Exploring the Utility of Crowdsourcing Frameworks to Inform the Construction of a Web-Based 3D Printing Application (3DCrowdGo).

by

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Healthcare trainees learn hands-on skills using simulators before attempting them on patients. COVID-19 shifted in-person learning to online presenting unique challenges, as equipping large cohorts of learners with simulators is prohibitively expensive and often impractical. Using three-dimensional (3D) printing to create simulators allows for cost-effective, accurate products that are easily customizable to learners' needs. I aimed to discover how to construct a crowdsourced online application, 3DCrowdGo, to fill the "research-to-simulation lab" gap in health professions simulation training via community-based 3D printing. Phase 1 involved a literature review whose resulting theories were ranked by simulation stakeholders to determine which were suitable for 3DCrowdGo. Phase 2 was an exploratory trial that demonstrated piloting of the initial efficacy of the app. Results from these phases were aggregated to develop a responsive, flexible solution that incorporates current best practices and provides affordable and effective simulators for the decentralized simulation model by mobilizing community members.

Keywords: simulation; healthcare; 3D printing; crowdsourcing; health professions education

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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KRYSTINA M. CLARKE

STATEMENT OF CONTRIBUTIONS

Part of the work described in both Chapter 4 and Chapter 5 have been submitted for publication as:

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I performed the majority of the synthesis, testing, and writing of these manuscripts.

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LIST OF ABBREVIATIONS AND SYMBOLS

COVID-19	Coronavirus disease 2019
3D	Three-dimensional
PPE	Personal protective equipment
HPE	Health professions education
MRC	Medical Research Council
App	Application
VLM	Virtual labour marketplaces
CT	Crowdsourcing tournaments
OC	Open collaboration
Ce-SIM	Centralized simulation
De-SIM	Decentralized simulation

Preamble

The context of this project has pivoted multiple times due to the unprecedented nature of the Coronavirus disease 2019 (COVID-19) pandemic, which will be evident throughout this dissertation. Over the span of this 2-year program, the solution remained the same while the context continued to evolve.

In May 2020, I officially started my master's thesis which was heavily related to the COVID-19 pandemic. Around that same time, COVID-19 had started escalating in terms of spread and severity. Because our governing bodies were not prepared for the circumstances, the stockpiles of personal protective equipment (PPE) were quickly diminishing, which left healthcare workers around the world vulnerable and at risk of getting sick and spreading disease to others. In response to a call for proposals from the Canadian government to mobilize researchers to join the battle against COVID-19, I proposed a solution to utilize 3D printers in private homes and businesses that remain idle most of the time to manufacture PPEs. This became my passion and the premise of my master's thesis, which aimed to examine the best ways to utilize 3D printing resources and assets to produce PPE components. This PPE shortage would be addressed by designing a web-based application called 3DCrowdGo, which has remained constant throughout our evolving contexts. The application would leverage this newer concept of crowdsourcing and apply it to 3D printing and rapid manufacturing to increase the PPE supply which would, in turn, meet the continuously increasing demands. To reach this point, I first needed to focus my research on the theoretical aspect of crowdsourcing to gain a better understanding of how it works and what makes it successful. Just over halfway through this degree, the PPE supply and demand chain eventually regained homeostasis, and was no longer a suitable problem to be solved using 3DCrowdGo. However, just because PPE shortages were no longer an immediate concern, there were many other lasting effects from the pandemic that did not have long-term solutions in place. At this point, virtual learning was still the main avenue of education delivery. Students who were now being forced by public health measures to stay home and learn online were missing an entire aspect of the learning process. Specifically, health professions education (HPE), students who would typically have access to in-person simulation labs to practice hands-on, technical skills were no longer in receipt of these opportunities. These simulation labs create a risk-free replication of an object or environment for practicing purposes and is becoming an integral part of the HPE learning process. This was an unprecedented circumstance that left the students with a gap in skill, and without an immediate solution for it. This is where the second context of the application of 3DCrowdGo was ignited as it was an opportunity to still combine crowdsourcing and 3D printing, but instead to help produce portable simulation models for these students to practice on anywhere, anytime.

In this dissertation, I have purposefully retained the chronology of these events, as I believe the context in which the work was done, and the content of the works cannot be separated. Therefore, the introduction is tailored to both PPE and simulation contexts; however, the research that follows is situated in the applications to health professions simulation.

Chapter 1: General Introduction

The COVID-19 pandemic has brought about many challenges and adaptations amongst daily life, work schedules, safety precautions, and education. Health professionals and front-line workers have been placed at the forefront of a global pandemic for the last two years, which has had tremendous implications on their health and safety. COVID-19 drained stockpiles of medical equipment and devices due to their exponentially rising demand during 2020 and into 2021. The healthcare industry was hit hard when shortages of personal protective equipment (PPE) such as medical masks, shields, ventilators, and hazardous material suits started to arise. These PPE shortages quickly exposed holes in Canada's supply chain that the government was trying to fill by encouraging pivots amongst local industries to make everything from finished products to raw materials (Allam Advisory Group [AAG], 2020). There had been many efforts to crowdsource materials as an attempt to close these shortages, with a spotlight on rapid prototyping and three-dimensional (3D) printing which allow for designing, testing, and manufacturing at the consumer level. This was the first time that home-based 3D printing communities united and mass-produced PPE, assistive devices, and clinical equipment (Vordos et al., 2020). Despite this, the shortage persisted long after due to the most significant reinforcers of a critical shortage of raw materials, strict quality control measures barring the sale of suboptimal units, and political agendas preventing PPE distribution (Reynolds, 2020; Walsh, 2020; Cecco & Borger, 2020). To bridge this gap, I first needed to focus my research on the theoretical aspect of crowdsourcing to gain a better understanding of how it works and what makes it successful.

1.1 What is crowdsourcing?

Crowdsourcing is defined as "the practice of obtaining needed services, ideas, or content by soliciting contributions from a large group of people and especially from the online community rather than from traditional employees or suppliers," (Crowdsourcing, 2022). If the word is broken down into its two components, it is understood that *crowd* is derived from the Middle Dutch word *crüden*, which means to hurry or to push, while *source* comes from the Latin word *surgere,* meaning to spring up or forth. With this in mind, it is easier to understand the true meaning of crowdsourcing because most of it lies within its roots. The term itself was first officially coined in 2006 by journalist Jeff Howe, who wrote an article in Wired magazine in which he described companies outsourcing tasks and activities to a large and undefined group of people (Howe, 2006). However, there are obvious debates within the literature about the definition of crowdsourcing and how it should be classified, perhaps because it is a relatively recent term, and the method is rather flexible and adaptable (Wazny, 2017). The general flow of this concept is quite simple and used more often than one may realize in everyday life. The first step to crowdsourcing is breaking down a larger project into multiple, independent tasks known as microtasks. Once microtasks have been established, a platform, which is now usually digital, is used to unite workers into one place and facilitate communication. These microtasks are then assigned via the digital platform to a larger group of workers, thus expediting the development process. Workers tackle the micro-tasks and present their solution through the platform, which is accessed and then assessed by the company or individual who created the tasks (Bauer & Gegenhuber, 2015). The key in this process is having a larger group of people working on a smaller subset of tasks to accelerate a potential solution. Although a relatively new concept used in today's business and science amongst other industries, crowdsourcing appears in many different forms for centuries. One of the earliest examples described was the Longitudinal Prize in 1714 where the British government offered a cash prize in exchange for the development of a reliable way to compute the longitude of ships at sea (Ciurea & Owsiński, 2019). This prize was rather avant-garde in that the government chose not to fund a single scientist to solve their problem, but instead ended up with an abundance of solutions for a likely similar or lesser cost.

Despite continually evolving crowdsourcing phenomena, Prpić et al. (2015) label and describe three main types of crowdsourcing:

(*1) Virtual Labour Marketplaces (VLM):* Individuals and organizations agree to perform work in exchange for compensation, generally thought to exemplify crowdsourcing's production model aspect. The crowd size is also substantial (e.g., Crowdflower has 5 million+ available labourers) which allows for rapid completion of microtasks. Participants usually take on independent tasks, thus they do not work as teams and remain largely anonymous.

(2) Crowdsourcing Tournaments (CT): Organizations post their problems to popular digital or, sometimes, in-house platforms which attract specialized crowds based on the platform's niche. When applied to innovation, these platforms have been termed open innovation platforms and represent both the idea generation and problem-solving aspects of crowdsourcing. There tends to be less participants at these sites than VLMs (e.g., Kaggle has 140 000 available labourers) and they are not always anonymous. Fixed amounts of money and prizes are usually offered to the crowd for the best solutions submitted.

(3) Open Collaboration (OC): Organizations freely post their problems or opportunities to the public and the crowd voluntarily contributions and thus do not typically involve monetary exchange. The size of these types of crowds can vary significantly depending on the open call for volunteers as well as the reach and engagement of the platform used (e.g., Twitter had 321 million users in early 2019, but there is no guarantee that they will pay any attention to or even use the app). Using social media to foster contributions is popular in this model. Participants thus have access to the same tools that the organization is using and, thus, can amplify the agenda through their own personal networks.

As a result of each of these means of information technology, problem solving, idea generation and production are sourced from crowds. Founder of Crowdsourcing Week, Epi Ludvik, describes it as a “great enabler to move us toward the well-being of every human on earth, simply by looking to the crowd for supply,” (Houlihan & Harvey, 2018). He also explains that the future is about participation and the ability to co-create through an increasingly connected world. This new method is challenging established business models due to the opportunity for re-evaluation and reinvention. Crowdsourcing has increased exponentially since Howe’s article published in 2006, likely due to its ability to lower costs, overcome barriers and borders, increase research scale and progression, make new discoveries, etc. (Wazny, 2017). Its recent exploding interest has also largely been facilitated by today's ever-evolving technology and increasing connectedness, with online platforms now comprising most crowdsourcing networks.

1.2 Foundations of Crowdsourcing

Implementation science is a growing discipline that uses theories, models, and frameworks to gain insight into which mechanisms are more likely to result in successful implementation of innovation, such as the proposed crowdsourcing solution to manufacturing (Nilsen, 2015). One of the original goals of implementation research was to discover what contributes to the success and widespread adaptability of crowdsourcing across multiple industries. According to one of the most prevalent implementation science frameworks – Consolidated Framework for Implementation Science (Breimaier et al., 2015) – the strength of evidence underpinning the innovation is the key characteristic of any innovation that determines the success of the implementation process. As a result, a thorough search of the literature revealed many theoretical fundamentals that likely play a role in the operation and implementation of crowdsourcing, which will be discussed in Chapter 4.

1.3 Structuring the Solution to Be Effective

There is currently a scholarly gap related to which theoretical underpinnings are most effective for the implementation of crowdsourcing. Because of this, we do not yet know how to build and structure the application in the best and most effective way using these foundations. The type of crowdsourcing model chosen (for example VLM, CT, or OC) will be based on the needs, and these needs will be derived from the theories. There are several different ways to classify these theories, thus a part of this research was dedicated to classifying and placing them so that they can be easily accessed when needed.

At the onset of this work, my hypothesis was that the application will most likely be structured with a hybrid model encompassing several different crowdsourcing theories together to provide a solid foundation supported by literature. It was critical to first establish knowledge of and become familiar with the contemporary crowdsourcing theories so that the solution can be built based on the most appropriate theory or combination of theories to address the context of both needs and crowdsourcing contributors/users. I have reviewed several theories, and each of these theories was weighed and speculated on by panels of simulation specialists and users based on their applicability and relevance towards 3DCrowdGo. I have placed each theory on a scale and assessed its underlying individual vs. societal motivators of participation as well as behavioural and economic factors that could influence the applications' success and potential implementation once constructed and tested. Next, with the input from the stakeholders, I planned to validate, then deem a specific theory (or a combination of theories) acceptable and practical in terms of its/their application to 3DCrowdGo. One of the reasons for selecting multiple theories, rather than a single theory, is that being aware of other theories that exist and how they function may allow for a pivoted and re-structured solution to address emerging and shifting content. For example, as described in the preamble to this dissertation, the original context was to produce PPE during COVID-19 (or future pandemics) using 3D printers that are underutilized in private homes. The solution must have a social aspect that focuses on relationships between individuals, groups, and organizations to be most effective. Contrarily, as the context changed from manufacturing PPEs to supporting the decentralized simulation model, perhaps an economic-based approach that coordinates economic agents and their transactions amongst each other would be more appropriate and acceptable. A single crowdsourcing application that is constructed based on multiple theoretical underpinnings, will provide a flexible option that can be rapidly deployed to fit the needs of the market.

Although this is where my master's work ends, this is not where the evolution of this research program ends. Once I have decided on these theoretical foundations to base the application on, in my doctoral studies I will then begin to create a framework to further support and validate its operation and plan steps for successful implementation in the real-world setting.

Chapter 2: Needs Assessment

2.1 Magnitude of the Problem

2.1.2 Personal Protective Equipment

There were three main factors reinforcing the shortage of PPE. Firstly, there was a critical shortage of raw materials, such as filters and polypropylene, that were necessary to produce PPE (Reynolds, 2020). Next, even after raw materials are sourced and production is successful, strict quality control measures can and have barred the sale of millions of suboptimal units. On May 18th, the government had received a total of 11.7 million N95 respirator masks, but 9.8 million of those did not pass quality control (Walsh, 2020). Thus, valuable and high demand materials, energy, and resources were being wasted on subpar products. In addition, there were some governments that banned exports of domestically manufactured PPE as a measure of providing for their own citizens first. An example of this occurred in April 2020 when former-USA President Donald Trump invoked the 1950 Defense Production Act. This halted manufacturing company 3M's exports of 3 million N95 respirator masks to Ontario — a bold move considering N95s are critical for frontline healthcare workers (Cecco & Borger, 2020). These three factors were contributing to the increasing and unmet demand, which in turn posed a severely increased risk of healthcare professionals being infected by and dying from COVID-19.

According to the Allam Advisory Group (AAG) report released in 2020 (AAG, 2020), 3.3 billion units were needed over those next 12 months, 1.2 billion of which for Ontario alone. A continuously growing PPE market was going to keep manufacturers struggling to meet the total demand for the foreseeable future. The AAG (2020) predicted that even with a restored supply and demand chain in some provinces, stockpiles likely were not going to be enough to last those next few months, and domestic and offshore imports at the time were not thought to be sufficient by 2021. This exponential growth coupled with a limited number of current Canadian manufacturers and an increased desire to be in control of our own manufacturing processes held a significant opportunity for Canadian-based companies. CEO of AGG, Omar Allam, explained in an interview in

2020 that at least 40 per cent of PPE should come from domestic production for the long-term to ensure a reliable supply for ongoing use and to fill the country's national stockpile, especially if a second wave or future pandemics arrive (Hill, 2020).

This problem discovery originated from an entrepreneurship program, the Brilliant Catalyst Incubator at Ontario Tech University, that I was accepted into and completed from May-August 2020. At the time, one of the main goals of the program was to conduct a needs assessment in the form of market research and customer validation for 3DCrowdGo as a solution to the PPE shortage. If you would like to learn more about this, Appendix A is a market report that was submitted at the end of the program which includes a summary of the findings, as well as my own digital adaptations of crowdsourcing fundamentals and data visualization. Though the report did not follow a traditional methodological approach, notable findings from this preliminary work that reinforced the PPE shortage issue included the following:

- The time and energy it took to access PPE had increased due to more thorough safe-keeping measures and logging which, in cases of emergency, sometimes led to medical procedures being carried out regardless of being unequipped.
- The quality of PPE shipped to and used in the hospitals became much lower than what was pre-COVID-19, and limits were placed on PPE even with quality reductions.
- Administrative personnel responsible for ordering PPE were experiencing supplies and costs at a premium (lower quantities for higher prices).

2.1.2 Simulators

The COVID-19 pandemic changed public health guidelines on social distancing measures and posed limitations on in-person gatherings which impacted traditional educational practices. Health Professions Education (HPE) learners' technical skills training has been hindered due to the inability to hold in-person, centralized simulation labs that would otherwise allow trainees to master technical skills before executing them on real patients (Dubrowski et al., 2021). Within the context of HPE, simulation in technical skills training is typically performed in centralized simulation centres. Since maintaining the quality of education and training of current and future health professionals is critical, academic institutions are exploring decentralized simulation practices where trainees could train anywhere if they have access to a simulator (Wang et al., 2022; Wade et al., 2022; Habti et al., 2021; Micallef et al., 2021). However, commercially available simulators may be too expensive for scaleup (Isaranuwatchai, 2014). At our institution, COVID-19 left 170+ first-year nursing students without access to a simulation laboratory and providing them with take-home simulators would cost USD$127,000/year (Barth et al., in press).

2.2 Solution

One proposed solution to the cost-sensitive production gaps is to utilize 3D printers in private homes and businesses that remain idle most of the time. This is known as crowdsourcing and the concept is similar to those of companies such as Uber or Airbnb, both of which proved to be very successful at leveraging periodically underutilized assets (e.g., cars and homes) to provide services to individuals that need them. This works by asset-owners registering their assets to a platform who are then able to lend their assets when not in use to people who want to or need to make use of them. For example, Uber allows individuals to use their own vehicles as a mode of transportation for others who need, but do not have access to, a vehicle of their own. This differs from a taxicab in that the Uber driver is using their own personal car to give other people rides – a newer concept rooted in outsourcing a function to a larger population that will influence this research.

Therefore, the premise of this thesis was to examine the best ways to utilize 3D printing resources and assets for the purpose of producing simulator components. This was addressed by designing a web-based application called 3DCrowdGo. At the conceptual level, the application would leverage this newer concept of crowdsourcing and apply it to 3D printing and rapid manufacturing to initially increase the PPE supply, and later the supply of cost-effective and customizable simulators, which will, in turn, meet the continuously increasing demands. Local 3D printing enthusiasts starting in Durham Region, Ontario would form an online community that would work beyond the supply limitations involved with current 3D printed innovations. 3DCrowdGo would allow 3D printer owners to lend their services, when not in use, to manufacture parts for

PPE that local hospitals need, and/or simulators that training institutions (e.g., university, college or hospital based) need. 3DCrowdGo would be a freelance web application hosted on Amazon Web Services (AWS) able to handle and distribute 1 000 printing tasks simultaneously.

The hypothesized journey map of the application is as follows. A 3D printing task starts off as an idea or a need from hospitals, doctors, nurses, etc. who will create an account with 3DCrowdGo. Through their account, they will be able to record their needs, make requests, and receive confirmation and status updates of their order. The application's algorithm will automatically match and distribute printing tasks to an appropriate certified 3D printer owner based on their availability, supply, and standards. Higher quality printers will be matched with larger or more complex tasks, while lower cost printers will be paired with simpler tasks. When a task is assigned to a suitable printer owner, they will be notified via 3DCrowdGo that they have a task waiting and will be given a time window to complete it. Once the task has been completed and the printer owner provides the corresponding printing services, they will notify drivers that it is ready for pickup, or they will deliver the product themselves – both of which will use a payment system that will be integrated into the app to cover material and delivery costs. If the task is not completed by the end of the window, it will be redirected to the next suitable printer owner to ensure that the tasks are being fulfilled as quickly and efficiently as possible. The end goal of the app is to collectively pool resources within a community to help bridge the supply gap and improve responses to the pandemic. However, as production needs may change, the commitment and motivations of the users may change from volunteer to paid services. Therefore, I decided that it would be critical to determine the theoretical underpinning and related mechanisms of the application first, hence the focus of this master's thesis.

2.3 Research Goals

The overarching thesis aims to discover how to construct a crowdsourced web-based platform, called 3DCrowdGo, to fill the COVID-19-induced gap in health professions simulation training via community-based 3D printing. To do this, I wanted to answer the research question: *How do we create a set of best practices to utilize* *crowdsourcing of 3D printers in the community at large to produce simulators for HPE students?* To address this overarching aim, four research sub-aims were developed:

- *What contemporary crowdsourcing theories exist in literature?* This was achieved by conducting a scoping literature review to uncover which theories exist that are involved in the operation, functionality, and success of crowdsourcing.
- *Based on potential stakeholders' opinions, which of these theories would be most suitable to use in the development of such an application?* To accomplish this, I used two approaches. First, I utilized Modified-Delphi method surveys that allowed field experts to rank and determine which crowdsourcing theoretical framework should be used in the app development process given the full context, which consists of the end users (hospital administration and 3D printer owners), the urgency, and availability of funding.
- *Does the implementation of Social Exchange Theory as a theoretical underpinning and Design-to-Cost as a method form a potential optimal design for 3DCrowdGo?* Propose a small-scale exploratory trial following previous design-to-cost work to allow for piloting of the initial efficacy of 3DCrowdGo.

Chapter 3: General Methods

3.1 Guiding frameworks

3.1.1 Adapted Medical Research Council (MRC) Framework for Design of Complex Clinical Interventions

To ground my work, I have searched for the most appropriate research framework. Although there are many, I have used the MRC Framework, as it is currently one of the most prevalent research process frameworks used in healthcare; therefore, the end point users (i.e., health professions educators) would understand the research process.

The 2008 Medical Research Council (MRC) framework proposed a nonlinear approach to designing and evaluating complex interventions that emphasizes: (1) identification of strong theoretical foundations to base the interventions on, (2) piloting; (3) integrating process and outcome evaluation; (4) acknowledging the importance of alternative, nonexperimental research methods; and (5) highlighting the importance of understanding the intervention's context (Craig et al., 2013). Haji et al. (2014) proposed a modified version of this framework to which I have closely adhered to help inform the structure, methodology, and timeframe of my thesis work. This modified MRC framework calls for an iterative approach to developing, refining, evaluating, and implementing simulation interventions. This adapted version acts as a guide that places emphasis on: (1) identification of theory and existing evidence; (2) modeling and piloting interventions to clarify active ingredients and identify mechanisms linking the context, intervention, and outcomes; and (3) evaluation of intervention processes and outcomes in both the laboratory and real-world setting. Figure 1 is a visual representation of the modified MRC framework in a series of cycles labelled A – *Theory and Modelling*, B – *Piloting*, C – *Evaluation*, and D – *Implementation*. Cycle A encompasses the development phase in which I have situated this thesis project, and cycles B to D will be foci of my potential doctoral work. There are two subphases within this development phase whose distinct purposes are as follows:

1. *Theory and/or evidence identification:* Identify the purpose of the research and primary research question(s) via a gap in the literature or problem that is grounded in theory or conceptual frameworks.

2. *Intervention modelling:* Conduct a thorough literature review to identify the evidence-base related to the research question and/or proposed intervention. Use the selected theory and knowledge of the evidence base to model the intervention by mapping out the intervention's content, structure, and delivery.

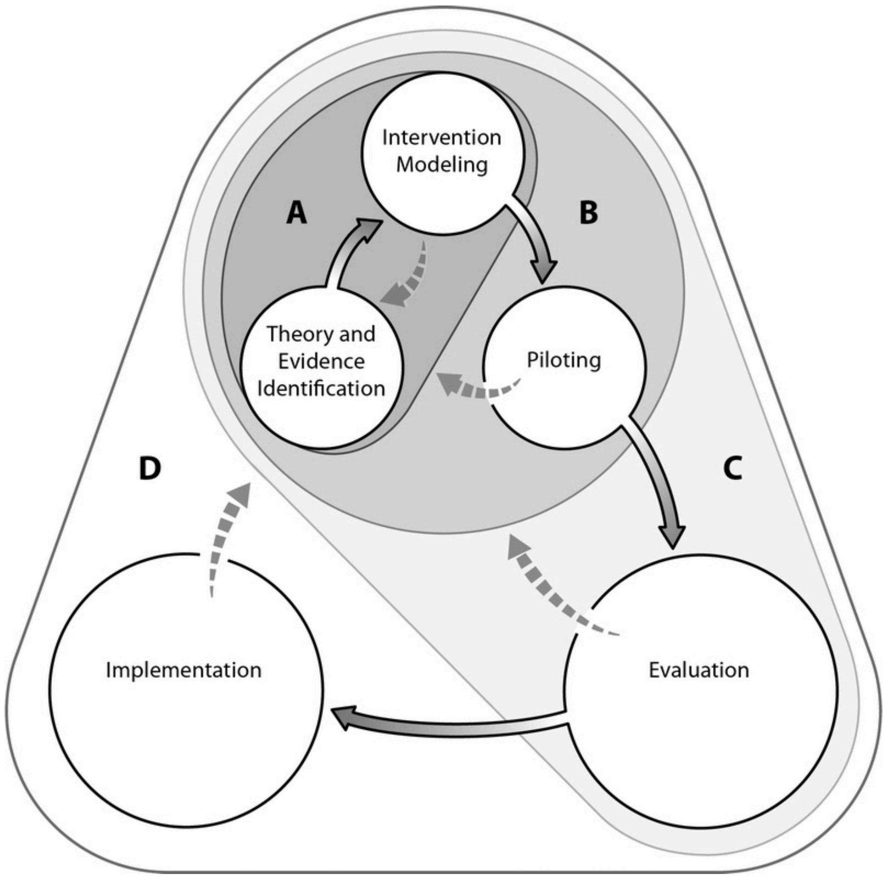


Figure 1: The Adapted MRC Framework figure adapted from Haji et al. (2014). Cycle A has been followed closely and served as the structural foundation of this thesis.

Cycle A in its entirety is addressed in a cyclical, iterative manner within Chapter 4 (Study 1) of this dissertation. I began my research journey in subphase one by mapping the gap of knowledge on how best to build a crowdsourced marketplace app for simulator production. Once the problem was identified, I wanted to develop a framework that could help inform the app development process and ensure a successful and functional product. To do this, I moved into subphase two and conducted a literature review to discover what theory(ies) underlies(y) the newly popular and successful concept that is crowdsourcing, and how those theories could be used in the design and development phases of 3DCrowdGo. By the end of Chapter 5 (Study 2), there are three resulting theories that were selected to act as models for 3DCrowdGo which will inform its content, structure, and delivery.

The next steps that proceed the scope of this work lies in the remainder of the adapted MRC framework starting with Cycle B — piloting. We have initiated this process in Chapter 5 via an initial pilot test case. In the future, we plan on completing this piloting cycle by testing for feasibility and acceptability, conducting a formative evaluation and outcome assessment to address design uncertainties, utilizing a comparison group, and finally, undertaking a summative evaluation to address methodological issues. Up until this point, future work plans for this phase include a cost-benefit analysis and phenomenological focus group interviews with both stakeholder groups — 3D printing experts and health professions education learners.

3.1.2 Development and Piloting framework

Because this thesis work presents a complex intervention with many different stakeholder groups and evolving contexts, I operationalized Cycle A: Development and Cycle B: Piloting of Haji's MRC framework from Figure 1 to meet the needs of the current context. I have incorporated these two specific cycles and their corresponding methods from this framework into a modified, truncated adaptation as seen in Figure 2. There are two main components to reflect the Development – which has three subcomponents – and Pilot phases: (1a) mapping the problem through a needs assessment, (1b) theory and evidence identification through a scoping review, (1c) intervention modelling through Delphi-method surveys, and (2) piloting via a small-scale piloting/exploratory trial. This model became the foundation off which my work was built and thus will be referred to throughout this thesis.

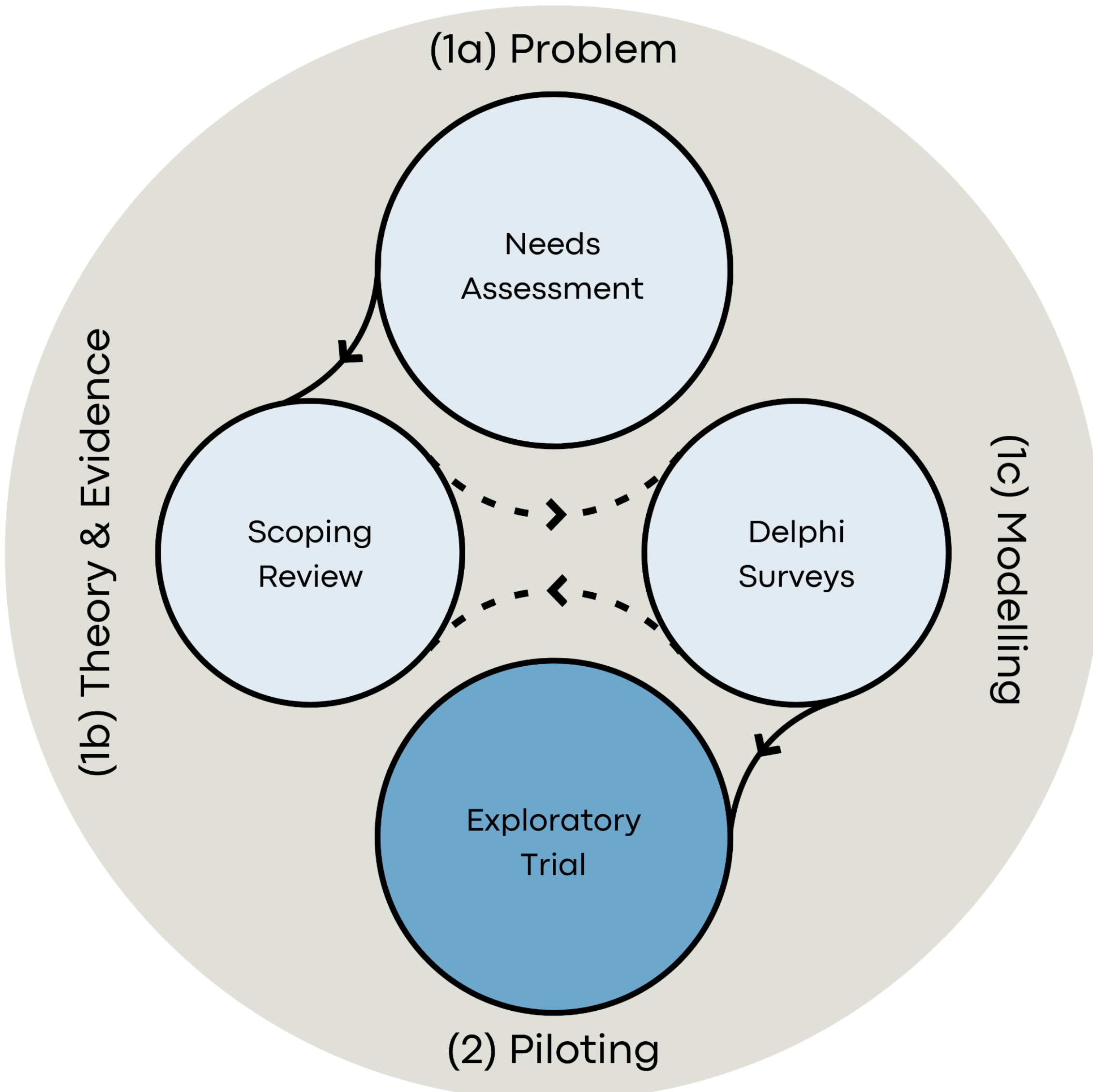


Figure 2: A graphic representation of the operationalization of the Development and Piloting phases of Haji et al.'s (2014) Adapted MRC framework. The first component and its sub-components representing Development are shown in light blue — (1a) Problem, (1b) Theory & Evidence, and (1c) Modelling. The second component representing Piloting is shown in dark blue. Inside the bubbles are the methods that were used for that specific component. Together, these components informed the course of this thesis and will be used as a reference tool.

The first component (1) represents the Development phase and is comprised of three dependent sub-components (a, b, c) which represent Haji's subphases. Since there was a significant amount of time and work at the start of this thesis dedicated to mapping the gap and uncovering the problem to be addressed, I created its own sub-component to accurately reflect its criticality. The second component (2) represents the Piloting phase. Described in the following four sections are the methods used for each sub-component of the Development phase and for the Piloting phase, how these methods have been applied in existing healthcare simulation research, and how I applied specific methods from Haji et al.'s (2014) recommendations in my own work.

3.1.2.1 (1a) Problem: needs assessment.

The first sub-component involved in Development was determining what the problem is that the research question(s) will address. To do this, Haji et al. (2014) recommends conducting a needs assessment of stakeholders to generate a clear purpose, research question(s), and hypothesis. An example to illustrate this recommendation is seen in the work of Fanning and Gaba (2007) who conducted a critical review of debriefing and gaps in the literature which supported the need to build specific models and theories for simulation-based learning. Appendix A highlights market research and customer validation interviews I conducted as part of the Brilliant Catalyst program in 2020. A preliminary and exploratory review of the literature led to the discovery and magnitude of the problem for the two different contexts of this thesis as explained previously in Chapter 2.1. Once the problem was identified, I was able to tailor the solution to address the proposed gaps and how to set it up to be effective in Chapter 2.2. Together, the problem and solution then directly informed the purpose and research questions as outlined in Chapter 2.3.

3.1.2.2 (1b) Theory & Evidence: scoping review.

The next sub-component is determining which theories or conceptual frameworks can be used to refine the hypothesis and design the intervention, as well as considering possible outcomes generated and competing theories to inform alternate interventions (Haji et al., 2014). The authors' recommendation is to perform a literature review that will discover theories to explain *how* and *why* the outcomes will be generated by the intervention. This recommendation is seen in commentary published by Dieckmann et al. (2007) examining the concept of simulation as a social practice, during which multiple theoretical perspectives were reviewed that helped inform research in the area. The means of evidence discovery in this thesis initially stems from theory identification which consisted of a thorough scoping review discussed in Chapter 4.2.2 (Study One). This led to the discovery of theories involved in the concept of crowdsourcing, which allowed me to understand *why* these theories are effective or not and *how* to implement them to optimize 3DCrowdGo development and success. In future work, I plan to develop different iterations of the app rooted in the different resulting theories from the review to see which is the best foundation.

3.1.2.3 (1c) Modelling: Modified-Delphi method surveys.

The final sub-component in Development is determining the desired effects and how they interact with the context. Haji et al. (2014) recommend a number of methods to implement this step (e.g. key informant interviews, case studies, surveys, etc.) in order to highlight the relationship between the components of the intervention and its context. An example in simulation literature is that of Kneebone et al. (2004) who presented their framework for simulation-based education and suggested that patient-focused simulation facilitates training in authentic simulated contexts that reflect the realities of clinical practice. In this thesis, quantitative Delphi method surveys with expert groups were employed to prioritize the previously identified theories which can be found in Chapter 4.2.3 (Study Two). The results from these surveys play a role in the desired effect of the app – timely 3D printing production of simulators – based on their different interactions with the context – a gap in technical skills training.

3.1.2.4 (2) Piloting: small-scale exploratory trial.

The second component is Piloting to determine the acceptability and feasibility of the intervention, its barriers and costs, as well as what its optimal design might look like. Many different methodological strategies can be implemented to carry out this component including focus group interviews with stakeholders, a cost-benefit analysis, and small-scale experimental studies (Haji, et al., 2014). Kneebone et al. (2006) exemplified small-scale studies in their piloting work by exploring the feasibility of their patient-focused simulation concept for skill assessment via a pilot study of the Integrated Procedural Performance Instrument (IPPI). In preliminary feasibility and acceptability testing of 3DCrowdGo, I piloted an exploratory trial to clarify design questions and understand how outcomes would be affected in different circumstances. This trial involved the recruitment of services of different user groups to produce simulators designed for year one nursing students, which is described in detail in Chapter 5.

Chapter 4: Study One — Using a Delphi Method Approach to Evaluate the Theoretical Underpinnings of Crowdsourcing and their Application to 3DCrowdGo.

[Verbatim as submitted to the Journal for the Society of Simulation in Healthcare]

4.1 Introduction

The COVID-19 pandemic has caused many challenges and adaptations in daily life, work schedules, educational practices, social interactions and, more importantly, safety precautions. Public Health guidelines on social distancing measures have posed limitations on in-person grouping, impacting traditional educational practices. For example, in Health Professions Education (HPE), technical skills training is supported by in-person, centralized simulation practices that allow trainees to master technical skills before executing them on patients. Unfortunately, this model requires trainees to attend simulation labs at educational or hospital institutions, which has become a significant limitation given the public health guidelines implemented in response to COVID-19. As it is imperative to maintain the quality of current and future health professionals, academic institutions are exploring the idea of using de-centralized simulation practices where trainees could train in any place, as long as they have access to a simulator. However, commercially available simulators are expensive and follow a one-size-fits-all model that does not fully address the trainees' needs at all levels, which creates a gap between the training experience that should be offered and the current resources available.

To bridge this gap, our lab has been using three-dimensionally (3D) printed models to create customizable simulators affordable for individuals and institutions. Simulation literature shows that technical skills acquisition does not require the highest levels of fidelity (Almarghoub, 2019), making three-dimensional printed models a feasible option. Furthermore, the level of fidelity required for accurate technical skills training is directly related to the level of expertise of the trainee (Munshi, Lababidi, & Alyousef, 2015), making the customizable characteristics of 3D printed models an asset to accurately meet the trainee’s needs. Interestingly, the main limitation encountered to produce these simulators is the lack of capacity to manufacture the number of simulators needed to support the HPE curricula. This was similar to the lack of manufacturing capacity faced by the Government of Canada (Allam Advisory Group [AAG], 2020) while trying to address the personal protective equipment (PPE) shortages experienced during the beginning of the COVID-19 pandemic, which was ultimately resolved using a crowdsourcing model. Crowdsourcing is a concept where services, ideas, or content are obtained through contributions from a large group of people rather than traditional suppliers (Crowdsourcing, 2022). Using rapid prototyping and 3D printing, a crowdsourcing model allows for designing, testing, and manufacturing at the consumer level, making it the first time that home-based 3D printing communities united and mass-produced PPE, assistive devices, and clinical equipment (Vordos et al., 2020). Due to its cost-effectiveness, increased efficiency and collaboration, design and manufacturing decentralization, and product customizability (Dodziuk, 2016), 3D printing is instrumental to the customization of the proposed simulators, and the ability to crowdsource is manufacturing.

The overarching goal of this study is to develop the theoretical foundations of crowdsourcing to serve as a template upon which a web-based platform (3DCrowdGo) can be designed and developed. To do this, we have developed a subset of two research aims: (1) conduct a literature review to discover what types of crowdsourcing theories exist and (2) develop Delphi-method surveys to prioritize which of the theories could be implemented into the design and development of 3DCrowdGo.

4.2 Methods

4.2.1 General Methodology

This study was divided into two separate phases to address both research aims outlined at the end of Chapter 4.1. For this study, strict emphasis is being placed on sub-components (1b) and (1c) of Figure 2 from Chapter 3.1.2 as they have served as the structural foundation of this study and align with the two phases respectively. As a reminder, sub-component (1b) is titled Theory & Evidence whose methods involved a scoping review to discover theories to explain *how* and *why* the outcomes will be generated by the intervention. This will be described in further detail in Phase One of this chapter (4.2.2). Sub-component (1c) is titled Modelling whose methods used were Modified-Delphi method surveys to highlight the relationship between the components of the intervention and its context. This process is described in further detail in Phase Two of this chapter (4.2.3).

4.2.2 Phase One (Literature Review): theory identification

A thorough scoping review was conducted to discover what types of theories exist that are involved in the operation, functionality, and success of crowdsourcing. A scoping review was the review method of choice as they are used to map or explore the extent of a field of research as well as clarify working definitions and conceptual boundaries of a topic or field (Cooper, 2021). The 5-stage review framework proposed by Arksey and O'Malley (2005) was followed during this process to help (1) identify the research question, (2) discover relevant studies, (3) select studies, (4) chart data, and (5) summarize and report results.

In accordance with this review framework, the first stage involved identifying the research question that will be addressed by this study because it acts as a guide for the search strategies. Next, to discover relevant studies, MEDLINE, PubMed, and Google Scholar were the databases of choice to perform the scoping review. Selecting studies involved keyword searches which included the following: "crowdsourcing," "collective intelligence," "theory of crowdsourcing," and "social behaviour." Search limits of "English" and "published within the last 15 years" were first applied. The data we charted were exported into reference manager software, Endnote X9, followed by DistillerSR literature review software through which a title review was conducted. After eliminating redundancies and abstract screening, full-text reviews were conducted. The final stage of the framework involves collating, summarizing, and reporting the results. After completing the full-text reviews, a final selection of results was made that would now act as potential construction techniques for 3DCrowdGo. A modified PRISMA diagram seen in Figure 2 was created to illustrate the review process and will be expanded on in Phase Two of the Results section. Finally, the resulting theories were then further researched, and the findings were recorded in Microsoft Word to later inform Phase Two.

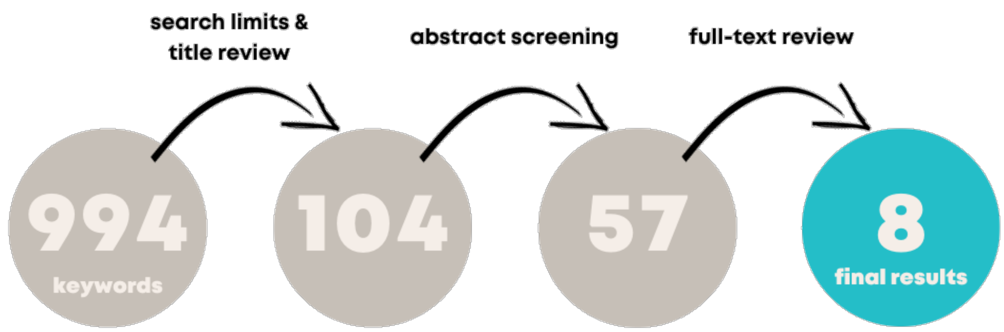


Figure 3: This modified PRISMA diagram illustrates the scoping literature review process and the steps taken to end up with the final eight results/theories.

4.2.3 Phase Two (Modified-Delphi Method Surveys): theory prioritization

The Modified-Delphi Method is defined by Hartman and Baldwin (1995) as a "consultative process that uses computer technology combined with a survey to obtain constructive participation in the input and consensus process that is often essential to the success of a planned change." The modified approach requires an initial list of items to be generated and presented to Delphi participants beforehand, whereas traditional Delphi approaches begin from scratch (Haji et al., 2015). This method is used widely in medical education where it is applied in needs assessments (Nayahangan, 2018), defining content for assessment instruments (Strøm, 2017), and to identify research priorities in medical education (Stefanidis et al., 2015; Anton et al., 2022).

In general, the modified Delphi method process starts with the selection of a group of experts, referred to as the Delphi panel, based on the topic being examined. Each panellist is sent a survey with instructions to comment on each topic based on their opinion, experience, or previous research. They return the surveys to the researcher who groups the comments and prepares copies of the information. An agreement between the panelists is determined a-priori and the facilitators determine if the agreement has been reached, or if the content needs to be modified and resent for further deliberation by the panel. This is known as a Delphi round, and these rounds are repeated as many times as necessary to achieve a general sense of consensus.

4.2.3.1 Participants.

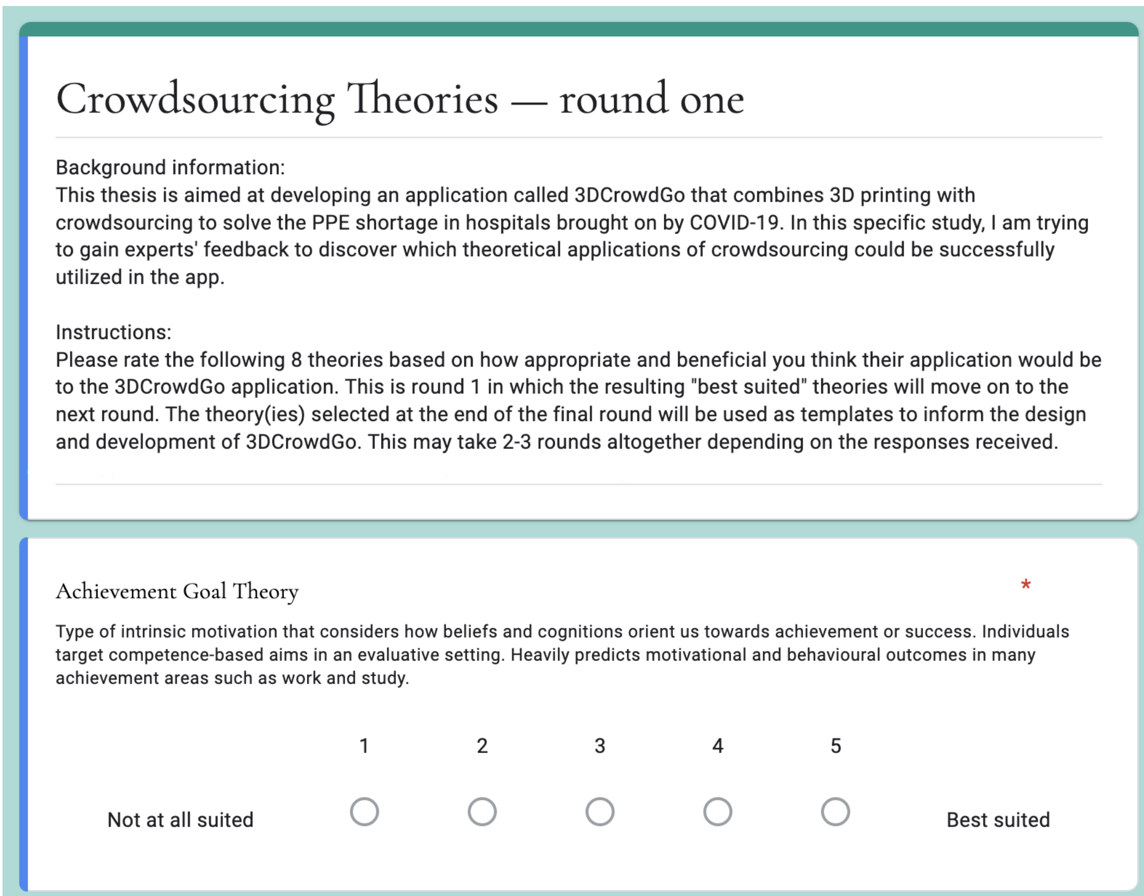
There were two separate participant groups that completed this survey: Group 1: Health field experts and Group 2: 3D printing hobbyists/experts.

Group 1: A convenience sample of 23 graduate students and faculty members participated in the Delphi protocol. They were recruited via a broadcast email from the faculties of Health Sciences, Life Sciences, and Business and Information Technology, Ontario Tech University. There were no inclusion or exclusion criteria.

Group 2: A convenience and snowball sample of five individuals was recruited via email, with the participant pool initiated from our maxSIMhealth lab. This snowballing technique (Goodman, 1961) was utilized by asking the identified experts to nominate one to three individuals from other institutions who fit the eligibility criteria to participate in the Delphi process. Two lab members whose expertise and work lie in 3D printing were retrieved through convenience sampling, and through those individuals, I was able to snowball the remaining three participants. Eligible participants were those who either have hobby- or work-related experience with 3D printing, which led to participants ranging from hobbyists, to graduate students, to engineers. There were no additional inclusion or exclusion criteria as this is a niche group to begin with.

4.2.3.2 Procedure.

Participants from each stakeholder group were provided with the research study context and asked which of the crowdsourcing theories would be most suitable. Invitations were sent via email with a 15-minute Google Form survey embedded, which allowed for the review of each of the theories. It was decided to conduct a maximum of three rounds, and two reminder emails were sent for each round. Non-responders in previous rounds remained as members of the panel and were re-invited to participate in the subsequent rounds. The survey appearance, description, and one of the survey questions can be seen in Figure 4. The participants were required to read the descriptions of the eight crowdsourcing engagement theories and then rate their relevance on a Likert scale, where 1 = not suited for 3DCrowdGo and 5 = best suited for 3DCrowdGo. In accordance with the Delphi method, participants were invited back for 2 more rounds, with the theories narrowing down each time, to reach a final consensus on 1 to 3 theories based on strengths and weaknesses. A separate Google Form was created for each round of both user groups. The initial form that was sent to participants in round one of both groups encompassed all eight theories. From there, the theories that did not pass through our success criteria were removed and the remainder were resent out as the Form for round two. This process continued until a consensus was reached. After each round when all the participants had submitted their survey responses, the data from the Google Forms were extrapolated and converted into corresponding Google Sheets for analysis.



Crowdsourcing Theories — round one

Background information:
This thesis is aimed at developing an application called 3DCrowdGo that combines 3D printing with crowdsourcing to solve the PPE shortage in hospitals brought on by COVID-19. In this specific study, I am trying to gain experts' feedback to discover which theoretical applications of crowdsourcing could be successfully utilized in the app.

Instructions:
Please rate the following 8 theories based on how appropriate and beneficial you think their application would be to the 3DCrowdGo application. This is round 1 in which the resulting "best suited" theories will move on to the next round. The theory(ies) selected at the end of the final round will be used as templates to inform the design and development of 3DCrowdGo. This may take 2-3 rounds altogether depending on the responses received.

Achievement Goal Theory *

Type of intrinsic motivation that considers how beliefs and cognitions orient us towards achievement or success. Individuals target competence-based aims in an evaluative setting. Heavily predicts motivational and behavioural outcomes in many achievement areas such as work and study.

	1	2	3	4	5	
Not at all suited	○	○	○	○	○	Best suited

Figure 4: Instructions and a sample question from the Google Form survey sent to participants in order to gather quantifiable data are pictured above. Results were used to narrow down which theories would be most suited for the development of 3DCrowdGo.

4.2.3.3 Statistical Analysis.

Main descriptive statistics of mean (μ) and standard deviation (σ) were used to describe the variable collected in the study and, thus, to evaluate each of the theories. Descriptive statistics were calculated in all survey rounds via built-in mean and standard deviation calculation functions in the Google Sheets software. To progress through each round after the data was analyzed, the theory must have achieved a mean score of 3.5/5 or more as this would signify a 70% agreeance level between participants. In addition, a low standard deviation of less than 1 was required to ensure data reliability. If any discrepancies occurred, such as a high standard deviation (>1), the theory was selected to progress to the next round only after it was further expanded and clarified to all participants to minimize possible confusion and error on the participants' end.

4.3 Results

4.3.1 Phase One (Literature Review): theory identification

In this section, each of the steps as seen in our modified PRISMA diagram (Figure 2) will be explicated in greater detail. The initial keyword search yielded a total of 994 results. After applying the search limits of "English" and "published within the last 15 years," 974 results remained and were exported into the reference manager software, Endnote X9. Once the import was complete, the results were then uploaded onto the DistillerSR literature review software platform through which a title review was conducted. If titles contained relevant words of "theory," "health," "simulation," or "success," they were included, while titles containing "crowdfunding" were excluded because this concept is too distinct for this study's context as it is strictly monetarily involved. After the elimination of redundant papers, a total of 104 results remained. After this, abstracts were screened for relevance and 47 results were eliminated. Finally, these remaining 57 results were reviewed in full and 8 theory results were left at the end of the review as possible guiding theoretical templates for 3DCrowdGo.

These resulting eight theories from the scoping review were then further researched to develop a comprehensive understanding of each so that they could be well articulated to the participants in Phase 2. Table 1 summarizes the wealth of information found on each of the theories, categorized by definition, description, and possible application to our app. The definitions and descriptions were inputted into the Google Forms for Phase Two, and the applications were omitted to eliminate bias when participants select theories. These eight theories became the subject of research for the next two phases of this study.

Table 1: A comprehensive alphabetical list of the eight literature review results which provides a definition, description, application to 3DCrowdGo, and reference(s) for each theory.

1. ACHIEVEMENT GOAL THEORY	
Definition	Achievement Goal Theory is when individuals target competence-based aims in an evaluative setting and heavily predicts motivational and behavioural outcomes in many achievement areas such as work and study [13].
Description	The two main achievement goals are known as mastery and performance. During competence evaluation, mastery-focused individuals develop a standard based on the requirements of a task or their own internal comparisons, while performance-focused individuals use standards and comparisons based on other individuals. Because both goals strive to either approach competence or avoid incompetence, a 2 × 2 model of achievement goals results: mastery-approach, mastery-avoidance, performance-approach, and performance-avoidance [14]. Mastery-approach goals are primarily linked to adaptive outcomes, performance-approach goals to a mix of adaptive and maladaptive outcomes, and the two avoidance goals to various maladaptive outcomes. Mastery-approach goals entail mastering a task and judging success based on effort and improvement over time. In contrast, performance-approach goals are focused on outperforming other individuals and measure success based on winning. A 2010 study [13] found that older workers with dominant mastery-approach goals scored highest in work engagement, social, and personal meaning of work.
Application	Individuals who demonstrate both mastery- and performance-approach goals are suitable for and would impact the success and retention of the crowd in 3DCrowdGo.
References	[13] Lange, Yperen, Heijden, & Bal, 2010. [14] Sommet & Elliot, 2017.
2. GAME THEORY	
Definition	Game Theory in the context of a labour relationship describes a “game” between workers and employers in which workers must choose how much (costly) effort to provide, and employers (who prefer high effort) cannot directly observe this choice [15].
Description	These games are focused on getting workers to show up and exert the effort needed to accomplish a task [15].
Application	This concept is important to consider when designing the app from an engagement perspective as it can inform our gamification methods via a rating system and leaderboards.
References	[15] Horton & Chilton, 2010.
3. MOTIVATION CROWDING THEORY	

Definition	Motivation Crowding Theory is built upon two fundamental principles — extrinsic and intrinsic motivation — directly correlated to the level of an individual's work engagement [16].
Description	Extrinsic motivation stems from factors outside an individual that lead to a specific outcome. Extrinsically motivated individuals work because they believe they will receive desirable outcomes including monetary rewards, promotions, bonuses, etc. In contrast, intrinsic motivation comes from within an individual who does something without the need or want of an external reward. Intrinsically motivated individuals tend to have higher job satisfaction and performance because they feel their job is interesting, challenging, and meaningful [16]. Thus, Motivation Crowding theory proposes that when already intrinsically motivated individuals are introduced to a financial reward, their motivation to fully engage in an activity is diminished [16].
Application	This theory is important to be aware of because sometimes monetary incentives can take away the pleasure and drive from performing a specific activity, so we will have to find a happy medium in order to keep both end-users of 3DCrowdGo engaged and productive.
References	[16] Putra, Cho, & Liu, 2016.
4. REINFORCEMENT SENSITIVITY THEORY	
Definition	Reinforcement Sensitivity Theory is comprised of three existing neurobiological systems responsible for differences in sensitivity to reward, punishment, and motivation [17].
Description	The first system is the Behavioural Activation System (BAS) which facilitates reactions to rewarding stimuli and regulates approach behaviour, also known as approach-approach behaviour. It is positively related to work engagement, effort, and persistence [17]. Next is the Fight-flight-freeze System (FFFS) which mediates reactions to aversive stimuli, also known as avoidance-avoidance behaviour [18]. Lastly, the Behavioural Inhibition System (BIS), or approach-avoidance behaviour, mediates conflict between the BAS and FFFS. An individual with a more reactive BIS has difficulty making a choice between two equally attractive/unattractive options [19].
Application	These biological systems are important considerations because targeting higher reward sensitivity individuals could be beneficial for platform owners. Improvements would result because workers' motivational outcomes would already be increased at no additional cost [20]. For example, an individual with a highly active BAS specifically is more energetic and driven when approaching desired stimuli [19]. Thus, these types of individuals would be great targets of 3DCrowdGo as they would already be highly motivated to work.
References	[17] Barashev & Li, 2018b. [18] Barashev & Li, 2017. [19] Reuter et al., 2015. [20] Barashev & Li, 2018a.
5. ORGANIZATIONAL LEARNING THEORY	
Definition	Organizational Learning Theory focuses on two main aspects of exploration and exploitation to understand creativity amongst inventors. Exploration is when new ideas emerge from established ways of thinking, while exploitation involves improving existing solutions [21].
Description	According to this theory, the innovation process begins with exploration when there is a lack of creative ideas. Once these ideas have been recognized, exploitation can occur because more certain results can be obtained by reusing and recombining existing knowledge [21].

Application	Although the printing tasks that hospital users request through 3DCrowdGo will be needs-based, having knowledge of this theory will allow us to pivot in the case of 3DCrowdGo extending beyond a hospital environment where there is a lack of readily available printing ideas.
References	[21] Bayus, 2010.
6. SOCIAL EXCHANGE THEORY	
Definition	Social Exchange Theory in the context of virtual knowledge exchange discusses the willingness of virtual community members to share valuable information with other members, who then expect help to be reciprocated in the future [22].
Description	In addition to earning material rewards for the exchange, psychological rewards such as trust, support, confidence, and prestige are also common. Thus, it is assumed that sustainable knowledge-sharing behaviours influence the formation of long-term relationships between members [22].
Application	This exchange concept is crucial for crowdsourcing because it is unlikely that the goodwill of 3DCrowdGo's users will keep the app successful for a long period of time. Social Exchange Theory highlights the need for the knowledge of both end-users to be compensated in either a material or psychological manner in order to maintain positive and productive relations. This will inform the incentives and compensation systems that are built into the business model of the app.
References	[22] Jinyang, 2015.
7. SOCIAL CAPITAL THEORY	
Definition	Social Capital Theory states that social relations between individuals have the potential to facilitate the accumulation of non-/economic benefits [23].
Description	An example of this is when an individual's social capital (money, knowledge, material resources, etc.) becomes available to someone else through their social relationship [25]. The individual's money or knowledge only converts from an ordinary resource into social capital once it is transferred through the relationship and becomes available to another individual. Social networks that are characterized by trust form the basis of social resource generation which then constitutes the core of social capital [23].
Application	This theory is applicable because 3DCrowdGo is essentially a virtual social network connecting hospital admins and 3D printer owners. Since they foster a sense of trust within the network, both end users' social capital expands because they exchange ordinary resources (knowledge, materials, money).
References	[23] Rostila, 2011.
8. TRANSACTION COST THEORY	
Definition	Transaction Cost Theory states that the ideal organizational structure achieves economic efficiency by minimizing the costs of exchange, where different transaction types produce monitor, control, and transaction management costs [24].

Description	This theory is especially important for businesses or companies deciding between in-sourcing or outsourcing economic tasks. Some transaction costs that favour the outsourcing of service include: no additional ongoing operational costs, staff lacking skills to provide the service, improvement of skills and knowledge, and increased productivity and technical support [25].
Application	This theory applies to and supports the foundation of 3DCrowdGo because it thrives on the idea of outsourcing 3D printing tasks that, in-house or in the traditional manufacturing industry, would have a much higher cost for hospitals. Beneficial transaction costs of 3DCrowdGo include its ability to provide hospitals with a method of communication to easily access materials and resources for PPE, all in a more timely manner. 3D printer owners will also have access to knowledge and a database filled with ideas for printing jobs that they can turn profitable, all while making use of their potentially very expensive assets.
References	[24] Young, 2013. [25] Mwai, Kiplang'at, & Gichoya, 2014.

4.3.2 Phase Two (Modified-Delphi Method Surveys): theory prioritization

4.3.2.1 Health expert group.

A summary of the descriptive statistics from the three survey rounds completed by the health expert participant group retrieved from the Google Sheets data is found in Table 2.

Table 2: Organized below are the descriptive statistics (mean=μ, SD=σ) extrapolated from the Google Sheets for each of the eight theories after 3 rounds of Modified-Delphi surveys. A dash (-) indicates that the theory did not meet inclusion criteria and was eliminated from that round. "Selected" indicates the theory was selected by the health expert participants (Group 1) to be most well-suited as a foundation 3DCrowdGo development. The number of participants who completed each round is represented by "n."

	Achievement Goal Theory	Game Theory	Motivation Crowding Theory	Organizational Learning Theory	Reinforcement Sensitivity Theory	Social Capital Theory	Social Exchange Theory	Transaction Cost Theory
ROUND ONE (n=13)								
μ	3.62	2.85	4.08	3.38	2.92	3.62	4.00	3.62
σ	0.71	1.41	0	1.41	0.71	0	0.71	0.71
ROUND TWO (n=8)								
μ	3.29	-	4.43	3.43	-	3.86	3.86	4.00
σ	0.76	-	0.53	1.13	-	1.21	1.07	0.58
ROUND THREE (n=7)								
μ	-	-	*selected*	-	-	3.20	4.60	*selected*
σ	-	-		-	-	0.69	0.47	
FINAL RESULTS								
μ	-	-	*selected*	-	-	-	*selected*	*selected*
σ	-	-		-	-	-		

Round One: 13 participants completed this first round. Game Theory and Reinforcement Sensitivity Theory both scored low means (2.85 and 2.92 respectively); thus, both were eliminated. Organizational Learning Theory scored a mean close to the cut-off and a high standard deviation (μ=3.38, σ=1.41), so this theory was included in round two after expanding on its explanation in the Google Form.

Round Two: 6 remaining theories were included in round two in which 8 participants participated in due to loss to follow-up. Based on the results, Achievement Goal Theory and Organizational Learning Theory were eliminated (μ=3.29, σ=0.76 and μ=3.42, σ=1.13 respectively) while Social Capital and Social Exchange Theory scored a high mean of 3.86 and with similar variabilities (σ=1.07 vs. σ=1.21 respectively). As seen in Table 2, there were 4 theories remaining at this point, and since the target was 3, both were included in the final round.

Round three: 7 participants completed this round as 1 was a loss to follow-up. The other 2 of the remaining 4 theories that were selected by default as most suitable to 3DCrowdGo were Motivation Crowding Theory and Transaction Cost Theory. Since these were now final selections, they were removed from the final Google Form survey to allow the participants to choose between the last 2. The results of Social Capital and Social Exchange Theory were very close, so I expanded on both of their descriptions within the Google Form to reduce the likelihood of the same result, then sent out the form to participants for them to decide which is the final suitable theory for 3DCrowdGo. This final round produced much clearer results (μ_{SCT}=3.20, σ_{SCT}=0.69 and μ_{SET}=4.60, σ_{SET}=0.47) showing that Social Exchange Theory would be the third and final theory selected by the health experts as most applicable to 3DCrowdGo development. A visual summary map of the theory selections during the multi-round Delphi surveys for this health expert participant group are illustrated in Figure 5.

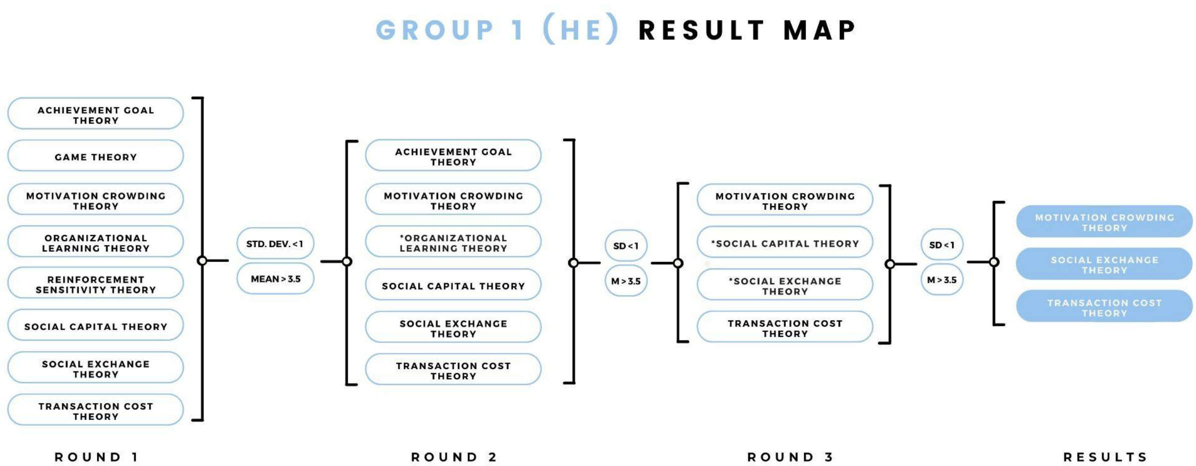


Figure 5: Rounds 1, 2, and 3 results from the health experts (HE) participant group show that Motivation Crowding Theory, Social Exchange Theory, and Transaction Cost Theory were deemed the three most well-suited for adaptation

in 3DCrowdGo. Theories marked with an asterisk (*) were those whose results were subjected to additional investigation due to discrepancies within statistical data.

4.3.2.2 3D printing group.

A summary of the descriptive statistics from the two survey rounds completed by the 3D printing participants retrieved from the Google Sheets data is found in Table 3.

Table 3: Organized below are the descriptive statistics (mean=μ, SD=σ) extrapolated from the Google Sheets for each of the eight theories after 2 rounds of Modified-Delphi surveys. A dash (-) indicates that the theory did not meet inclusion criteria and was eliminated from that round. "Selected" indicates the theory was selected by the 3D printing participants (Group 2) to be most well-suited as a foundation 3DCrowdGo development.

	Achievement Goal Theory	Game Theory	Motivation Crowding Theory	Organizational Learning Theory	Reinforcement Sensitivity Theory	Social Capital Theory	Social Exchange Theory	Transaction Cost Theory
ROUND ONE (n=5)								
μ	2.60	1.60	4.40	2.80	2.80	2.60	4.20	3.40
σ	1.12	0.55	0.89	1.64	1.10	1.55	1.30	1.14
ROUND TWO (n=5)								
μ	-	-	4.80	3.00	-	-	3.80	2.60
σ	-	-	0.71	2.83	-	-	0.71	1.41
FINAL RESULTS								
μ	-	-	*selected*	-	-	-	*selected*	-
σ	-	-		-	-	-		-

Round One: 5 participants completed this first round. Immediately after conducting round one, the following 4 theories were significant outliers and thus eliminated from the next round. Achievement Goal Theory (μ=2.60; σ=1.14), Game Theory (μ=1.60, σ=0.55), Reinforcement Sensitivity Theory (μ=2.80, σ=1.10), and Social Capital Theory (μ=2.60, σ=1.52) all scored very low averages with all but one standard deviation result exceeding the cutoff. That said, the mean for Game Theory was the lowest of all rounds in both groups making its low variability a reinforcer that it is also not suitable for use in 3DCrowdGo. There were also 2 theories with discrepancies in this first round. Since Organizational Learning Theory had a very high standard deviation (σ=1.64) and the Transaction Cost Theory mean was on the cusp of the cut-off despite a high standard deviation (μ=3.4, σ=1.14), we elaborated on their descriptions in the Google Form and progressed them to the next round.

Round two: 5 participants completed this last round. The remaining 4 theories were included in the Google Form for this round and sent back to participants for them to decide on the final suitable theories for 3DCrowdGo. Again, very clear results were revealed as 2 were rated more favourably. Motivation Crowding Theory and Social Exchange Theory both had high means (μ=4.80 and μ=3.80 respectively) and low standard deviations (σ=0.71 for both) which made them clear winners over the other 2 theories. As a result, these were the final theories selected by the 3D printing group as most applicable to 3DCrowdGo development. Another visual summary map illustrated in Figure 6 reflects this 3D printing hobbyist and expert participant group's theory selections as surveying progressed.

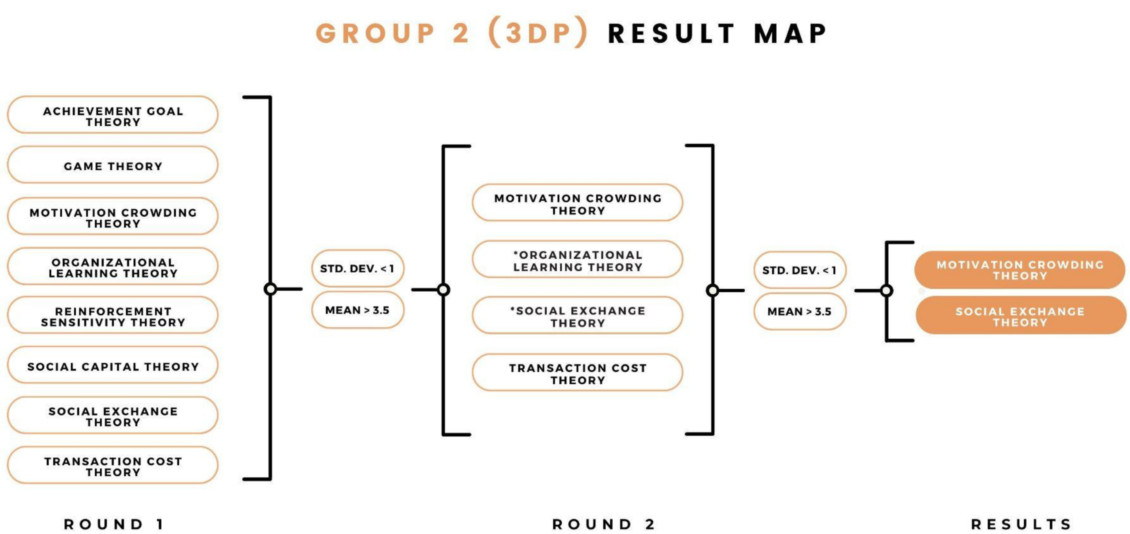


Figure 6: Rounds 1 and 2 results from the 3D printing (3DP) participant group show that Motivation Crowding Theory and Social Exchange Theory were the two most well-suited theories for adaptation in 3DCrowdGo. Theories marked with an asterisk (*) were those whose results were subjected to additional investigation due to discrepancies within statistical data.

4.3.3 Cumulative Results

In summary, the three rounds with the participants in Group 1 showed that Motivation Crowding Theory, Social Exchange Theory, and Transaction Cost Theory were deemed the three most well-suited for adaptation in 3DCrowdGo. Similarly, the results with participants in Group 2 showed that Motivation Crowding Theory and Social Exchange Theory were the two most well-suited theories for adaptation in 3DCrowdGo. The results across our two different participant groups — with varying degrees of expertise in different industries — followed similar elimination patterns. After combining the results together, the three final theories that both health and 3D printing experts deem most well-suited to serve as a foundation of 3DCrowdGo development are: Motivation Crowding Theory, Social Exchange Theory, and Transaction Cost Theory. Now that these theories have been established, in future work they will inform the construction of 3DCrowdGo as a flexible platform that can be redeployed when the context changes. Two theories can be used to construct a version of 3DCrowdGo that relies on volunteerism. Specifically, the panel identified (1) Motivation Crowding theory, built upon both extrinsic and intrinsic motivation, and (2) Social Exchange Theory, which discusses the willingness of virtual community members to share valuable information with others who then expect help to be reciprocated in the future. On the contrary, Transaction Cost Theory, which states that the ideal organizational structure achieves economic efficiency by minimizing the costs of exchange, was selected by the panel to support building a version of the platform when the manufacturing is linked to monetary exchanges. For example, in a non-emergency scenario, Transaction Cost Theory can be used to compensate producers for their efforts, while Motivation Crowding Theory will be used when financial resources are constrained. In Chapter 5.4, a pilot test case is proposed that uses Social Exchange Theory as the basis of the app.

4.4 Discussion

Due to mandatory social distancing measures implemented by public health authorities, it is not currently possible for HPE students to attend face-to-face training sessions at their educational or hospital institutions. This has left many students with limited opportunities for learning technical skills that would otherwise be available if they were not required to stay home. Our proposed solution to this gap in simulation training is to develop a crowdsourced web app, 3DCrowdGo, that produces 3D printed simulation models for remote learning. Before we could build the app, we first wanted to learn why and how crowdsourcing functions to best inform its construction.

This work was guided by three aims: (1) discover what types of crowdsourcing theories exist, (2) categorize and analyze these theories, and (3) prioritize theories for implementation. A literature review was first conducted using MEDLINE, PubMed, and Google Scholar databases to determine which theories make crowdsourcing successful and to narrow down results to those most applicable to our context. This identified eight theories, all of which were proposed as candidate theories to base the application on. Next, these theories were assessed during Modified-Delphi method surveys of health field experts and 3D printing experts and hobbyists. Both groups reviewed each theory to determine which ones would offer the most successful crowdsourcing approach in the context of simulation-based education. After three separate rounds, participants came to a consensus on three final theories as best suited for 3DCrowdGo. The first one was Motivation Crowding Theory which is built upon 2 fundamental principles — extrinsic and intrinsic motivation — that are directly correlated to one's work engagement level (Putra, Cho, & Liu, 2016). Social Exchange Theory was also selected which, in the context of virtual knowledge exchange, discusses the willingness of virtual community members to share valuable information with others who then expect help to be reciprocated in the future (Jinyang, 2015). The final selected theory, called Transaction Cost Theory, states that the ideal organizational structure achieves economic efficiency by minimizing the costs of exchange (Young, 2013).

4.4.1 Specific Limitations

Limitations within this technical report are largely due to the fact that crowdsourcing is a relatively novel concept, especially in the healthcare industry. Therefore, there is a limited amount of scholarship and available publications that pertain to this specific work. Much of the research that has been done on crowdsourcing is in the business and engineering industries and is oftentimes found to be conjoined with crowdfunding — two concepts distinct enough that only one was deemed suitable to study in this context. This means some of the available research is not applicable to the work that we are doing. One of the major limitations to note is the relatively small sample size of 3D printing users collected for Phase Three of this study. Since this is a niche group of individuals who needed to have a specific interest or involvement with 3D printing, locating, and recruiting them was a challenge. Recruitment for these individuals began on the online social media platform, Reddit, because it is easy to search up and target specific hobby groups. Though it was easy to find these groups, our recruitment efforts were unsuccessful as it is hard to maintain the connection with anonymous users. Hence why resorted to convenience sampling through which we were able to recruit a small yet diverse participant group who were at an arm's length of our lab at the university.

4.5 Conclusion

Hands-on learning plays a significant role in the success of health professions education learners; however, the COVID-19 pandemic has impacted the education model for the foreseeable future. The following 3 were deemed by both groups as most suitable for our context: Motivation Crowding Theory, Social Exchange Theory, and Transaction Cost Theory. These final theories will be used as informing guides for how to design and construct the 3DCrowdGo app. As a result, this will help inform a flexible, app-based solution that will be responsive to stakeholder needs, incorporate current best practices of crowdsourcing, and ultimately solve this social issue of technical skills training insufficiency by mobilizing community members.

Chapter 5: Study Two — Applying and Testing a Crowdsourcing Platform to Support Home-Based Simulation: an exploratory study.

[Verbatim as accepted to the Journal for the Society of Simulation in Healthcare]

5.1 Summary Statement

The purpose of this COVID Brief Report was to: (1) highlight challenges of transitioning the delivery of simulation from centralized, in-person laboratory to decentralized, home-based, online format; (2) suggest a solution that involves the use of crowdsourcing community-based three-dimensionally (3D) printers to produce affordable simulators; and (3) present exploratory research and a test case aiming to identify crowdsourcing frameworks to accomplish this. The first (2) purposes were submitted to the Journal for the Society of Simulation Healthcare as a special edition COVID Brief Report. For the purpose of this thesis, I expanded on these to develop the third purpose – a test case – that aligns with the second component, (2) Piloting, of the Development and Piloting framework. This pilot test shows the potential of the proposed solution using a design-to-cost approach to scale up the decentralized simulation practices during and beyond the COVID-19 pandemic. This test case could serve as a methodological foundation for 3DCrowdGo when built upon Social Exchange Theory. As a largely uncharted territory, the test case highlighted successes and areas for improvement that need to be addressed through both theoretical and empirical research and testing before full implementation and scale-up.

5.2 Background

The onset of COVID-19 pandemic posed limitations on in-person, centralized (Ce-SIM) practices. Because maintaining the quality of education and training during the pandemic and in the future is critical, academic institutions explore decentralized simulation (De-SIM) practices, where trainees could train anywhere as long as they have access to simulators, instructions, and feedback. However, commercial simulators may be too expensive for De-SIM scale-up. For example, during the initial phases of the COVID-19 pandemic at Ontario Tech University, Ontario, Canada, 175 first-year nursing students had no access to a simulation laboratory. Providing all these students with the four simulators linked to their curricular objectives would cost USD$120 000, which was deemed not feasible by the simulation program administrators (Barth et al., 2022). Employing services of a local research and innovation laboratory (maxSIMhealth.com), 3D printed simulators were used to reduce these costs to USD$5000.

In our case, one of the main limitations of employing the university-based 3D printing laboratory to sustain the De-SIM practice is the lack of capacity to manufacture the number of simulators needed. However, a viable solution may be provided via crowdsourcing, where services, ideas, or content are obtained through contributions from a large group of people. This report aims to highlight how to construct 3DCrowdGo to support the De-SIM practices and presents a trial case study by which 3DCrowdGo can be utilized. Our solution operates similarly to Uber or Airbnb, both of which proved to be widely successful at leveraging periodically underutilized assets to provide services to individuals that want/need them. 3DCrowdGo leverages infrastructure (i.e., 3D printers) owned by hobbyists and businesses when not in use to manufacture simulators.

5.3 Construction and Research Goals

In the initial stages of this research, we conducted a scoping review to determine which crowdsourcing theories would make the platform successful in the context of De-SIM practices during and after the pandemic, as described in Chapter 4.2.2. We identified eight different crowdsourcing theories in Chapter 4.3.1 that provided templates for unique ways of engaging the end-users. To initiate the trial, a selection between Motivation Crowding Theory, Social Exchange Theory, or Transaction Cost Theory needed to be made to inform the way in which the app flow would be designed. Given the context of a time constraint due to the pandemic for rapid production of simulators, the trial was constructed based on Social Exchange Theory which relies on sustainable knowledge-sharing behaviours to form long-term relationships between parties (Jinyang, 2015), as opposed to a theory rooted in monetary incentives which will be discussed in Chapter 5.5.2.

Though this serves as one of the potential theoretical foundations for 3DCrowdGo, there is value in testing a methodological approach specifically for 3D printing take-home simulators done by Barth et al. (2022) from our maxSIMhealth lab. This work has recently been accepted for publication in the Cureus Journal for Medical

Science and discusses the process for integrating take-home simulators into a decentralized simulation-based education model. To do this, a design-to-cost approach was utilized resulting in the production of parsimonious, functional, and cost-effective simulators. Specifically, the funds that were provided dictated cost management of the design and manufacturing processes while still producing simulators that met quality and functionality expectations required by the experts (Boucher et al., 1991). This sets this research apart from other simulator production work in that typical simulator production models follow a design-to-value approach where not much regard is paid to the cost but instead to building the best possible product (Micallef et al., 2021). Design-to-cost coupled with Social Exchange Theory allows for a 3DCrowdGo iteration in which there is no exchange of funds, but a mutually beneficial relationship is established. Although producers covered the cost of the models, they were left with research projects that required evaluation and testing as well as novel scholarship and publications in this research field. Therefore, it is possible to initially build the app off volunteerism and mutually beneficial relationships without monetary incentives. This process that Barth et al. (2022) followed served as the basis of this small-scale trial. The overarching research aim of this trial was *to discover how 3DCrowdGo could combine the theoretical foundation of Social Exchange Theory with the design-to-cost approach to scale up De-SIM practices*.

5.4 Methods

5.4.1 General methodology

In continuance with the Development and Piloting framework I proposed earlier in Chapter 3.1.2, this study falls under its second component, (2) Piloting, and thus informed the design of the trial as well a possible iteration of the 3DCrowdGo app. The goal of this component is to determine acceptability, feasibility, barriers and costs, as well as optimal design. In preliminary feasibility and acceptability testing of 3DCrowdGo, an exploratory trial was conducted to clarify design questions and understand how outcomes would be. As a result of this, a 3DCrowdGo iteration rooted in Social Exchange Theory could become, or at the least help shape, the optimal design.

5.4.2 Procedures

This exploratory trial was carried out in our maxSIMhealth research lab, and my piece of the work was following the process that would be ideally implemented into the 3DCrowdGo app if proven to have a successful outcome. The trial involved the recruitment of services of different user groups to produce three simulators – wound care and male and female urethral catheterization – for first-year nursing students at Ontario Tech University, Ontario, Canada. These digital assets were designed and developed by graduate students with 3D printing expertise from the maxSIMhealth lab in an iterative, cyclical process that I have illustrated in Figure 7. The format of the following section will begin with (1) an explanation of the specified step in Figure 7, followed by (2) how it was done in the study by Barth et al. (2022), and finally (3) how 3DCrowdGo can incorporate those methods while being built upon Social Exchange Theory. Included in these step summaries will be the participants involved in the trial, analysis of feedback, and preliminary results.

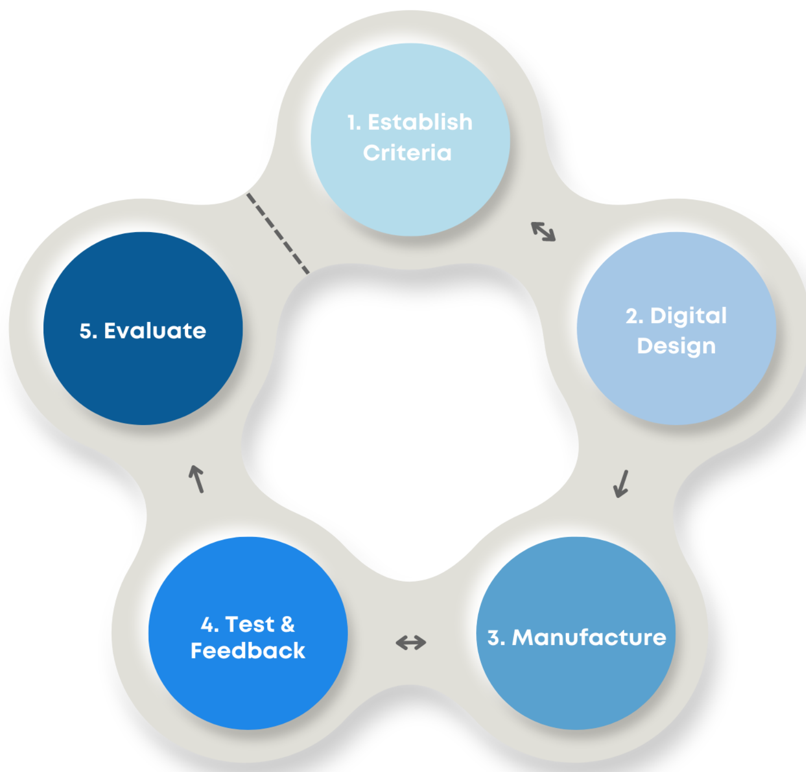


Figure 7: A graphic representation of the Design-to-Cost iterative approach followed by Barth et al. (2022) to design and test a 3D printed simulator. This process lays a methodological foundation for 3DCrowdGo when incorporating Social Exchange Theory to crowdsource manufacture 3D printed simulators.

5.4.2.1 Establish Criteria.

The first step in this trial involved the establishment of criteria, specifically the simulator requirements and constraints as requested by the experts. It requires an initial discussion between the manufacturing team and the expert/content team, and it must take place at the beginning to ensure that the instructions are clear. In Barth et al.'s (2022) work, this took the form of an initial meeting with the university program director, nursing educators, and simulation instructors. As a result of this meeting, they established the following design requirements: (1) simulators must be inexpensive with a budget of USD $5600; (2) the simulators' functions should be similar to their commercially available equivalents; (3) customize features to minimize the potential for errors in use; and (4) add a bladder onto the catheterization simulators.

In terms of implementing the criteria establishment step into 3DCrowdGo, a field will be embedded into the app where the consumer (individual making the request) will list out their requirements for the model they are requesting. This will help ensure that the producer (local hobbyists, small businesses, or hospital-based 3D printing laboratories) has a clear understanding of what to include in the design features. In cases where the consumer does not have a specified set of criteria for their simulator, an open-source file (e.g., from Thingiverse.com) can be used as a starting point which can be adapted later.

5.4.2.2 Digital Design.

The second step involved the development of digital prototypes of the simulator model based on the criteria provided earlier. In Figure 7, there is a two-way arrow between these steps to represent the high probability that this will be a repetitive and evolving phase during which the digital prototypes are continuously improved before the manufacturing process begins. That said, it is better for more back and forth to occur between the expert and the manufacturer at this point since there would be no wasted raw materials if changes do need to be made. In Barth et al.'s (2022) work, this step is revisited three times to accommodate feedback from the nursing educators before the digital prototypes could be manufactured.

In 3DCrowdGo, this step could look as follows: a chat box feature would be implemented to facilitate communication between the producer and consumer which will accommodate this back-and-forth nature of adaptations to the digital prototype.

5.4.2.3 Manufacture.

The manufacturing step in this trial consisted of constructing the physical model using specific or requested materials. This step should only occur once the digital prototype has been solidified by both the expert and manufacturing teams to minimize wasted time and resources. If the request involves a multitude of simulators, it is suggested to only produce the minimum amount necessary initially as there will likely be suggested revisions to the model during the next test and feedback step. Barth et al. (2022) began this step by 3D printing molds of the simulators. Then, after mixing pigments into silicone, silicone was poured into the molds, cured after a set amount of time, then removed from the mold to reveal the finished simulator. The manufacturing process when using 3DCrowdGo will vary depending on the requested simulator.

This exoskeleton style of 3D printing-based manufacturing would be used when the simulator requires a skin-like material as most accessible 3D printers do not have the capability to print of soft, flexible materials such as silicone. When these materials are not required, standard filament will be used to print the simulator as it is most common and easy to purchase, and easy to set up.

5.4.2.4 Test and Feedback.

This testing and feedback step requires the involvement of the expert group, or the end-user, to test out the manufactured simulator and provide initial feedback. Note the two-way arrow between these steps as the feedback provided from the tests will inform the manufacturing process before it is fully evaluated and scaled up. Barth et al. (2022) had two nursing program educators test the physical simulators. After testing was complete, the received feedback suggested the following: (1) the wound simulator was too small, (2) all simulators should be fixed to a surface (3) the stimulator stiffness should represent human tissue (4) the catheterization simulators leaked, and (5) the male urethra was too tight. Considering this, all of the feedback was addressed, either fixed where possible or eliminated entirely where not possible (e.g., bladder was removed because of leakage problem). The updated simulators were manufactured again then re-tested with nursing educators to ensure they meet the learning objectives of the nursing curriculum. Once the physical simulators were deemed adequate through multiple rounds of testing and feedback, the full amount (175 sets) of simulators were manufactured.

This process would look similar when implemented into 3DCrowdGo. To minimize the time involved between manufacturing and testing and feedback, the consumer will have access to the simulator that the producer is creating via the app. In other words, once the producer is satisfied with the revisions made to the digital prototype, they will share the 3D file with the consumer for viewing via the app and request feedback at that point. This will occur as many times as possible until the consumer feels all the criteria have been met. Because this communicative process is done through the app, it is not likely that there will be an opportunity for the consumer to test the model in person. Thus, it is important to work closely during the second and third steps to ensure that the simulator functions as expected once it is received. In cases where in-person testing is feasible, there will be an option in the app to set up a meeting during which the producer brings the physical simulator for the consumer to test on the spot. During this meeting, the consumer will provide feedback on the spot after testing and record these notes in the app so that the producer has access to and can reference later.

5.4.2.5 Evaluate.

The final step involves formal evaluation of the 3D printed simulators to discover whether the simulators that have been manufactured are acceptable and feasible. Barth et al. (2022) performed evaluation via an online survey to gather both qualitative and quantitative feedback on the three simulators. 175 nursing students in the curriculum used these sets of simulators from home to practice skills for the 2020-2021 academic year. After one week of independent practice, the researchers emailed an online survey to the class to gather feedback on the anatomical features and perceived usefulness. These surveys consisted of a multitude of questions, but results demonstrated that, although a low response rate, these models were deemed appropriate for learning. Surveys indicated that students felt they were all anatomically correct for learning purposes, the soft tissue texture, colour, and stiffness were adequate, and the weaknesses were the leaky catheterization and the size of some anatomical features. It was suggested to provide a self-paced, online instructional video repository to support each model.

Evaluation of simulators produced via 3DCrowdGo will be critical as this crowdsourcing model is anticipated to be the first of its kind in the form of an online platform for rapid development of simulators for HPE learners. A likely strategy for evaluating the printed simulators will be to follow similar strategies that Barth et al. (2022) implemented (qualitative and quantitative online surveying) to assess if the simulator is functional and acceptable. The simulators produced via 3DCrowdGo that do not require evaluation in order for the consumer to use it will be stored as files in an online repository on maxSIMhealth.com through which undergraduate or graduate students can undertake the evaluation testing portion as a project.

5.5 Results

This small-scale exploratory trial following the methodology implemented in Barth et al.'s (2022) work showed that a design-to-cost design and manufacturing approach utilizing a multidisciplinary team can be integrated into a curriculum in a De-SIM model. This process as depicted by Figure 7 resulted in simulators that were evaluated and deemed adequate training tools which can be utilized remotely by learners. The steps described in this exploratory trial represent the beginning of a shift from a centralized to decentralized simulation-based education model. Thus, in following these steps to combine Social Exchange Theory with methods centred around a design-to-cost approach, it is likely that the app could achieve the same successful feasibility and acceptability outcomes.

5.5.1 Specific limitations

Although this exploratory trial piloting demonstrates the initial efficacy of our approach, it highlighted several limitations. For example, since the production was based on volunteerism, the timing of delivery could not be enforced. This would not be the case when using a pay-per-service approach, as payments would be linked to timely delivery. Another issue that could arise is the governance of intellectual property (IP). In previous work within our lab, one of the producers, a small spin-off company that already exists in the 3D printing and simulation commercial space, assumed ownership of the designs, and pursued commercialization efforts without proper IP ownership transfer after the pilot. Because of this incident, a-priori negotiations will be made and out of an abundance of caution, we will employ a CC BY-NC-SA license to ensure that the digital representations of the simulators shared with the producers are credited to the creators, are used exclusively for non-commercial uses, and adaptations must be shared under the same terms.

5.5.2 Design-to-Cost VS. Design-to-Value

As mentioned earlier, this design-to-cost approach in Figure 7 was modelled off of Social Exchange Theory based on the context of COVID-19. Taking into consideration that this will not always be the context at hand, this cyclical, iterative process should be adaptable based on different theories to meet different circumstances. To demonstrate how this process could be extrapolated to a context where COVID-19 no longer places a time constraint, a different theory and approach would be more suitable to model the process off of. For example, of the three selected theories from Chapter 4, Transaction Cost Theory would be selected as it is more concerned with monetary exchange (Young, 2013). With this theory as the new foundation of the designing and testing of simulators process, a design-to-value approach would be followed (as opposed to design-to-cost) where more resources are available for clinicians and designers to build the best possible product without much regard for the cost (Micallef et al., 2021). To accommodate this new design-to-value approach based off of Transaction Cost Theory, Figure 8 was created to illustrate new additions specific to this context including IP agreements, deadlines, payments, and quality control. The same 5 steps remain, but some now involve sub-steps which can be seen by the branched-out bubbles.

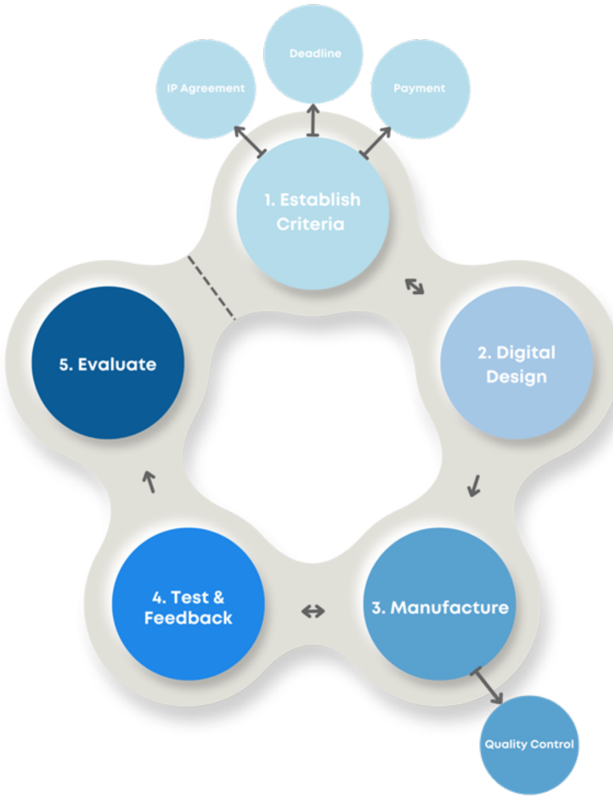


Figure 8: A graphic representation of the Design-to-Value iterative approach that builds off of Barth et al.'s (2022) work to design and test a 3D printed simulator. This process lays a methodological foundation for 3DCrowdGo when incorporating Transaction Cost Theory to crowdsource manufacture 3D printed simulators.

Now that two approaches have been presented for designing and testing 3D printed simulators under different environments and circumstances, it is important to highlight what 3DCrowdGo will look like at each step of their cycles. Figure 9 compares the design-to-cost and design-to-value models by breaking down each of the 5 steps involved and what the app will look like during each step. The highlighted text on the right half of the figure are the additions made to meet a Transaction Cost Theory context. The hopes of creating a design and test process with two contrasting theories and approaches are to provide more flexibility and adaptability when 3D printing models under circumstances with differing contexts and access to resources.

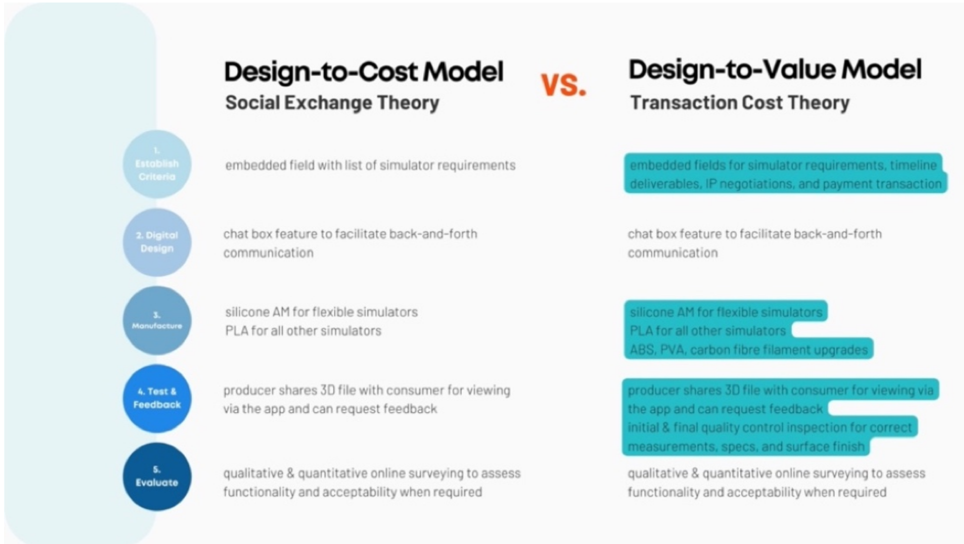


Figure 9: A side-by-side comparison of the Design-to-Cost (based on SET) and Design-to-Value (based on TCT) iterative approaches that 3DCrowdGo can follow when designing and testing a 3D printed simulator. Both approaches entail the same 5 steps illustrated by the bubbles on the far left, but the Design-to-Value model has additional areas of concern which are highlighted on the righthand side. Both processes serve as options for 3DCrowdGo's methodological framework to crowdsource manufacture 3D printed simulatord. The environmental context (e.g. cost or time constraints) will determine which model should be applied to the design and test process.

5.6 Conclusion

In summary, as it relates to 3DCrowdGo, the results from the trial embedded in Barth et al.'s (2022) work show that the solution may have the potential to scale up the De-SIM practices during and beyond the COVID-19 pandemic. As an uncharted territory, there are several areas that need to be addressed through both theoretical and empirical research and testing before full implementation of this approach. These areas are related to the governance of IP, timely production cycles, quality control of the final products and associated liabilities, as well as post-production assembling of more complex simulators.

Chapter 6: General Discussion

The COVID-19 pandemic caused an abrupt shift from in-person to online/hybrid learning models across the world presenting a significant impact on hands-on, experiential learning (a.k.a. simulation). In healthcare, doctors, nurses, and other healthcare professionals use simulation to learn invasive procedures before attempting them on patients. Simulation is defined as a replication of a task or an event for the purpose of training and assessment. It requires the use of a simulator and a script or storyline. Shifting from in-person (referred to here as a centralized model) to on-line (decentralized model) presents unique challenges in this context, as equipping large cohorts of learners with standard, commercially available "one-size fits all" simulators is prohibitively expensive and often impractical. My lab focuses on using innovative technologies, such as three-dimensional (3D) printing, to optimize costs of simulators while at the same time ensuring that they are as effective as the commercial. In addition, this approach produces customizable simulators that address learning needs and has the potential to maintain and improve educational standards while reducing the healthcare education system's expenses. However, the capacity to manufacture adequate amounts of simulators required to support curricula may be a barrier.

My master's work aimed to discover how to construct a crowdsourced online platform, 3DCrowdGo, to fill the "research lab-to-simulation lab" gap in health professions simulation training via community-based 3D printing. To address this overarching aim, three research questions were developed:

- *What contemporary crowdsourcing theories exist in literature?*
- *Based on potential stakeholders' opinions, which of these theories would be most suitable to use in the development of such an application?*
- *Does the implementation of Social Exchange Theory as a theoretical underpinning and Design-to-Cost as a method form a potential optimal design for 3DCrowdGo?*

These research questions were based on the MRC framework, which provided an overarching research guide and tool for this thesis. Initially, the Adapted MRC framework proposed by Haji et al. (2014) was utilized. It was important to ground my work in this framework as it is currently one of the most heavily used research process frameworks healthcare which means the end point users will be able to understand the research process. This framework fosters research grounded in established theories of instruction and learning and allows for the investigation of underpinning mechanisms in simulation interventions before evaluating their effectiveness. The iterative nature of this framework is critical because it allows for learning through multiple cycles of testing ideas or piloting trials with different variables applied. This approach also allows researchers to evaluate how interventions may work under different contexts and provides insight into what might be improved in future designs.

To meet the specific needs and context of this thesis, the Adapted MRC framework was further truncated to appropriately reflect the steps followed throughout the last two years. Specifically, cycle (A), or the Development phase, and cycle (B), or the Piloting phase, were retained from the framework and modified to match our research goals, which I have titled the Development and Piloting framework as seen in Figure 2. There are two main components and sub-components along with their accompanying methods to reflect these phases:

- *Development* via…
    - (1a) mapping the problem through a needs assessment,
    - (1b) theory and evidence identification through a scoping review,
    - (1c) intervention modelling through Delphi-method surveys, and
- *Piloting* via a small-scale piloting/exploratory trial.

This framework became the foundation off which my work was built and became a reference tool throughout. Operationalizing this framework gave clarity on how to answer each of the research questions. To address what crowdsourcing theories exist in the literature, a scoping review was undertaken to discover which theories exist are involved in the operation, functionality, and success of crowdsourcing. To determine which crowdsourcing theories would be suitable for 3DCrowdGo development, I conducted Modified-Delphi method surveys that allowed field experts to rank and determine which crowdsourcing theories should be used in the app development process given the full context, which consists of the end users (hospital administration and 3D printer owners), the urgency, and availability of funding. Finally, to determine if combining Social Exchange Theory as a theoretical approach with design-to-cost as a methodological approach results in a potential optimal design for 3DCrowdGo, a piloting trial from previous work in our lab was followed to develop an iterative process for 3D printing simulators as seen in Figure 7.

The first and second questions were addressed in Study Two of this thesis. First, through a scoping review which resulted in eight different crowdsourcing engagement theories which will potentially provide templates for unique ways of engaging the end-users. The next question involved the assessment and ranking of these theories during Delphi method surveys with health field experts and 3D printing experts and hobbyists to determine which ones would offer the most successful crowdsourcing approach in the context of simulation-based education. After 3 rounds, participants came to a consensus on the following 3 theories as best suited for 3DCrowdGo. First was Motivation Crowding Theory which is built upon 2 fundamental principles — extrinsic and intrinsic motivation — that are directly correlated to one's work engagement level (Putra, Cho, & Liu, 2016). Social Exchange Theory was also selected which, in the context of virtual knowledge exchange, discusses the willingness of virtual community members to share valuable information with others who then expect help to be reciprocated in the future (Jinyang, 2015). The final selected theory, called Transaction Cost Theory, states that the ideal organizational structure achieves economic efficiency by minimizing the costs of exchange (Young, 2013). These theories are intended to form future iterations of 3DCrowdGo that can be adapted in different contexts.

Now that I had three possible theoretical foundations for the app, I wanted to test a newer methodological approach in conjunction with one of these. The final research question was addressed in Study Two during which small-scale exploratory pilot work done by our lab group was conducted and closely followed to inform the basis of 3DCrowdGo rooted in Social Exchange Theory. Given the context of the global pandemic, there was a critical need to produce simulators for HPE students who were forced to learn from home at a loss of technical skills practice. Because of this constraint, Social Exchange Theory was selected as the theoretical foundation of 3DCrowdGo because there is no monetary exchange involved, but a reciprocal relationship that provides help instead. A recent work from the maxSIMhealth lab by Barth et al. (2022) provides a proposed methodological framework that could be successfully implemented into 3DCrowdGo. Thus, the focus of this study was to analyze the processes and methods used by the researchers to inform the construction of 3DCrowdGo rooted in this specific theory. I summarized the cyclical and iterative process that the researchers followed into Figure 7 which serves as the basis of this study. I extracted five distinct steps that Barth et al. (2022) implemented in their work and created a graphic illustration to be followed by my proposed test case of 3DCrowdGo using Social Exchange Theory.

Step one (criteria establishment) aims to determine the requests of the expert and their requirements and constraints for the desired simulator. In Barth et al.'s (2022) work, this took the form of an initial meeting with the experts and as a result, established the four specific design requirements that were to be followed. For 3DCrowdGo, I proposed that this step would take the form of a fillable field embedded into the app in which the consumer (individual making the request) lists their simulator requirements to ensure that the producer (local hobbyists, small businesses, or hospital-based 3D printing laboratories) has a clear understanding of what to include. If the consumer does not have a specified set of criteria for their simulator, an open-source file can be used as a starting point. Step two (digital design) involves the development of digital prototypes of the simulator on the requirements. The researchers revisited this step three times to accommodate feedback from the experts. 3DCrowdGo could follow step two via a direct-messaging feature between the producer and consumer which will accommodate the back-and-forth nature involved here. Step three (manufacture) consisted of constructing the physical model using specific materials once the digital prototype has been solidified. Barth et al. (2022) began this step by 3D printing molds of the simulators, then pouring silicone inside to create the simulator. The manufacturing process when using 3DCrowdGo will vary depending on the requested simulator, but this mold-based 3D printing would be used to make skin-like simulators. When not required, standard filament will be used to print the simulator itself. Step three (test and feedback) requires the expert group/end-user to test the simulator and provide initial feedback. For this, the researchers had two nursing program educators test the physical simulators who then provided feedback on the size, usability, stiffness, and functionality. These updates were made to the simulators then re-tested to ensure they meet the curriculum's learning objectives. Once the physical simulators were deemed adequate, full-scale production began. To minimize the time involved between manufacturing and testing and feedback in 3DCrowdGo, the producer will grant access to the 3D digital file via the app for the consumer to view and provide feedback at that point. In cases where in-person testing is feasible, there will be an option in the app to coordinate a meeting during which the producer brings the physical simulator for the consumer to test on the spot, and the consumer will provide immediate feedback. Step five (evaluation) involves formal evaluation to discover acceptability and feasibility of the simulators. An online survey was used as an evaluation tool by the researchers to gather qualitative and quantitative feedback on the simulators. After one week of use by nursing students, they were asked to complete the online survey to gather feedback on anatomical features and perceived usefulness. Despite a few weaknesses, final results demonstrated that these models were deemed appropriate for learning. Evaluation of simulators produced via 3DCrowdGo will likely follow similar a strategy to assess if the simulator is functional and feasible.

Putting all the results from studies one and two together, I was able to successfully answer my research question. The overarching goal of this thesis was to discover how to construct a crowdsourced web-based platform, called 3DCrowdGo, to fill the COVID-19-induced gap in health professions simulation training via community-based 3D printing. Overall, this research provided a few alternative theories to build 3DCrowdGo. First was Motivation Crowding Theory which is built upon 2 fundamental principles — extrinsic and intrinsic motivation — that directly impact one's work engagement level (Putra, Cho, & Liu, 2016). Next was Social Exchange Theory which, in the context of virtual knowledge exchange, discusses a reciprocal relationship in which virtual community members are willing to valuable information with others who then expect help to be reciprocated in the future (Jinyang, 2015). The final selected theory was

Transaction Cost Theory which states that minimizing the costs of exchange is the ideal organizational structure to achieve economic efficiency (Young, 2013).

In the end, the goal of the 3DCrowdGo app is to collectively pool resources within a community to help bridge supply gaps and improve pandemic responses. However, as production needs may change, the commitment and motivations of the users may change from a volunteering model to a pay-for-service model. This is the reason behind my initial desire to have multiple possible theoretical foundations for the app so that if and when the context changes again, as it has many times already, there will be a suitable template already chosen by expert panels to adapt the app to and match the context. Study Two provides an example of what this model looks like as, given the context of the pandemic and associated time constraints, I shifted the theoretical framework of the app to be rooted in Social Exchange Theory. During this scenario, there is no change of hands in terms of funding, but instead a mutually beneficial relationship is established based on the concept of providing help now to get help later. This was seen implemented many times to solve the PPE shortage at the beginning of the pandemic as individuals were willing to contribute to a solution out of goodwill. Future work will focus on testing the other versions of the app that are supported by the other theories which will allow for longevity when goodwill can no longer be relied on.

Although this notion of volunteerism was initially effective, it highlighted several limitations. For example, delivery timing cannot be enforced when individuals are volunteering their time, but it can be if a pay-per-service approach is utilized instead. IP governance has also been an issue in the past in our lab which emphasized the need for a-priori negotiations and employment of a CC BY-NC-SA license to ensure that the digital representations of the simulators shared with the producers are credited to the creators, used for non-commercial purposes, and adaptations must be shared under the same terms.

Through my research work, I determined how to effectively leverage crowdsourcing with local 3D printers (professional services, libraries, hobbyists) and use these resources to produce simulators through 3DCrowdGo. My investigation consisted of a 2-phased approach that coincided with the Development and Piloting framework proposed earlier. Results from both phases were aggregated to develop a responsive, flexible solution that incorporates current best practices and solves the “research-to-simulation lab” gap of providing affordable and effective simulators for the decentralized model of simulation by mobilizing community members.

Future directions

I will continue to follow the modified Adapted Medical Research Council framework for the development of complex clinical interventions (Haji et al., 2014) where I’ll transition from the theory & modelling cycle to the piloting, evaluation, and implementation cycles. Having a thorough understanding of how to build this flexible 3DCrowdGo app successfully will now lay the foundation for my Ph.D. work which will focus on the design, development, and testing of 3DCrowdGo. I am eager to start this work during which I plan to conduct an environmental scan of app stores, develop three different iterations of 3DCrowdGo rooted in each theory from Chapter 4.3.1 to inform the final app, conduct usability testing, and start leveraging the community to manufacture simulators.

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Appendix A: Market Report

AUGUST 31, 2020

MARKET REPORT

3D PRINTING:

A POTENTIAL SOLUTION TO THE PPE SHORTAGE

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3DCROWDGO
FIREFLY FUNDING RECIPIENT

The COVID-19 pandemic has brought about many challenges and adaptations amongst daily life, work schedules, and, more importantly, safety precautions. Health professionals and front-line workers have been placed at the forefront of a global pandemic for the last four months, which has had tremendous implications on their health and safety. COVID-19 has drained stockpiles of medical equipment and devices due to their still-increasing demand. The healthcare industry was hit hard when shortages of personal protective equipment (PPE) such as medical masks, shields, ventilators, and hazardous material suits started to arise. These PPE shortages quickly exposed holes in Canada's supply chain that the government is trying to fill by encouraging pivots amongst local industries to make everything from finished products to raw materials (Allam Advisory Group [AAG], 2020).

There are three main factors currently reinforcing the shortage of PPE. Firstly, there is a critical shortage of raw materials, such as filters and polypropylene, that are necessary to produce PPE (Reynolds, 2020). Next, even after raw material have been sourced and production is successful, strict quality control measures can and have barred the selling of millions of suboptimal units. On May 18th, the government had received a total of 11.7 million N95 respirator masks, but 9.8 million of those did not pass quality control (Walsh, 2020). Thus, valuable and high demand materials, energy, and resources are being wasted on subpar products. In addition, there are some governments that have banned exports of domestically manufactured PPE as a measure of providing for their own citizens first. An example of this occurred in early April when Donald Trump invoked the 1950 Defense Production Act. This halted manufacturing company 3M's exports of 3 million N95 respirator masks to Ontario — a bold move considering N95s are critical for frontline healthcare workers (Cecco & Borger, 2020). These three factors are contributing to the increasing and unmet demand, which in turn poses a severely increased risk of healthcare professionals being infected by and dying from COVID-19.

There have been many efforts to crowdsource materials as an attempt to close these shortages, with a spotlight on rapid prototyping and three-dimensional (3D) printing which allow for designing, testing, and manufacturing at the consumer level. Although 3D printing has been especially popular for making PPE, assistive devices, and clinical equipment, the shortage still exists despite all these efforts. Even leading manufacturers and unrelated companies who have heightened production levels have not managed to solve the shortage we are still seeing today.

To gain a better understanding of what this shortage looks like in local hospitals in the Greater Toronto Area, I conducted research and interviews with different members of hospital communities. Through this research, I discovered that the time and energy it takes to access PPE has increased due to more thorough safe-keeping measures and logging. In theory, it makes sense to increase protection of supplies that are in high demand but low stock. However, I learned that in cases of emergency, it is very difficult to access PPE and, sometimes as a result, medical procedures are carried out regardless of being unequipped. Several individuals also noted that the quality of PPE shipped to and used in the hospitals is much lower than what it used to be pre—COVID-19, and limits are being placed on PPE even with these quality reductions. I also learned that administrative personnel responsible for ordering PPE are experiencing supplies and costs at a premium. For example, of a small order for 100 face masks (two boxes of 50), only 30 were available for fulfilment and at a higher price. I conducted research with 3D printer owners as well via Reddit to gain some insight and perspectives into materials, costs, compensation, and operations. This was important for understanding why 3D printing has not been able to solve the shortage thus far and, according to individuals who had experience with printing for hospitals during the pandemic, quality control and duration were the two main inhibitors of success.

According to the Allam Advisory Group report released in 2020, 3.3 billion units will be needed over the next 12 months, 1.2 billion of which for Ontario alone. A continuously growing PPE market will keep manufacturers struggling to meet the total demand for the foreseeable future. The AAG (2020) predicts that even with a restored supply and demand chain in some provinces, stockpiles likely will not be enough to last the next few months, and current domestic and offshore imports may not even be enough by 2021. This exponential growth coupled with a limited number of current Canadian manufacturers and an increased desire to be in control of our own manufacturing processes holds a significant opportunity for Canadian-based companies. CEO of AGG, Omar Allam, explained in a recent interview that at least 40 per cent of PPE should come from domestic production for the long-term to ensure a reliable supply for ongoing use and to fill the country's national stockpile, especially if a second wave or future pandemics arrive (Hill, 2020). Thus, there is a significant market opportunity that lies in domestic rapid manufacturing of PPE to increase stockpiles and availability to Canadian healthcare and frontline workers so that, if and when a new emergency arises, we are prepared.

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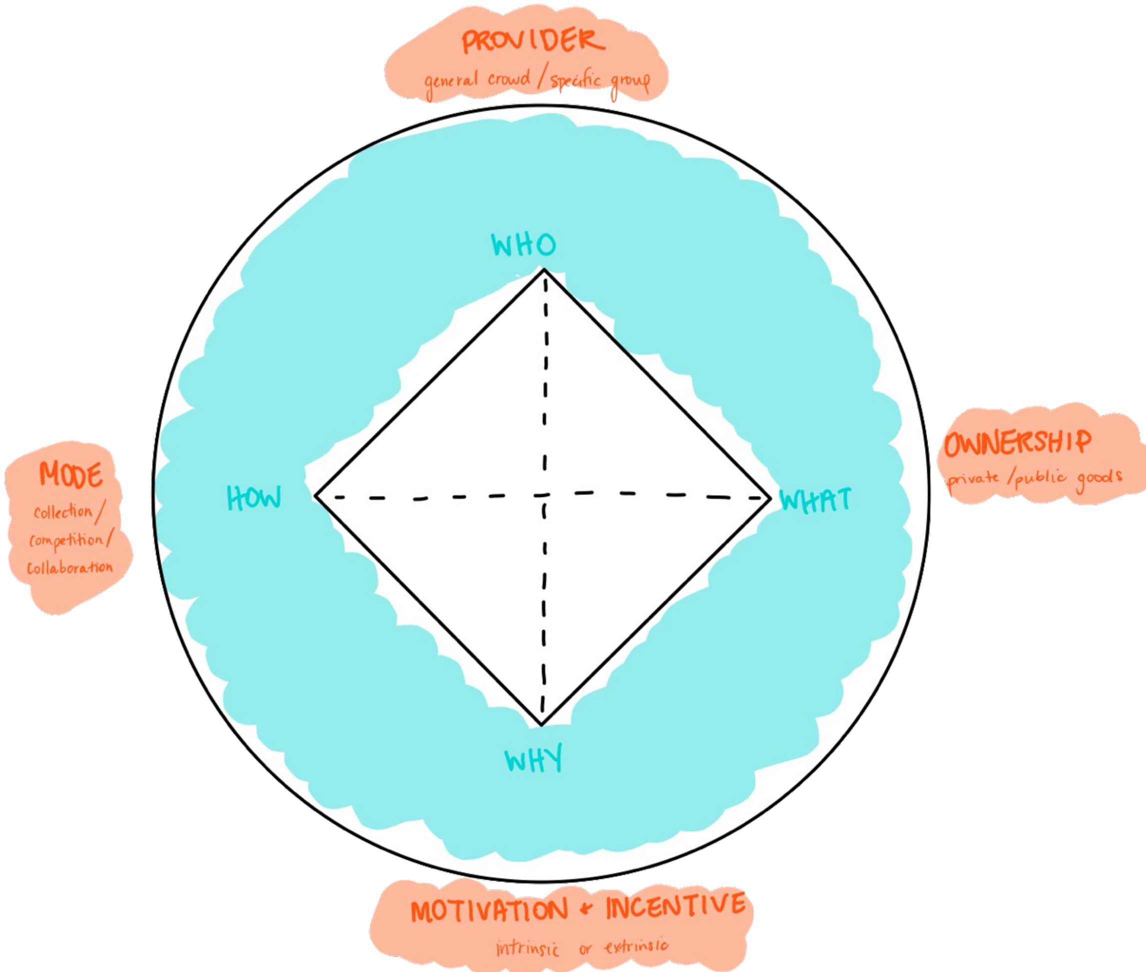

Figure 1: Fundamental dimensions in crowdsourcing. Adapted from Malone et al. (2010).

— *Who is performing the task? Why are they doing it?*

— *What is being accomplished? How is it being done?*

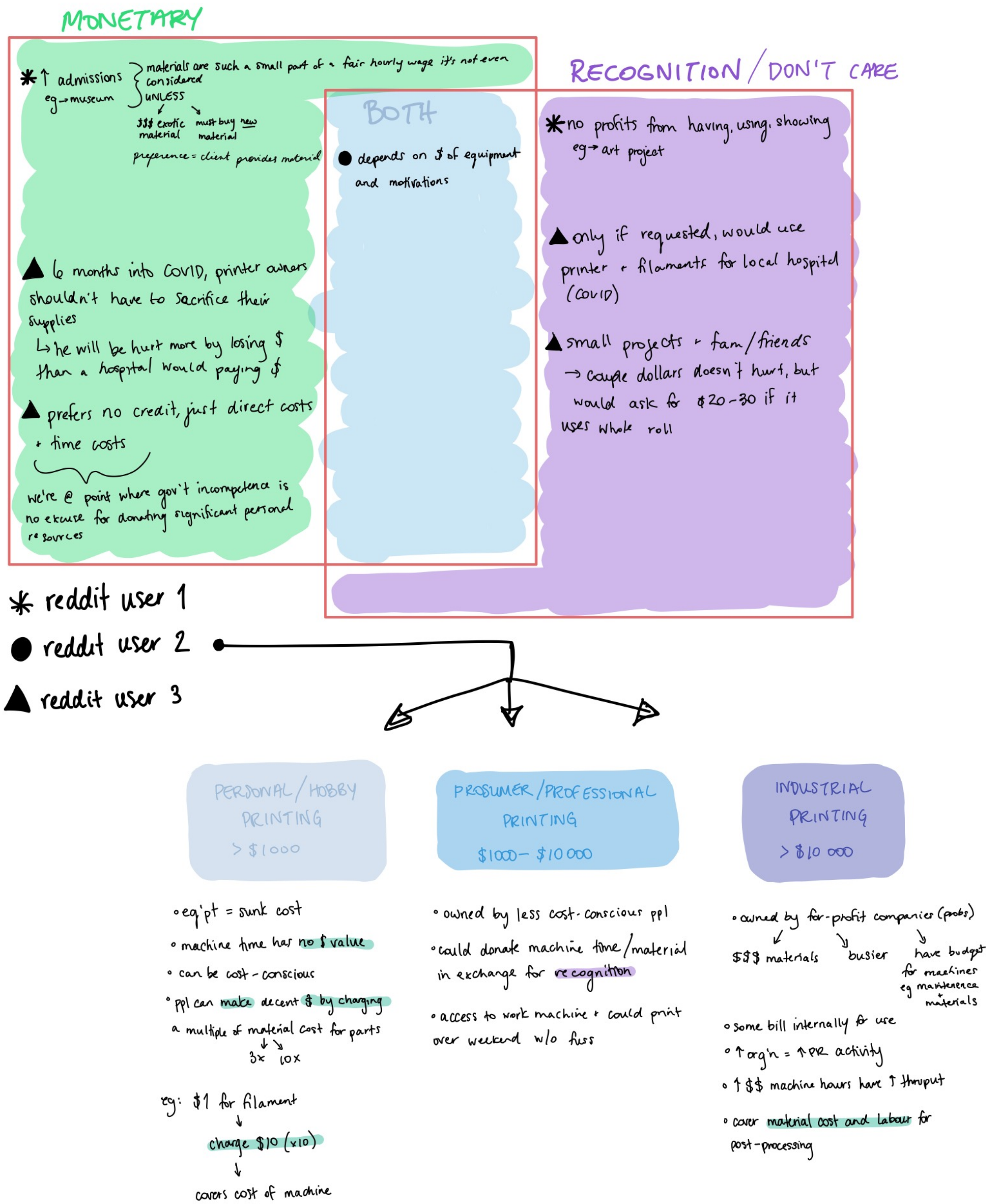

Figure 2: Data visualization of 3D printer users' compensation preferences retrieved via Reddit.