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3D PRINTING IN LOW RESOURCE HEALTHCARE SETTINGS: ANALYSIS OF POTENTIAL IMPLEMENTATIONS

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3D PRINTING IN LOW RESOURCE HEALTHCARE SETTINGS: ANALYSIS OF POTENTIAL IMPLEMENTATIONS

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Abstract

3D printing has gained significant momentum in the past ten years expanding into a wide variety of sectors throughout the globe. The technology uses additive manufacturing techniques alternative to the subtractive and formative techniques used in traditional manufacturing. This methodology eliminates significant waste material, greatly improves lead times, and allows for manufacture of customized parts and complex geometries that are outside of normal engineering standards. Furthermore, one small 3D printer can easily be programmed to create a wide variety of parts in different materials. The unique advantages of 3D printing make it especially ideal for use in low resource contexts where many products are either unavailable or imported through complex supply chains. With 3D printing, products can be designed and manufactured locally at lower costs providing the community what they need when they actually need it.

After spending two years in the Peace Corps in rural Tanzania, I realized the need for locally manufactured and culturally appropriate products and equipment. From previous research, it was clear that 3D printing has many potential applications in low resource health applications, and many have already successfully implemented 3D printed parts and products throughout the world. Yet, little has been studied on how 3D printing can be sustainably and functionally implemented into a low resource healthcare system. Without proper implementation and structure, 3D printing will remain largely conceptual and will not meet its full potential.

In this report, I propose three business models for the implementation and structure of 3D printing in low resource healthcare settings: In-House Operator, Independent Operator, and Print Farm. The models were developed based on previous research performed by experts in the field. I, then, set out to test these business models and to better understand the 3D printing environment for low resource healthcare settings.

Ultimately, Kisumu county in Kenya was chosen for the study due to the existing 3D printing infrastructure, the government's interest in utilizing 3D printing in their healthcare system and their need for improved supply of medical parts and equipment. I spent four months in Kisumu county visiting seven hospitals with two 3D printing workshops. Two of the models were tested directly, the In-House Operator model and the Independent Operator model. I worked with local medical professionals, engineers and government officials to create and test medical parts and products. Observations and informal interviews were documented along with prints and print information.

Human centered design criteria were used to assess the business models. All three of the business models proved to have their own distinct benefits and challenges for low resource healthcare applications. Ultimately, they all provide local manufacturing of medical parts and products for local facilities fulfilling the goal of improving medical care with proper medical equipment. However, there are a number of considerations necessary to decide which implementation is the most sustainable in each specific context. Others can utilize these findings to begin implementing more robust 3D printing systems in low resource healthcare contexts throughout the globe.

1 Introduction: 3D Printing and Low Resource Contexts

3D printing (3DP) has been touted as a solution to many of the world's major problems: poverty, hunger, and even climate change (Liang, 2016; Phan, 2015). Throughout the globe, people have begun utilizing 3DP in extraordinary ways; Hydroponic systems for agriculture have been printed in Canada, prosthetic limbs for refugees in Syria, and even, a house in the United States (Phan, 2015; Refugee Open Ware, 2018). Its benefits span throughout all sectors and industries. 3DP's greatest advantage is its potential to completely alter how and where goods are manufactured leading many to call it the next Industrial Revolution (Birtchnell & Hoyle, 2014; James & Gilman, 2015). It may eliminate the need for complex supply chains allowing people to create the parts they need quickly and locally; hence, it has great potential for international development and humanitarian response efforts (Birtchnell & Hoyle, 2014).

1.1 3D Printing

3DP, or additive manufacturing (AM), is a group of manufacturing techniques that use Computer Aided Design (CAD) drawings to build 3-dimensional objects layer by layer. This is alternative to traditional manufacturing which uses subtractive or formative techniques. A CAD model is created and sliced to different thicknesses. The slices are then used as the geometry for each layer and the machine deposits the material in the specified geometries. Various deposition techniques are used depending on the material and outcome required, yet all use similar processes. Some examples include Stereolithography (SLA), Liquid Polymerization (LP), Fused Deposition Modeling (FDM), and Selective Laser Melting (SLM)(Perdana et al., 2018). A number of different materials can be used in 3DP including plastics, resins, metals, and ceramics (Wong & Hernandez, 2012).

3DP offers many advantages compared to traditional manufacturing techniques. The process of 3DP reduces waste material and eliminates the need for tooling design (Petrovic et al., 2011). The 3DP machine builds the part as directed from the computer which requires little to no operator interaction during manufacture. In addition, the same machine can easily be programmed to make a variety of parts with vastly different geometries. Many design restrictions such as overhangs and internal spaces of traditional manufacturing are eliminated in 3DP allowing for more design freedom. Due to its short production time, 3DP is also ideal for rapid prototyping and design adjustments (Bhadeshia, 2016).

3DP offers the possibility to greatly democratize production and manufacturing. 3D designs can easily be shared through the internet digitizing, simplifying and accelerating the supply chain (Berman, 2012). As a result of localized manufacturing, products no longer need to be shipped through complex supply chains, but rather can be produced at a nearby facility. The technology can reduce upfront capital costs and create leaner manufacturing (Naude, 2017; Thomas & Gilbert, 2014). Lean manufacturing utilizes 7 key concepts: Overproduction, Transportation, Rework/Defects, Over-processing, Motion, Inventory, and Waiting. 3DP can significantly impact these concepts. As 3DP can create a final part with only one machine, manufacturing can be localized to more areas greatly reducing transportation needs and associated costs and hazards. 3DP allows for on-demand manufacturing removing overproduction and the need for inventory. Unlike traditional manufacturing which generally produces high quantities at once, 3DP creates small quantities per print and adjustments can easily be made reducing the number of defects and amount of rework needed (Thomas & Gilbert, 2014). 3DP also alters the divisions of labor by making design and manufacture more readily accessible to individuals and communities (Birtchnell & Hoyle, 2014). Figure 1 highlights stages of the current supply chain with potential advantages of 3DP (James & Gilman, 2015).

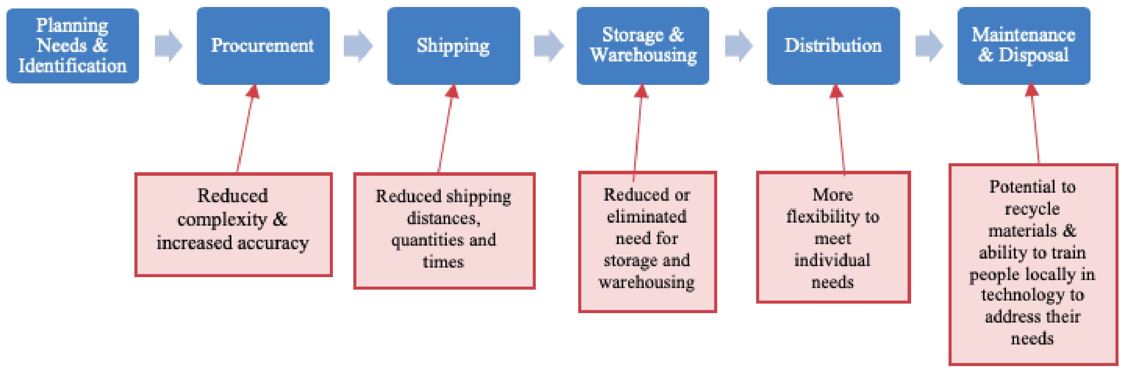


Figure 1. Potential Advantages of 3DP to Current Supply Chain
Adapted from James, E., & Gilman, D. (2015). Shrinking the Supply Chain: Hyperlocal Manufacturing and 3D printing in Humanitarian Response. Retrieved from www.reliefweb.int

Although 3DP has many advantages over traditional manufacturing, it has not yet reached its full potential. Like other emerging technologies, it still has many hurdles before it can catch up with traditional manufacturing methods. Size is one major limitation to 3DP as the print can only be contained within the frame of the machine. Some larger machines exist but are more costly and require more space and electricity (Attaran, 2017a). Due to the layer by layer nature of 3DP, the machine has significantly slower speeds than many traditional techniques (Thomas & Gilbert, 2014).

Traditional manufacturing techniques such as injection molding require an initial investment of time and money to create the mold, but can then produce high quantities very quickly at a very low cost. Alternatively, 3DP does not require any significant investment or setup, but it cannot produce the high quantities at the speed of traditional manufacturing. Injection molding can create several parts in under one minute as compared to 3DP which can create one 1.5-inch cube in approximately one hour (Campbell et al., 2011). Although 3DP technologies continue to advance, it is unlikely that 3DP will ever produce at the speed of traditional manufacturing. Therefore, 3DP is ideal for lower production volumes, customized parts, and smaller part dimensions (Bhadeshia, 2016; Pereira, 2019; Thomas & Gilbert, 2014). Both traditional manufacturing and 3DP have benefits and drawbacks. The two techniques are summarized in Table 1.

Table 1. Comparison of Traditional Manufacturing to 3D Printing

	Traditional Manufacturing	3D Printing
Manufacturing Technique	Subtractive or formative	Additive
Waste Material	Medium to high	Low
Tooling Needed	Yes	No
Lead Times	Long (Months-Years)	Short (Days-Weeks)
Ease of Innovation & Customizability	Difficult	Easy
Ability to print complex geometry	Difficult	Easy
Quantity	High	Low
Speed of Manufacture	Moderate-High	Low
Size of Products	Small-Large	Small-Medium (Restricted by printer size)
Initial Cost of Machinery	Very high	Low-Moderate

There are many 3DP machines available that vary greatly in functionality, durability, size and quality. Generally, the higher quality and more durable printers are more expensive (Attaran, 2017b). However, 3DP technology is predicted to improve greatly over the coming years with much focus on quality, speed and automation. With these advancements, 3DP will become more cost effective and accessible (Bhadeshia, 2016).

1.2 3D Printing for Low Resource Contexts

Although 3DP techniques were first developed over 30 years ago, only recently has there become such widespread global use. In the past 10 years, there has been significant expansion due to advances in the technology and reduction in costs to access the technology (Attaran, 2017a). The 3DP market is predicted to continue growing at over 20% in the coming years with notable expansion in the automotive, healthcare and aerospace industries (Wohlers, 2016). Even with continued growth and accessibility, 3DP has not yet spread extensively throughout the developing world where it is predicted to have large societal impacts.

3DP represents a bottom-up development approach as it improves community participation, expands learning opportunities and localizes financial access (Birtchnell & Hoyle, 2014; Larrison, 1999). There is great potential for 3DP in both humanitarian response and international development. Perhaps most beneficial is its ability to decentralize manufacturing and produce locally. The hyperlocal manufacturing possible through 3DP has been called a “hybrid development strategy” as it reduces poverty through providing goods needed while also improving local capacity (James & Gilman, 2015; Johnson & Magleby, 2004).

Small and medium sized businesses make up 78% of the full-time employment in low-income countries, and small business development has proven to be a key driver of economic growth in these regions (Polak, 2008: USAID, 2016). 3DP offers the opportunity for local manufacturing leading to new business opportunities and new job opportunities with minimal required infrastructure (Campbell et al., 2011; Ishengoma and Mtaho, 2014). It reduces the need for upfront capital investments of time and money and decreases the dependency on foreign supply chains which can be time consuming and costly (Bhadeshia, 2016).

Producing products locally also allows for culturally appropriate designs to be made while lowering costs and providing products that are difficult and expensive to retrieve. A 3D printed infant clubfoot brace was recently developed in response to a high prevalence of clubfoot low resource countries, particularly Kenya. Without the brace, long-term deformities can develop, but in rural areas, braces can be very difficult to find or very expensive. The alternative brace functions properly, can be made locally, and is significantly more cost effective than the alternatives (Savonen et al., 2019). Not only does 3DP allow for culturally appropriate design, but the localization allows for production of what is needed when it is needed (Bhadeshia, 2016; Campbell et al, 2011; Ishengoma and Mtaho, 2014). Refugee Open Ware (ROW) and Field Ready have explored 3DP's on-the-spot capabilities through applications in humanitarian response. For refugee and post-disaster camps, 3DP has been utilized to develop prosthetic limbs, pipe cutters, and water spigots (James & Gilman, 2015; Refugee Open Ware, 2018).

1.2.1 Examples of 3D Printing in Low Resource Contexts

Although 3DP has yet to be fully realized in low-resource contexts, there have been many trials to begin spreading the technology throughout the world in both international development and humanitarian response contexts. Below are some of the most relevant and noteworthy trials of 3DP in low-resource contexts.

The Maker Movement for Maternal, Newborn and Child Health was launched in 2014 through Concern Worldwide, a humanitarian organization that focuses on emergency response, child survival and nutrition. The project's aim was to connect clinicians with biomedical engineers at Kenyatta National Hospital in Nairobi, Kenya in order to develop low-cost, locally-fabricated medical spare parts (Concern Worldwide, 2016). One manufacturing technique used was 3DP. The major achievement of the project was a suction machine that was approved for clinical testing (Concern Worldwide, 2016).

TechforTrade is a UK-based charity which focuses on utilizing emerging technologies such as 3DP to empower impoverished communities (TechforTrade, 2019). They created a low-cost, open source, durable 3D printer that is made from e-waste and have ongoing development of recycled PET-filament using plastic bottles (Rogge et al., 2017). In 2015, they piloted the Digital Blacksmiths Network in Africa (Kenya, Ghana and Tanzania) with the goal of creating a collective of engineers and entrepreneurs and providing them access to training, technology and support (Digital Blacksmiths, 2019). The network has helped to establish three companies all of which are utilizing and expanding 3DP technologies in their respective countries: African-Born 3D in Niarobi, Kenya; STICLab in Dar es Salaam, Tanzania and Klaks3D in Accra, Ghana (TechforTrade, 2019).

As discussed previously, Field Ready and Refugee Open Ware are focused on humanitarian response applications utilizing 3DP. Field Ready is working to localize manufacturing in humanitarian response in order to create what is needed where it is needed. Their research has spanned various sectors and countries such as prosthetics in Syria, solar lighting in the Philippines, spare IV bag hooks in Haiti (James and Gilman, 2015). Refugee Open Ware has focused on training in these response areas (Refugee Open Ware, 2018).

Gearbox is one of the largest makerspaces in Africa and is located in Nairobi, Kenya. As a makerspace, it offers locals the use of digital manufacturing tools such as 3DP to design, test and prototype their ideas (Gearbox, 2019). Furthermore, they hold trainings, provide technical support and offer mentoring and incubation space for new businesses (Gearbox, 2019). In addition to Gearbox, 1,750 makerspaces called ‘Fab Labs’ (digital fabrication laboratories) have opened in over 100 countries. The Fab Labs are part of MIT’s educational outreach and serve as a technical prototyping platform for people to learn and innovate. They offer industrial-grade tools, open source software and connection to a global community (Fab Foundation, 2018). They offer 3DP technology along with a number of other fabrication tools and technologies. The model has been effective in spreading access to digital fabrication technologies, but many of these facilities are located in major cities and do not provide opportunity for rural or lower-resource areas (Savonen, 2019). There are also local companies such as QTron Industries in Nairobi which create and sell personal, easy to use locally-designed 3D printers. These companies also tend to be located in major cities and generally, are not accessible to locals in more rural areas.

Academic studies on the use of 3DP in development that have physically been performed in developing countries are few and far between. One published study was performed in Tansen, Nepal by the University of Michigan. A commercially available 3D printer was used at a mission hospital for 3-months with an operator/trainer from the University of Michigan. Local technicians were trained in 3D designing, modeling and printing. A wide variety of parts were created and a few such as a push-button replacement for a pulse-oximeter remained in use after the trial. The hospital retained the printer, but no additional information regarding the project has been published (John et al., 2017).

Kijenzi is a startup social venture expanding 3DP in Kenya (Kijenzi, 2019). Cofounder, Ben Savonen, has led significant research through Pennsylvania State University to enhance the understanding of the 3DP environment in low resource settings. The research has focused on understanding what low resource communities need, what parts can be made successfully using 3DP and the intersection between the two (Kats et al., 2019; Savonen, 2019). Much of their investigation has been centered around healthcare products in Kisumu county in Kenya. Not only does Kijenzi create needed medical supplies using 3DP, they also train Kenyans to utilize the technology. In conjunction with Michigan Technological University, Kijenzi created a portable, low cost, resilient 3DP designed for use in humanitarian response (Savonen et al., 2018).

3DP is a promising technology and may have a significant role in manufacture in low-resource settings. From manufacturing specialty goods to creating local business to providing on the spot medical spare parts in a crisis zone, 3DP has applications that span far and wide. However, much research is still needed in order to determine how to successfully implement 3DP in these various settings, specifically which business model should be used to effectively utilize the technology.

1.3 Project Motivation

The motivation for the project was prompted by my experience as a United States Peace Corps Volunteer in the United Republic of Tanzania. The country of Tanzania is located in Eastern Africa on the Indian Ocean. It is bordered by Kenya, Uganda, Rwanda, Burundi, Democratic Republic of Congo, Malawi, Zambia and Mozambique as seen in Figure 2.

Tanzania is a large country comprising 947, 300 km^2 with over 55 million people from over 120 ethnic groups (CIA, 2019b). Although a diverse country, Tanzanians feel a strong sense of national identity and connection (Malipula, 2014). In addition to a diversity of people, Tanzania is home to a diverse landscape comprised of the great plains of Serengeti National Park; numerous mountain ranges including Mount Kilimanjaro, the highest point of Africa; the jungles of Gombe National Park; and the Ngorongoro Crater, the world's largest intact caldera (Worldatlas, 2019).

Figure 2. Map of Africa highlighting Tanzania.
Image source:
https://www.worldatlas.com/webimage/countrys
/africa/tz.htm

Tanzania is a young and rapidly growing country with over two-thirds of the population currently under 25 and one of the highest birth rates in the world at 5.01 children born per woman (Tanzania Population, 2019). However, even with economic growth at over 5%, the high population growth has caused poverty rates to remain around 26% (CIA, 2019b; National Bureau of Statistics, 2019). The country currently lacks infrastructure to properly educate its growing young population. Recently, Tanzania implemented free secondary education increasing secondary school enrollment in alignment with the United Nations Sustainable Development Goals (SDGs). However, they are unable to accommodate the growing enrollment, and there continues to be a great lack of educators, school resources and career options available (Human Rights Watch, 2017).

During my time in the U.S. Peace Corps, I spent two years teaching secondary school in central Tanzania in Kijota, a rural village in the Singida region. Kijota is highlighted in the map in Figure 3. The Singida region falls in the semi-arid area of Tanzania. Kijota is a small village with only about 3,000 people living within the village and 11,000 within the ward. A majority of people work in farming and agriculture. However, due to the arid climate, agriculture is limited and challenging. Due to the small size of the village, there is no health clinic, no village market, and very few shops. In order to purchase most goods and to access services, people must travel to Singida town (29km) or one of the neighboring villages (5 km minimum). However, the village has fairly consistent electricity through TENESCO and very good access to all cellular phone carrier networks (Peter, 2016).

Figure 3. Map of Tanzania indicating Kijota Secondary School.
Image Source: Google Maps

Throughout my service, I taught a number of STEM (Science, Technology, Engineering & Math) subjects at the secondary education level, including Biology, Mathematics, Physics, and ICT (Information and Computer Technology). The Tanzanian Ministry of Education has pushed ICT development in recent years (Chatama, 2014; Maseko, 2017). Through the initiative, many schools are being provided with desktop computers, laptops and wireless internet. Kijota Secondary School was included in the initiative and was given 2 computers which could each work remotely on 4 screens, a wireless router with limited wireless access, and 5 laptop computers. One major issue to the ICT development is a lack of teachers trained in ICT. However, many teachers and students showed interest in learning ICT, and many teachers had self-taught ICT skills. Before I arrived, students had studied for ICT on their own with one short, 15-year old textbook. Another issue to the ICT development is a lack of skilled technicians and a lack of parts to repair the computers. Throughout the two years, only half of the computers were ever usable and no technician ever came to look at the computers.

In addition to teaching, I was also involved in a number of secondary projects including school library development, youth empowerment clubs, science laboratory activities, construction of a recycled water-bottle water catchment tank, and creation of reusable menstrual pads for female students. One of the major challenges faced in completing all of these projects was the difficulty of obtaining tools, parts and materials needed. Projects and teaching required basic items such as spigots, knobs, snaps, and simple teaching aids such as models and rulers. Yet, these items were difficult to procure in Singida Town (the capital of the region, let alone Kijota, and going to town required transportation costs, travel time and additional time in town to search for many of the items. In addition, many items were expensive to purchase outside of Tanzania's major cities, such as Dar es Salaam.

3DP offers a unique potential in places such as Tanzania with its ability to create local jobs, improve the accessibility of a wide variety of products and expand knowledge of new technologies. In towns such as Singida or Kijota, community members could create customized parts specific to their needs. Many items previously difficult to obtain such as spigots and school and medical equipment could be created locally and new jobs would be created in the process.

2 Healthcare Applications of 3D Printing in Kenya

3DP shows remarkable prospective for manufacturing in low-resource contexts spanning a wide range of sectors. Much of the previous research on 3DP in low resource contexts has focused on healthcare, and for good reason, as 3DP has the potential to address many of its complex challenges particularly in low-resource areas. It has the potential to reduce costs, repair broken-down equipment, simplify the procurement process and provide locally appropriate designs (Savonen, 2019). The uses of 3DP for healthcare applications in low resource settings are numerous, and many 3D printed products have been implemented in healthcare throughout the world. However, how to properly implement 3DP technology into low resource areas has yet to be researched.

Based on previous research and other's experiences, I have proposed three business models for the proper implementation of 3DP in low resource healthcare settings. I then set out to test those business models in Kisumu, Kenya utilizing IDEO's human centered design criteria.

2.1 3D Printing for Healthcare in Low Resource Contexts

In African countries, fewer than 50% of people have access to modern healthcare facilities (Clausen, 2015). Medical devices and equipment are often among the most needed items in low-resource settings. In Kenya, medical facilities were found to carry only 77% of the equipment deemed necessary by the WHO (IHME, 2014). Without proper medical equipment, medical professionals cannot perform proper medical care (Perry & Malkin, 2011).

With over 95% of medical equipment imported from other countries, low resource areas face extremely high costs for medical devices and equipment which include shipping and handling, storage, taxing, and inflation rates (Malkin, 2007; Savonen, 2019). All of which could be alleviated through localized manufacturing with 3DP which would ultimately reduce the costs of medical devices and equipment (Baden et al, 2015).

In addition to a lack of equipment, many low resource areas face difficulties maintaining equipment. According to Perry and Malkin (2011), over 40% of medical equipment in low resource areas is broken down or out of use. Maintaining imported devices and equipment can be particularly challenging because there is often a lack of spare parts (World Health Organization, 2006). With 3DP these parts could be created to exact specifications (Bhadesia, 2016). With local input, 3D parts can be made that are both needed by the facilities and more culturally appropriate (Malkin & Keane, 2010).

2.2 Proposed Business Models for Implementing 3D Printing in Healthcare Systems

Previous research on 3DP for healthcare has focused on its potential uses, and many have created and implemented useful designs such as prosthetic limbs in Syria and a clubfoot brace in Kenya (Refugee Open Ware, 2018; Savonen et al., 2018). However, little to no research has been performed on HOW to properly implement 3DP technologies in low-resource areas. Who will operate the 3D printer? Where will the printers be located in relationship to medical providers and patients? Who will be responsible for the printers? How will operators be trained in 3DP? How will this be sustainable? These are all questions that have yet to be answered. Although there are many revolutionary designs and proposed uses for 3DP, their actualization will remain largely conceptual without the research and development into proper implementation systems.

Therefore, I have proposed three business models for the implementation and utilization of 3DP. The three models are based on previous strategies of implementation and research in the field. The three models are as follows:

1. In-House Operator
2. Independent Operator
3. Printer Farm

2.2.1 In-House Operator

Medical facilities would have their own printer(s) on hand and print the parts themselves. In-house biomedical technicians or engineers would operate the machines at the hospital or medical facility. In this model, the production and manufacturing are as close as possible to the end users, and medical professionals have the possibility to directly influence the design process. Because the engineers and technicians are already employed within the hospital, they have an intimate understanding of the parts and equipment, as well as a strong relationship with the medical professionals. With the machines in the facility, engineers and technicians can work with the medical professionals to easily create, test and adjust parts required throughout the hospital.

The research done by the University of Michigan in Nepal used this model and reported that "installation of a 3D printer and training in CAD software has proven beneficial in a resource limited hospital (John et al., 2017)." However, proper training of engineers and technicians is required. Due to their already large workload, engineers and technicians would use the 3D printer as needed resulting in low production volumes. Each medical facility or a group of facilities would need to purchase one or more printers for use, and the printers may be difficult to service based on location. The facilities would need to have proper electricity connection eliminating some more rural facilities.

2.2.2 Independent Operator

An independent operator would be some individual – engineer, entrepreneur or small business – who owns and operates their own private printer and provides medical parts and products to local, nearby hospitals. Most often the independent operator model would involve an already established small business adding 3DP to their business. The machines remain local and nearby to end users, but operators do not have as direct of communication with end users such as patients and medical professionals. Operators may have some knowledge of the local health facilities, but would not have the intimate connections of in-house staff making the design process more challenging. Alternatively, the independent operator could potentially spend more time focusing on printing than an in-house engineer and therefore, could produce at larger capacities than at the hospital.

A supply chain would be implemented in order to design, manufacture and deliver the needed parts to the local facilities. The facilities would need to order and purchase from the operator directly and each operator would purchase their own 3D printer(s). Customizability and altering of designs would be available, but there would be longer turnover time than with the printer located in the hospital.

2.2.3 Printer Farm

The printer farm model utilizes multiple 3D printers set up in one location. The farms would be located in larger cities and would provide to a group of medical facilities, such as those in the district. A company would run the print farm with few operators working varied shifts. The operators would have significant training on the machines, but less knowledge of the medical facilities, systems and staff as the other two models. The operators would focus on design and printing and could run many machines at one time allowing for a significantly higher production capacity than the other two models.

A greater initial investment would be required, as many printers would need to be purchased and a new employee would need to be paid. The farms would require higher energy requirements with multiple printers and would need more consistent electricity to produce efficiently. The farms would be located in larger cities, farther away from rural facilities. Therefore, the farms would be farther from the end users, but servicing could be performed in-house.

The three proposed business models each have their own unique advantages and drawbacks which are highlighted in Table 2. I set out to study the potential for implementation of 3DP using these models.

Table 2. Summary of the three proposed business models for a low resource healthcare system

	Hospital Operator	Solo Operator	Print Farm
Proximity to End Users	Very Near	Near-Moderate	Moderate
Proximity to Servicing	Far	Varies	Near
Operator Background	In-House Biomedical Engineer or Technician	Local Entrepreneur or Engineer	Trained Company Employee
Operator's Hospital Knowledge	High	Moderate-Low	Moderate-Low
Production Capacity	Low	Moderate	High
Who Pays for Printer	Hospital	Operator	Company
Number of Printers	Few	Few	Many
Number of Medical Facilities Supplied	Few	Varied	Many

2.3 The Study

In 2018, I spent 4 months in Kisumu, Kenya from August to December testing the implementation of the three proposed business models and their effectiveness in the Kisumu county healthcare system. Two different 3D printers were used for the study: the Kijenzi printer, created for low-resource, low-access settings such as humanitarian response and the QTron, a Kenyan-made printer from QTron Industries in Nairobi. IDEO's criteria for human-centered design was used to evaluate the tested business models. The methods used to complete the study are described below.

2.3.1 IDEO Criteria

Three criteria were used to compare the sustainability and functionality of the business models tested in the study:

1. Desirable
2. Feasible
3. Viable

These criteria are based on IDEO's work on human-centered design (HCD) which indicates that successful innovation lies at their intersection (IDEO, 2009). This model has been used previously to evaluate both products and projects, and it emphasizes the needs and desires of the end users (Brown, 2009).

Desirability is argued to be the most important criteria, yet it may be the most difficult to evaluate (IDEO, 2009). It is concerned with how the solution satisfies the needs of the end users. It poses the question, What "makes sense to people and for people" (Brown, 2009)? This criteria is particularly complex because there is such variance in the desires of not only different cultures, but also different individuals. The following questions have been identified to evaluate desirability of a solution (IDEO, 2009):

- Will this solution fill a need?
- Will this solution fit into people's lives?
- Will this solution appeal to the people?
- Will the people actually want this solution?

The next criterion, feasibility, focuses on what is "functionally possible in the foreseeable future" (Brown, 2009). Feasibility considers the technology, the organizations, and the infrastructure available to implement the solution. Three questions were identified to evaluate feasibility (Brown, 2009):

- Is the technology available and within reach?
- Is the infrastructure available for the solution?
- Are the organizations prepared to implement the solution?

Viability, the final criterion, examines the economics of the solution and is therefore, especially important when considering low-resource settings. To determine viability, costs, profits, time, energy and resources are all considered. The following questions were identified to evaluate viability (Brown, 2009):

- Is this a worthwhile use of resources?

- How much does the solution cost and who pays for what?
- Will the solution align with the organizations' strategic goals and objectives?

This framework was used to assess data and information collected from the study.

2.3.2 Site Selection

Kenya was selected for the study because of its existing 3DP infrastructure and its prominence as a leader in technology and innovation in East Africa (AB3D, 2019) Kenya is Tanzania's neighbor to the north as seen in Figure 4. Tanzania and Kenya have many geographical, cultural and societal similarities, therefore, I was able to utilize much of the knowledge and experience I gained during my Peace Corps service in completing my project in Kenya.

Kenya covers an area of 580,367 km^2 with a total of 48 million people making it considerably smaller than Tanzania with a more concentrated population (CIA, 2019a). The wealth inequality is considerably more distinct in Kenya with 46% living below the poverty line and 40% unemployed. With high unemployment and over 60% of the population under the age of 24, both Tanzania and Kenya are in need of new economic sectors for the large population of youth to enter the workforce (DFID, 2017; United Nations, 2016).

Figure 4. Map of Kenya.
Image Source: https://www.alamy.com/stock-photo/kenya-map.html

Kenya's capital city of Nairobi is home to QTron Industries, AB3D, Kuunda 3D and other companies that are creating, developing and utilizing 3DP. Although Kenya is leading East Africa in 3DP development, 3DP has barely been utilized or explored outside of the capital city of Nairobi. Therefore, it was decided to test outside of Nairobi in a setting more representative of the entire country in Kisumu, Kenya's third largest city. It is located on the shores of Lake Victoria and was once a hub for trade in East Africa (Amlani, 2019). As one of the larger cities, Kisumu has the infrastructure to implement 3DP. Technology innovation spaces such as LakeHub and FabLab Winam are changing the environment in Kisumu and opening the doors for new innovation and development. Unlike Nairobi however, Kisumu is surrounded by more rural districts and more accurately depicts the population as a whole. Kisumu offers the opportunity to test outside of major international supply chains and understand the needs of a greater number of people.

Research and development performed by Kijenzi has greatly advanced the 3DP environment in Kisumu. Government officials, medical professionals and medical facilities in the county have experience with 3DP and have shown interest in advancing its use making it ideal for the project site.

2.3.3 3D Printers

Two different printers were used in the study. The Kijenzi 3D printer referenced above was chosen because of its portability, durability and low cost. The printer was designed for low-resource, low-access settings and has previously been used in Kisumu to produce medical parts. Two of these printers were used. In order to assess the sustainability of 3DP in Kenya, a Kenyan-made printer was used from QTron Industries in Nairobi.

The printers have similar capabilities. Both the QTron and Kijenzi printers utilize fused filament fabrication (FFF) based on the freely available and open source RepRap designs (QTron, 2019; Savonen et al., 2018). The QTron which is pictured in Figure 5 uses the Cartesian RepRap design which is the more commonly used version. The print head moves in the x- and y- axes and the bed moves along the z-axis. The print bed is a 16 cm square and the overall print area is 7680 cm^3.

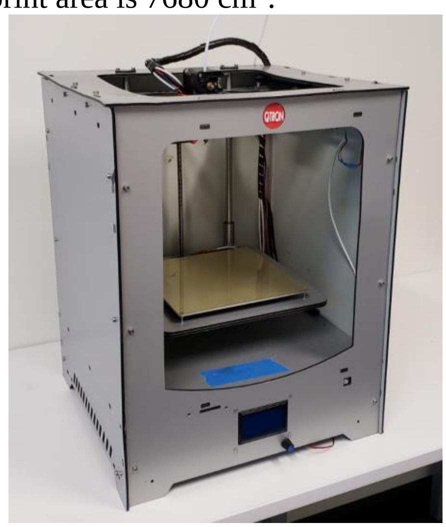


Figure 5. QTron 3D printer

Alternatively, the Kijenzi is based on the delta RepRap design which utilizes three parallel axes of motion, pictured in Figure 6. Three arms slide up and down along parallel rails to move the print head in the x-, y- and z-axes, and the print bed of the Kijenzi remains stationary. The circular bed of the Kijenzi has a diameter of 25 cm with a total print capacity of 12, 266 cm^3 (Savonen et al., 2018). Delta RepRap designs tend to print faster whereas the Cartesian RepRap designs tend to have higher print quality (Anzalone et al., 2019).

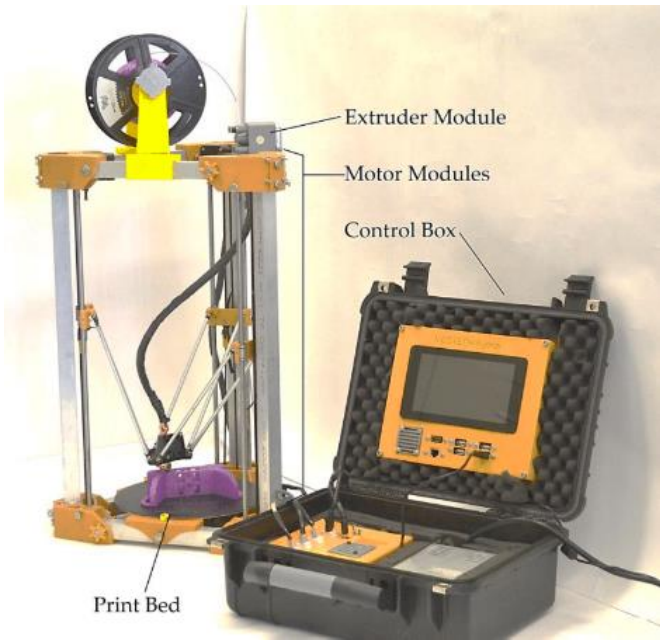


Figure 6. Kijenzi 3D printer
Image Source: Savonen et al, 2018

The QTron manually calibrates whereas the Kijenzi requires manual calibration. Overall, the QTron is a more user-friendly machine. It is fully enclosed and connects to easy-to-use software. It is not made to be transported often. Alternatively, the Kijenzi is designed for engineers with more experience. It requires some coding and many more manual adjustments and steps. The major advantages to the Kijenzi printer are portability, durability and modularity. The printer can easily be broken down into components and easily set up again. All of the components are either basic hardware or 3D printable parts for replacement. The Kijenzi allows for easy adjustment and maintenance for a somewhat skilled user. A summary of the two machines can be seen in Table 3. Both machines have similar print capabilities and were assessed for their usability throughout the study.

Table 3. Comparison of the QTron and Kijenzi 3D printers

	QTron	Kijenzi
Printer Design	RepRap Cartesian	RepRap Delta
Print bed shape	Square	Circular
Print bed dimensions	16 cm x 16 cm x 30 cm	25 cm diameter x 25 cm
Total print capacity	7,680 cm3	12,265 cm3
Calibration	Automatic	Manual
Previous 3DP experience required	Little to none	Some experience required
Source Location	Nairobi, Kenya	???
Cost	$1200	$800 + transport

2.3.4 Testing

Two of the three proposed business models were directly tested during the study at two different locations. The two models tested were the in-house operator model and the independent operator model. These two models require minimal initial investment and only a few printers are required. Because of the close proximity to the hospitals, these two models do not require complex delivery systems or supply chains, can function with only one operator, and allow for significant feedback from end users including medical professionals and patients.

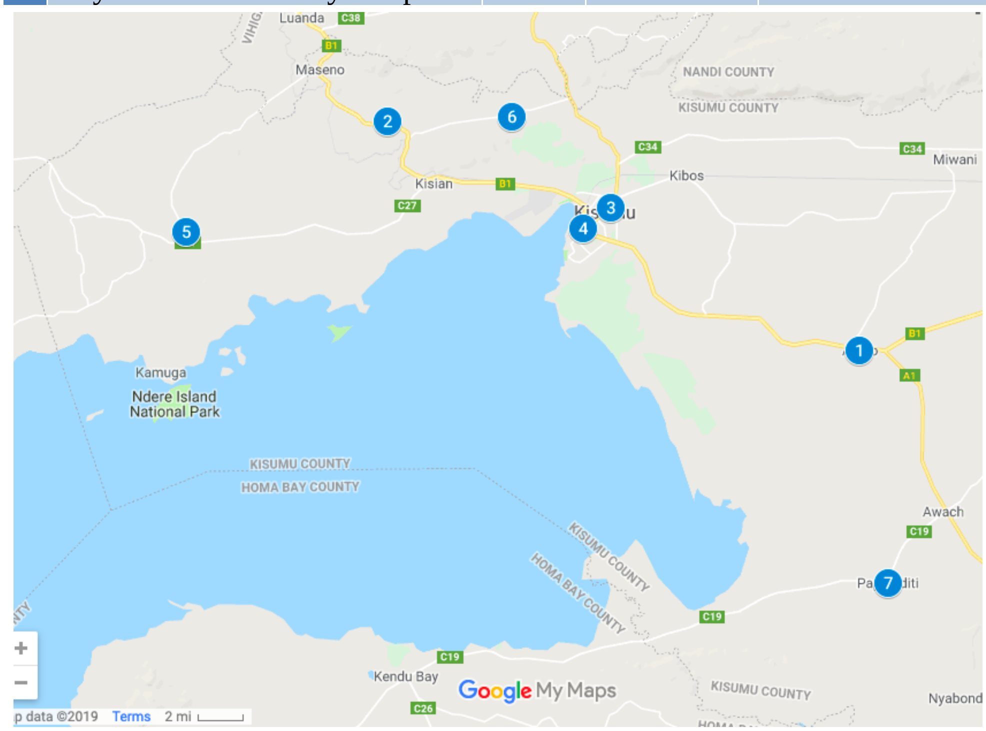
The in-house operator model was tested at Kombewa District Hospital semi-rural, public hospital. It serves all of the lower-level, public medical facilities within the district and is located approximately 35 km, or one hour by public transport, from Kisumu city. The lead doctor at Kombewa District Hospital showed significant interest in utilizing 3DP within the hospital and the hospital provided an office space for development and production using 3DP. I visited Kombewa District Hospital 4-5 days per week using public transportation and worked with the biomedical engineer and medical professionals at Kombewa District Hospital to create and test 3DP medical parts and supplies. The QTron and one of the Kijenzi printers (Kijenzi 1) were utilized at Kombewa.

The independent operator model was tested at my temporary residence in Milimani area in the center of Kisumu city. This area of the city is centrally located and home to many NGOs and small businesses making it safe and accessible. I utilized the 3D printer in Milimani in the mornings, evenings, weekends on on-the-side. The second Kijenzi printer (Kijenzi 2) was utilized in Milimani.

In addition to Kombewa Hospital, I frequently visited 6 other public hospitals in the county as well as a few other smaller medical facilities. Figure 7 lists the 7 major public hospitals visited as well as their level and size and the hospitals on the map.

Figure 7. Summary of the 7 Hospitals visited during the study.
Image Source: Google Maps

	Hospital	Level	Size (# of beds)	Distance from city center (km)
1	Ahero County Hospital	4	30	23
2	Chulaimbo Sub County Hospital	4	26	19
3	JOOTRH	5	457	1
4	Kisumu County Hospital	4	195	0
5	Kombewa District Hospital	4	60	32
6	Nyahera Sub District Hospital	4	16	25
7	Nyakach Sub County Hospital	4	22	43



Throughout the study, prints were recorded along with the printer used, the outcome of the print and any issues encountered. Parts were tested with medical professionals, engineers and patients. Informal interviews were performed in order to understand the county's medical system, as well as to have a better understanding of the needs of the hospitals, medical professionals and patients.

3 Results & Analysis

The proposed business models were tested in Kisumu, Kenya for 4 months. Based on print data, informal interviews, and experiences the models were analyzed. First, the print data from three months of the trial is assessed. Afterwards, the IDEO human-centered design criteria are used to evaluate the three proposed business models and their effectiveness for implementing 3DP into low resource healthcare.

3.1 3D Print Results

All prints were recorded along with the printer used and any issues that arose. Print failures were organized into 4 general categories: electricity, printer, design, and compatibility. A power outage or shortage indicates an electricity failure. Printer failures are related to the printer's function only and are not related to the design. These include filament clogs, belt slips, worn out end stops, broken parts, or malfunctions. Design failures indicate an engineering or design flaw, i.e. too thin of walls, ambitious overhangs, or overly complex geometry. Finally, compatibility problems are neither specific to the printer or the design, but rather a combination between the two. These could be slicing issues or adherence issues that are not attributable to the design or the printer.

Downtime of each printer was also recorded. The Kijenzi printer located in Kombewa was referred to as Kijenzi 1 and the Kijenzi printer located in Milimani was referred to as Kijenzi 2. The data is summarized in the tables below. Table 4 shows the print data separated by month and by printer. Table 5 shows overall print data for the trial, not separated by printer. Print efficiency refers to the percent of prints completed out of attempted prints.

Table 4. Print data for each printer

	Month	Completed	Failed - Electricity	Failed - Printer	Failed - Design	Failed - Compatibility	Total Prints Attempted	Print Efficiency (percent, %)	Downtime (days)
QTRON	*September*	16	5	6	1	0	28	57	13
	October	8	3	8	2	4	25	32	15
	November	NA	NA	NA	NA	NA	NA	NA	ALL
Kijenzi1	*September*	7	5	3	2	4	21	33	6
	October	24	9	5	3	8	49	49	6
	November	28	11	8	6	7	60	47	7
Kijenzi 2	*September*	27	6	6	3	6	48	56	4
	October	42	5	3	2	9	61	69	3
	November	49	3	9	8	8	77	64	8

Table 5. Summary of all print data

	Total Prints	Total Completed	Failed Electricity	Failed Printer	Failed Design	Failed Compatibility	Print Efficiency
September	97	50	16	15	6	10	53
October	135	74	17	16	7	21	54
November	137	77	14	17	14	15	53
Total	369	201	47	48	27	46	

During the 3 months, 369 total prints were attempted and 197 were completed with approximately 53% efficiency. Electricity, printer issues and compatibility were significantly higher causes of failure than design failure. The failures were consistent across months. Compatibility problems increased in October and design problems increased in November.

The Kijenzi 2 printer, located in Milimani (Kisumu center), completed more prints than the other two printers. It was able to print nearly as many prints as the two other printers combined in September and October, even though, the other 2 printers were collocated. The print efficiency for the Kijenzi 2 was 63% over the trial, about 20% higher than both the Kijenzi 1 and the QTron. The Kijenzi 2 was able to be used 7 days per week close to 24 hours per day. Alternatively, the printers located at the hospital were only able to be used 4-5 days per week for about 6-8 hours per day.

At Kombewa, the two printers could be used simultaneously. However, it required one operator to prepare prints for each printer as well as performing any maintenance, meeting with medical professionals, and visiting departments. If the operator was also the in-house biomedical engineer, they would have additional work to perform, as well. Because of the daily time constraints, only a few parts could be printed per day at Kombewa within the 6-8 hour window. Prints needed to be timed such that long prints could be performed overnight. If there were any issues with the designs or prints, the print schedule had to be adjusted and postponed. When electricity went out, the prints could not be readily restarted. This made the printers at the hospital less efficient and print scheduling became more challenging.

The QTron had significant downtime and had to be returned to the manufacturer for servicing twice in the trial. It began having leveling and adhesion issues in October and the problems were unable to be resolved. The technicians attempted to solve the problems remotely, but eventually, the printer had to be replaced in October. A new printer was received, but within a few weeks, the problems arose again. A technician then visited Kisumu to fix it on site, but again, problems persisted. The printer was eventually sent back for maintenance and received at the end of the trial. The printer appeared to work functionally at that time, but no significant testing was performed.

The Kijenzi printers had substantially lower downtime than the QTron. The Kijenzi printers did require maintenance throughout the trial, however, the printers were easier and quicker to fix overall. This is most likely due to the printer designs. The Kijenzi printers are not user-friendly for someone with no experience. Their calibration is time consuming and required frequently. More training and initial training is needed for the Kijenzi than the QTron. The QTron is designed to be user-friendly with less previous knowledge required. Because of this, the QTron is more challenging to repair. The Kijenzi printer is designed to be easily repaired on the spot. A majority of the parts can be 3D printed for replacements and many parts are interchangeable. Additionally, the wiring and control board are readily accessible for maintenance. Alternatively, the QTron's parts are not easily replaceable and it is difficult to access the internal elements. It is designed for servicing to be done by the manufacturer only. Therefore, all maintenance takes additional time and most requires the company's trained personnel or someone with advanced understanding.

From the print data, it is evident that the Kijenzi 2 located in Milimani was the most effective during the trial. It was able to produce the most parts and be utilized the greatest amount of time. However, even the Kijenzi 2 had a relatively low print efficiency.

3.2 Analysis using IDEO Framework

The IDEO framework for HCD was used to examine the proposed business models for their potential implementation into healthcare systems in Kisumu county. Each criteria is discussed below as the In-House Operator model and Independent Operator model are compared and contrasted. The Printer Farm model, which was not tested directly, is then analyzed. Finally, the highlights and benefits to all three are compared and summarized.

3.2.1 Desirable

Through research, informal interviews and observations, it is clear from my experience and other's that 3DP for healthcare is desirable for the medical facilities in Kisumu county in Kenya (Kats et al., 2019). Hospitals, medical professionals, biomedical engineers and local government in the Kisumu county showed great interest in incorporating 3DP into their healthcare system. Many preferred the idea of having the 3D printer on-site, but overall, they were excited about the potentials of the technology.

In both the In-House Operator model and the Independent Operator model, I was able to have direct communication with end-users and codesigning was possible. When visiting on-site or off-site facilities, I was able to meet and communicate directly with end-users, both medical professionals and patients for feedback and new ideas. With the In-House model, the design process is as close as possible to the end user. In many circumstances, it was beneficial to be on-site for designing. I was easily able to reference the professionals for additional questions while designing and could show potential prototypes or design changes in the same day. Additionally, my tools were always available for proper measurements, photos, testing, etc. One challenge was that some parts required additional hardware which was only readily available in town.

Being located on-site allowed access to the in-house biomedical engineers and technicians who have a strong understanding of the needs and wants of the hospital. They have expert knowledge of the equipment in the hospital (broken and functioning), and they have relationships with the hospital staff. Being off-site made it challenging to develop relationships with many of the medical professionals and departments, whereas being on-site allowed me to gain more trust and communication.

Many engineers and local entrepreneurs also showed great interest in 3DP technology and the opportunity for becoming an Independent Operator. It offers them the opportunity to expand their business into new markets. However, most would require training to design and operate the 3D printer.

Desirability of the two models is summarized in Table 6. There are a number of benefits for both models, and a number of additional benefits to the In-House Operator when considering desirability.

Table 6. Detailed IDEO comparison of the In-House and Independent Operator models according to Desirability

Desirable			
	In-House Operator	***Independent Operator***	***Both***
Benefits	• Local engineers, hospitals and administration are open and interested in the idea of having 3D printers in-house • In-house engineers have strong understanding of needs and wants of the medical professionals at their clinics. • Designing can be as close as possible to the end user. There can be direct communication between the engineer and end user. • Customizability can be done on-site making it simpler for the designer. • Designs can easily be tested and reiterated.	• Entrepreneurs can expand their business and make many parts including medical parts. • Some level of codesign and feedback with engineers, medical professionals and end-users.	• The design process is closer to the end user allowing for more feedback than currently available. • Parts can be more readily accessible. • Necessary medical parts and products can be made that are currently unavailable. • The machines can make a variety of parts and products.
Drawbacks	• It will be difficult for the engineers to run the printers because many do not have time to learn and operate new technology in addition to their current job duties.	• Independent operators would have to learn the technology beforehand, in order for this to be effective.	• Although the machines can make a variety of parts and products, there are still a number of items the hospitals need that the 3DP cannot fabricate.

3.2.2 Feasible

3DP technology already exists in Kenya. QTron, AB3D, and Kuunda are Kenyan-run 3D printer companies in Nairobi. A few Fablabs exist in Kenya, including one in Kisumu, allowing 3D printer access in those areas. In addition, many companies import 3D technology. The basic infrastructure for the technology such as electricity and internet access exists throughout the country. In addition, much 3DP software is open-source and designs are easily shareable. Designers, engineers and operators can easily download and access information, files and designs.

There are a number of challenges in feasibly implementing 3DP for healthcare in Kisumu. Electricity exists throughout Kenya and within most hospitals, however, it is not consistent. It may shut down for 10 minutes, 1 hour, or 1 day with no forewarning. Medical parts, in particular, can be complex and often require long prints. As is seen in Table 4, about 13% of prints failed due to electricity. In Kombewa, over 18% failed due to electricity compared to only about 8% in Kisumu, indicating that electricity is significantly less consistent outside of the major city. Therefore, it is easier for Independent Operators to optimize their location whereas the In-House Operator model has no flexibility in location and may not be possible at some facilities. However, the Independent Operator would require a supply chain in place for ordering, designing, operating and delivering the parts.

The printers require specific training and knowledge that is not readily available in rural areas of Kenya. Specialized training is required to run the machines and even for an experienced engineer (with manufacturing and CAD experience), the printers require a learning curve. Design for 3D is unique and different compared to regular design constraints. Hospitals already have in-house biomedical engineering departments with in-depth knowledge of the hospital's needs. Alternatively, entrepreneurs may not have as much experience with the parts or products and may have very little or significant background in engineering. However, both independent operators and in-house operators will have varying skills and knowledge. In public hospitals, in particular, turnaround can happen quickly and unexpectedly. The engineers at rural hospitals also tend to have less expertise than those in town.

Although the in-house engineers and technicians have knowledge of the specific hospitals, their skills and knowledge varies greatly which would make training challenging. In addition, in-house engineers and technicians are often very busy as there is significant work for them. Hence, 3DP would add additional work for them in learning the machine, designing the new parts and operating the machine. Alternatively, Independent Operators will have even more variance in skills and background. They also may not have understanding of hospital's needs and wants.

The product needs will vary from hospital to hospital. What is needed at one hospital may not necessarily be needed at another. Feedback and communication with each medical facility will be necessary. The In-House Operator model makes this easier, but does not make it scalable for other facilities. Although localized printing in hospitals brings the design close to the user, some prints can be particularly slow. The end user may not be able to wait for the part to finish printing and would require the user to return the next day. According to medical professionals in the area, this was a major concern, as many people will not return to the facility. Additionally, Kenya has strict product regulations for medical equipment. It may be challenging to create a consistent quality process for both models.

The machines used all required significant servicing and maintenance which was not currently available in Kisumu. The technicians for QTron were located in Nairobi and the technicians for Kijenzi were located in the USA. The Kijenzi printers had detailed user manuals that included common problems and how to fix them making it significantly easier to maintain. I did not find the user manual for the QTron helpful when dealing with printer issues. Although information sharing is easy, even across continents, communication proved to be challenging with those outside of Kisumu. There was a lag in response for both and often a difficulty in properly communicating the issues and needs. Furthermore, there is no infrastructure for obtaining raw materials which are currently only available in Nairobi, and no infrastructure for disposal of waste.

The entire 3DP operation is a significant amount of work for just one operator in both settings. It requires identification of new products, product development and improvement, CAD/design (or access to a design team), operation of the printers, post processing of parts, quality checks and delivering of parts. This is in addition to printer upkeep. It is difficult for one independent entrepreneur or one in-house engineer to adequately perform all of the duties required. I found it extremely challenging to balance all aspects of the work.

Hospitals and medical facilities throughout Kenya and Kisumu county currently have a major issue with significant broken-down equipment. 3D offers potential to fix many of the broken machines, but without specifically trained personnel and technicians, the printers may become additional broken machinery in hospitals.

Table 7 compares the two models with respect to feasibility. There are many challenges for both models in regard to feasibility, particularly due to infrastructure, training, and the complexity of medical parts.

Table 7. Detailed IDEO comparison of the In-House and Independent Operator models according to Feasibility

Feasible			
	In-House Operator	***Independent Operator***	***Both***
Benefits	• Hospitals have in-house biomedical engineering departments with in-	• Location can be selected to best fit the needs of the 3DP. This includes proper electricity, access	• 3DP technology exists in Kenya. • Much of the software for 3DP is open-source and

	depth knowledge of the hospital's needs. • Engineering tools are readily available. • In-house trained engineers, medical professionals and end users are available and involved in the design process. • Customizability can be done on-site. • Designs can easily be tested and reiterated.	to internet, and access to medical facilities. • Codesign is possible with the right operators and open communication systems.	designs can easily be shared. • Electricity access exists throughout Kenya even in rural areas. • Internet access (access to data) is readily available throughout Kenya even in rural areas. • 3D printing is ideally suited to making low-volume specialty items that are typical in medical and laboratory settings.
Drawbacks	• Currently, hospitals have significant issues with broken machinery. 3D offers potential to fix many of the broken machines. However, without specially trained personnel and technicians, the printers may become additional broken machinery in the hospitals. • In public hospitals in particular, turnaround can happen quickly and unexpectedly. This can cause an issue if one engineer is trained but then a new engineer is assigned to that hospital. • The engineers at rural hospitals tend to have less expertise than those in town. Often even broken machinery is sent to the main hospital in the city to be fixed by a more experienced engineer.	• The independent operator would need a supply chain in place to order and deliver parts as well as get product feedback. • The operator's skills and knowledge may vary drastically.	• Electricity exists throughout Kenya, however, it is not consistent. • The printers require specific training and knowledge that is not readily available in rural areas of Kenya. • Medical parts and products tend to be more complex, have more constraints and requirements and have strict regulation, particularly in Kenya which has stricter product regulation than its neighbors. • Filament only exists in Nairobi and a constant source of inexpensive filament may be difficult to procure. • There is no infrastructure for the disposal of waste products or waste filament. • It is difficult for one independent operator or one hospital engineer to adequately perform all of the duties required.

3.2.3 Viable

One of the greatest advantages to 3DP for low resource healthcare facilities is the low cost. Although there is an initial cost for the 3DP, if used correctly, the printer can produce a variety of medical parts and products rapidly and save very expensive machinery. By producing the products in-house or even nearby at a local independent operator, costs associated with shipping, importing and warehousing are eliminated.

Once the machines are purchased, both the in-house operator and the independent operator could afford to purchase the raw material required. The raw material is not readily available in Kisumu but can be ordered from Nairobi. Kombewa hospital was willing to pay for the raw materials, but their major concern was how they would be able to purchase a printer. The current cost of 3D printers varies greatly and most often, reflects quality of printer and the printer’s usability. The Kijenzi and QTron printers are priced at $800 and $1200, respectively. It is most likely that a different printer completely would be needed, and it would be difficult for individual public hospitals in Kisumu to afford a 3D printer. Most likely an outside investor or the government would have to provide the printers at public hospitals. Independent operators may be able to afford to purchase a printer, but more information would be necessary to understand who could or could not.

The machines used in the study both had downtime and required maintenance and upkeep. Print problems lead to wasted prints, wasted materials and a substantial amount of lost work time. The local QTron printer was not up to the standard of the Kijenzi printer. Nevertheless, the Kijenzi printer requires greatly skill and training, as well as constant upkeep. However, importing printers is not ideal due to the added costs associated.

For most in-house biomedical engineers, it would not be useful to take them away from their current job duties to learn and operate the 3DP. This may vary as some hospitals have more potential than others. The two hospitals in Kisumu, Kisumu County Hospital and JOOTRH, have larger biomedical and maintenance departments. JOOTRH also instructs new biomedical technicians and engineers. Hospitals such as these with larger staff and more advanced technicians may benefit from utilizing the 3DP.

The in-house model aligns strongly with the goals and objectives of the facilities, medical professionals and the Kisumu Department of Health. The technology provides various parts and products that would otherwise be expensive or difficult to obtain. With 3DP, medical professionals can influence the design process allowing for locally appropriate medical equipment. The biomedical engineers are able to fix many broken machines. Additionally, new parts and products can be developed enabling the facilities to expand their services.

Similarly, independent operators would choose to invest in 3DP. Therefore, it is likely that 3DP will align with their individual goals and objectives. Based on my experience with local engineers and small businesses, 3DP would be beneficial to their businesses. They could also expand their services using 3DP. As it is a new technology, they would have a unique, niche market different from the many other businesses nearby. It would offer them new skills and opportunities.

Table 8 analyzes the viability of the two models. Both face challenges with viability as highlighted below. As described, the major challenge is the cost of the initial printer and any maintenance or upkeep.

Table 8. Detailed IDEO comparison of the In-House and Independent Operator models according to Viability

Viable			
	In-House Operator	***Independent Operator***	***Both***
Benefits	• Hospitals would only have to pay for raw material and would be able to readily create necessary items. • Hospitals would save money on many expensive parts and products. • Hospitals could expand their services with new and improved products and parts designed with input from local medical professionals and patients.	• The machine could be used in a number of markets expanding business opportunities.	• The localized manufacturing significantly reduces transportation and import costs and taxes. • By making spare parts available, there is an opportunity to save very expensive medical equipment that would otherwise be garbage. • One machine can make a number of different items.
Drawbacks	• Hospitals must initially invest in the printer and then pay for service, maintenance and raw material costs.	• Independent operators would need to initially invest in a printer.	• The original cost of an adequate machine would be expensive for a hospital to buy. It may also be expensive for an individual operator. • The quality of prints from the local printer, QTron, were not up to the standard of other imported printers leading to wasted prints, wasted material and significant amounts of lost time and lost profit. • If high quality, imported printers are used it increases upfront cost for the machine and makes it even more difficult and expensive to service.

3.2.4 Printer Farm Model

The Printer Farm model was not directly tested in the study. However, a number of comparisons and conclusions can be made based on the testing of the other two proposed models.

3.2.4.1 Desirable

Similar to the other two models, this model would also provide needed medical parts and products to health facilities in the area. Although many professionals expressed the most interest in an in-house operator, they were most excited about the potential of accessing the items needed for the hospital. Hospitals would not need to add any infrastructure as they would for in-house operations. However, in this model, the end user is the farthest from the design process. It will be more challenging for the operator to get direct feedback and information from the healthcare professionals. Locally appropriate designs can still be created and medical professionals can still be involved in the process at the printer farm facility.

3.2.4.2 Feasible

As discussed above, both of the printers used in the study had a number of issues. However, those and others are available, as well as the infrastructure for a concentrated print farm. These farms would need to be located in a city such as Kisumu and would need to assess electricity requirements and potentially require a generator for electricity outages and shortages. These items are available in the Kisumu area.

The operator/designer would have less access and interaction with the medical professionals and facilities and therefore, would not understand the problems as well as the other models, particularly the in-house model. However, the operator/designer would most likely be a more trained individual with significant understanding of the machinery. A designer or operator would need to visit the hospitals similarly to the independent operator in order to have direct communication with the staff and end users.

Alternatively to the other two models, in this model the operator would be solely devoted to printing and designing. With numerous printers, there would be a significant increase in production. The concentrated nature would greatly improve quality control for the process. Design alterations and changes or new designs would be easy to create as the operator is focused only on designing and printing. But, the distance from the end user would slow down testing and iterations.

A system would need to be in place for ordering, storage, transportation, delivery, feedback, product requests and facility/medical professional interactions. This would increase the complexity of the operation significantly compared to the other two models. There is a potential with increased production capacity to have more than one operator or designer sharing roles or with specialized roles.

3.2.4.3 Viable

This model would require the highest initial investment. A larger workspace would be required to hold the machines and more printers would be required. The location would require a larger amount of electricity. Operators would need to be more knowledgeable and require additional training. After opening of the operation, only raw material would be required.

In this model, the organization would most likely be focused solely on 3DP and/or manufacturing. They would purchase their own machine and materials. Therefore, the solution would provide medical parts and products to the surrounding area while also benefitting the operator's goals.

3.2.5 Summary

The three proposed models all present unique opportunities for implementing 3DP into healthcare facilities in Kisumu, Kenya. Regardless of the implementation system, all three would improve access to a wide range of medical parts and products that are currently expensive and difficult or impossible to obtain. All three provide local manufacturing of medical parts and products in the Kisumu area which is a nearly untouched market, and all three would open new industry and jobs in the area.

Due to the localization of manufacturing, the time from design to end user is significantly faster. If implemented correctly, all of the models would allow direct interaction and feedback from end users and would allow medical professionals in the area to be a large part of the design process. This would be simplest and most effective utilizing an In-House Operator model but could be done effectively with the other two models.

New infrastructure would be required for all of the models. The In-House Operator model would require hospital space to be made. The Independent Operator model would require a space for the printer as well as an ordering, storage and delivery process. The Printer Farm model would require a larger space and also an ordering, storage and delivery process. Codesigning is possible in the three models, but the latter two would require additional infrastructure to allow for codesigning with medical professionals, as they will not be collocated.

As seen in the study, new printers may need to be explored. The two used in the study could be obtained, but each have their own difficulties making them less than ideal for this use. Training will need to be implemented and that structure will vary greatly based on which model is used.

Depending on the business model used, the business structure will vary including purchasing, maintenance, delivery etc. Table 4 briefly compares how the 3 models could be structured. Knowing the structure of each business model will be helpful in understanding which implementation is ideal for various situations.

The In-House model would require the hospital, government or an outside donor to contribute in order to buy the printers, as most local public hospitals could not afford the printers. An outside organization would need to implement proper training to the biomedical engineers and technicians. Additionally, the government would need to begin implementing training in their education system. The hospital or government would be responsible for purchasing raw material from Nairobi. The hospital would then be able to create any parts or products from the filament. However, this model would not create notable revenue for any investor. It would be difficult to implement a proper quality control system for the parts because each engineer or technician would use the printers differently. The in-house operator would understand the printer, but may not be able to perform all maintenance and upkeep required. In many of the hospitals, there would be no technician available and therefore, upkeep may be challenging and expensive.

The In-House model, if implemented properly, allows for customized design for each facility. However, it also offers the largest opportunity for adding broken machinery to health facilities in Kisumu which is a major concern. Therefore, I believe an outside organization would be necessary in implementing this model and the organization would need to have strict structures in place to provide printers, training, maintenance and recycling of equipment. Otherwise, the local government would need to strongly commit to overtaking the responsibilities.

The Independent Operator model would most likely be implemented by an existing small business, investor or organization in the area who would purchase the printer and raw material. The hospitals would purchase the parts from the local independent operator. Hence, they would need to create systems for ordering, purchasing, and delivering the parts to the facilities, as well as a system for feedback and communication with the professionals at the facilities. Quality control would also be difficult in this model, as there would be a number of unique individuals operating the machines with varied skills. It would be necessary to develop a quality control system. The local operator would also be responsible for upkeep of the machine or finding a skilled technician. As most operators would be located in major cities, such as Kisumu, they would have some access to skilled technicians. The local operator would make profits from the hospitals purchases and would be able to expand into other markets using the printer. Although the printer may break down, it is unlikely that the broken machinery will not be used in someway and parts will most likely be recycled and reused.

Alternative to the other two, it is likely that the Printer Farm model would be implemented by a private company, not by one individual. The company would need an initial investment in order to purchase the printers and develop the space for the farm. Raw material, upkeep, and maintenance tasks would be the responsibility of the company, and they would have easy access to skilled technicians. Employees can be chosen and trained to a higher level. However, they may not have a strong understanding of the facilities and their needs. Quality control would be simpler as all production would happen in one central location. The hospitals will purchase the parts and products, and the company will make profit from the parts. Additionally, because of the high print capacity and the skilled and employed technicians, it will be simpler to begin moving into new markets and creating new revenue streams. The printer farm has the ability to produce the most prints at the highest quality due to the trained operators, high quality printers, and verified and consistent quality control.

However, all three of the business models could bring medical equipment to Kisumu that would otherwise be unavailable or expensive. The models have unique advantages and all have significant potential depending on the specific scenario.

Table 9. Comparison of the potential business structure of the three proposed business models.

	In-House Operator	Independent Operator	Printer Farm
Who purchases printer?	Hospital, Government or Donation	Independent operator Investor	Private company
Who pays for raw material?	Hospital, Government or Donation	Independent Operator	Private company
Cost for the hospital	Raw material	Parts & products, minimal transport	Parts & products, minimal transport
Quality Control?	Some	Little	High
Who is responsible for maintenance or repairs?	Hospital, Government or Donor	Independent Operator (potentially investor)	Private company
Access to skilled technician for repairs?	Difficult access	Some access	Easy access
Who makes profit?	No one	Independent operator and/or investor	Private company
Potential for new markets	Little	High	Very high
Potential for broken down 3DPs or unused 3DP	High	Medium	Low

4 Conclusions

As technology continues to advance in 3DP and additive manufacturing, how and where we manufacture goods may be altered significantly. Engineers, scientists and professionals continue to create amazing devices for healthcare, particularly low-resource healthcare, using 3DP technology. Many have attempted to use 3DP in both international development and humanitarian aid scenarios. Yet, there is little understanding of how to properly implement this technology in low-resource settings.

In this work, I set out to understand the printing environment in Kisumu county of Kenya and understand different implementation strategies. I proposed three business models - In-House Operator, Independent Operator and Print Farm. These models of implementation were tested using the IDEO human-centered design criteria and compared and contrasted.

I found that all three of the proposed models have differing benefits and drawbacks that are each relevant in varying low-resource contexts. Based on criteria such as funding, infrastructure of local facilities, government involvement and overall resources, one can utilize these findings to decide which implementation model is ideal in that specific setting. By laying out this selection process, it will be easier for future teams to begin applying 3DP technologies in other low-resource settings throughout the globe allowing more people to have access to the potentials of this technology.

This study helps advance the overall understanding of the 3DP environment in low-resource contexts, particularly for healthcare applications. It helps to better understand how we can implement this technology into healthcare facilities in low resource settings and highlights challenges faced in doing so. As more people use this work to implement the technology, additional research will help add to these findings and further the understanding of the 3DP environment in low resource settings.

4.1 Future Work & Considerations

To fully understand how and where 3DP should be applied, further research is necessary and a number of factors must be considered including print quality, training, waste management and recycled filament, and culturally appropriate implementation.

It is imperative to find a printer that is more reliable, produces high quality prints and is affordable for low resource healthcare settings. Currently, both the QTron and Kijenzi have drawbacks for proper implementation. The QTron was not reliable and had far too much down time. Major adjustments would need to be made by the manufacturer to ensure that the printer can function at its best quality. The Kijenzi was efficient, however would be very difficult for someone with no background in engineering and manufacturing. Often, it required minor adjustments and upkeep that takes away time from printing. In order for the Kijenzi to be used, significant training or a skilled technician would be necessary. An analysis should be done to weigh the benefits and drawbacks of these and other printers available on the market. It is important to consider importation, transportation and upkeep of the machines as well as usability in the field.

Additionally, the Printer Farm model should be tested directly. Although we can speculate from my experience with the other models, we cannot properly assess the model until testing has been completed. In addition, all models should be tested using local operators to better understand their functionality and sustainability. It is necessary to understand whether these models work without outside engineers and operators.

Proper training systems must be researched and developed. Without effective training, the machines will not be used properly, prints will be of poor quality, products may not be beneficial and machines may even become derelict. As many low resource areas already struggle with significant amounts of broken-down machinery, it is vital to have management of the machines and avoid broken-down, unused 3D printers.

In addition, the world is currently facing a crisis of waste management. Many 3D printers utilize plastics as their main materials. It is crucial that research advances in recycled 3D printing filament. With recycled filament, plastic water bottles and other plastic waste could be recycled and used in 3D printing.

It is important to consider that applications and implementation may vary in other low resource areas or in different contexts. To apply this model in other areas of the world, additional similar studies would be needed allowing us to understand the effects of culture and geography on this technology. Furthermore, similar studies would be needed to verify the use of these business models or similar models for applications outside of healthcare.

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