To address the variation in the handle cross-section shape and sizes, cable ties are employed to affix the device to the tool. The ties ensure that the bands can be securely fastened to many sizes and shapes of tools. Because of their length, cable ties afford a great potential handle width (see arrow in Figure 31). The added benefit is that they are low-cost and in plentiful supply (LoR 12.1) (Magdalia Campobasso, personal communication, 10th December 2020).

A range of 14 tools were then trialed and fit with a device. The resistance band fit snugly and securely on. With respect to the fit of the band on non-straight handle shapes, tools featuring an extreme slant of handles such as small scissors, or curved handles such as pliers did not cause fitting issues thanks to the “float” afforded by the zip ties. See the Figure 31 for a visualization of the float afforded by the zip ties.

While a more accurate representation of tool dimensions could be determined through a qualitative survey of hand tools, for this thesis scope it is not deemed as necessary. The importance of having a band that closely matches the dimensions of the tool is of slight significance for product performance. Likewise, the versatility afforded the cable ties means that the band can be fit to handles that are both above and below the applied size. A test of this assumption will be performed in TRL #6 in a user-test in the context.

This thesis’ research determined that the hand exerciser should be offered in:

- A range of resistance forces (LoR 1.7)
- Determined resistance forces (LoR 1.7)

For these reasons it is necessary to test, determine, and standardise the resistance force of each part of the concept. To achieve this, a material evaluation and laboratory testing was performed. To give this testing a scope and targets with which to aim for, the specific forces required were determined. These forces relate to the squeezing force applied by the hands to the resistance band while it is attached to a tool (Figure 32).

It was decided that a total of 5 hand exercisers with different resistance forces should be developed and included in the concept. This number relates to the common coding-system for therapeutic equipment, whereby different strength products are represented by a different colour (B. Angienda, personal communication).
These products are commonly sold in sets of 5, from lightest Yellow, to hardest black (Pro Healthcare Products, 2009).

A reference product with similar functionality using the same colour-coding system was selected. The TheraBand (Theraband, 2021) provides specific resistance force data for each grade of their product, and so offers a qualitative method to compare the strength of each product.

For this application, the relative strength of each product and associated colour was adapted (Theraband, 2021).

Next, a target hand grip strength was chosen, which could also be used to determine the relative strengths of the others using the TheraBand data. Based on a study by Rice, Leonard & Carter, (1998), 20lb, or 89N of isometric hand grip strength is the baseline requirement for a hand to be considered functional in an occupational therapy context.

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The decision to place this functioning target force as grade 3 (mid) reflects the desire for this product to help patients recover fully into daily life. Simply being “functional” does not suggest full recovery. A study by Lauretani et al. (2003) determined that peak grip strength for healthy adults aged 20-102 was 40.9 Kg for males (401N), and 23.2 Kg for females (227.52N). When comparing a “functional” grip force of 89N to the peak grip strengths identified in this study, a functional grip is not reflecting the full capability of a hand. Thus, the maximum resistance of this product concept set should be higher than simply achieving a functional grip, as demonstrated in the above table. The maximum resistance will be determined in accordance with TheraBand coding.

This “functional” value however does not consider the effect of age or gender on hand strength. The ultimate decision for which band to use should be left to the discretion of the OT.
Once the concept had established an approximate shape and size, an investigation was performed to evaluate and benchmark various 3D printing materials which could be applied to the production of the hand exerciser. Five materials were chosen for the testing:

- Ninjatek Cheetah (TPU)
- Ninjaflex (TPU)
- Fillamentum Flexfill (TPU)
- Reload 3D (TPE)
- Taulman (PCTPE)

These materials were selected based on their availability at trusted suppliers for Kijenzi (Ben Savonen, personal communication, 24th November 2020), and the availability of material property data relating to each. The Reload3D TPE was chosen as a low-priced option, however the firm has since stopped trading.

As outlined in the TRL #3 LoR evaluation, it was desired to explore the requirement specifying that: The device should afford 25,550 use cycles (50 daily cycles). This requirement is challenging to fully investigate given the time-scope of this thesis, however a test was performed to gather a basic understanding of how the elastic materials resist deformation. The hypothesis is that parts that could return close to their original ID after a duration under compression would resist deformation in a longer term of use.

Material testing and evaluation

Five test samples were printed using the same printing parameters to ensure testing fairness. The only variable that was changed was the printing temperature, which varied per material. These samples were then clamped in place for a period of 24 hours. The position of each sample in the clamp was kept similar to ensure testing fairness. Next, the inner diameter (ID) was measured for each part. After the 24 hours had elapsed, the parts were unclamped and allowed to recover. The new ID was recorded for each part after 6, 24, 48 and 72 hours. The results of this test are shown in figure 38.

From this testing, both the Ninjatek Cheetah, and the Ninjaflex resisted deformation well, with the latter returning to 92.75% of its original size.

A range of other variables were also considered in the evaluation included. Each material was awarded a score out of 5 for the factors of printability (the risk of print failing due to warping, extrusion issues), and the quality of the surface finish (free of blobs, layer lines, artefacts).

Based on Ninjaflex’s ability to resist deformation and return to its original shape, combined with its high printability (LoR 9.4) and wide range of colours (1.7), good surface finish (LoR 1.1.1 - 11.3), it was selected for further investigation in the resistance force testing (see TRL #5).

Ninjaflex Cheetah is also a valid contender and will remain in consideration based on the results of this testing.

Figure 36: Test samples after the clamping period

Figure 35: The clamped samples
Table 5.2: 3D printing material comparison chart.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Type</th>
<th>Cost/KG (EU)</th>
<th>Printability</th>
<th>Surface Finish</th>
<th>Colour options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ninjatek</td>
<td>Cheetah</td>
<td>€ 89,00</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Ninjatek</td>
<td>Ninjaflex</td>
<td>€ 89,00</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Fillamentum</td>
<td>Trafficfill</td>
<td>€ 67,98</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Taullman</td>
<td>PCTPE</td>
<td>€ 97,50</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Reload 3D</td>
<td>TPE</td>
<td>€ 65,00</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 37. 3D printing material comparison chart.

Figure 38: Results from the material testing - percentage of nominal diameter vs. time.

Online customizer prototype

With the decision made earlier in TRL #4 to include multiple product sizes, and multiple product resistance forces (LoR 15), the stage was reached to develop an online product customizer and webshop that could handle these parameters (LoR 9.3). After TRL #3, the product had taken on one main articulation and form. This meant that the customizer's functionality could be created.

Using the product configurator for Wordpress (Marc Lacroix, 2021), a selection system was built whereby users can assign product characteristics by specifying between layered images with transparent backgrounds. Similar to the layers functionality of Photoshop, the different aspects of a product could be changed by changing the image layered for that particular feature.

The product customizer plug-in was installed to the developer app for WordPress, running on a local PC. The online functionality of the website was priced out of the budget for this project, whereas the developed kit was free to use.

Testing of the system revealed insights including:

- Creating the product render images to include on the site is a time-consuming activity. This will add to the cost of a product through increased design effort.
- It may be more cost-effective in the long run to purchase up-front a site that allows for CAD files to be uploaded and design logic to be changed automatically.

When a customer places an order and makes a payment using PayPal or M-Pesa, an email will be sent to Kijenzi from the WooCommerce site, detailing the order.

Online customizer prototype

A base component was designed, onto which the hand exercisers can be neatly stored. This component was developed for the following reasons:

- To keep the exercisers together during transport (LoR 6.2, 71)
- To create a rehabilitation program for a patient, a custom base can be ordered. The size, shape and quantity of the rings on the base can reflect a treatment plan for the patient. This plan can include a determined set of hand exercisers to be used in a given time frame. The patient can then take the device home with them from the hospital.

Creation of the base component
To begin the integrated modeling development, the concept was 3D modeled as a parametric design. At the outset, certain values were defined, including:

- Printer nozzle width
- Vertical print tolerance
- Horizontal print tolerance
- Product diameter
- Product thickness
- Cable tie width
- Cable-tie thickness

Based on these parameters, the design was modeled using equations. One such equation expressed the width of the hole for the cable tie as:

$$\text{Width} = (\text{horizontal\_print\_tolerance}^2) + \text{cable\_tie\_width}.$$ 

In this approach, any changes to these variables could be made at a top-level. The model would automatically adjust to reflect these changes.

Following this part creation, the manufacturing workspace of Fusion360 was explored. Material properties (printing parameters) and machine properties were compiled in the program to create pre-sets which could be easily accessed. These pre-sets were referenced from the Prusa Slicer program. With these pre-sets selected, the parametric model was sliced and a Gcode file was created. The print path can be assessed to ensure that the part has been prepared properly.

Next, to connect a 3D printer to the integrated modeling approach OctoPrint was established on a Prusa i3 Mk3.

OctoPrint was first flashed to the Pi via USB, and the local WiFi settings were configured. Next, the Pi was connected to the rear of the 3D printer control board with 18mm GPIO pins, and the 3D printer was connected via WiFi to the OctoPrint server.

An API for Fusion360 was
The validation of this development successfully completed the following tasks:

- Modeled a parametric model using Fusion360
- Prepared a print file based on this model in the additive manufacturing environment
- Transferred the file to the 3D printer via wireless connection

Validation

next installed to the CAD program. This API linked the 3D printer to the additive manufacturing environment of F360 by means of the connected printer’s OctoPrint API key and IP address.
**Goals**

TRL #5 sought to use the working concepts developed in TRL #4, and trial and prove them in a simulated environment. For the product concept, the performance requirements of resistive force were to be investigated. A live test of the online customizer and integrated modeling system were also performed with an SME.

**ESA Definition**

Component and/or breadboard functional verification in laboratory environment [ESA 2021].

**Resistance testing**

The hand exerciser chosen in TRL #4 constitutes a 3D-printed TPU band. Thanks to the material’s elasticity, repeatedly deforming it affords the ability to exercise hand mobility and increase strength. By increasing the cross-sectional area of the band, the resistance force can be increased. As a patient progresses through a rehabilitation they can make use of stronger bands as their strength and mobility increases.

In order to develop a hand exerciser that is offered in different resistance strengths (LoR 15, 17, 12) it is first necessary to be able to identify the forces needed to deform each size and strength of band. Identifying which forces correspond to a certain cross-sectional area will enable the resistance requirements in chapter 6, TRL #4 to be met.

The first activity completed in TRL #5 set out to identify the force needed to compress grade 1-5 for each size of band.

A benchmark CSA for each grade was established in increasing increments of thickness, with each increment based on the width of one 3D-printer nozzle. The hypothesis was that for each new nozzle path, the band would increase in thickness. For the lowest grade, three perimeter lines were chosen as the minimum thickness, as a lower CSA would sacrifice durability (LoR 15.2).

Two methods were identified as applicable to identify the resistance forces of the prototypes.

The first is with Finite Element Analysis (FEA), which is a digital means to test material properties and performance under conditions such as stress, vibration and temperature. FEA can be done with common CAD software such as SolidWorks, Fusion360, and Ansys.

The second means to identify the resistance force is manually. In this method, 3D printed prototypes can be evaluated in a simulated bench-top trial with force measurement equipment.

Because digital models of the part in all its configurations of size already existed at the time of this decision, the first option of FEA was chosen. There would be a significant time and cost incurred to make the prototypes for the manual testing method.
Using the parametric model of the hand exerciser, a digital simulation of a non-linear static stress analysis in Fusion360 was established (see figure 43). After trialling it became clear that FEA posed challenges to assess the resistance strength for the following reasons. Within the time scope allowed for this development, these challenges would prove too great to overcome:

- The non-linear simulation function of the software required raw stress-strain test data which was not available at the time.
- The digital simulation function of the software required raw stress-strain test data which was not available at the time.
- The digital simulation did not incorporate the differences between a 3D model and a 3D print, so a representative study could not be performed. Each of the 15 parts were 3D printed and weighed, with an average difference of 12.85% to that in the 3D model. Caused by: part shrinkage after cooling, non-homogeneous infill, and inconsistencies in material extrusion. See appendices item 4 for more.
- A simplified model of the part had to be created to ensure that the program could handle the calculations without crashing. As this model did not reflect the real concept, it was noted to perform representative study.
- Simulation in Fusion360 is not optimized for the large displacements seen in this analysis.

For these reasons, a manual testing was next explored.

**Manual testing**

To begin this testing, each concept was printed in Ninjaflex filament. The parts of the band undergoing the most deformation were printed with 100% infill to reduce buckling between the perimeter walls (see figure 45). A digital force gauge in conjunction with a vertical press was employed to measure the force applied to the bands as per figure 45. This jig was modified with 3D-printed parts to ensure that each exerciser tested was held in the same orientation and position. Initially, a spacer block was inserted inside the compressed part which was used to ensure that the deformation was the same for each study. However, this spacer was interfering with the results and was discarded.

For these reasons, a manual testing was next explored.

### Results of the Testing

<table>
<thead>
<tr>
<th>Size</th>
<th>Strength</th>
<th>Recorded (N)</th>
<th>Target Force (N)</th>
<th>Difference (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>5 Max</td>
<td>74</td>
<td>139.81</td>
<td>64.6</td>
</tr>
<tr>
<td>Large</td>
<td>4</td>
<td>60</td>
<td>110.2</td>
<td>50.2</td>
</tr>
<tr>
<td>Large</td>
<td>3 Functional</td>
<td>38</td>
<td>88.97</td>
<td>51</td>
</tr>
<tr>
<td>Large</td>
<td>2</td>
<td>23.3</td>
<td>72.02</td>
<td>48.7</td>
</tr>
<tr>
<td>Large</td>
<td>1 Min</td>
<td>4</td>
<td>68.04</td>
<td>64</td>
</tr>
<tr>
<td>Medium</td>
<td>5 Max</td>
<td>53.8</td>
<td>139.81</td>
<td>85</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>46</td>
<td>110.15</td>
<td>64.2</td>
</tr>
<tr>
<td>Medium</td>
<td>3 Functional</td>
<td>36.7</td>
<td>88.97</td>
<td>52.3</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>20.7</td>
<td>72.02</td>
<td>51.4</td>
</tr>
<tr>
<td>Medium</td>
<td>1 Min</td>
<td>4</td>
<td>68.04</td>
<td>64</td>
</tr>
</tbody>
</table>

Each part was compressed using the press, and the force was recorded. This was repeated three times and the average force was calculated and used in the results.

The testing for the size small bands was not within the scope of this testing. TPU is over twice the price of typical PLA or ABS material, and for this evaluation the data for the size was not deemed as more critical than the size medium and large. Budget would be applied to other more pressing research topics.

Results of the testing below demonstrate that the Ninjaflex samples did not bear a high enough resistance force to meet the goals outlined in chapter 6, TRL #4.
Two causes for the insufficient resistance strength are possible given the testing method:

1. The Ninjaflex material is not stiff enough
2. The cross-sectional area of each part is too low.

Because the parts were printed with 100% infill density at the deforming locations, it is unlikely that adjusting the printing parameters could achieve a stiffer part.

What must be considered however, is the weak supporting evidence for the claim that 20lb of strength defines a functional hand. (see TRL #4 ‘Establishing force requirements’). Should this value change, the required product strengths will change, and so will the outcome of this trial.

The developed online customizer and integrated modeling approach was tested with an SME as the TRL level #5 evaluation. In an online video call with the Kijenzi printing facility manager, David Okia, the entire system could be demonstrated and trialled.

To meet the validation level of TRL #5, a laboratory, or non-contextual demonstration could be performed. As such, a distanced/remote test would suffice. Remote access to the hosting laptop was given to the participant, who could then make use of the online customizer (running on a local program), and the parametric model on a local Fusion360 instance.

The feedback from the testing was positive, with the participant remarking that the system was applicable and suitable for integration to Kijenzi’s processes.

A number of shortcomings were established (see chapter 8.3) in the part slicing functionality of the Fusion360 program. The conclusion from the follow-up discussion was that for low-volume, personalized products the method would be useful to reduce the number of steps.

With respect to the connected-printer aspect of the Integrated Approach, it was noted that Kijenzi’s efforts so far have not progressed past a single connected-printer in facility. The company was still exploring options to merge multiple printers to one central management platform. Should the Integrated Approach succeed, it would need to enable this functionality.
In preparation for the ultimate TRL #6 evaluation to be conducted in Kenya, the necessary parts needed to be produced. This activity also served as a test of the digital distribution system that Kijenzi employs. To ensure that the testing could be completed within the allotted time, the printing job received extra attention and foresight.

In total, 5 parts were printed. These included a size M grade 1, 3, 5, and associated base, and a size L grade 3. The approximate total cost of these parts was 20USD, which represents the target device price outlined in the project introductions.

The printing job was discussed with the printing facility manager after the feedback session, where he could advise on his facility’s capability and capacity. Likewise, it was discussed as to which materials were present at the farm and could be used for the testing.

The print files were prepared using the integrated modeling method to reflect these details, and the files were transferred. The parts were then 3D printed on-location at the printing farm.

The conclusions from the exercise are reflected in the evaluation of the method in chapter 8.

Validation of the Integrated Method

User testing

A user evaluation of the device was performed to assess the opportunities for incorrect setup or use.

4 test participants were asked to setup and use the device, with basic instruction given. Their errors in setup were noted, and events where they expressed confusion about use were identified. These issues included:

• Two participants failed to seat the nylon fixation band head in its indentation.
• One member did not cut the ends off the cable ties.
• One participant left too much cable tie remaining after cutting.
• One participant remarked that it was challenging to seat the nylon fixation band head in its indentation.

The conclusions from this testing assist in the creation of the final recommendations in chapter 8.6.
TRL #6

ESA Definition

Technology demonstrated in relevant environment (ESA 2021).

Goals

TRL #6 was the final design phase of this project, and set out to deliver and test a prototype of the hand exerciser in the context of Kenya. The evaluation of this pilot help to form the basis of the conclusions in chapter 8.

Final user test

The final validation of the hand exerciser sought to test the product in the hands of a patient in the context of Kenya, under the guidance of an OT. Boaz Angienda is an OT at the Kisumu County General Hospital, and volunteered as the test participant. Boaz had played an active role in the research for this thesis so far, and likewise assisted other Kijenzi projects in the past.

This evaluation looked to assess the setup of the hand exerciser, and evaluate its use in a clinical setting with real users in a two-week trial. The conclusions form the basis for the recommendations in chapter 8.3.

It was also desired to test the online customization software, however as the test participant was using their mobile phone for the call, the remote access functionality could not be used.

Following the production of the prototypes at the end of TRL #5, an accompanying leaflet of product information and instructions (see appendices item 5.1) were provided to the test participant to assist setup and use. A follow-up questionnaire (see appendices item 5.2) was also provided so as to assist with the follow-up discussion.

The discussion revealed that:

- The product was tested with four patients in total, each suffering from both injuries and neurological conditions, namely stroke and cerebral palsy.
- The device was used in conjunction with other devices as part of a therapy activity.
- Both single-finger and whole-hand exercises were used.
- Scissors and pliers were used with hand exerciser. A patient used the pliers to turn a nut seated on a bolt-and-nut board.
- The base component adds to the cost of the device and could be made simpler with simply using a cable-tie to bind the parts together.

Conclusions

- The occupational therapist confirmed that the HandBand had made a significant contribution to the recoveries of multiple patients. The hand exerciser was a marked improvement to the current equipment and tools available in the hospital.
- The product could be used and understood by patients with minimum intervention from the practitioner.
- The device proved capable of, and easy to affix to commonly used hand grip tools.
In TRL #5, the resistive forces for the hand exerciser were identified, and concluded to be too low. This conclusion is based on the force requirements identified in chapter 6, TRL #4. A hypothesis was formed which posited that a stiffer material would achieve a higher resistance force.

To meet these requirements this, a subsequent force evaluation was performed with another material from the evaluation in chapter 6, TRL #4. The vertical press and digital spring gauge were once more employed. Five samples of the size large part in grades 1-5 were printed using the same parameters as the previous test in TRL #5.

The connected product system was then tested to see if it would incur longer lead times. A Gcode file was prepared and this file was transferred to the connected Prusa i3 Mk3 printer using the developed OctoPrint method. The time taken to print the file was recorded.

The testing method was also maintained. Ninjatek Cheetah is a similar material to Ninjaflex trialled previously, albeit a stiffer alternative. The hypothesis that a stiffer material would create a higher resistance force proved true. Figure 50 details the results of the force evaluation, where increased forces needed to compress the device are detailed.

These increased forces however do not meet the force requirements. This shortcoming will be addressed in chapter 8.

The time taken was recorded. The results of this testing are listed below. A size small, medium and large grade 1 part were printed for each trial.

<table>
<thead>
<tr>
<th>Size</th>
<th>Strength</th>
<th>Slicer estimate</th>
<th>SD Card</th>
<th>OctoPrint</th>
<th>Difference (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1</td>
<td>82 mins</td>
<td>82.31.55</td>
<td>82.55.14</td>
<td>00.21.41</td>
</tr>
<tr>
<td>Medium</td>
<td>1</td>
<td>117 mins</td>
<td>117.35.73</td>
<td>117.40.54</td>
<td>00.05.19</td>
</tr>
<tr>
<td>Large</td>
<td>1</td>
<td>183 mins</td>
<td>183.21.75</td>
<td>183.28.45</td>
<td>00.07.30</td>
</tr>
</tbody>
</table>

Ninjaflex Cheetah is a similar material to Ninjaflex trialled previously, albeit a stiffer alternative. The hypothesis that a stiffer material would create a higher resistance force proved true. Figure 50 details the results of the force evaluation, where increased forces needed to compress the device are detailed.

These increased forces however do not meet the force requirements. This shortcoming will be addressed in chapter 8.

The connected product system was then tested to see if it would incur longer lead times. A Gcode file was prepared and this file was transferred to the connected Prusa i3 Mk3 printer using the developed OctoPrint method. The time taken to print the file was recorded.

Next, the file was transferred to SD and printed. The time taken was recorded. The results of this testing are listed below. A size small, medium and large grade 1 part were printed for each trial.

<table>
<thead>
<tr>
<th>Size</th>
<th>Strength</th>
<th>Recorded (N)</th>
<th>Target Force (N)</th>
<th>Difference (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>5</td>
<td>78.7</td>
<td>139.81</td>
<td>64.6</td>
</tr>
<tr>
<td>Large</td>
<td>4</td>
<td>55.3</td>
<td>110.2</td>
<td>54.8</td>
</tr>
<tr>
<td>Large</td>
<td>3</td>
<td>38</td>
<td>88.97</td>
<td>51</td>
</tr>
<tr>
<td>Large</td>
<td>2</td>
<td>34.7</td>
<td>72.02</td>
<td>37.4</td>
</tr>
<tr>
<td>Large</td>
<td>1</td>
<td>16.7</td>
<td>68.04</td>
<td>51.4</td>
</tr>
</tbody>
</table>
## Risk analysis of the 3D printing process

A risk analysis was made for the final 3D print to ensure that LoR 9.4 can be met. These risks and their proposed mitigating actions are formulated based on experience printing the 103 individual print jobs throughout this project.

<table>
<thead>
<tr>
<th>Description</th>
<th>Build plate detachment</th>
<th>Material stringing</th>
<th>Material jam</th>
<th>Stubborn support material</th>
<th>Poor surface quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>During printing, the extruded material will come free from the plate and move freely</td>
<td>Thin string artefacts and blobs on the surface of the 3D print as the nozzle travels</td>
<td>The material jams in the extruder gears and gets fed through the extruder body</td>
<td>Remnants of support material left after removal of the printed supports</td>
<td>Blobs and artefacts on the surface of the print</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk</th>
<th>High</th>
<th>High</th>
<th>Medium</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
</table>

| Effect | The extruded material can build up around the nozzle and hot end causing damage | Lower surface quality of the 3D print, and potential for waste | The material will spool inside the extruder body and then jam, causing the print to fail | Lowered surface quality of the printed part, and poor fitting onto other tools | Product will not be usable, and waste will be incurred. Poor mechanical properties |

| Cause | Poor bed adhesion, incorrect temperature settings, ambient temp. too low | Too high printing temperatures or speeds, or worn nozzle | High tension on the material caused by the extruder gears, too high print speeds | Too low contact-Z distance between material and part, TPU has high layer bonding | Too high printing temperature, or the filament has taken on water |

| Mitigating action | Apply a thin layer of glue stick to a clean print surface for each new print, and increase bed temps. by 5°C | Lower print temperature and speeds and replace the printer nozzle | Reduce printing speeds and lower tension on the extruder gears | Increase contact-Z distance in the supports, or increase support grid-spacing | Lower printing temperature, and dry the filament |
The use of the TRL methodology outlined in chapter 6 resulted in the development of a product/service/system concept which is outlined in this chapter. This concept aims to satisfy the requirements, overcome the challenges, and achieve the goals outlined in chapter 5. An evaluation of the concept will be performed in chapter 7, where the main research question can be concluded: “to what extent can FDM 3D printing be applied to assist Kenyan occupational therapists in the provision of therapy to individuals with hand dexterity and strength challenges?”
The HandBand product, service, system (PSS) concept is a holistic structure which affords the provision of patient-specific hand therapy. Through the use of the therapy device, an online configurator, and a production system, the concept’s full design articulation is achieved in a low-cost and feasible manner. The three-part proposition aims to provide impact for key stakeholders in both the Kenyan healthcare picture and the Kijenzi context.

As figure 54 details, the three parts have a layered relationship. The product exists within the sphere of the online customizer. With this functionality, the customer can unlock increased product value. Likewise, the online customizer exists within the sphere of the integrated system. The application of the Integrated method reduces the steps involved in and the cost of producing customer-specific products.

As figure 54 outlines, this holistic system is desired to work with not only the hand-band concept, but many more. This will enable a low-cost manner for product personalization to continue in the future.

The PSS was designed to enable the envisioned scenario in chapter 5.1. Overleaf is a visual representation of the PSS’s use from a patient perspective.
The OT visits the online customizer, and the product characteristics are selected. The patient-specific device is made in the Integrated method to regain mobility in the digits in the early stages of an injury. 

Patient and OT discuss treatment, and a program is established to build hand strength and wrist coordination once mobility has been restored. As an assistive tool to train hand function and coordination in the reintegration to ADL. As a permanent feature to exercise hands while performing ADL, and to assist in the use of challenging tools.

**TIME**

- **DAY 1**: Therapy planning, Product ordering, Production, Single-finger exercises, Whole hand gripping, Therapy sessions.
- **WEEK 1**: Therapy planning.
- **WEEKS 2 and 3**: Therapy planning.
- **WEEK 4**: Therapy planning, Product ordering, Production, Single-finger exercises, Whole hand gripping, Therapy sessions.

**RESIS.**

- **Light resistance**
- **Mid resistance**
- **Mid-heavy resistance**
- **Heavy resistance**

**PRODUCT**

- **HandBand**
- **Kijenzi customizer**
- **Integrated approach**
- **HandBand**
- **HandBand**
- **HandBand**
- **HandBand**

**TAS K**

- Single-finger exercises
- Production
- Therapy planning
- Therapy sessions
- ADL aid
- Whole hand gripping
- Single-finger exercises
- Therapy planning
- Therapy planning
- Therapy planning

**POS**

- **Product**
- **Service**
- **System**
- **Product**
- **Product**
- **Product**
- **Product**

**DESC.**

- Patient and OT discuss treatment, and a program is established.
- The OT visits the online customizer, and the product characteristics are selected.
- The patient-specific device is made in the Integrated method.
- To regain mobility in the digits in the early stages of an injury.
- To build hand strength and wrist coordination once mobility has been restored.
- As an assistive tool to train hand function and coordination in the reintegration to ADL.
- As a permanent feature to exercise hands while performing ADL, and to assist in the use of challenging tools.
7.1 The HandBand

The HandBand is a 3D-printed hand exerciser which allows occupational therapists to fit a hand therapy program to a patient. By embodying a low-cost product, access to quality healthcare is improved. Furthermore, by adapting the product to suit the needs of the individual patient, outcomes can be improved.
This versatile resistance band has been designed to adapt to a broad range of therapy purposes. First and foremost, the device can transform any common hand tool into a hand-strengthening device by affixing it between the moving parts. In this manner, basic ADL with a meaningful outcome can be used as a therapy exercise in place of isolated exercise. The device can also be used as a standalone therapy band for finger mobility training and strength building exercises.

The HandBand is offered in 5 resistance strengths and 3 different sizes. In accordance with a colour-coded system, the variety in resistance strength allows for OTs to administer different therapeutic activities along all stages of a recovery. This colour code is the same as the colour coding already employed by common OT tools, such as therapy bands and therapy putty. As such, OTs will be able to understand and make effective use of the various resistances strengths.
Grade 1 (Lightest)

Grade 2

Grade 3

Grade 4

Grade 5 (Hardest)
These size and strength characteristics can be cherry-picked by a customer to suit a specific patient or purpose using an online-customizer.

The HandBand is based on a parametric model which allows for unique user needs to be quickly integrated.

30mm 45mm 60mm

Figure 55: The HandBand size offerings and their associated dimensions

Envisioned exercises

Scissors - cutting

Pliers - ADL board - picking and placing tiles

Snips - making with wire
Benefits of the envisioned solution

- The solution is versatile, and adaptable to a wide range of use-cases and patients.
- The device is simple to create and relatively safe to print (see chapter 6. TRL #6 - 'Risk analysis of the 3D print').
- The concept is low cost (see chapter 7.4).
- Only two nylon restraint bands (cable ties) are needed to affix the device to a tool, which are low-cost and readily available in Kenya.
- Product interventions can help to improve patient recovery (see chapter 3.3).
- Isolated hand exercisers are an inadequate solution for rehabilitating hand mobility and strength (see chapter 3.3).
- General-issue products are not created to meet the specific needs of a patient (see chapter 5).

Rationale for the envisioned solution

- The therapists must have a gripping tool that they can use for the exercise.
- The therapist must have two small nylon restraint bands (2.5mm / 3.6mm).
- To use the device, injuries must be sufficiently healed to the point where resistive exercise will not pose a risk of re-injury.
- The customer should be able to access an internet-based configurator and purchase goods using M-Pesa or debit card.
- The exercise should be safe for dominant and non-dominant hands.

Requirements & prerequisites:

- The therapists must have a gripping tool that they can use for the exercise.
- The therpaist must have two small nylon restraint bands (2.5mm / 3.6mm).
- To use the device, injuries must be sufficiently healed to the point where resistive exercise will not pose a risk of re-injury.
- The customer should be able to access an internet-based configurator and purchase goods using M-Pesa or debit card.
- The exercise should be safe for dominant and non-dominant hands.
This web-based system is a means for Kijenzi’s customers to specify their requirements in a visual environment and then purchase them just like a normal webshop.

7.2 The Kijenzi Customizer
From one parametric 3D model (created with the Integrated Method), a range of design options can be created and then displayed online. The customer can then build their product to their liking empowering them to take control of product design, without the added costs. With this customiser, a user can complete an order, and process payment with M-Pesa, PayPal or debit card.
Benefits of the envisioned solution

- This system reduces the time necessary for translating customer requirements into design requirements, with a clear and definitive order statement, as chosen by the customer.
- This system is scalable, meaning that more customer orders can be accepted and processed without having to increase the staff necessary to process them.
- Patient-specific parts can be made low-cost, as this system reduces the labour cost needed to process and custom-fitting parts.

Rationale for the envisioned solution

- Healthcare professionals do not have the skills nor the software to create custom components to suit individual patients or applications themselves using 3D printing.
- The price of a customized product is too high for LMII contexts where low-cost is the key determination of product viability due to the design effort and time required to produce one-off parts.

Requirements & prerequisites:

- The customer has internet access and can complete online transactions.
- The product will be sold in enough quantity to justify the effort spent on parametric modeling and making the webshop.
- The market demand for customizing this device exists.

Costs:

- Webshop plugin (once off)
- WooCommerce site (annually)
- WordPress site (annually)

With over 95 possible configurations for one product, hosting a customisable product such as the HandBand on a webshop using the standard method of dropdown selection boxes is not suitable. What is different to a normal webshop, is how these product characteristics are shown. Unlike a standard webshop, the Kijenzi Customizer can handle adjustments to product characteristics within one product page.

Adding three 'quantity' options offers 3 possible product combinations.

Adding a 'Size' option to this offers 9 possible configurations.

Adding a 'Colour' choice offers over 155 possible configurations, per size.

If standard dropdowns were to be used, differentiating between and understanding what these 465 options mean can become overwhelming.

The product configuration options can be expressed in this formula:

\[ C = S \sum_{n=1}^{Q} N^n \]

- \( C \) = the possible amount of configurations
- \( S \) = amount of sizes options
- \( Q \) = the amount of quantity options (triple, double, single)
- \( N \) = the quantity of color options

Figure 59: Product options
The Kijenzi Customizer streamlines the steps needed to produce a customised product. These tasks flows highlight the improved workflow.
7.3 The Integrated Method

The integrated approach is a holistic production method, incorporating an internet connected printer and streamlined part preparation process.
The process begins with Kijenzi receiving an order through their online webshop. Using a parametric model in Fusion 360, the model can quickly be altered to suit the customer’s requirements. The adjusted parameters include diameter, size, strength, and associated strength annotation.

The part is then prepared for printing in the Fusion 360 manufacturing environment. In this environment, machine settings, material properties are selected and a G-code file is prepared. Next, GCode is generated and the tool-path can be visualised using the OctoPrint API, the part can be sent to a WiFi connected printed in the connected farm.

Figure 60: A Fusion360 Parametric model

Figure 61: Parameters that can be adjusted using the parametric model

Figure 62: Slicing in the Fusion360 environment


**Connected Farm concept**

OctoFarm is a local server with a web interface that coordinates the 3D printers in the farm. Up to four printers can be connected to one Pi computer, which is then connected to the server. This web-based interface allows for print files to be uploaded and printers to be managed over a local connection.

The site can display such information as the printer telemetry and job status, and can give insight into fleet information such as material usage, fail statistics and print metrics.

---

**Benefits of the Integrated Method**

- Increased production efficiency and reduction in human efforts.
- Streamlined coordination of multiple printers.
- Scalable increase in printer capacity without requirement for more operators.
- Reduced downtime and printer failure thanks to maintenance alerts.
- Safer print farm running thanks to remote video monitoring and control of the printers.
- Less file saving and STL data generation.

---

**Rationale for the Integrated Method**

Operating a 3D printing farm is a complicated and laborious process. For each stage of the production process, from customer order to preparation for shipping, a person is needed to complete a task. This human effort incurs a direct cost, and bottlenecks output. Kijenzi have outlined their desire to develop a scalable hub that can be implemented into many contexts, while still ensuring that their products can be produced for the lowest possible cost.

The benefits offered by partially digitizing the farm management could assist Kijenzi in overcoming the problems faced by rapidly expanding production systems. Likewise, by reducing the human activity and steps involved in the production process, Kijenzi can increase their output, and produce and sell goods at a lower cost.

---

![Figure 63: The proposed connected farm architecture](image)

**Requirements & prerequisites:**

- Fusion360 license
- Local computer server with stable internet connection.
- Raspberry Pi Model 4 (39,95€) x1.
- Raspberry Pi power supply (9,95 €) x1.
- USB B- USB A cable (2,5 €) x4.
- OctoFarm server (free).
- Working PC for use only as a farm server.
Task Flows

The Integrated Method streamlines the steps needed to produce a customised product. These task flows highlight the improved workflow.
## 7.4 Cost evaluation

### Kijenzi pricing structure
<table>
<thead>
<tr>
<th></th>
<th>Material costs</th>
<th>Farm-specific costs</th>
<th>Non-farm-specific costs</th>
<th>Printer time cost</th>
<th>Failure cost</th>
<th>Total cost to print (build time)</th>
<th>Sales margin (20%)</th>
<th>Sales price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material costs</td>
<td>$0.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.91</td>
<td>$11.52</td>
</tr>
<tr>
<td>Farm-specific</td>
<td>$3.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-farm-specific</td>
<td>$3.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Printer time</td>
<td>$1.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure cost</td>
<td>$0.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost to</td>
<td>$9.61</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Integrated Method pricing
<table>
<thead>
<tr>
<th></th>
<th>Raspberry Pi Model 4</th>
<th>Raspberry Pi power supply</th>
<th>USB B- USB A cable</th>
<th>Cost per 4 printers</th>
<th>Total Farm cost</th>
<th>Kijenzi Customizer Pricing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hosting</td>
</tr>
<tr>
<td>Farm-specific costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Extra Price functionality</td>
</tr>
<tr>
<td>Non-farm-specific costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Domain registration</td>
</tr>
<tr>
<td>Failure cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sales margin</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### HandBand Pricing

<table>
<thead>
<tr>
<th>Type</th>
<th>Print time</th>
<th>Material cost</th>
<th>Cost to produce</th>
<th>Sales price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size S</td>
<td>80 - 97 minutes</td>
<td>$0.42 - $0.53</td>
<td>$4.68 - $5.69</td>
<td>$5.61 - $6.83</td>
</tr>
<tr>
<td>Size M</td>
<td>137 - 180 minutes</td>
<td>$0.63 - $1.00</td>
<td>$7.90 - $10.57</td>
<td>$9.49 - $12.68</td>
</tr>
<tr>
<td>Size L</td>
<td>204 - 280 minutes</td>
<td>$1.13 - $1.56</td>
<td>$11.96 - $19.73</td>
<td>$14.35 - $19.73</td>
</tr>
<tr>
<td>Base</td>
<td>37 - 157 minutes</td>
<td>$0.38 - $2.00</td>
<td>$2.17 - $7.66</td>
<td>$2.89 - $14.10</td>
</tr>
</tbody>
</table>

The following is an analysis of the costs to produce and purchase the HandBand based on the Kijenzi pricing structure. The range in price represents the difference in price per resistance grade. The lowest price given represents a grade 1, and the higher represents a grade 5.

This analysis has the following parameters:
- Based on Ninjatek Cheetah
- 50% infill in the wings
- 0.3mm layers
- 100% infill in the deformation areas
- Printed with paint-on supports
This final chapter of the thesis evaluates the prepared concept against the requirements and goals set out in chapter 5. Reflecting on this outcome will assist in answering the main research question of this thesis. Likewise, the research and design process will be evaluated to assess the integrity and validity of the thesis conclusions.
The ultimate evaluation for the HandBand concept was performed in a clinical facility in Kisumu, Kenya. This two-week trial (see chapter 6, TRL #6) sought to test the hand exerciser product in a low-resource healthcare setting. In a prominent regional hospital, the device was used as a therapeutic intervention by predisposed patients undergoing hand rehabilitation. The testing was completed under the instruction of a certified occupational therapist.

An online follow-up discussion was hosted with the participating healthcare professional after the two-week trial, where a questionnaire was completed in-person online.

The outcome of this evaluation for the product was clear and decisive:

The occupational therapist confirmed that the HandBand had made a significant contribution to the recoveries of multiple patients. The hand exerciser was a marked improvement to the current equipment and tools available in the hospital.

The product could be used and understood by patients with minimum intervention from the practitioner. Furthermore, it proved for patients with both neurological conditions and injuries to be a pragmatic tool with which to complete hand therapy. The OT also confirmed that the device could be lent or given to the patients for continued treatment at home.

The device proved capable of, and easy to affix to, commonly used hand grip tools. A scissors and pliers were used in conjunction with a HandBand to operate a 3D-printed ADL board in guided therapy sessions. The healthcare professional was able to make use of the nylon band feature for secure attachment.

A negative aspect relating to the concept was the extra cost incurred by the base component. A more cost-effective solution could be created to reduce the cost further.

To overcome the challenges in geographic mobility posed at the time of this project, a certified and experienced healthcare professional carried out the testing. The results of the testing and gathered insights were then evaluated to form the conclusions of the testing.

To build on the conclusions of this evaluation, in-person testing could be completed to gather deeper insight into the use of the device. Likewise, the questionnaire should be posed to the patients to understand their experience with the device.

It is unclear from the testing as to the true benefit of the range of resistance strengths. The testing period should also be conducted for a longer time, so as to explore the durability of the device after repeated use (LoR 3.1, 3.2) and when exposed to the Kenyan climate (LoR 2.1, 2.2).

Figure 64: Desirability, viability, feasibility (IDEO, 2021)

“I really love the customiser, I think that’s great. One thing that we have been looking at with Kijenzi for the last few months is trying to find out how to add more easy customisation to our products, as that adds another additional layer of value to our products.”

Ben Savonen - 16th April 2021

“...it’s a simple and effective tool, it is not complicated. It does not require a lot of technical input in regards to guiding your client to use it.”

Boaz Angienda - 27th April 2021
To evaluate this customisation service concept, two evaluation sessions with domain experts were hosted.

An evaluation of the online customisation service was performed with the Kijenzi manufacturing facility manager during TRL #4. After a demonstration of its functionality, a working prototype of the customisation system was tested by the expert. The testing concluded with the expert confirming that the system offered an enhanced capability for the Kijenzi manufacturing facility.

Furthermore, thanks to the in-depth analysis of the company processes in chapter 4, the proposed system could be integrated within the firm with minimal incurred cost or effort. This evaluation cemented the potential for this service system concept to create positive impact in the Kijenzi context and for its customers. To build on this conclusions, the service system could be tested:

- With more products bearing different parameters
- In trials with healthcare professionals
- In trials with customers in Kenya

These achievements would be satisfied by increasing from the achieved TRL level #4 to a TRL level #6. Thus the roadmap for a further evaluation should aim to progress to this TRL level while incorporating the named stakeholders.

The expert evaluation process for the integrated modeling process and the connected printer facility employed the same domain experts as the previous evaluation.

At TRL #4 the printing facility manager was given a live demonstration of the system, and was given control of the integrated modeling process and the connected-printer system. The facility manager affirmed that the Integrated Method offers substantial improvements to the design and manufacturing workflow of the company. Its application would ensure a more streamlined design and manufacturing workflow.

The expert revealed that their efforts so far to move from one connected printer to two was a challenge for which no solution had yet been found. Thus, this proposed service solution using the free OctoFarm site can be seen as a solution to the obstacle inhibiting Kijenzi’s development of a connected printer farm.

All three experts spoke about the theory that a server-connected printing system would result in longer printing times (creating a higher product cost) compared to using an SD card for file transfer. These concerns, however, contrast with the results of the benchmarking in chapter 6, TRL #6.

Similar to the evaluation of the online customization system, the Integrated Modeling system could be enhanced by further exploration in the target context.

All of the three experts gave positive feedback and confirmed the potential for the system to create impact for the firm and customers alike. Further evaluation should also assess the benefits of the system for its effect on product cost. A comparison between the time saved by designing and printing products with the integrated method versus engineering parts to meet customer requirements is a fitting way to evaluate the concept definitively.
8.2. LoR evaluation

1. Performance:
   1. The device should allow a minimum ceiling of 88.97N of resistive force.
   2. The device should allow the user to form a fist against a resistive force, in a manner that employs the hand's extensors and flexors to flex the fingers, the intrinsic muscles to contract the fingers at the MCP joint, and the Flexor pollicis brevis muscle to flex the thumb.
   3. The device should achieve grip strength training through a meaningful activity of daily living.
   4. The device should incorporate a means to identify and improve progress by means of degree of mobility or resistive strength.

2. Production
   1. The device should be produced for less than 20,00 USD (16,49 Euro, 2,203,00 Kenyan Shilling).
   2. The device must consider print failure in its embodiment to protect the printing machinery from crashes, and ensure production continuity.

3. Ergonomics
   1. The device should allow the fingers digits to flex in various degrees, increasing from the index finger to the pinky finger.
   2. The device should include a cognitive ergonomic affordance to suggest the correct use orientation.
   3. The device should consider the anthropometry of the target users and the design/manufacturing method should allow personalization of the device fit these people.
   4. The therapeutic intervention need to consider the multi-planar biomechanics of a hand/wrist.

4. Environment
   1. The device must withstand temperatures of 80°C with no structural deterioration or change in appearance.
   2. The device must withstand UV degradation and changes to color.

LoR evaluation

The list of requirements prepared in chapter 5 served as a guiding force throughout the development of the HandBand concept. In this evaluation, they will be critically assessed against the LoR. An abridged version of the LoR is included below, please see appendices item 21 for the full list.

Legend:
- Satisfied
- Partially satisfied
- Not satisfied

LoR progression:

To achieve the following requirements that failed the evaluation, see below.

2.1. The device should be produced for less than 20,00 USD (16,49 Euro, 2,203,00 Kenyan Shilling).
   Reason for partially meeting requirement: while each unit of the HandBand costs less than 20.00USD cost to produce, adding multiple units can push the price past the target. Indeed, while individually the products meet the target, a set of X units does not. Thus, the requirement is partially met.
   To satisfy this, there should be real-world testing of the integrated method, exploring its effect on the cost-price of the product. This system concept does promise to reduce these production costs, but this must be proven.

4.1. The device must withstand temperatures of 80°C with no structural deterioration or change in appearance.
   Reason for failure: the 3D printing material is heat susceptible with a heat deflection temperature of 74°C, and the device will not survive direct sun in hot car interiors.
   To satisfy this requirement, it should be explored if a substitute material exists which can survive the hot environments of car dashboards in the sun.

4.2. The device must withstand UV degradation and changes to color.
   Reason for failure: Ninjaflex Cheetah is susceptible to UV deterioration. Long-term testing is required to evaluate the extent of this and the effect on the product performance.
8.3 Critical evaluation and discussion of results

The HandBand concept received confirmation of competence and praise from the healthcare professional after the two-week TRL #6 trial in a clinical setting. Further in-person testing with patients could help to add to and clarify this conclusion.

The concept did not meet the strength requirements set out in chapter 6, TRL #4. Using both Ninjaflex, and Ninjatek Cheetah material did not produce a part that was stiff enough to meet the grading structure of the TheraBand coding. These strength requirements are based on information extracted from a study by Rice, Leonard & Carter (1998). However, further studies supporting this publication is scarce. There should be more research into hand strength requirements.

Individually, a single HandBand meets the 20USD target set out in the project requirements. When more units of the product are purchased, the price can increase past the target. Thus, care should be taken to offer a product suite that reflects the purchasing power and needs of the customers.

The integrated modeling approach was designed to translate customer requirements into a 3D print in the shortest possible time. This is achieved with a 3D modeling method and a connected printer farm. While this in theory should reduce the costs incurred to produce a 3D-printed product, this comes at the price of functionality and control over the print preparation process, as outlined below in figure 64.

There is a very slight increase in the print durations and cost (see chapter 6, TRL #6). While the process of transferring files to the 3D printer has removed manual steps, different material colours must still be loaded into the printer to match the order. This can add cost. Should one part of the system, or the internet connection fail, the printing facility could come to a standstill.

Based on these shortcomings, the most suitable application for this envisioned process are those with:

- Small parts, one-off
- Single material with pre-set and trusted profiles
- Low-complexity prints
- Multiple parts that will be printed the same way

The integrated modeling approach was designed to translate customer requirements into a 3D print in the shortest possible time. This is achieved with a 3D modeling method and a connected printer farm. While this in theory should reduce the costs incurred to produce a 3D-printed product, this comes at the price of functionality and control over the print preparation process, as outlined below in figure 64.

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Based on these shortcomings, the most suitable application for this envisioned process are those with:

- Small parts, one-off
- Single material with pre-set and trusted profiles
- Low-complexity prints
- Multiple parts that will be printed the same way

The Kijenzi Customizer was developed so as to allow Kijenzi customers to specify product characteristics to suit their individual needs and tastes while ensuring low costs. The developed solution does bear negative aspects which should be addressed for the system to be successful:

- Time and effort is required to create the product visualizations to enable the webshop’s visual configurations
- There are a finite amount

of product configurations available with the current approach. Should a customer desire something outside of the offered presets, the standard modeling approach must be employed.

- The method of communicating the properties or performance of the device must be made non-technical and simple.

The method of communicating the properties or performance of the device must be made non-technical and simple.
8.4 Conclusions

This topic will revisit the research questions posed in this thesis to provide final project conclusions.

Main research question

This main research question for this design project asks to what extent can FDM 3D printing be applied to assist Kenyan occupational therapists in the provision of therapy to individuals with hand dexterity and strength challenges.

3D printing can enable the production of low-cost, patient-specific products that can be used in the provision of therapy to individuals with hand dexterity and strength challenges. A supporting service system can increase this impact by allowing for the creation and production of these products in a low-cost manner.

Desirability, feasibility, viability

The proposed concepts also meet IDEO’s trifecta (figure 64), meeting the final evaluation outlined in chapter 1.3. The expert evaluations demonstrate that the concepts are desirable.

The proposed product/service/system concept of the HandBand, Kijenzi Customizer, and the Integrated Approach have been designed to meet these conclusions from the research chapter. The effect of these designs allows for healthcare professionals to provide higher quality, patient-specific healthcare in a cost-effective manner using FDM 3D printing. With this thesis’s proposal, FDM 3D printing is once more proved as valid and a capable method to produce low-cost goods for the primary healthcare industry in line with the Frugal Innovation Methodology.

Contributions to new knowledge in the field

This thesis concludes with several novel articulations of FDM 3D printing for occupational therapy in Kenya, developed in line with the Frugal Innovation Methodology.

An analysis of the context in which the methodology was performed, and next the low-cost enabling technology of 3D printing was studied. Defining a problem statement relating to these topics offered an opportunity for a frugal product innovation. Value and affordability were maximised in the design process to deliver this innovation.

Through analysis of current tools and consultation with healthcare professionals, underlying issues in common occupational therapy equipment were pinpointed. The HandBand hand exerciser concept is proposed to overcome these shortcomings and offer an improved way for patients to rebuild hand strength and mobility.

A new method to improve patient recoveries in occupational therapy was developed. Based on research involving contextual study of occupational therapy in Kenya, and in conjunction with expert interviews, the core patient needs and root problems associated with OT in Kenya were brought to light. The Kijenzi Customizer enables patient-specific products to be visualised, ordered and produced in low-resource settings.

The Integrated Approach provides Kijenzi with a method to enable customized products to be produced in a more efficient manner, which can contribute to lower product cost. Through analysis and evaluation of the company’s current procedures and exploration of forefront technologies, a means to help the company expand and grow was envisioned with the modeling approach and connected-farm concept.
Validity of the research conclusions

The contextual study of Kenya made use of online material and expert interviews. As such, the conclusions for chapter 2’s conclusions to the question “how can Frugal Innovation best be applied to the Kenyan context?” should be cautious of containing gaps in knowledge and bearing bias. A field trip to the Kisumu location would ensure to enrich the research depth and conclusions.

While the conclusions for the research question in chapter 3 “what pathologies of the hand exist, and how is therapy performed?” are valid, further user-research is necessary to see the full picture of the context.

The research method for chapter 4 concerning additive manufacturing was not dependant on a field trip or user-research. The research method was instead able to consult online media and SMEs in a meaningful way and so the conclusions can be seen to be representative of the full picture.

Design process

To overcome the restrictions facing global travel which were present at the time of this thesis, a digital supply chain and online communications replaced in-person testing of the concept in the context. The project was able to conclude in a meaningful and valid way with the final expert evaluations.

Because of these factors, the design process can be seen as theoretically sound and practically validated thanks to the input of the experts. To build on this, there could be an in-person user trial completed in the context of Kenyan healthcare with the designer present.

The application of the TRL methodology had a positive and successful outcome with regards to the volume of the output (developing three articulations of product/service/system). Working in such a controlled and gated process ensured that design cycles were focused and efficient, so that the project requirements could be satisfied in the given time.

A limitation of the TRL methodology is that it creates an environment where exploration and experimentation can be subdued. In order to meet the regular validation stages set out throughout the process, the workflow is conservative priorities results over experimentation.

In the context of this thesis, I am satisfied that sufficient exploration and ideation was carried out to create unique and novel product solutions. Designers should however carefully consider whether the TRL is aligned with their ambitions the context of a project.
8.6 Recommendations

The following recommendations have been prepared which address the identified shortcomings in the design proposal and method. Listed below is how to build on the findings and conclusions from this thesis.

The HandBand product

To maximise the security of the HandBand’s fit on hand tools, perform a more in-depth and extensive sampling and measurement activity. This will establish a more representative sample of the dimensions of common hand tools.

With clinical insight, reassess the hand strength requirements for patients undergoing hand therapy. Use this insight to re-evaluate the strength grading system for the HandBand and define a framework for strength progression and goals.

Inconsistencies in the 3D printing process meant that the resistance forces for the HandBands were not as expected. More research is needed to be able to standardise product function.

Perform further clinical testing of the handBand, focusing on the patient and their product experience throughout an entire rehabilitation.

Launch the HandBand product as a stand-alone product without the supporting customisable system. In this trial, prepare a suite of all five, or a determined selection of strengths before integrating the online system. This will assist in seeing the true value of the concept without extraneous noise.

The Kijenzi Customizer

User testing with healthcare professional should be performed to assess the functionality of the site.

To reduce the manual steps in producing customised products, an automatic link should be created which inputs the data from a customer’s order into the parametric model in F360.

The Kijenzi customiser to assess whether the conclusions on its success are limited to the HandBand only.

The Integrated Modeling Method

Further testing of a more diverse portfolio of products should be performed with the Integrated Modeling method.

With little extra effort required to 3D model in a parametric manner, a study could trial beginning all parts in this manner and evaluating the potential to implement parameterisation/customisation across all Frugal Innovations.

The Integrated Method should remain on the lookout for updates to the manufacturing workspace of Fusion360 to maximise its functionality.

The connected farm system

PRUSA research has confirmed the release of a dedicated connected-farm system later in 2021. This system is designed specially for the PRUSA printers used at the Kijenzi farm. It is advised to explore the functionality of this system when it is released, and see how it can be integrated with the HandBand and Integrated Method.
8.5. Reflection

It is frightening to see just how quickly a week can disappear, just as the last week of this thesis has. Yet, when I think back to the early days at the start in wet November weeks, Vrijmibo really could never come quick enough. What also feels like it happened in a heartbeat is my time in Delft.

When I finished my bachelor studies, the weight of work was on my shoulders. I was not in love with my location, didn’t feel peace with my network, and hadn’t found something that I wanted to spend the rest of my life doing. So, I came to Delft for more breathing room. When I wrote my application letter for the program, I detailed my plans to specialise in 3D printing during my studies. The plan culminated in a graduation assignment which would develop a product using 3D printing. I am fully certain that I have met this plan and my goals. I can feel pride that younger me knew exactly what he was talking about, even if he really had not so much as an idea about how life would be in Delft. Moving country scared me to death, but I lept at the experience with blind faith and a plan.

This graduation project also required a huge amount of blind faith. It concerned a new context, a new country, a new field of healthcare, and new people. There was no Brightspace lesson plan written for this topic. Maybe the biggest learning from the thesis was to trust my own intuition, but give it a healthy dose of consideration and make a plan of action. Have confidence in your own ideas and thoughts, no matter how much uncertainty you feel - but come up with a plan of action to act on them. Conditions will never be perfect, you might not get the ideal start, outcome, or result - but trust that if you can come up with a plan, is a good way to start. Plus, while I might have both a plan, and have no clue, to others it might seem that I have a plan.

I experienced that having the right people around you can do more for a project (or your own life) than intrinsic skill or devotion. My friends and family played an instrumental part in my thesis. I did also learn the importance of giving your time to others. This project claims to have helped people, but at the end of the day, the concept lies in the hands of others who decide if it will make an impact. It is most likely going to end up as a self-serving venture to get me a degree. I often felt during the project that I was burdening people with my research - taking time and effort from busy people time and time again. On several occasions I used back favors which I had built up from helping other people with their thesis. This reframes my way of thinking, to see giving assistance or skills to people not as a selfless act, but as necessary and something that should be done as often as possible. Does this giving and taking literally ensure balance in the universe? Or does the sense that you are in balance because you gave what you took influence your own comfort and worldview? That is hard to say after working for a week straight - but I am sure I can come up with an answer in the coming summer months.

I extended my studies at TU Delft by one year. This incurred not only extra cost, but also removes the ability to acheive Cum Laude. While this achievement was not my ambition starting my studies, knowingly shooting yourself in the foot is not a decision to take lightly, and it comes with a feeling of shame. This was a conscious choice though - I didn’t feel ready to go into the world in the timeframe that I was supposed to. There was too much of the world in Delft to see and experience. I got to do a lot of that during my thesis.

The pinnacle of the project for occured me was while I was driving to collect camera equipment for the showcase video. I truly felt Ikigai - the Japanese principle meaning “a reason for being”. 3D printing, filming, visualisations and so on are my happy place. I could take control of my own actions in my own skin, with my own skills. Increasingly over the last few months I feel like I am in exactly my right place at the right time embracing blind faith, with the right people and a plan.

"None but the brave deserve the fair.”
- John Dryden
References


1. **Performance**

1.1. The device must be structurally stable to afford a maximum resistance strength of $X$ Newtons.

1.2. The device should allow a minimum ceiling of $88.97\text{N}$ of resistive force.

1.3. The device should allow a user to make as close to a full fist as possible during gripping prehension.

1.4. The device should allow the user to form a fist against a resistive force, in a manner that employs the hand’s extensors and flexors to flex the fingers, the intrinsic muscles to contract the fingers at the MCP joint, and the Flexor pollicis brevis muscle to flex the thumb.

1.5. The device should allow the resistance force to be identified, and changed.

1.6. The device should achieve grip strength training through a “meaningful” activity of daily living.

1.7. The device should incorporate a means to identify and improve progress by means of degree of mobility or resistive strength.

2. **Environment**

2.1. The device must withstand temperatures of $80^\circ\text{C}$ with no structural deterioration or change in appearance.

2.2. The device must withstand UV degradation and colouring.

3. **Life in service**

3.1. The device should bear a service life of 2 years.

3.2. The device should afford 25,550 use cycles (50 daily cycles).

4. **Maintenance**

4.1. The device must be maintainable, disassemble, or repairable with basic tools (phillips/flat head screwdriver, allen key (metric size 2mm-6mm), pliers, snips).

4.2. The device should be easily repairable with basic skills and mechanical knowledge.

4.3. The device should ensure that multiple types/sizes of fasteners and fixers can be used interchangeably if required.

4.4. The device must be maintainable and repairable with commonly found consumable spares (zip-ties, rubber bands, strings, tapes).
5. Target production costs
   5.1. The device should be produced for less than 20,00 USD (16,49 Euro, 2,203,00 Kenyan Shilling)

6. Transport
   6.1. The device should be compact, enabling simple carrying in personal bags.
   6.2. The device should not contain loose parts which can be lost during transport.
   6.3. The device should not contain delicate protruding parts that can be damaged during transport.
   6.4. The device should withstand vibration and impacts arising from driving on uneven road surfaces.

7. Packaging
   7.1. The device should be packaged to ensure safe transport from the production facility to the health centre or patient’s home, considering the environment (high heat, humidity, dust) and rough transport.

8. Quantity
   8.1. The device should be produced to supply each of Kenya’s 900 registered occupational therapists with multiple sizes of the device as needed.

9. Production Facilities
   9.1. The device will be produced in its entirety in the Kijenzi Kisumu 3D printing farm using desktop printers such as the Prusa i3 MK3s.
   9.2. The device must be produced using commonly found 1.75mm thermoplastics, such as PLA, PETG, and ABS.
   9.3. The device should allow for the customer to easily select/configure design characteristics without the need for advanced 3D design software or CAD skills.
   9.4. The device must consider print failure in its embodiment to protect the printing machinery from crashes, and ensure production continuity.
   9.5. The device should minimize post-processing and assembly steps.

10. Size and weight.
   10.1. The device or its components should not exceed a volume of 250mm x 210mm x 210mm.
   10.2. The device must minimize the weight, while still meeting the minimum structural requirements (plus a factor of safety).
   10.3. The device must not weigh more than 1.75kg.

11. Aesthetic appearance and finish.
   11.1. The device must be visually styled to integrate into the healthcare setting.
   11.2. The surface finish should be smooth and free from gaps, holes and printing blobs.
   11.3. The product should be easily cleaned to preserve a clean surface finish.

12. Materials
   12.1. In Kenya 3D printed products that make use of external extraneous parts such as fasteners, springs etc. must consider the use of multiple non-homogenous parts that can achieve the same purpose.
   12.2. The device should be printable with a wide range of common FDM 3D printing filaments, including ABS, PLA, PETG, ASA & PC.
   12.3. Ideally, these materials should be interchangeably applicable with no major detrimental effect on product performance.
   12.4. Materials should be non-toxic.
   12.5. Materials should be non-flammable.
   12.6. Materials should be resistant to surgical spirits and common disinfectants.

13. Standards, rules and regulations
   13.1. To ensure timely adaptation to the market, this device should remain classified as a Class A device under the Kenyan Ministry of Health, Pharmacy and Poisons board.
   13.2. Full design documentation must be upheld to assist with certification in later stages.

14. Ergonomics
   14.1. The product should offer comfortable use when applying large grip forces.
   14.2. The product should sit securely in the hand under grip prehension.
   14.3. The device should consider the anthropometry of the target users and the design/manufacturing method should allow personalization of the device fit these people.
   14.4. The device should allow the fingers digits to flex in various degrees, increasing from the index finger to the pinky finger.
   14.5. The therapeutic intervention need to consider the multi-planar biomechanics of a hand/wrist.
   14.6. The device should include a cognitive ergonomic affordance to suggest the correct use orientation.

15. Safety
   15.1. The device should be demonstrated and configured under the supervision of a suitable qualified and certified healthcare professional.
15.2. The device should not pose a health risk should a component break during use.

15.3. The device should not over-stress joints or cause unwanted side effects as a result of its use.

16. **Reuse, recycling**

16.1. The product should be portable, to allow patients to continue treatment at home.

16.2. The design of components to be 3D printed must consider their printability. Print failure results in waste of material and operator time, and must be reduced at all cost.