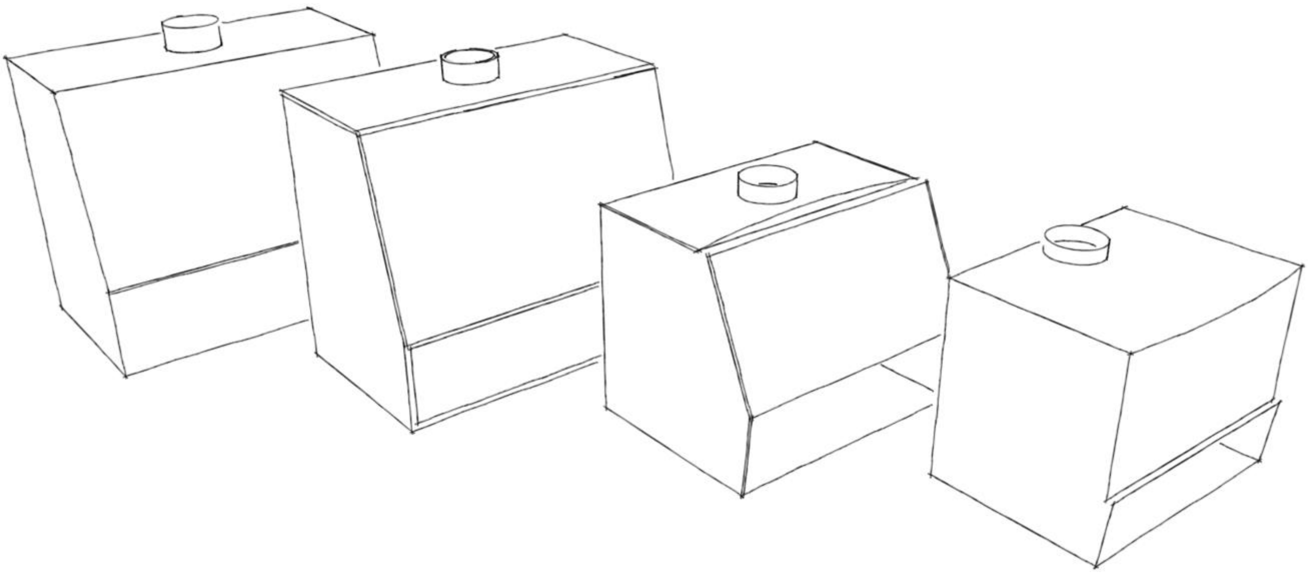

Frugal Design in practice

From theory to increased biosafety in tuberculosis laboratories in Peru

Master’s thesis in Industrial Design Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Design iterations of a ventilated workstation

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Abstract

This thesis has examined Frugal Design (FD), both in theory and practice, to grant a deeper understanding of how to implement the approach. The research included a literature review and a case study, with a focus on developing a Frugal Design biosafety enclosure for TB laboratories in Peru that currently lack this necessary piece of equipment. The main goal of the thesis has been to answer two research questions:

What is Frugal Design?

How can it be utilised by designers?

Research through design has been the method of this thesis. It was initiated with a literature review based on a structured database search for "frugal design". The proposed definitions and methods from the literature study were then applied in a product development project covering the design of a biosafety enclosure. In this manner the FD approach has been tested in practice to draw conclusions about its implementation. Results from the theoretical and practical work have been used to analyse the FD approach in terms of definitions, methods, possible tools, and its utility.

The research generated two main findings:

A new design of a Frugal ventilated workstation that is easy to produce and implement in laboratories in need of a biosafety enclosure, in Lima and other parts of Peru.

A new proposed Frugal Design framework defining FD using seven FD factors and a number of tools to achieve these factors. Further more a model of the FD process including several FD process elements, that explain what a designer can do to best use FD principals and to create FD designs.

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Abbreviations

Abbreviation	Term	Meaning
AFB smear	Acid fast bacilli smear	Method for processing TB
BOP	Base of the pyramid	refers to the bottom segment of the global distribution of wealth
BSC	Biosafety cabinet	Enclosure where biological agents safely can be handled
CDC	Centers for Disease Control and Prevention	
DIY	Do it yourself	Refer to the carrying out of a task by oneself
FD	Frugal Design	A design approach concerned with… subject of this study
FVWS	Frugal ventilated workstation	The ventilated workstation that was developed during the case study

MDR	Multidrug-resistant TB	TB where the bacteria is resistant to “first line medication”
NGO	Non governmental organisation	
TB	Tuberculosis	
UCD	User centred design	Design approach where the user is in focus
VWS	Ventilated workstation	
XDR	Extensive-resistant TB	

1. Project Introduction

Frugal Design, hereafter referred to as FD, is an exciting design approach that is said to have the potential to revolutionise the way we create products. It promises to unlock new opportunities for companies by bringing greater affordability, accessibility and sustainability to underserved market segments. Many also argue that FD can better suit the needs of resource scarce contexts, and create more robust supply chains. Yet others state that with sustainability at its core, FD can optimise the use of materials, reduce waste and create products that can withstand the test of time. If this is true, how can we make it happen? While we can suspect that FD holds some of the keys to the future of design, the path to achieving it is not clear. This thesis sets out to explore the possibilities of FD, delving into what it is, and how designers can harness its potential to create products that are fit for the future.

Frugal

[froo·gl] - adjective

sparing or economical with regard to money or food.

Definition of frugal, Oxford languages

Medical care is a human necessity and many of us can expect to be taken care of when we face injury or disease. This care is possible thanks to the resources spent on providing such services to us. Healthcare's dependency on resources is reflected in the various qualities of healthcare that can be provided in different societies around the world. Problematically, in places where resources are lacking, the human necessity for care still remains. This leads to cuts within healthcare in order to prioritise the most important care services. Regrettably, these cuts can harm the healthcare professionals we rely on in our time of need. This is the case in peripheral tuberculosis labs in Peru, a country with a high burden of tuberculosis. In small health centre labs around Lima and other parts of the country, laboratory personnel work to diagnose and help their patients while constantly facing a significantly higher risk of contracting a potentially deadly disease due to a lack of proper biological safety equipment.

Sadly, the massive negative effects of poverty and other types of resource scarcity are not limited to health, these factors affect people's quality of life in general and design is one tool that we can use to try to affect these dire situations for the better. One approach within design doctrine that seems to hold high potential, specifically for the design of products and services intended for resource-scarce contexts, is as mentioned, FD. FD, while still a somewhat confusing concept and a design practice in progress, provides tools and methods that may be the keys to addressing the dangerous work situation that healthcare workers face in many tuberculosis laboratories in Peru. The main objective of this thesis is to develop the FD approach further, and in doing so, also improve the safety of healthcare workers that are risking their own well-being when helping others. The chapters that follow will set the stage for this work, an investigation into what happens at the intersection between FD, product development of biosafety equipment, and the resource-scarce healthcare system in Lima and other parts of Peru, (figure:1.1).

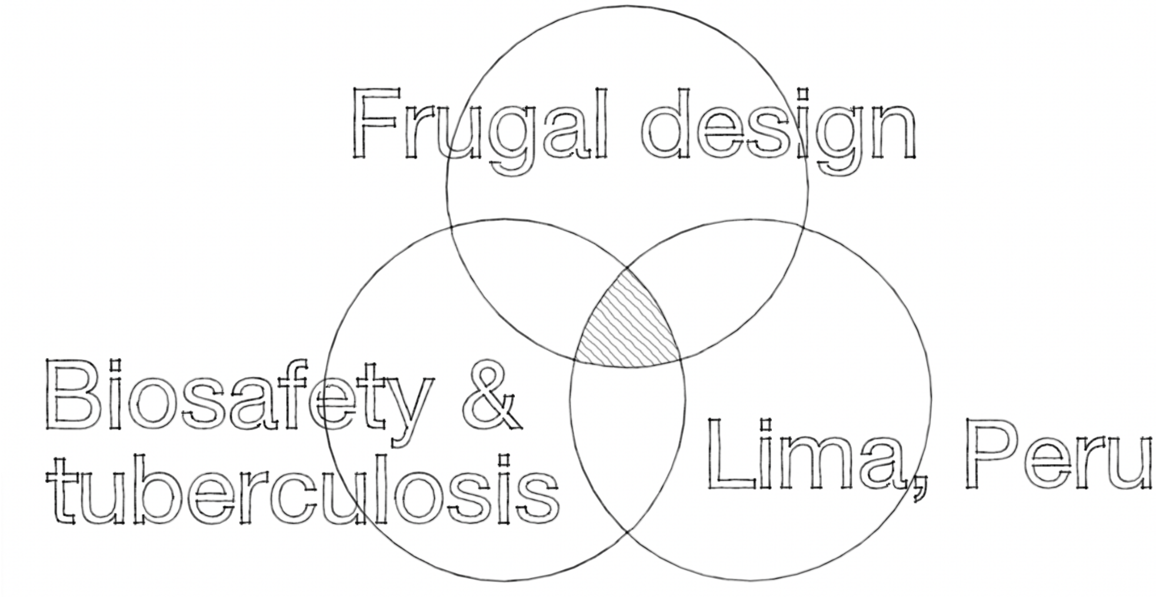


Figure 1.1 What happens when Frugal Design and biosafety equipment meet in the context of Lima, Peru?

Background

The full potential of FD is unknown to us, but it is indicated that it may be an important tool for designers in the future, perhaps also for designs intended for parts of society that do not regularly face resource scarcity. In this section, the background as to why research on- and development of the FD approach is needed, what goal and aim we have set for this work, and what it all has to do with tuberculosis will be covered. The methods used and why these methods were chosen, also highlighting limitations in the work that are likely to have affected the outcome will be brought up. Finally, some ethical considerations regarding this project, especially in regard to its healthcare nature will be introduced.

Why is Frugal design a relevant approach for designers?

The FD approach seems to differ from other more conventional design approaches, mainly in its almost unadulterated focus on reducing resource consumption. The name of the game is to do this without compromising the vital essence of the product, whether that be the functionality, aesthetics or any other aspect that is essential in that particular design case. The result of this focus on resources (material, monetary, institutional, etc.) is a design approach that has the potential to make products and services more available, possibly increasing the quality of life for the huge mass of people in this world that are underserved (Fig 1.2).

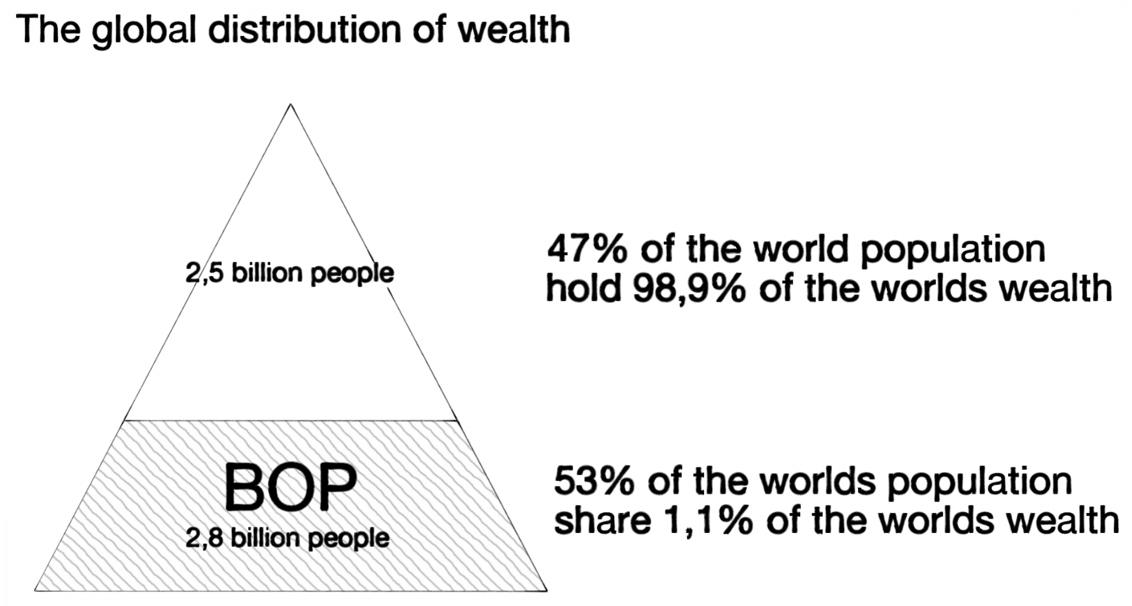


Figure 1.2 The global distribution of wealth shows that a majority of the world's population, also known as the "base of the pyramid" holds only a fraction of the world's resources (CSRI, 2021)

One good example of a FD that has raised the quality of life in this segment of users is the incubator designed by paediatrician Sathya Jeganathan. Dr Jeganathan, working with nurses and electricians, managed to decrease the infant mortality rate in her hospital by half after implementing an in-house designed incubator, built from locally sourced materials and a 100W light bulb (Radjou et al., 2012).

FD might also prove useful in more developed economies. As pointed out by Radjou et al. (2012), there will be a growing need for frugal innovations as we face more scarcity and thus increasing prices of natural resources that in turn make dependent products more expensive.

In recent years we have also seen for ourselves how even some of the richest nations on earth can face scarcity in a crisis. During the COVID-19 pandemic, ventilators and even simple face masks were in short supply in many parts of the developed world (ECDC, 2020), this has sparked innovation towards products with greater affordability and availability. One example is open-source and freely distributed plans for a Do it yourself (DIY) ventilator (MIT Emergency Ventilator, 2022).

Tuberculosis, one of the world's top infectious killers

Tuberculosis (TB) is the infectious disease that after COVID-19 causes the most deaths every year, even more than HIV/AIDS. In 2021, 1.6 million people died and 10.6 million people fell ill with TB (WHO, 2022). The disease is an infection caused by the bacteria *Mycobacterium tuberculosis,* which primarily affects the lungs (CDC, n.d). The disease is curable and preventable (WHO, 2022), however, no effective vaccines are available (WHO, 2012). The disease is mainly prevalent in low- and middle-income countries which account for 98% of reported TB cases. Peru is one of the countries in South America with the highest prevalence of TB. The presence in low and middle-income countries leads to the work against the disease often facing resource scarcity and lack of desired equipment, such as biosafety cabinets, which is the case in Peru. FD can therefore have a key role to play in the development of products necessary to fight TB in low- and middle-income countries such as Peru.

Goal and aim

The overall goal of this thesis is to use design research to gain a deeper understanding of FD and to develop it further as a tool for designers. A key part of this goal is the creation of a biosafety enclosure for low resource tuberculosis laboratories that currently lack the necessary safety equipment, in order to improve the work safety for healthcare professionals using FD. If FD can be used to create more sustainable products that use fewer resources, this project has the potential to be a valuable contribution to the growing body of knowledge on this design approach. We hope to achieve this by answering two main research questions throughout this work.

Research questions

The research questions were stated as follows in order to help understand FD and to bring forward important learnings about the approach, useful for the future.

RQ1: What is Frugal Design?

RQ2: How can Frugal Design be utilised by designers?

Method - for the overall project

In order to answer our questions about FD we will adopt a combined approach of theoretical review and research through design (fig 1.3). The theoretical part will consist of an extensive literature review on FD, detailing what FD is and how it is proposed to be performed. This knowledge will be used to define it and to build a framework for the adoption of FD into design practice. The learnings from this theoretical work and the framework for FD practice will be used and tested during the second, larger part of this thesis, the research through design, performing a case study. This part of the thesis takes the form of a product development project guided by the FD framework generated from the theoretical review. This FD case study will cover the development of a biosafety enclosure and notably, every consideration and design action, especially in regard to FD, will be recorded in a diary in order to be able to recollect, follow and analyse the process. This diary, the final design of the project, and any FD learnings gained during the development of the design will be analysed and synthesised with earlier results from the theoretical work in order to answer the research questions of this thesis, chiefly, How can a designer use FD?

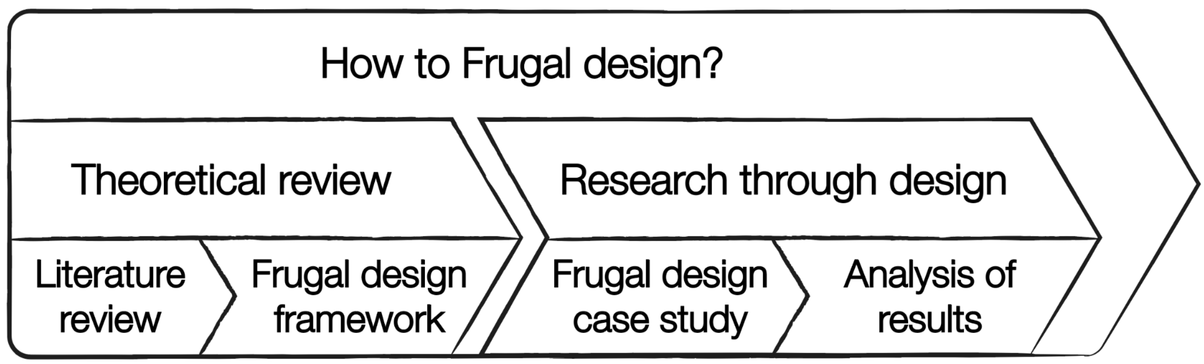


Figure 1.3 Process model describing the method of this thesis

Limitations known before project start

Frugal Design research

For the literature review, only “frugal design” was used as a search string. Even though Frugal innovation many times is used interchangeably “Frugal innovation” was excluded because this term often was brought up without delving into any details of a design approach very deeply, and because it was used more widely to describe very different concepts, not necessarily connected to design practice at all. Including Frugal innovation in the search string would have given a much higher number of articles with low relevance for our purposes. The focus on FD gave us a manageable number of articles dealing with only FD as a topic, specifically of use to design practitioners, which has been key for the project.

Case study in Lima, Peru

The product development of this project was limited to only dealing with solutions that were taking advantage of local possibilities and resources. No further possible solutions were investigated, such as for example a foreign stakeholder like a NGO developing and manufacturing a biosafety enclosure abroad and then importing and implementing the solution. Granted, this could also have been a possible way to increase the number of biosafety enclosures within the Peruvian TB healthcare system, but our focus has been to investigate what interventions are most efficient in overcoming barriers that exist today, that are also achievable by means that are available within the confines of this project, i.e. most likely no million dollar production runs involving foreign NGOs and imported goods.

Language barrier

It is noteworthy that the work has been performed in English and in Spanish. The authors of this thesis (and designers of the project) were not proficient in the Spanish language when this project was started, and many important activities, such as interviews, were required to be in Spanish as many users did not speak English. Language has been a substantial but diminishing barrier throughout the project.

Sustainability

The United Nations 17 sustainable development goals cover a range of topics from eradicating poverty to working for clean and affordable energy provided around the globe (UNDP, 2022). Within literature, FD is often brought up as a sustainable design approach that will lead to less environmental impact due to reduced material consumption and increased product availability for more people creating both environmental and social sustainability. In addition to reducing resource consumption and increasing product affordability, FD can be more multifaceted. Frugal innovations can contribute to local entrepreneurship through local production, and this locally-based production and engagement play an important role in reducing poverty and providing opportunities for income generation in development markets (Jagtap & Larsson, 2018). Frugal innovation has also been described in terms of a tool to give resource-constrained people in emerging markets the chance to consume affordable products directly fitted to their needs (Weyrauch & Herstatt, 2016). If used in this manner, FD could play an important role in social sustainability.

Ethics

FD for resource-constrained context entails several aspects of ethics to consider and is introduced here. Especially when designing for such a context from an outsider's perspective, would not the users and actors in the context be better suited for this work? Should two engineering students fly from Sweden to Peru to perform their master's thesis to research this topic and design a biosafety enclosure? Why not students from Peru?

When it comes to the research topic of FD and the case study concerning biosafety, it brings forward several aspects of what's right and wrong from an ethical perspective. These questions span from the effects of applying frugality in health care and safety equipment to designing solutions utilising local manufacturing in a context where work conditions may not be regulated or complied with to an acceptable level. When reading this report, this should be kept in mind. In the discussion of chapter 4, this topic will return and will be discussed in more detail.

How this report is to be read

This report is structured into four main chapters. It can be read in three different ways depending on if the reader is interested in a deeper understanding of the whole project and FD, or rather only learning about new insights about FD, or lastly to learn about the newly developed biosafety enclosure called the Frugal ventilated workstation.

1. A deep understanding of FD and its surrounding theory.
    -> Read the report from top to bottom .

2. Understand how FD works in practice including a FD framework explaining the FD process.
    -> Read only chapter 4 - discussion, and 5 - conclusion.

3. Learn about the new biosafety enclosure called FVWS, developed during the case study.
    -> Read only chapter 3 - Case study and delve into detailed material in the appendix.

2. Frugal Design theory

FD, a design approach often mentioned in relation to resource-scarce contexts, and developing markets, has seen a spike in interest during the last decade, see Figure 2.1. The increased interest is likely because the FD approach appears to be a very important tool for the type of product development that will see increasing relevance as the issues of sustainability and the global climate crisis only become more acute and acknowledged. It is also argued that the FD approach can provide product accessibility for users in resource-scarce environments, often referred to as the bottom of the pyramid, and provide corporations accessibility to these segments of consumers, making the frugal concept attractive for businesses also (Bolaños, 2013). Thus, FD is becoming a more important concept and mindset for designers to adopt.

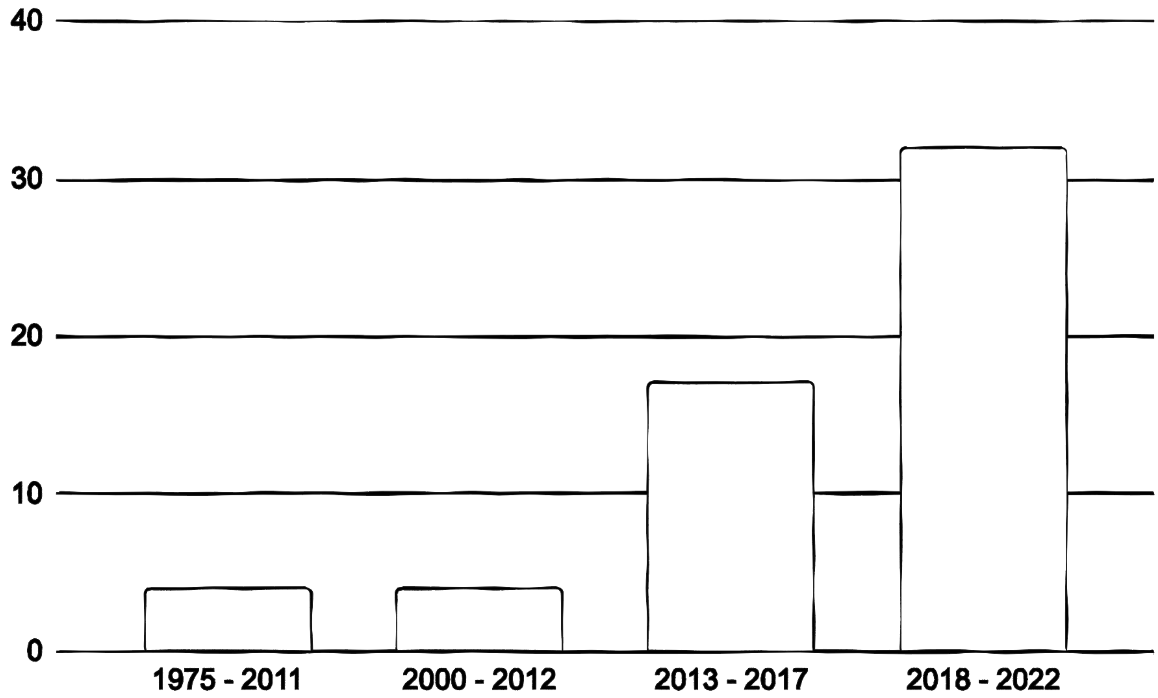


Figure 2.1 The number of articles with the phrase "frugal design" in the title, abstract or keywords, by years. The databases used correspond to those used for this review.

Different concepts of frugality have existed in many disciplines and formats for a long time (Soni & Krishnan, 2013). The concept of thinking frugally while designing or developing innovations isn't new and can't be ascribed to a specific year of implementation. However, the term frugal engineering is believed to be derived from the former head of Nissan-Renault, Carlos Ghosn, describing it as achieving more with fewer resources (Kumar & Puranam, 2012).

Product development approaches and tools suggested in relation to resource-scarce contexts are numerous, including Frugal design, Frugal innovation, Frugal engineering, Jugaad innovation, Appropriate Technology, Design for the Bottom of the Pyramid, Reverse Innovation, Low-cost innovation, Constraint-based innovation and more, see figure 2.2 below. Some approaches are similar and even share many characteristics, while others differ more.

Regardless, many of these terms have been used more or less interchangeably, especially when referred to in a peripheral manner. This causes confusion and hardship when seeking to understand and perform FD. Due to this confusion, this literature review seeks to clarify what FD is in particular and how a designer should act to achieve it.

This chapter is structured as follows; First, a contextual review of design approaches related to FD to give an understanding of the bigger field of design approaches often mentioned around FD and resource-scarcity. This is followed by the method for the review. The results from the found FD literature are grouped and presented through what every author says about the definition and characteristics as well as process and methodologies. In the discussion, we conclude the “FD factors” we perceive defining FD through discussing commonalities among different authors. Lastly, we summarise a FD framework that constitutes the theory base that will be used in the case study to further explore the FD approach.

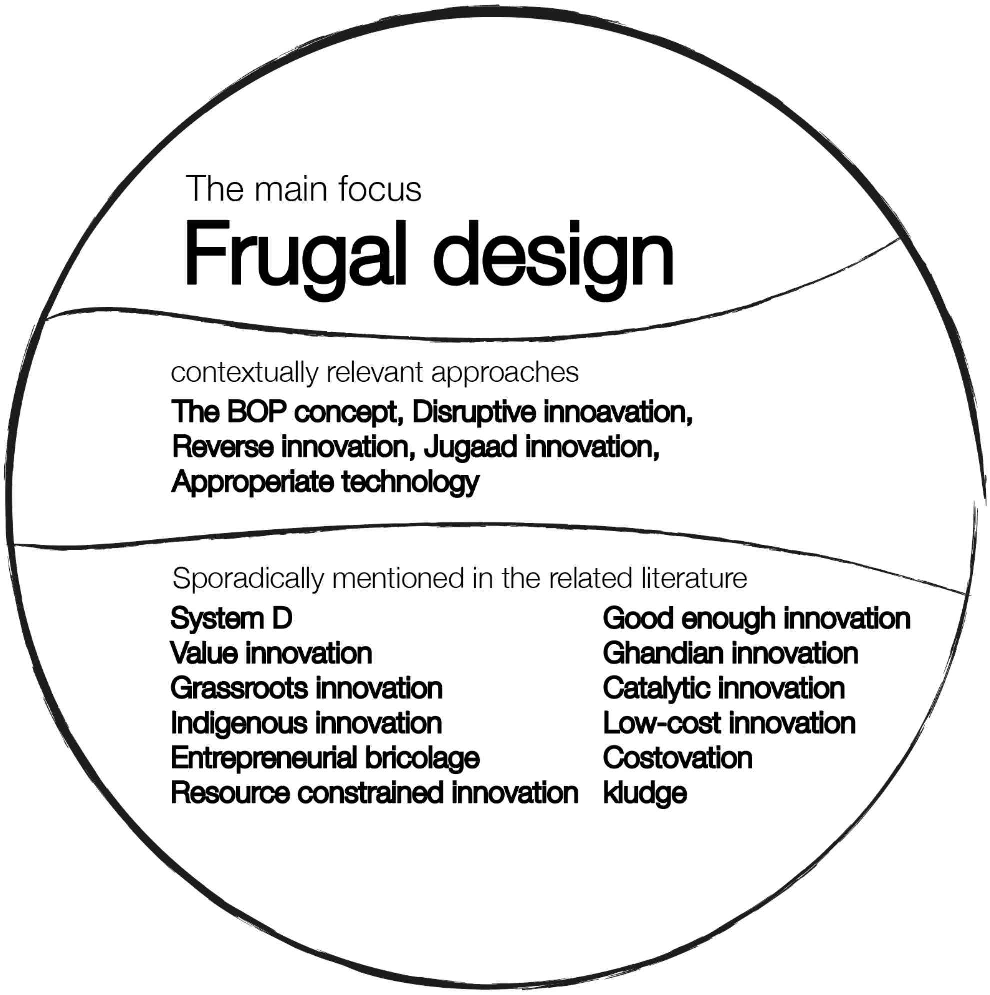


Figure 2.2 The sphere of scarcity, different approaches that have been encountered within the literature, and on what level they relate to FD.

Objective

The objective of this literature review is to determine Frugal Design's definition, characteristics, processes and methods in order to form a framework that can be used as a design approach for a real development project.

Questions for this review:
Q1: What is Frugal Design?
Q2: What tools, methods and processes can be used to achieve Frugal Design?
Q3: How can Frugal Design be implemented in a design project?

Contextual review of concepts related to Frugal Design

The lack of a standardised definition of FD and the in many cases overlapping definitions in between different approaches prompted us to also review other design concepts closely related to FD in order to gain clarity and understanding of the whole sphere of closely related approaches. These other design approaches were selected subjectively, identified principally by these approaches being discussed or mentioned in the 19 publications identified by the literature review. The approaches covered (see fig. 2.2) are The bottom of the pyramid concept, Disruptive innovation, Reverse innovation, Jugaad innovation and Appropriate technology. The different approaches have been developed and popularised to varying extents. In comparison to these approaches, FD is still a relatively new concept which is demonstrated in figure 2.3. In one section each, the contextual approaches will be presented in terms of their brief history, some concrete characteristics, and why they are interesting to briefly touch, to gain understanding of FD.

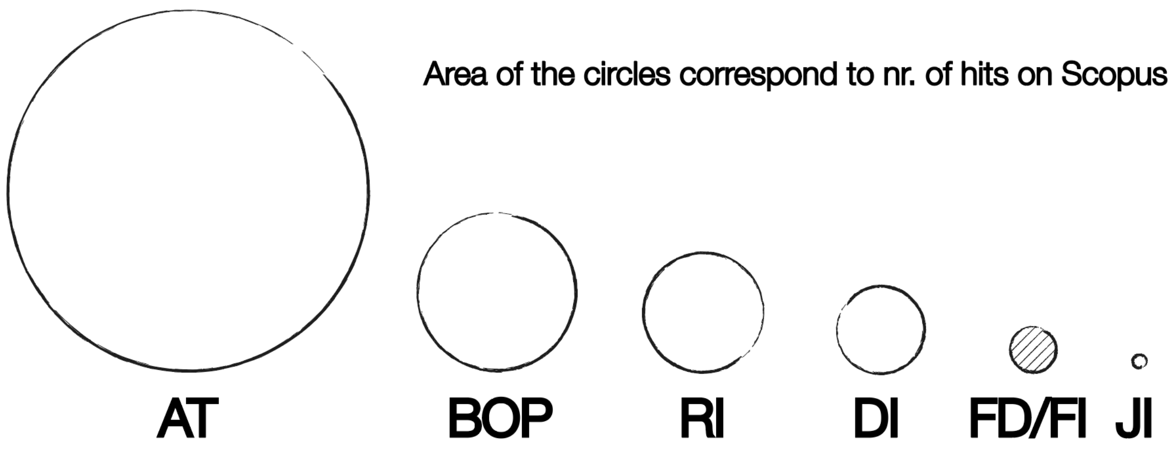


Figure 2.3 Prevalence of the different approaches when searching them on Scopus. Appropriate technology (AT), Bottom of the pyramid (BOP), Reverse innovation (RI), Disruptive innovation (DI), Frugal Design/Frugal innovation (FD/FI) and Jugaad innovation (JI).

Disruptive Innovation

Disruptive Innovation theory has its origins in the 1990s. Bower & Christensen (1995) discuss how companies can maintain their current customers while also preparing for the customers of tomorrow. This should be done by considering possible disruptive technologies on the horizon, avoiding being overtaken by a growing competitor with better technology. How this issue could arise was put forward briefly and clearly by Christensen et al. (2015), who describe disruption as a process where a small company with limited resources challenges the market's established actors. An entrant can target a niche customer segment that is ignored by established market actors, thereby gaining a foothold by delivering a more suitable market offer. With time the entrant's offer can grow more technically advanced or cheaper, delivering solutions that fulfil the needs of the mainstream customer. When this occurs, Christensen et al. argue that disruption has occurred.

What makes disruptive technology interesting and relevant for this review is the idea that it seems to grow more naturally in resource-scarce and specifically developing markets (Ramdorai & Herstatt, 2015). Note that Disruptive Innovation is also argued to be an example of Reverse Innovation (Govindarajan & Euchner, 2012).

The resource scarcity and lack of purchasing power have historically made customer segments in developing markets at the bottom of the pyramid less desirable targets for large incumbent corporations, resulting in neglect regarding research & development and marketing for those segments (Christensen et al., 2015). The entrants that Christensen mentions can fill this void in the developing market, gaining market share while also developing their offering to one day compete with the incumbents. One example of this is the Narayana Hrudayalaya hospital group. The first Narayana Hrudayalaya hospital was initiated by Dr. Devi Shetty in Bangalore, India, in order to make healthcare more affordable to the masses. Through business model innovations, Narayana Hrudayalaya decimated the cost of eg. open heart surgery when compared to United States healthcare (Khanna et al., 2005). This is relevant as Narayana Hrudayalaya launched a hospital in the Cayman Islands in 2014, allowing locals as well as under-insured Americans to receive care at these more affordable prices. Notably, the Cayman islands Narayana Hrudayalaya hospital has seen net profitability since 2017 (Narayana Hrudayalaya Ltd, 2022)

While Ramdorai & Herstatt argue that Disruptive Innovation is more likely to happen at the bottom of the pyramid, Christensen et al. (2015) argue, revisiting the topic 20 years after their first article, that it is actually necessary to start at the bottom of the pyramid, and if it does not originate from serving the bottom of the pyramid, it cannot be a Disruptive Innovation. They provide the example of UBER and argue that while the company has grown immensely, and competes fiercely with incumbent taxi providers, it is not a Disruptive Innovation as it did not originate due to a neglected need in a low-end market, and did not need to see quality improvement over time in order to catch on with mainstream customers. Christensen et al. (2015) state that Uber has been developed for the first world and then diffused downward, it has not filled a market gap where conventional taxi providers have consistently exceeded the expectations and needs of the customers.

If we subscribe to this view and agree that Disruptive Innovations must be developed for the users at the bottom of the pyramid, then it is important to remember for the purposes of this review, that a product developed for the bottom of the pyramid is not necessarily also to be considered frugal. One example is LifeStraw, an affordable product that purifies contaminated water making it drinkable (Hoffman, 2011). The product was originally developed to provide access to safe drinking water for the bottom of the pyramid but has since seen success in the mainstream consumer market for outdoor enthusiasts, survivalists and even the bottled water market since their launch of a refillable bottle with integrated LifeStraw (VF, 2011). While the LifeStraw is affordable, it requires a very high investment in research and development, and technology expertise to produce, which means it must be distributed to the places where they are needed, making the users dependent on external intervention, for this reason Soni & Krishnan (2013) argue that it is not a frugal solution.

Reverse Innovation

Reverse innovation is a term popularised by Vijay Govindarajan and Chris Trimble. Govindarajan & Euchner (2012) describes the concept as an innovation that happens due to needs below the top of the socio-economic pyramid. The innovations found appealing at the lower levels of the pyramid are then diffusing to richer markets as well. This is supported by Tiwari et al. (2017). Govindarajan & Euchner describes the importance of understanding the consumer, not only for achieving affordability but also taking into account a number of factors such as availability of electricity, distribution limitations etc. This is in accordance with Weyrauch & Herstatt (2016) who describe reverse innovation as frugal innovations that have found their way to the developed markets. The concept of reverse innovation has many similarities to disruptive innovation, as stated previously, disruptive innovation is even argued to be an example of reverse innovation (Govindarajan & Euchner, 2012)

An example of what can be considered reverse innovation is the handheld ECG machine developed by a multinational corporation (GE India) for an emerging market. The product was very successful for the initially intended market but has since also seen great success when launched in developed markets as well (Malodia et al., 2020).

While this reverse innovation success of GE India is a fact, little is known of the factors resulting in such success, knowing which products will succeed in the developed market, and how to achieve this type of innovation in a company is difficult to determine (Von Zedtwitz et al., 2015; Furue & Washida, 2014)

Jugaad innovation

Jugaad innovation is the best known of several similar concepts, such as Jua kali in Kenya, and Gambiarra in Brazil (Radjou et al., 2012). The term Jugaad is a Hindi word that refers to a non-conventional solution, workaround or hack. Signifying creativity in the face of scarcity, it has been described as an approach to frugal innovation and entrepreneurship, most notably in the book *Jugaad Innovation, think frugal, be flexible, generate breakthrough growth*, by Radjou et al. (2012). In the book, the authors argue that large corporations have much to learn from this creative and sometimes “law-bending” approach to problem-solving.

One example of a product design that the authors of the book refer to as both Jugaad and frugal innovation is the incubator mentioned in the introduction, designed by Dr. Sathya Jeganathan (Radjou et al., 2012). Dr. Jeganathan, a paediatrician who wished to decrease the infant mortality rate in her hospital, found that imported incubators were too expensive and unsuited for the conditions in rural India, thus Dr. Jeganathan took upon herself the role of the designer. Together with nurses and electricians, she created a design for an affordable yet effective incubator using locally sourced wood, Plexiglas and a 100W light bulb. This innovative and frugal design cut infant mortality rates at the hospital by half when implemented, and at a fraction of the cost of a conventional incubator. This is one example of what could be considered Jugaad, and most would agree that it is a very good and honest solution to the problem.

There is however critique of other examples of Jugaad. Joseph (2018) criticises the way Jugaad is referred to and “romanticised” by academics, stating that Jugaad innovation is showing that our society forces smart people to innovate in a way that people in a richer part of the world would not have to do. Joseph describes that what the term Jugaad really refers to originally is often unsafe, sub-optimal, indurable and in some cases even illegal or dishonest. The author’s examples include vehicles built with scraps that lack safety features and informal insurance providers offering insurance for commuters at a low premium, allowing them to risk travelling without a ticket as they are ensured payout in the unlikely event that a ticket inspector catches them. These are aspects that seem less reconcilable with the often positive notions of FD.

Tiwari et al. (2017) also voice some hesitation in connecting the Jugaad term too closely with frugal innovation, arguing that Jugaad is not about “affordable excellence”. This is supported by Krishnan (2010) & Birtchnell (2011), emphasising that the original conception of Jugaad is something that is not necessarily an entirely legal, fair or sincere attempt at good products and services. The grassroots improvisational definition of the term Jugaad is pressed further by Krishnan who argues that Jugaad reflects Indian talent to find the way around hard-navigated and penetrated governmental rules and regulations.

Appropriate technology

Appropriate technology is a movement with a long history, often partly attributed to Mahatma Gandhi. This attribution is also done by the movement's more official founder, the economist Fritz Schumacher. The approach Schumacher proposed had the intention to be community developing, making use of progressive development and use of local resources and skills to create jobs (Dunn, 1978). The technology is perceived to be appropriate and able to fulfil the community development goal if it is, except from creating jobs, also using local resources, is easy to maintain, affordable, agreeable with existing infrastructure, small-scale, sustainable and making use of scarce resources efficiently (Akubue, 2000).

The idea is about designing products that are labour intensive and adopted to the bottom of the pyramid market to create socio-economic gains due to more available work and locally adapted products that are possible to produce on-site. It does not necessarily put any requirements on the quality or functionality of the product as often the case for FD.

The bottom of the pyramid concept

The 'base' or 'bottom of the pyramid' concept originated in 2004 with the work of C.K Prahalad and Stuart Hart. Prahalad's book, *Fortune at the Bottom of the Pyramid: Eradicating Poverty Through Profits* (2004), popularised the term. In the book, Prahalad suggests that big multinational corporations can gain profitability while simultaneously building prosperity in developing markets by tending to the low-income customer segments that are part of these markets. Prahalad states that this was proposed to be a type of "win-win" scenario, where multinational corporations "partner" with the poor is very much needed, as a way to access the fastest growing markets in the world (Prahalad, 2004).

The bottom of the pyramid concept is aimed at the base of the socio-economic pyramid and views them as untapped consumers (Jagtap & Larsson, 2018). Prahalad emphasises the concept's beneficial aspects of bringing products and services, and thus prosperity and poverty alleviation to the 'low-income masses' by reducing costs. However, the primary stated incentives are to bring revenue and market share to the multinational corporations managing to operate in these markets (Ramdorai & Herstatt, 2015). One example of how this has been done is the single-use packages of shampoo and soap that are sold by Unilever in developing markets, this is needed in order to meet the purchasing power available to those that cannot spend eg. a week's worth of wages on a larger bottle (Basu & Srivastava, 2005). This example is indicative of the concept's mindset of taking an existing conventional product from the upper levels of the pyramid and making it affordable to the low-income segments, a top-down approach. The approach results in solutions that are attractive solely to the base of the pyramid and do not apply to segments with greater purchasing power, nor is it intended to (Tiwari et al., 2017).

Through studying businesses operating at the bottom of the pyramid, Anderson & Billou (2007) argue that the companies that have managed to serve the poor profitably have succeeded due to using approaches that deliver something they call the 4A's: - availability, affordability, acceptance, and awareness. Anderson & Billou define the 4A's as availability; to what extent the product or service is made accessible for the consumer to consume, Affordability; to what extent the product or service is affordable for the consumer. Acceptability; do all involved stakeholders in the value chain want to acquire, sell, or distribute the product? Awareness; is the customer able to be made aware of the existence of the product? Thus, these 4A's have several similarities about definition to what is included in FD

One basis of criticism offered by Karnani (2009) is that it is in the nature of the bottom of the pyramid concept that big corporations should intervene to “aid” the bottom of the pyramid, arguing in contradiction to Prahalad, Karnani affirms that the concept does not involve the bottom of the pyramid aiding and lifting itself (Karnani, 2009). With this criticism, Karnani emphasises that the only way of lifting the bottom of the pyramid out of poverty is through creating employment and income at the bottom of the pyramid. Jagtap & Larsson (2018) agree that more locally based production and engagement play an important role in reducing poverty and providing opportunities for income generation.

Ramdorai & Herstatt (2015) lifts another criticism of the bottom of the pyramid concept, stating that it does not differentiate helpful from harmful substances such as alcohol and tobacco products, which are leveraged indiscriminately to low-income consumers who may have a lower chance to make informed choices (Ramdorai & Herstatt, 2015). Karnani (2009) supports this argument about tobacco and lifts Coca-Cola as an example of a multinational corporation operating at the bottom of the pyramid to distribute a product that is “harmful for the poor”.

The Design thinking process

To better understand FD and its processes and methods, they are preferably seen in the light of a recognised design process. It is crucial to have an understanding and a joint picture of what we refer to as “a regular design process” or “design thinking” to understand FD.

The purpose of the design process is that it should end up with a product. This can be anything from a system to a physical artefact, an environment or a service, a method or a process etc. and the product is the outcome from the work through the design process. The essence of the design process is a mindset. Each individual design project has its own characteristics and needs certain methods and techniques, but the overall design process, the mindset, can be the same. It is the human needs, preferences and conditions that stand as the starting point for the design work (Wikberg-Nilsson et. al, 2015).

The first step in the process is to investigate and reflect upon who the users and stakeholders of the intended final designs are. With a clear understanding of the system of use, i.e users, stakeholders and environment etc, the needs and requirements that the product must fulfil can be investigated. The design of the product shall rely on this learning for the investigation phase, and not on the arbitrary opinions of the designer. The design process consists of four steps that shall guide the designer rather than steer, see figure 2.4. The design process is an iterative process, i.e the steps are not executed fully linearly. Instead, the different phases can occur several times and the results from a phase are the base for iteration (Wikberg-Nilsson et. al, 2015).

The first phase, “*Plan the project*” is about gaining an understanding of the project aim and goal through setting the stage, i.e choosing strategies, defining project roles and responsibilities and investigating available resources for the project. Through phase one, the designer has an understanding of the project brief and the intention of the project. The question of why can be answered. During phase two, “*Explore the context*”, the context for the project is investigated with the goal of gaining an understanding of the situations, people, and environments. The outcomes from phase two are identified needs and driving forces for the users, as well as the context limits. After phase two, the designer can, correctly informed, describe the problem. During phase three, “*Create ideas*” the designer explores what solution alternatives there are and how a solution can be designed to meet the needs determined in phase two. Within this phase, a lot of ideas and alternative solutions should be explored. The solutions are then evaluated in relation to the needs and requirements in order to narrow down the solution space. During phase four, “*Prototype concepts”*, the best ideas and concepts are prototyped and evaluated. This is done to test the solution and the experience it entails. This phase is executed without and with the intended users. Iterations are then done with the learnings from the prototyping and the design is then refined. Note that the outcomes from all phases are reassessed during the project in an iterative manner, i.e the design process cannot be described as linear (Wikberg-Nilsson et. al, 2015).

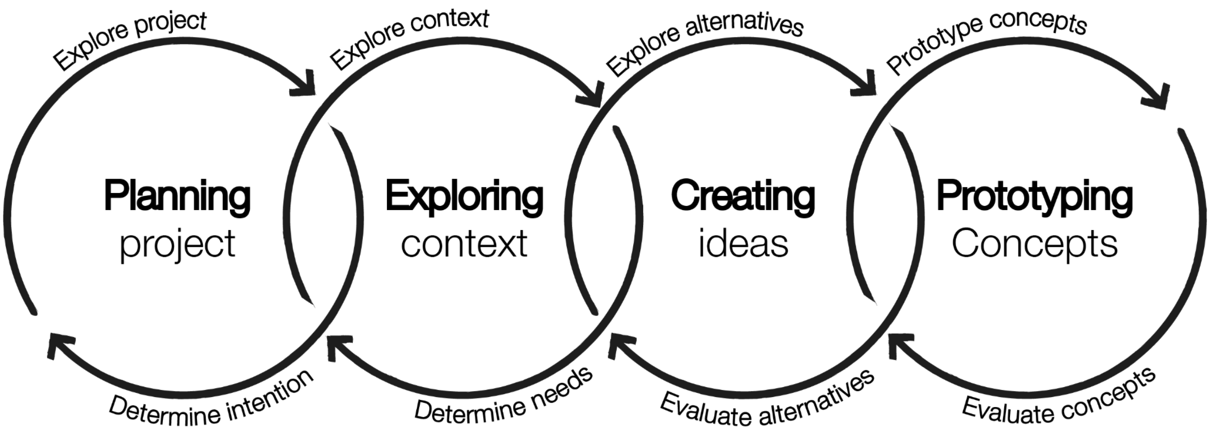


Figure 2.4 Model of the design thinking process (translated from: Wikberg-Nilsson et. al, 2015)

Human-centred design

Human-centred design is a design approach that, through the basic design thinking mindset, focuses the design work on the humans' needs and conditions and exemplifies that a design approach can have its own focus and still rely on the foundation of design thinking in its process. The purpose with human-centred design is to make sure that the machines, tasks and environments are designed with the humans as the starting point and that the designs are adapted to the humans, rather than forcing the humans to adapt to the machines and environments etc. Therefore, a human-centred designer understands the differences between us humans, such as differences in preferences, different ages, sizes, gender, experiences, cognitive ability, physical ability, cultural expectations etc. (Wikberg-Nilsson et. al, 2015).

Conclusions Design thinking

The design process is a general process that suits several different design approaches. Even if a certain design approach has a special focus, most rely on the same mindset of design thinking. What special design approach is used can be consciously or unconsciously chosen, but the first two phases should give the designer knowledge and the possibility to choose the orientation for the project goal and what design approach is suitable to achieve this.

Methodology - Frugal Design literature review

The following databases were searched for literature about FD: Scopus, Web of Science, Science Direct, Google scholar, JSTOR, ERIC and PubMed. In addition, grey literature found using the search term “frugal design” was also included.

Among database findings, any articles referring to “frugal design” in either title, abstract or keywords, and that also explicitly described the meaning of the phrase/concept to any extent in the article, were included. There were no geographical or language restrictions. All found articles were written in the English language.

Search terms used: The search term used was “frugal design” in the publication title, abstract or keywords.

Search strategy: No limits or restrictions in dates, region or type of publications for the search were used.

Analysis: To analyse the process and methodologies a KJ-type analysis was used. Similarities of proposed processes and methodologies were grouped together to see what authors/researchers are suggesting.

Eligibility criteria

Inclusion criteria: The inclusion criteria for this review were restricted to publications that contained “frugal design” in the title, abstract or keywords and that included a clear focus on the definition, description or explanation of what FD is.

Exclusion criteria: Articles that only briefly mentioned FD without also explicitly describing the meaning of the phrase/concept to any extent in the article were excluded.

Results Frugal Design literature review

In total, 19 literary sources were found (see figure 2.5 and table 2.1). Out of the 19 sources, 14 came via the database search. They were found via Scopus, Web of Science, ScienceDirect and Google Scholar. No results were yielded using JSTOR, ERIC or PubMed. In addition to the database publishings, 5 additional sources were included through manual searches and secondary sources. These five manual sources regarded specifically biosafety/medical products & development in resource scarce environments, themes that were not the focus of the main literature search.

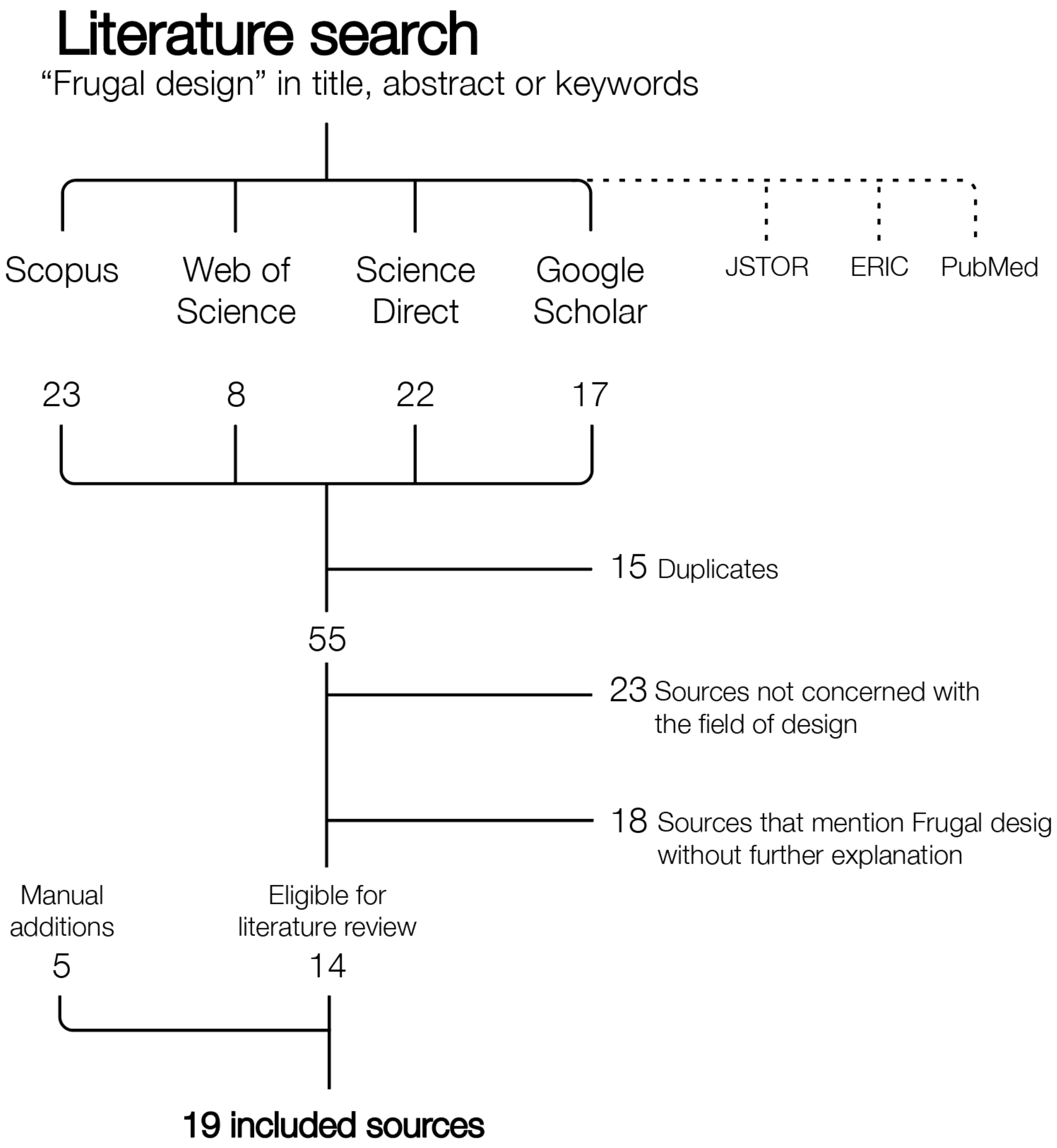


Figure 2.5 Flowchart of search method.

Authors	Title	Type	Source
1. Bolaños (2013)	The Investigation Of The Practice Of Frugal Innovation Across Cultures And The Introduction Of An Instructional Model For Streamlining The Design Process	Dissertation	Database
2. Rao (2013)	How disruptive is frugal?	Journal article	Database
3. Lecomte et al. (2013)	Towards a Better Frugal Design using Persona	Conference paper	Database
4. Soni & Krishnan (2013)	Frugal innovation: aligning theory, practice, and public policy	Journal article	Manually found
5. Pradel & Adkins (2014)	Towards a design for frugal: review of implications for product design	Conference paper	Database
6. Zeschky et. al., 2015	From Cost to Frugal and Reverse Innovation: Mapping the Field and Implications for Global Competitiveness	Journal article	Manually found
7. Lecomte & Blanco (2015)	Dealing with non-trade-offs for frugal design	Conference paper	Database
8. Ramdorai & Herstatt (2015)	Frugal Innovation in Healthcare	Book	Manually found
9. McKinley (2016)	Frugal Design and Robotic Surgery	Dissertation	Database
10. Weyrauch and Herstatt (2016)	What is frugal innovation? Three defining criteria	Journal article	Manually found
11. Rao (2017)	Advances in Science and Technology Through Frugality	Journal article	Database
12. Leliveld & Knorringa (2018)	Frugal Innovation and Development Research	Journal article	Manually found
13. Rao (2018)	Science Is Indispensable to Frugal Innovations	Journal article	Database
14. Graeff et al. (2019)	Research into Design for a Connected World	Book	Database
15. Santiago et al. (2019)	Exploratory study of the integration of frugal innovation in the design of products for the BOP	Conference paper	Database
16. Brem et al. (2020)	How to design and construct an innovative frugal product? An empirical examination of a frugal new product development process	Journal article	Database
17. Singh & Das (2020)	An Approach to Develop Accessible and Affordable Products	Journal article	Database
18. Singh et al. (2020)	A Framework for the Improvement of Frugal Design Practices	Journal article	Database
19. Stanislow et al. (2021)	Can Regulatory Efforts Motivate Innovation? The Case of Ventilator Innovations During COVID	Journal article	Database

Table 2.1 Table of sources for the literature review.

Frugal Design - What is it and how is it performed?

A completely independent definition or view of FD is hardly tangible in a single piece of literature. In this section, we will bring forth encountered definitions, characteristics and views on FD, as well as proposed FD processes and methods from the found literature. Only 15 of the articles present or suggest processes or certain methods for FD. The found definitions, characteristics as well as processes and methods for FD are presented briefly for each author below.

Bolaños (2013)

Definitions and Characteristics:
Bolaños (2013) describes a frugal innovation as a low-cost design, developed and offered to a low-income population, with a direct and indirect focus on sustainability, defined as social-, environmental- and economic sustainability. Further on, Bolaños characterises frugal innovation as utilising materials that are recyclable and available in abundance. Shortly a type of innovation that makes a helpful product accessible to a broader group of users by being available at an extremely low price. Bolaños also states the potential for frugal innovation to raise profits for corporations.

Processes and Methods:
Bolaños (2013) suggests a design model for frugal innovations containing five steps named: 1. *Define the Problem*, 2. *Brainstorm and Generate Ideas*, 3. *Application of Criteria and Constraints*, 4. *Evaluation* and 5. *Development of a Frugal Innovation product.* In step 1 Bolaños emphasises the importance for a designer to understand the customer. The author advocates the use of the method “Voice of the customer”, similar to a regular design process. In the next step of brainstorming and ideation, it is advised to include the future users of the product. What differs from a regular ideation phase is that it’s emphasised to also determine what available resources there are in the context, what the customer will be willing to pay and discover what similar products that exist and why they are not in use. As the third step, Bolaños proposes making use of FD characteristics as requirements to narrow down the solution scope of the ideas created in step 2. Instead of working with trial and error in terms of prototypes Bolaños proposes using the Life cycle analysis focusing on environmental, social and economical sustainability to avoid time and monetary resources being consumed in prototyping.

Rao (2013, 2017 & 2018)

Definitions and Characteristics:
Rao (2013) presents a wide perspective of frugal innovation, including approaches such as reverse innovation, scarcity-induced innovation and others. Rao suggests that Frugal innovation can be used to satisfy the needs of low-income customers, in essence stating that minimal use and or reuse of resources, simpler designs addressing core functions, a low price, sustainability and good usability are features of a frugal innovation. Rao also emphasises that frugality does not rule out the use of advanced technologies if this can aid in achieving frugal innovation and a

lower price. In 2017, Rao brings up some characteristics of so-called “advanced Frugal innovations” and argues that Frugal innovation can appear in advanced applications as well. Advanced frugal innovation is described as low cost, leveraging advances in technology and they are created by workers with advanced knowledge in relation to the advanced technology that is created. Rao returns to the subject again in 2018 writing that a frugal innovation can be anything from grassroots- to sophisticated innovations, bringing up examples ranging from clay refrigerators to particle colliders. The cost is lower due to a “no-frills structure”. Rao argues that frugality is a trade-off between benefits (such as accessibility) and the weakness that is imposed on frugal innovations through the frugal process, as material and construction margins are lowered with the aim to lower the price, indicating that this sets higher demands on the designer in regards to safety margins and the like.

Processes and Methods:
Rao (2013) describes a “Methodology for undertaking frugal-innovations” which is based on 3 process steps; “Modelling of functionality”, “Frugal product feasibility” and “Optimization of basic design”. In the first step, it is suggested to use traditional methods and techniques used for product design with the goal to list all parameters that will affect the functionality and the desired performance level to these. For the next step, Rao argues that all sectors might not be suitable for a FD alteration, such as aerospace, healthcare and defence due to the high requirements of performance set on these types of products. Therefore it is advised to, when the functionality and performance level is set, determine if the problem at all is suitable for a FD venture. In the last step “Optimization of basic design” the design shall be optimised to obtain a cheaper product by using the requirements of functionality as fixed constraints and optimising factors such as manufacturing, quality and robustness to lower the costs and increase affordability.

Rao (2017) elaborates on advanced frugal designs, describing that an advanced frugal product needs to be developed using an extensive understanding of the materials used, the future use, as well as stresses posed upon the product in worst-case scenarios. This is because the frugal approach involves a reduction of material usage which in turn affects the safety factor. This means that the designer must model, experiment and successfully predict what the design must handle in order to succeed which stands in contrast to a design process where some uncertainties can be countered by increasing the safety factor.

Rao (2018) also suggests that the FD approach should have an active focus on material savings through alternative manufacturing, alternative designs and savaging and re-use of material.

Lecomte et al. (2013)

Definitions and Characteristics:
Lecomte et al. (2013) describe FD as a formal way of improving design processes. The authors illuminate four important dimensions of local adaptation and FD; local manufacturing know-how, knowledge of the context and how it should affect the design, the choice of the components to create a just-enough product, and lastly, the characteristics of the users.

Processes and Methods:
Lecomte et al. (2013) emphasise the necessity of understanding the context and argue that using persona as a tool during the design process is useful for the frugal designer to form a realistic understanding of the context relevant to the development.

Soni & Krishnan (2013)

Definitions and Characteristics:
Soni & Krishnan (2013) presents a broad perspective of frugal innovation as a concept to comprise a frugal mindset, a frugal process and a frugal outcome. A process can be designed to be frugal while the outcome of the process is perhaps not. Soni & Krishnan exemplify their ideas with the lean production model that Toyota cars adopted. The process of “lean production” of cars was frugal, but the cars, the products produced, were not. They state that frugal innovation as the outcome can be of different kinds, such as appropriate technology, disruptive innovation, bottom of the pyramid innovation or reverse innovation. The authors define frugal innovation as “meeting the desired objective with a good-enough, economic means” and “low-cost, good-enough products or services”

Processes and Methods:
Soni & Krishna (2013) propose several factors that are said to increase the possibility to succeed with the creation of FD. Except for external factors hard to change for the designer such as a context with weaker property rights, they mention the importance for the designer to be located in a resource-scarce environment, i.e the intended context to encourage a frugal mindset.

Pradel & Adkins (2014)

Definitions and Characteristics:
Pradel & Adkins (2014) conclude through three different previous authors' definitions, their own definition of frugal innovation consisting of three characteristics. Firstly a minimised use of resources consumed during the whole product's life cycle. This is said to include not only material resources but also institutional and economic resources. Secondly, a low-cost product, both during the acquiring and the use phase. Thirdly, functionality that is comparable to or better than standard products.

Processes and Methods:
Pradel and Adkins (2014) present two found methods of FD. The first one is what Rao (2013) presents in the article “How disruptive is Frugal?” as presented above. The other process presented is a product development process, by Siemens developed for its SMART project. Pradel and Adkins describe the process as phases where need identification is the first step. During this phase, the core values are to be identified by research centres from developing countries. The next phase is focused on reducing the manufacturing cost, by for example using more cost-efficient materials. The third phase focuses on combining simple technologies for the assemblement of the product. Pradel and Adkins also conclude 7 frugal innovation principles which they propose to follow and use as a tool for designing and obtaining frugal innovations. The principles they propose are a minimal use of resources including material, financial and institutional resources in the concept, the integration of the consumers in the resource-scarce context, adapting a frugal mindset (seeing resource scarcity as a possibility), designing to lower the cost through eliminating expensive parts and materials through the whole life cycle, combining technologies, elimination of functions perceived as unnecessary and finally adopting a system perspective during the design process to see the product as a part of this system. They also mention the importance of striving for usability during the design work.

Zeschky et. al., (2015)

Definitions and Characteristics:
Zeschky et. al., (2015) argue that frugal innovations are not just good-enough or re-engineered products sold with fewer features at a lower price than already existing products. Instead, frugal innovations are products or services specifically designed for resource-constrained environments from the beginning, where focused core functions meet customer needs rather than simply lowering the price. According to Zeschky et al. frugal innovations are novel from a technology and market perspective and typically build on a new product architecture, even though the solution utilises existing technology most of the time. Traits typically said to constitute a frugal innovation are: the utilisation of cost-effective raw materials with local sourcing, local production, use of standard components, size reduction, new applications such as portability and tailoring for environments with poor infrastructure. The frugal value proposition is described as, a new type of product that solves a previously unsolved problem in emerging markets, The novelty of the product means that if it is successfully transferred to a developed context, it can create totally new markets.

Processes and Methods:
While not proposing a clear step-by-step process, Zeschky et. al., (2015) suggests that aside from performing a conventional design process, a frugal designer needs to perform the work within the context in order to understand and meet the relevant needs. Furthermore, the author states that the designer shall take influence from the available resources in the context, whether they be materials, infrastructure or otherwise. With this understanding of the context and the resources available for the design, the designer should develop the product with a focus on core functions, cutting any functionality that is not crucial.

Lecote & Blanco (2015)

Definitions and Characteristics:
Lecote & Blanco (2015) defines FD as a search for "just-enough" between essential values satisfying the needs of the customer and the lowest cost possible for low-income people in developing countries. It's about finding the point of good-enoughness which they argue to be a balance between the performance and affordability of a product.

Processes and Methods:
Finding the point of "good-enough" is proposed to be done by three strategies: design by aggregation (adding essential and additional customer values), design by an extension (adding essential values to existing values), design by focalization (Solve essential values and additional values separately and, which the authors described as three strategies to navigate the balancing for different projects.

Ramdorai & Herstatt (2015)

Definitions and Characteristics:
Ramdorai & Herstatt (2015) define frugal innovations as products that consume a minimum of resources (both financial and material) at the same time as fulfilling acceptable quality standards and point out that frugal innovations are emerging from BOP markets. They also imply simplification and affordability to define a frugal innovation.

Processes and Methods:
Ramdorai & Herstatt (2015) suggest that the model for the pricing of a product needs to be reversed in FD. The authors suggest that a conventional product may be produced and then have a margin added on top of the production price in order to generate the retail price. The price of a frugal product should instead be derived from what is an affordable price for the intended consumer. From this affordable retail price, a required margin should be subtracted, the rest is then what a designer has available for the production of the design. The authors mean that in order to do this, designers need to embed themselves within the context and build a thorough understanding. Ramdorai & Herstatt promote the use of the 4 A's framework, designing and evaluating towards the values of Affordability, Acceptability, Awareness & Availability during the design work. The authors finally propose that the implementation of limits within the design space may spur innovation, exemplifying using the limitations and requirements set on Tata engineers during the development of the Tata Nano.

McKinley (2016)

Definitions and Characteristics:
Mckinley (2016) emphasises that FD is an approach performed in close connection to the context, with deep empathy for the potential users. The author also puts forward a number of "tenants of frugal design", expressing that FD represents; product accessibility for individuals with lower income (not only to be consumed but also to better their living conditions), engagement and iteration with the potential users to create context-relevant frugal products,

use and re-use of locally available resources and solutions, product infrastructure development that supports future growth, eg. through modularity, visually appealing products and robust products developed through diverse collaboration.

Processes and Methods:
McKinley (2016) presents five aspects to use as a guide during the development process and a few clear recommendations on how to perform FD work. In what McKinley calls the “Five Considerations of a Frugal Designer”, McKinley emphasises 1. *Empathise with Need:* the need for designers to embed themselves within the context and feel the needs along with the user. 2. *Focus on What is Available:* while within the context, the designer is then to identify available resources, salvageable equipment, tools, re-applicable information, etc. 3. *Quickly Generate Conceptual Prototypes*: The designer should strive to progress to conceptual prototypes quickly, starting with simple tools such as sketches and then progressing to prototypes. 4. *Design for Modularity:* In order to maintain frugality and save resources, prototypes should be modular and allow revisions and tests of new ideas without requiring an entirely new prototype. 5. *Frugal Design Represents Accessibility:* The author ends by stating that frugal designers should work transparently and willingly share information with others for the betterment of all.

Weyrauch & Herstatt (2016)

Definitions and Characteristics:
Weyrauch and Herstatt (2016) argue for a definition with three broad criteria that altogether define what a frugal innovation is. They state the three criteria; substantial cost reduction, concentration on core functionalities and an optimised performance level are criteria that must be fulfilled for an innovation to be called frugal. Due to the fact that frugal innovations have entered developed markets, Weyrauch and Herstatt argue for the importance of using universal criteria when defining frugal innovation, without the need for innovation being connected to a certain market, such as emerging markets, in which frugal innovation initially has been discussed.

The first criterion; a substantial cost reduction defines a significantly lower initial purchase price, reduction of the total cost of ownership and minimising the use of monetary and material resources. Weyrauch and Herstatt conclude that the purchase price should be at least ⅓ compared to existing solutions available on the market. The second criterion, concentration on core functionalities, is described as a product that only has functions that are perceived as absolutely essential for the user. The third category, optimised performance level, refers to a performance level of functions that is exactly aligned with what is needed in the intended context. Weyrauch and Herstatt argue that these criteria give effects such as usability, saving of resources, and lower environmental impact.

Weyrauch & Herstatt use the MittiCool, a clay cooler using water evaporating instead of electricity as an example of how to decide if an innovation is frugal or not, using the three criteria of *substantial cost reduction, concentration on core functionalities* and *optimised performance level*. The MittiCool cost at launch was 2,500 Rs (Indian rupee) compared to a conventional fridge of the same size for at least 6000 Rs. The clay fridge does not use electricity and has therefore a very low cost of ownership. Thus, the MittiCool has a substantial cost reduction of almost 60 %. Further on, the MittiCool is aimed to cool mainly fruit, vegetables and dairy, and has only room for that. The cooling without electricity suits the local Indian context it was aimed for and without a freezer compartment or lighting, the cooler meets the criteria of concentrating only on core functionalities. The cooler keeps the temperature between 5 to 8 degrees Celsius, which is enough for the intended use and the size of the cooler is enough for the users. i.e, the cooler's performance is adapted to the local conditions and therefore the criteria of optimised performance level is also met. The MittiCool can therefore, according to Weyrauch & Herstatt (2016), be said to be frugal.

Processes and Methods:
Even though not mentioning deeply how, Weyrauch & Herstatt advocate an active usage of the three criteria during a design process as a method of FD. The criteria should be merged into the design process and could thereby be used to achieve FD.

Leliveld & Knorringa (2018)

Definitions and Characteristics:
Leliveld & Knorringa (2018) describe frugal innovation as something very universal, pertaining to the design of products, services, systems and business models. These designs are for low-income customers throughout the world, and they provide high user value through affordable solutions by reducing complexity and costs throughout the lifecycle of the product, while also enhancing functionality. The authors conclude that frugal innovation is hard to predict and the processes of different frugal innovation projects may contradict one another.

Graeff et al. (2019)

Definitions and Characteristics:
Graeff et al. (2019) argue that FD aims to offer sustainable and social products for the poorest in the world by developing products that meet the essential needs of the customer. They argue that the main defining factors are: “affordability, sustainability, profitability, resourceful effectiveness, and social impact”.

Processes and Methods:
Graeff et al. (2019) argue that to achieve a successful frugal design, defined by the balancing between essential value for the customer and reduction of cost, a problem-solving approach with a focus on resourcefulness will help. Further on to work with a business model that makes use of local synergies.

Santiago et al. (2019)

Definitions and Characteristics:
Santiago et al. (2019) propose eight FD key criteria: Affordability, Availability, Acceptability, Awareness, Aspirational, Functionality, Scalability & Sustainability as a way to define a FD.

Processes and Methods:
Process-wise, the authors pose a number of questions in relation to the key criteria that designers should ask themselves during the design process in order to achieve a successful FD. One example related to the criteria of functionality is "Can the product be maintained and repaired locally?".

Brem et al. (2020)

Definitions and Characteristics:
Brem et al. (2020) describe frugal innovation in conjunction with terms such as Jugaad and grassroots innovation, as concepts that develop products and services that are based on constraints in the settings they are designed for and in. In particular frugal innovation regards some principal characteristics such as cost, functionality, performance and technology. The authors propose that local collaboration, and thus material availability, local aesthetic values and core functionality are characteristics of a successful frugal product

Processes and Methods:
Brem et al. (2020) performed an empirical examination of a frugal product development project and among other conclusions delivered some concrete recommendations for the FD practice. In what resembles a common user-centred design process, based on an understanding of user needs and requirements, Brem et al. suggest that after brainstorming the designer should use "divergent" ideation tools in order to break mental routines and thus really identify what functions are critical and which are not. The authors also bring up the approach of co-creation and propose that for FD. User involvement should be practised in all parts of product development, from ideation to construction, the latter of which is perhaps not so common in co-creation projects.

Singh & Das (2020)

Definitions and Characteristics:
Singh & Das (2020) describe FD as low-cost innovation where complexity and unnecessary parts are eliminated to reduce costs, but without compromising the functionality, performance or usability of the product. Singh & Das also brings up robustness, sustainability, accessibility and local manufacturing as descriptive of FD.

Processes and Methods:
Singh & Das (2020) does not emphasise a specific design process but does lift the importance of integrating with the users of resource-constrained context at the beginning of the design process when designing for the bottom of the pyramid. Furthermore, it is argued that the

designer needs to find needs and requirements from the user studies in the product development process.

Singh et al. (2020)

Definitions and Characteristics:
Singh et al. (2020) argue that frugal innovation focuses on the people at the bottom of the pyramid and that frugal innovations are restricted to those contexts they were initially designed for and not intended for a global business. Singh et al. also argue that the current FD approach is too focused on the criteria for frugal innovation that Weyrauch and Herstatt (2016) proposed, namely cost reduction, functionality and performance. They identify and argue that seven key elements characterising frugal innovation contribute to a more socially inclusive design with better acceptability among a more diverse set of users. These 7 are functionality, usability, performance, affordability, accessibility, aesthetics and robustness.

Stanislow et al. (2021)

Definitions and Characteristics:
Stanislow et al. (2021) state that FD is a resourceful type of innovation, allowing manoeuvring around the constraints of resources and institutions, describing frugal innovation as central in the development of many innovations we saw during the COVID-19 pandemic. Stanislow et al. also state that FD can bring benefits such as improved usability, accessibility, and lower price and thus long-term profitability in the markets.

Connections between extracted processes and methods

The most significant and repeatedly proposed processes, methods and tools that were brought up in the literature are presented in table 2.2 below. A few interesting suggestions that are connected to the other main categories are also presented. Essentially, a design process that utilises or has several similarities with a regular design process could be found throughout the literature. Furthermore, the utilisation of FD characteristics to guide the design process. Several authors advocate for a more intense context focus surrounding the use situation, an immersion and physical presence in the context is advocated to learn about more than the user. A different price model which affects the design process is suggested by two authors. Actively working towards cost reduction and utilisation of available resources is also brought up.

Note that table 2.2 only includes what is explicitly brought up in the literature. It is worth noting that it does not necessarily mean that an author does advise against or disagrees that a factor does not have importance for FD just because it’s not mentioned explicitly.

Authors	Mainly a/part of a "regular design process"	Extra context focus	Utilising FD Characteristics	Using a different price model	Cost reduction as an active part of the process	Identifying possibilities and constraining the ideation space
Bolaños (2013)	Problem definition, Ideation, Evaluation and product realisation		To narrow down ideas	Identify acceptable price		Ideation around with what is available
Rao (2013)	Determining needs and requirements as a base for further design work		Determine if FD is suitable through FD factors		Lower all cost that isn't regulated by initial needs and requirements	
Lecomte et al. (2013)	Understand needs and requirements by utilising personas					
Soni & Krishnan (2013)		Must be at site				
Pradel & Adkins (2014)	Need and requirement identification	Must be at site	Use 7 principles		Via material selection, reducing financial-, material- and institutional consumption	
Zeschky et. al., (2015)	Define the requirements from the local users	Should be at site to understand	Aim towards obtaining FD factors		Strip down expensive aspects of a design	Identify and use available resources
Lecomte & Blanco (2015)			Balance core functionality and affordability to obtain "good enough"			
Ramdorai & Herstatt (2015)		Embed yourself in the context	4 A's framework for design for BOP	Price - Margin=Cost		Set constraints to facilitate FD
McKinley (2016)	Start investigating requirements spec, prototype early	Embed yourself in the contex				Identify and work with available resources
Weyrauch and Herstatt (2016)	Follow a regular process		Use FD criterias for all steps in the process			
Rao (2018)					Focus on reducing material consumption	
Graeff et al. (2019						Business model through local synergies
Santiago et al. (2019)			Reflect through FD factors			
Brem et al. (2020)	Understand the user, specify requirements, Ideation, divergent ideation tools	Co-creation also during construction	Identify and include FD criterias in the process			

Table 2.2 Frugal Design processes and methods proposed within the reviewed literature

Discussion Frugal Design theory

In order to conclude a theoretically based FD framework for usage within real design projects we will discuss what should define and characterise FD, and what process and methods that can be advised to be used to develop a frugal product.

Frugal Design definitions and characteristics

No uniform definition of FD has been found in the theory, however, several similar characteristics and definitions have been recurring. Most of the definitions and characteristics that we see as recurring can be found in a combination of two articles that we perceive as key articles for this review. These two articles are: *What is frugal innovation? Three defining criteria* by Weyrauch & Herstatt (2016) and *A Framework for the Improvement of Frugal Design Practices* by Singh et al. (2020). The articles are connected since Singh et al. bring up the work by Weyrauch & Herstatt and argue that their definition is too focused on certain characteristics and later suggests an extended definition. However, the two together give the reader a good base to understand what we see as the most common and accepted characteristics and definitions of FD throughout the theory.

FD is often mentioned in relation to emerging markets and BOP. However, the need for FD should grow beyond these bounds as consciousness and the need for sustainability and a circular society increases. The fact that FDs have made their way from BOP markets to developed markets (Weyrauch & Herstatt, 2016; Radjou et al., 2012) supports this. The characteristics used to define a FD should therefore not limit the use of the FD approach to a certain context. The factors brought up by Weyrauch & Herstatt (2016) and Singh et al. (2020) are attributes and factors defining a FD in a manner that does not exclude the designer from using the design approach in any context.

Most of the factors and attributes brought up by other authors are related to or are the same as the ones brought up by Weyrauch & Herstatt and Singh et al. We argue that a framework consisting of 8 factors that represent a relatively accepted view of the characteristics of FD can be derived directly from combining these two articles and should be tested as a FD framework. These eight are: Core functionality, Optimised performance level, Usability, Accessibility, Affordability, Acceptability, Robustness and Sustainability. These 8 factors of FD will be separately discussed below in relation to the various author’s views of the characteristics and definitions of FD.

Affordability

Affordability seems to be one of the most important characteristics of FD. Most of the authors subject to this review mention affordability in one way or another. Weyrauch & Herstatt (2016) as well as Singh et al. (2020) state affordability as a core characteristic of a FD. Both Weyrauch & Herstatt and Pradel & Adkins (2014) talk about a substantial cost reduction compared to existing alternatives in both initial purchase price and total cost of ownership. Weyrauch & Herstatt argue that the price should be at least lowered to ⅓ compared to existing solutions available on the market. However, mentioning affordability as an important characteristic of FD, without specifying how much lower the price should be (Ramdorai & Herstatt, 2015; Leliveld & Knorringa, 2018; Graeff et al., 2019; Singh et al., 2020), is more common.

Synonyms such as low price, low cost or economic sustainability are also used to characterise a FD (Bolaños, 2013; Rao, 2013; Soni & Krishnan, 2013; Zeschky et. al., 2015; Pradel & Adkins, 2014; Brem et al, 2020; Singh & Das, 2020). However, we see these attributes in accordance with affordability, and that affordability explains better the goal of the design. A lower price is often argued to be achieved by simplification, elimination of unnecessary parts and a “no-frills structure” (Rao, 2013; Singh & Das, 2020; Ramdorai & Herstatt, 2015; Leliveld & Knorringa 2018). We argue that these should be seen as possible but not required tools to achieve Affordability. Zeschky et. al., (2015) mention utilisation of cost-effective raw materials with local sourcing, local production, use of standard components and size reduction typically constitutes a frugal innovation. These are factors that can create a more affordable product, but that is very context-dependent, and should therefore also be seen as possible tools or methods to achieve affordability rather than defining a FD or as rules of how it should be obtained.

Core functionality

A rationalised view of functionality, i.e to only include the functions that resolve only the most essential needs, is brought up in some way by most of the authors. Both Weyrauch & Herstatt and Singh et al. argue that a certain focus on functionality should be ascribed to a FD as they include “a concentration on core functionality” and respectively “functionality” in the definitions. Zeschky et. al., (2015) also describe frugal innovations as products with a focus on core functions and in similarity, Brem et al. (2020) include functionality, as a principal characteristic. Pradel & Adkins (2014) mention functionality as key for a frugal innovation but presents a slightly different view arguing that it should be comparable to or better than standard products. We think that only functionality is a way to broad definition since it can be argued that all designed products have some functionality. Core functionality, however, points out the characteristic of the functionality in a way that differentiate it from other products. Therefore do we think that Core functionality is a better wording.

Graeff et al. (2019) argue that FD aims to develop products that meet essential needs, which we interpret as the exclusion of functions that address other functions that do not fulfil the essential needs i.e leaving only the core functionality to be included.

Simplification and a reduction of complexity are emphasised by several authors to characterise a FD (Rao, 2013; Ramdorai & Herstatt, 2015; Leliveld & Knorringa, 2018; Singh & Das, 2020). One can argue that reduced complexity and increased simplification of a product is a way to achieve core functionality. For example, by removing a cup holder in a car, the core functionality of the car, i.e transporting is clarified. Reduction of complexity and simplification can therefore be seen more as a tool to achieve a core functionality.

Both Soni & Krishnan (2013) and Lecote & Blanco (2015) lift just-enough or good-enough as attributes of a FD. We argue that the only inclusion of the most essential functions to meet the most essential customer needs is to create something that is just good-enough or just-enough in terms of functionality.

Optimised performance

Weyrauch and Herstatt (2016) define an optimised performance level as a performance level that is exactly aligned with what is needed in the intended context, no better. Performance as a characteristic of FD is also brought up by Singh et al. (2020) and Brem et al. (2020), indicating the topic as important for FD.

Good-enough and just-enough mentioned as a typical characteristic of a FD is brought up by both Lecomte et al. (2013) and Soni & Krishnan (2013). Even though they do not mention an optimised performance level explicitly, the choice of a component that creates a just-enough product is arguably a component that has an optimised performance level to deliver just what is needed to fulfil the core functionality. An optimised performance level of a product component will also assure an as-low-as-possible consumption of resources which due to Rao (2013), Pradel & Adkins (2014) and Ramdorai & Herstatt (2015) are an important factor of a FD. Optimised performance level can be named in many ways, but we argue that optimised performance level covers all these other labels and is the most general and easy to understand wording, especially in relation to core functionality. Therefore optimised performance should be used.

Zeschky et. al., (2015) argue that size reduction is a typical trait that constitutes a FD. However, we argue that size reduction rather should be seen as, when suitable, a tool to obtain an optimised performance level.

Accessibility

The factor of accessibility could be argued to be one of the most important. Without accessibility, the user and other stakeholders will never see the value and benefits of a good design, regardless of how it performs in other aspects. Different views of what drives accessibility and if it is a core in FD or a consequence of other characteristics are brought up. For example, the view Bolaños (2013) presents states that frugal innovations are accessible to a broader group of users, for example through the use of abundantly available materials, similar to Rao (2013) that points out that many of the qualities of frugal innovation work towards greater accessibility, especially to low-income customers, again mentioning minimal/reuse of resources, as well as simpler designs, ease of use, and a low price.

Mckinley (2016) expresses that FD represents product accessibility for individuals with lower income and emphasises (much like Bolaños, Rao and Zeschky et, al,. on use and re-use of locally available resources and solutions, availability being the key word. Singh & Das (2020), in their description of FD, bring up accessibility in general, but also specifically for “users with inadequate resources” and again the authors mention local manufacturing as a factor for greater accessibility. Since there are so many ways to achieve accessibility proposed, and most factors are affected by the contexts, we argue that accessibility as the defining factor is more useful for more diverse design projects since it is context-independent. Utilising local manufacturing and locally available materials etc. should therefore rather be seen as tools since they aren’t the only way of achieving accessibility and may not fit all contexts as a proper way to create a FD.

Even though many of the authors mention accessibility as a consequence of for example local manufacturing, utilisation of locally sourced raw materials and use of standard components, we argue that it is better to use a definition of FD that focuses on what is important for the user. What is important for the user is accessibility, not the methods to achieve it.

Singh et al. (2020) that propose accessibility as one of their seven key elements of frugal innovation, point out it as an element that contributes to a socially inclusive design which shows why accessibility is an important factor and a suitable choice of the label since socially inclusion also is brought up as a characteristic for FD in terms of including low-income customers through designing products adapted for them.

Robustness

The aspect of robustness is only explicitly expressed by a minority of the authors, however many of the sources argue for different defining aspects of FD that we and several of the sources argue to be part of robustness and something we consider a worthwhile focus in FD.

Mckinley (2016) describes robustness as a feature that comes from FD work. We would like to extrapolate Mckinley's “tenant of frugal design” regarding modularity to also have to do with robustness as this allows easier fixes of a product or system if particularly strained or broken modules of the design can be replaced without necessitating a completely new product. Therefore would we like to argue that modularity could be seen as a tool to achieve robustness, while robustness being a defining factor of FD.

Several authors use simplicity or reduction of complexity to describe FD (Lecomte & Blanco, 2015; Ramdorai & Herstatt, 2015; Leliveld & Knorringa, 2018; Brem et al., 2020; Singh & Das, 2020; Singh et al., 2020). We argue that this reduction of complexity could also be encompassed by the overarching umbrella of robustness. It is likely that less complex products generally have fewer possible points of failure. In addition to this, a more easily understandable product will allow problems to be observed and understood, possibly leading to these problems being detected, and prevented before causing issues, or being fixed after the fact, without bringing in external expertise for example.

Rao (2013) interestingly and correctly brings up that frugality is a trade-off between benefits (such as we have discussed earlier) and the weakness that is imposed on frugal innovations through the frugal process where material savings and affordability are in focus. Rao proposes that frugal innovation sets higher demands on tolerances and material understanding if the safety factors are to be lowered in order to facilitate other aspects of frugality.

Singh et al. (2020) emphasise robustness as one of their seven key elements of frugal innovation. However, only a minority of the sources specifically describe robustness as a defining factor for FD. We argue that robustness is affected by many of the attributes and actions proposed in relation to robustness, such as the usage of locally and abundantly available materials, and local manufacturing (Bolaños, 2013; Rao, 2013; Zeschky et. al., 2015; McKinley, 2016; Brem et al., 2020; Singh & Das, 2020). These methods give designs robustness as locally available resources, whether they be material, infrastructural or otherwise, likely simplify the supply chain, facilitating maintenance and repair. However, for the user, it is arguably robustness that is the important product characteristic rather than the method to obtain it. Therefore robustness is a better defining attribute for FD rather than methods such as utilisation of local resources.

Aesthetics

An aesthetic that is pleasing, or at least not unpleasing is important if a design shall have a fair chance to have a successful encounter with its customer. If the product, despite perfect functionality isn't accepted due to poor aesthetics, a solution will be a failure. The problem with products with poor aesthetics and the importance of not neglecting the work towards pleasing aesthetics, even in a resource-constrained setting, when working with FD is brought up by several authors. Singh et al. (2020) argue that there is a need for a more socially inclusive definition of FD than what Weyrauch and Herstatt offer and by including aesthetics in their core factors of FD, Singh et al. argue that better acceptability among a more diverse set of users is obtained. Brem et al. (2020) also argue that one of the principal characteristics to consider in FD is aesthetics and emphasises the importance of adherence to local aesthetic values. Mckinley (2016) requests deep empathy for the potential users with the aim of creating context-relevant frugal products that are visually appealing for the users, further strengthening the inclusion of aesthetics as a factor defining FD.

We argue that aiming for a good aesthetic of a product is important to consider when working with FD and that the aesthetics should be anchored in local values. The fact that FD often is surrounded by terms such as "good enough" and a lot of focus on cost savings, we think the importance of including aesthetics as a FD factor, therefore, is crucial to guard this user value and not totally overlook the aesthetics and end up with an admittedly cheap design but without user acceptance.

Sustainability

Weyrauch and Herstatt (2016) do not include sustainability as one of their key factors of a FD but they emphasise that factors focusing on a substantial cost reduction, concentration on core functionalities and optimised performance level are criteria that indirectly give effects on the saving of resources and a lower environmental impact. Graeff et al. (2019) argue that FD aims to offer sustainable products and sustainability is similarly mentioned by Rao (2013) where Frugal innovation by a minimal use and or reuse of resources is argued to lead to sustainability. However, sustainability is a broad concept and we think that sustainability can stand as a factor of its own, including e.g a sustainable work environment within the manufacturing and not only environmental sustainability which is argued to indirectly be achieved by less material consumption etc. This view is in accordance with how Bolaños (2013) describes sustainability as one core characteristic of a frugal innovation where sustainability is defined as social-, environmental- and economic sustainability. Bolaños also characterises frugal innovation as utilising materials that are recyclable which could be seen more as a way to obtain environmental sustainability. A broader definition of sustainability, e.g working conditions can be argued to be even more important in contexts where working conditions not always can be ensured to be good. Therefore should a designer be aware of what effects their design will entail within all dimensions of sustainability.

Usability

Usability is a very important part of any design that will see human interaction. However, when reviewing the literature on FD, some authors describe usability more as an effect of FD, rather than a conscious effort. As an example, Weyrauch and Herstatt (2016) argue that frugal innovation criteria give different beneficial effects, the authors specifically mention usability as one of these. Similarly, Stanislow et al. (2021) state that FD can bring benefits such as improved usability and that this in turn will benefit the profitability of the product. Contrarily, Singh et al. (2020) claim that usability is one of the key frugal innovation elements that instead leads to a more inclusive and acceptable design, making it a factor rather than an outcome. This view of usability as a conscious and important part of the design process is a view that we also subscribe to. Interestingly Singh & Das (2020) describe that frugal innovation involves lowering complexity and removal of unnecessary parts and that this must not compromise usability among other aspects. The authors clearly consider usability important, one could, however, discuss whether lowering complexity usually risks detrimental effects on a product's usability, or if it rather is likely to benefit usability.

Frugal Design - Processes and methods

When it comes to processes and methods proposed to be used for creating FD, the literature is vague compared to definitions and characteristics. Few solid attempts to understand the FD process have been found. Only one article presented a real-world design case testing and presenting learnings of how to do FD. By digging out all proposed processes and methods from the found literature and searching for consistency, we are arguing that the FD process to a high extent follows what we call a regular design process but with several emphasised differences, where the FD theory proposes some more specific actions within the general design practice. This will be discussed for each theme below.

Part of, or based on the conventional design process

The processes and methods of FD are emphasised and described in various manners. Before focusing on the purer frugal elements of design, we want to note that a majority of the sources describe FD as a design process that has its base in conventional design thinking or with elements that are commonly used within a regular design process (see table 2.2).

Design thinking practitioners will feel familiar with Bolaños (2013) description of the FD process which involves activities such as problem definition, ideation, evaluation, and iteration before product realisation. Congruent with this, Rao (2013), Pradel & Adkins (2014), Weyrauch & Herstatt (2016) and Brem et al. (2020) all bring up these aspects that are inherent to design thinking and all affirm that user needs and requirements need to be identified and should be the basis for further progress in the design work. Lecomte et al. (2013) also highlight the user's needs and requirements while suggesting that these could be determined using personas. Zeschky et. al., (2015) are also in accordance with the design thinking aspects of frugal but stress the importance of evaluating the user requirements locally. McKinley (2016) also covers design thinking's focus on needs and requirements and underlines activities such as early prototyping.

Utilising Frugal Design characteristics

In terms of process, the use of FD characteristics is advocated as a method within the FD process by several authors, and even though the authors have slightly different views of what constitutes the FD characteristics, as discussed above, the overall similarities make it reasonable to review the suggested use of FD characteristics as a part of the FD process. Several authors (Pradel & Adkins, 2014; Zeschky et. al., 2015; Ramdorai & Herstatt, 2015; Weyrauch & Herstatt, 2016; Brem et al., 2020) suggest the use of FD characteristics as a general tool and guidance for performing and evaluating FD, and that therefore these characteristics should be present during the design process. However, please note that it is not specified exactly how these characteristics should materialise in the design process. The use of the FD characteristics as a general tactic for immersion into the context and for guiding actions taken within a regular design process is strengthened by Bolaños (2013) that suggests that the characteristics should be used to narrow down ideas, which is an activity generally done in a regular design process as well. Further on, Santiago et al. (2019) suggest that FD factors can be used to reflect upon the work during the process. We argue that both Bolaños and Santiago et al. suggest using the FD characteristics as how a designer makes use of stated needs and requirements within a regular design process. We argue that this can be seen more as an already set list of needs and requirements but without defined limits. Then an active use of FD characteristics from the beginning of the process to find limits of these needs and requirements, and within the ideation and evaluation phase. In accordance with how a designer is using set requirements, Lecomte & Blanco (2015), while proposing a focus on core functionality and affordability argue that a balancing act between those factors is necessary to obtain "good enough". We think that this indicates that the usage of the FD factors has to be done in the same way as requirement lists in a regular design process. I.e, for different projects, different requirements are weighted differently and a constant balancing act between different requirements is necessary.

Rao (2013) is the only author that suggests the use of FD characteristics that cannot be seen in other design processes, namely to determine if FD is a suitable design approach through the use of FD characteristics. Rao argues that not all products are suitable for FD, such as the aerospace market etc. It is reasonable to reflect upon the properness of FD as a design approach for certain product development. However, it also strengthens the generally advocated use of the characteristics as a tool for eg. evaluation.

Extra context focus

Many of the authors emphasise the need for extra focus and immersion in the context to be able to design frugally. It is obvious that a strong understanding, not only for the users but also for the context and what design possibilities it entails is advocated. Several authors argue that it is needed to be at the site, in the context where the users are to be successful with FD (Soni & Krishnan; 2013; Pradel & Adkins, 2014; Zeschky et. al., 2015; Ramdorai & Herstatt, 2015; McKinley, 2016). Brem. et al (2020) bring an extra context focus and context presence to a practical level arguing that Co-creation with users and stakeholders during construction is beneficial for the FD process. Even though it’s not fully consistent to what extent the designer should be present in the context which is in focus there is a consensus that it is more important than in a regular design process. Even though not all authors emphasise a certain context focus, no one argues against it. We, therefore, conclude that a frugal designer should take the context into extra consideration and preferably immerse into it during the process.

A frugal pricing model

One could argue that a conventional way of pricing a product is to see where there is a market gap, then produce a product for that market gap, add a desired profit margin on top of the production cost and this gives you the price of that product in that market. A few of the authors specifically describe a different pricing model where the price is not derived from the cost of production but instead from the price that the intended users are able to afford. Bolaños (2013) is one of the authors who makes a point of identifying the “acceptable price”. Ramdorai & Herstatt (2015) specify this as the formula: affordable price - profit margin = production cost, not the other way around.

Cost reduction as an active part of the process

Affordability is one of the characteristics of FD most commonly mentioned and it is thereby indirectly mentioned by many authors during the proposed use of FD characteristics. However, cost reduction as an active part of the FD process is also mentioned explicitly by three authors. Rao (2013) argues that all costs that aren't constrained by the initial needs and requirements shall be lowered, and Pradel & Adkins (2014) emphasise the importance of cost reduction and lifts material selection as a possible way. Zeschky et. al., (2015) focus more on simplicity suggesting stripping down expensive aspects of a design. This could of course include choosing a cheaper material but also include product architecture and component choice. The fact that cost reduction is mentioned as a separate tool to achieve FD by authors that also suggest using FD characteristics shows the importance of this element. However, how cost reduction should be achieved is not fully consistent, and we argue that all strategies are preferable as long as they don't contradict too much with the other characteristics. Material selection and simplicity should however be seen as tools to achieve a cost reduction, i.e one important part of achieving affordability. Rao (2018) suggests a focus on reducing material consumption as key in the FD process, but we argue that reducing material consumption doesn't serve its own purpose and then rather should be seen as tools for cost reduction and in its extension affordability, as well as a tool for obtaining a more sustainable product and an optimised performance level.

Identifying possibilities and constraining the ideation space

FD seems to differentiate itself from conventional design as many authors make a point of the processes dependent on identifying possibilities through available resources, whether they be material, manufacturing, know-how or otherwise, as opposed to ideating and designing with a solution space that is only limited by the adoptable global frontier of technology and knowledge. The need to identify and utilise what resources are locally available seems to be important and a possible path forward in the FD process since Bolaños (2013), Zeschky et. al., (2015), McKinley (2016) and Graeff et al., (2019) are highlighting it as important for FD. Limiting the solutions by constraining them to utilise the available resources could be seen as a method to limit the ideation space early in the design process. Ramdorai & Herstatt (2015), argue that setting constraints for the process is a way to facilitate FD and spur innovation, even though they are lifting arbitrary constraints as a way to reach this state. These more or less arbitrary limitations may well spur innovation as they remove some of the uncertainty that is inherent to most design processes. However, one can question if this innovation will be successful as the constraints and thereby the innovative outcome is not based on constraints from the intended context. If we look at the Tata Nano, the Indian microcar that was designed for being affordable for people that yet couldn't afford a car (Singh & Srivastava, 2012), that Ramdorai & Herstatt propose as an example of Frugal innovation based on the initial arbitrary requirements set by the Tata leadership. Instead of being a success, the Tata Nano was rejected by the people it was intended to please (Singh & Srivastava, 2012). Since the Tata Nano had to undergo a lot of revision in order to meet the true market needs and create a successful product, it is questionable if arbitrary limitations are a viable way to create Frugal innovation. However, even if the Tata Nano wasn't a total success, doubtless, these limitations created an innovative product that showed that it is possible to re-think and push limits within the design to create new affordable products by using limits to spur innovation.

The idea of utilising what's available or defining constraints arbitrarily seems to be about shrinking the ideation space to a limit of what's possible or realisable and adapting the later ideation to that, rather than in a regular design process where the ideation phase is advocated to be totally without constraints. Many of the authors are reviewing FD in light of resource-constrained environments and BOP markets. In that case, it seems more feasible to identify possibilities and then constrain the ideation space through what's identified, rather than using arbitrary limits. However, how such a process should be executed in a resource-abundant context is harder to imagine, and maybe in these cases, arbitrary limits could be beneficial as a tool to challenge the development process.

Pradel & Adkins (2014) suggest focusing on reducing more than only financial resources as proposed by several other authors. They advocate a reduced consumption of financial, material and institutional resources. Using fewer institutional resources could possibly also be a way to constrain the solution space if used early in the design process. This can be seen more as a whole system thinking of making the solution more frugal in several aspects and making sure that the end solution is based on what will work in reality without dependency on too many stakeholders. To be able to do this, it is reasonable to say that all easily accessible resources that are available must be guiding the ideation process.

Conclusions Frugal Design

The FD approach seems to differ from other more conventional design approaches mainly in its almost unadulterated focus on reducing all types of resource consumption in order to give designs greater reach and use.

Implied by its name, FD is a type of design practice with its base in a regular design process. The design approach has its own focus areas and tools to direct the outcome and the focus of the design process, but the core still relies on the basis of design thinking and a regular design process. However, it is advocated to have an even stronger focus on the context and physical presence than what necessarily is advocated within a regular design process. Most importantly, a different approach for generating ideas seems to be an important part of the FD process, where the ideation space is constrained early in the process, defined by either identified possibilities/contains or by arbitrary constraints. The iterative ideation process, as done in a regular design process as well, is then acting within these borders in the work of developing the product.

There are eight FD factors, defining the characteristics of the FD outcome that should be used constantly within all phases of the design process to guide the actions taken. The factors are to be considered in the planning, investigation, ideation, evaluation and all subordinate activities. These are; Core functionality, Optimised performance level, Usability, Accessibility, Affordability, Aesthetics, Robustness and Sustainability. These defining factors, in combination with a design process with extra context focus, form a fundamental framework of “how to do” FD. The benefits of using the 8 factors detailed here, and not other similar characteristics proposed in the theory, is that these are independent of a certain type of context or product type. Therefore, this forms a framework that isn’t bound to a resource-scarce environment. This makes FD useful for more designers working in all contexts and thereby with the chance to affect more design projects and products.

A few guiding principles that in many cases act in symbiosis with these factors can be considered, if they fit the project or the context, to obtain adherence to the FD factors during the design process. These should be seen as tools to obtain the characteristics that constitute a FD. Utilising local resources can for example contribute to better accessibility and affordability. It is however worth noting that affordability isn’t equal to local manufacturing and that there might be a context where local manufacturing increases rather than lower costs. A focus on cost reduction is essential for FD and the work towards cost reduction should always be there, thus this will help obtain affordability. A frugal pricing model, derived from what is defined as an affordable price, could also be seen as a tool for the designer to understand what constitutes affordability.

A theoretical Frugal Design framework

Below are the 8 factors defined more precisely as well as some examples of tools to achieve these factors as proposed in the theory.

Affordability

Definition: The solution must be affordable for the user. This includes not only the acquiring phase but during the entire life of the product.
Tools: local manufacturing, utilising available resources (both material, financial and institutional), decreasing numbers of parts (complexity), size reduction, reducing material consumption.

Core functionality

Definition: The design shall consist of only the core functions that fulfil the necessary and important needs of the user, no “nice-to-have” features should be included.
Tools: reduction of complexity, simplification

Optimised performance level

Definition: The performance of the design shall be in equilibrium with the core functionality. The functionality should be able to perform “just enough”, rather than “a little extra”. This means lowering the margins.
Tools: reduction of size, reducing material consumption.

Accessibility

Definition: The design must be easily and practically accessible for the user/customer. This means that the user must be able to easily acquire the product in terms of buying, shipping etc.
Tools: locally available resources, local manufacturing

Robustness

Definition: Robustness means durability over time. The product must withstand wear and tear and as well be easily repairable when needed.
Tools: less complexity, local know-how, resources and manufacturing, aim for modularity

Aesthetics

Definition: The design must entail, by the user, acceptable aesthetics
Tools: local aesthetic preference

Sustainability

Definition: The product, manufacturing and use must be sustainable. This includes both social and environmental sustainability.
Tools: cost-reduction, resource-saving, acceptable working conditions, reducing material consumption.

Usability

Definition: The design should be easy to use and understand for the user.
Tools: Minimal amount of parts.

3. Case study - A Frugal biosafety enclosure

The case study presented in this chapter covers the FD product development process of a biosafety enclosure for laboratories involved in first-line tuberculosis diagnosis that lack this type of desired protective equipment today (in order to make the work environment safer). The project is aimed for and executed in Peru in particular, but would arguably be valid for other contexts as well.

One of the main aims of this case study is to draw conclusions and learn from how the FD approach can be utilised for a designer in practice. This includes determining the FD process and exploring what tools that can be proven useful and which pitfalls to watch out for. The product development process will be described in 4 phases in order to clearly represent what activities, tools and learnings that took place and how. The way of presenting it via phases views the process chronologically. However, a design process is iterative and parts of the work may have happened sequentially, simultaneously and/or iteratively.

The need for a new ventilated biosafety enclosure design

The background for this case study is the fact that many healthcare facilities in high-burden tuberculosis areas face a resource-scarce reality with few or no possibilities to acquire and properly maintain biosafety enclosures to reduce the risk of being infected while performing laboratory work (CDC, 2010). There is a need for innovative approaches to develop affordable biosafety and biosecurity capacities appropriate for areas of the world with limited resources (IFBA, 2010). This is indicated by more affordable, bespoke and non-standard containment systems that have come into use for various reasons in recent years (WHO, 2020). The biosafety cabinet is one example of the type of expensive equipment that, due to inaccessibility to this type of equipment, has been improvised and to some extent designed and produced in-house, for example during the outbreak of the COVID-19 pandemic (Dubey et al, 2020). These innovative ventures into biosafety equipment reinforce the sense of need for such products (Angra, 2011). There has also been at least one example of a more high-end product development project for a robust and economic variant of a BSC performed by the CDC. This product, the ventilated workstation (VWS), is available for purchase from the company Germfree. However, in Peru, the context that is the subject of this case study, there are many laboratories where these products can’t be found, despite practitioners and users expressing a great desire for this type of equipment. This is a clear indication that there is work to be done and a solution to be found.

Project brief

The first contact with the design case came in the form of a brief description of the problem provided by the Lima-based research group Innovation for health and development (IFHAD). From the many years of research and fieldwork that the group had done on the topic of TB, they saw a need for an “appropriate low-tech biosafety cabinet”. Their problem brief was based on observations and covered the following issues;

- Labs are often more like ordinary rooms where lab work is performed without biosafety enclosures.
- If biosafety enclosures are used, it is not always certain that they function properly, giving a false sense of security or causing fear.
- Biosafety enclosures are a good aid when working with, for example, stool or urine samples, and even more important, when working with more dangerous samples eg. TB.
- Infections among lab personnel are common

Observation - a need and desire for a solution

Observations of frugal/home-built/artisanal primary or malfunctioning containment devices shows the need and/or desire for a proper robust biosafety enclosure for laboratory settings, regardless of available resources. Below are some pictures of different home-build/artisanal and malfunctioning solutions that were encountered during the project in Peru, see figure 3.1. Three of them (the ones at the top, and down to the left) are examples of artisanal biosafety enclosures observed in Lima and Iquitos Peru. None of them is equipped with mechanical ventilation. Down to the right, a malfunctioning biosafety cabinet class II can be seen. This cabinet demonstrates the problem with complex equipment that in an affordable manner can’t be maintained or repaired. The cabinet was used in an Acid-Fast Bacilli (AFB) smear laboratory for TB without a front and with a malfunctioning electrical fan. The cabinet was too expensive to repair and served only as a bench, without giving any protection to the laboratory personnel.

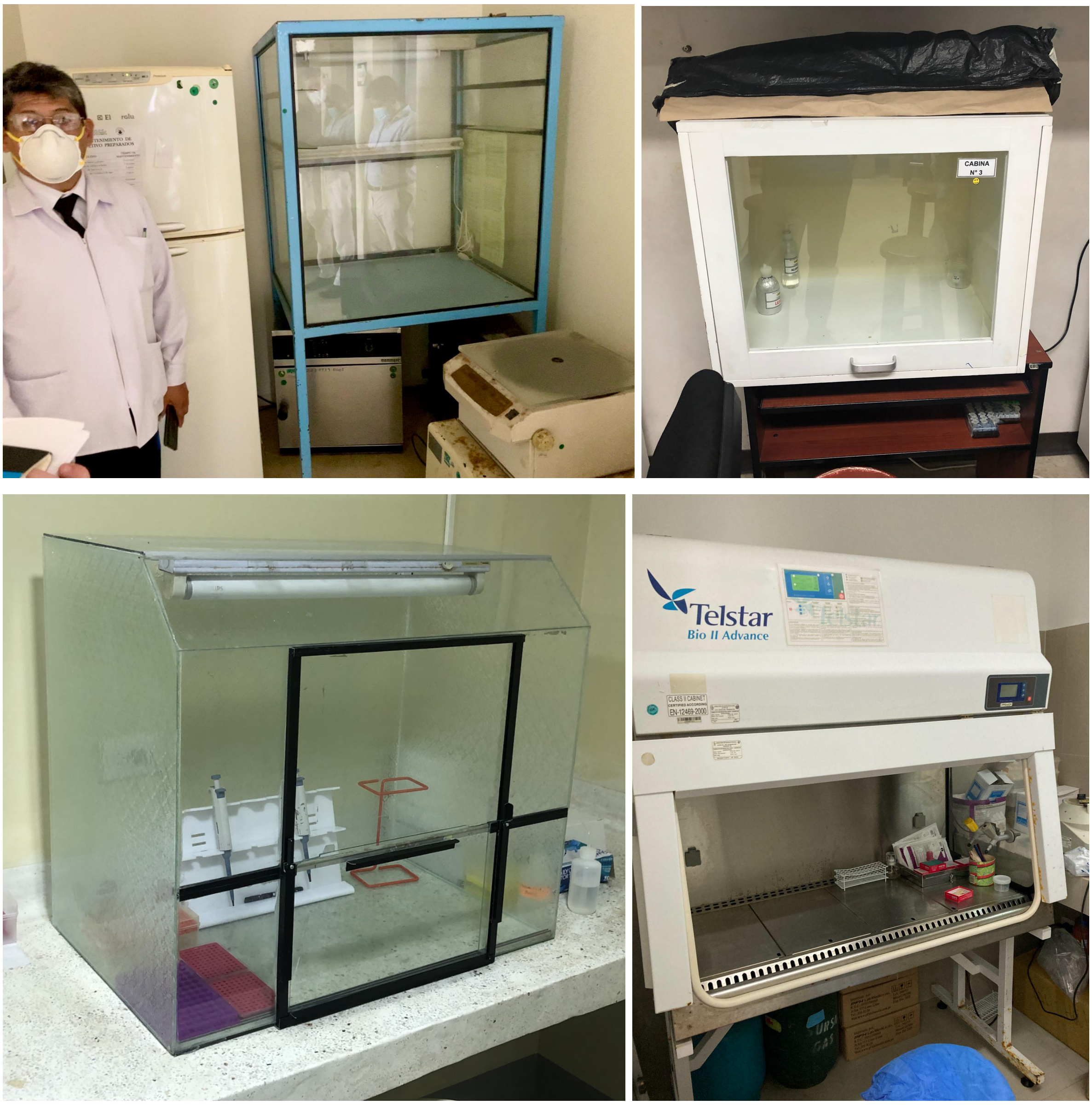


Figure 3.1 In-house designed safety enclosures, designed to protect the sample or the operator. All were encountered in various labs around Lima and Iquitos

Why Frugal Design is a suitable approach

The need for biosafety equipment is apparent, but for some reason (a reason that is to be explored in this case study) the solutions that are offered on the market have proved inaccessible to the users in this particular context. This problem of accessibility could likely be addressed in various ways, but the research into FD has shown that it can be a well-suited approach for addressing issues of accessibility and bringing solutions to less-tended markets. Whether the issue regards affordability, logistics, or any other aspect, we are led to believe that the FD approach is a good tool to face this issue.

The pandemic showed a need for FD biosafety enclosures

Dubey et al. (2020) describe that when the COVID pandemic reached India, many laboratory managers were forced to perform frugal innovation to protect staff. One such innovative measure was the provisional substitution of biosafety cabinets with cardboard boxes fitted with hypochlorite spraying devices. There was no exhaust extraction from the cabinet and the decontamination occurs inside the box after each work session. This demonstrates a recent example of the need for affordable biosafety enclosures for more uses than just for tuberculosis as well as the difficulties and desires that surround this type of equipment making it hard to acquire.

Background

In order to allow a better understanding of the information presented in this case study and the following parts of this thesis, the next few sections will briefly cover important background information. This information includes:

- The situation in Peru and why the context may affect product development work.
- The disease of tuberculosis, why it is a risk and how to decrease that risk.
- Biosafety, the procedures and equipment that allow safe tuberculosis work.
- Conclusions presenting the overall product architecture of a biosafety enclosure.

Peru context

Peru is a country with 33 million (year 2021) inhabitants and a total land area of 1 285 216 km^2 and the BNP per person is 6127 US dollars (year 2020). Thus, Peru's land area is almost three times bigger than Sweden's and with a smaller economy compared to Sweden's BNP per person of 52 274 US dollars (2020). Peru is defined as an upper middle income (The world bank, 2022). However, there are big wealth gaps between groups of people, and the geographical location affects the living standard which differs a lot from area to area. Lima is a well-developed city with a large middle- and upper class but poverty is highly present in the outskirts of the capital and in the rest of the country. The Andes and the highland divide the country from north to south, with rainforest in the east, and a coastal zone with desert to the west (Landguiden, 2022). The infrastructure varies greatly around the country and is affected a lot by the varied and wild nature. Lima is a city overcrowded with vehicles, often causing traffic jams. In the large jungle city of Iquitos with more than 483 000 inhabitants (World population review, 2022), the population has no access to the rest of the country's road network, instead, transportation must be done via air or river. The Andes, crossing from north to south cause a natural barrier making transportation and logistics a challenge. The capital city, Lima, which is a coastal city with a great connection to the rest of the world in relation to imports and exports, is a big city with a population of more than ten million inhabitants. This means that most materials and components are available or accessible through freight. However, society suffers from corruption and bureaucracy.

A noteworthy fact is that the economy of Peru is highly informal. This barrier to economic development has been worsened by the pandemic.

To share a brief view of how it is to work as a FD designer in the context of Lima, a few examples illuminates how a designer's work may be different in relation to how it might be in Sweden.

Lima and its informal sector offer many small-scale manufacturing facilities and vendors of technical equipment or materials. This offering of manufacturing technology, equipment and resources is extremely accessible along with their know-how and experience. This treasure is found easily on the street, offering what to many may seem like unprecedented possibilities for prototyping and easy access to manufacturers.

Figure 3.2 Small stall selling fans and blowers of varying sizes is just one of many such stalls within the same block in central Lima.

Another example that illustrates how a designer's work can be affected by the context, and the importance of working at the site in a less organised and more unpredictable context like Peru are the non-standardised usage of power outlets that are used in the country. Figure 3.3 illustrates four different outlets that are all usual to encounter. It is not uncommon to find different varieties used in the same building, or even in the same room. This exemplifies a type of understanding of a context that is hard to gain without being at site.

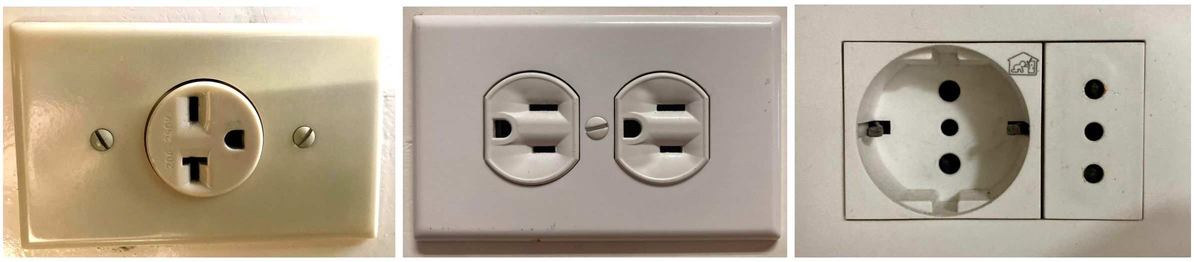


Figure 3.3 Three different types of 230 V power outlets that can be found in Peru.

To conclude, the Peruvian context, while being a handy term to refer to, is actually misleading as the context is so different in various parts of the country and even within the city of Lima, more so than what you might find in for example Sweden. What is clear is that a designer must take care to design for a certain context based on the knowledge extracted from that specific context. Any assumptions about other contexts, even neighbouring ones, are likely to be wrong.

Tuberculosis

Tuberculosis (TB) is an infectious disease that causes the most deaths every year (except from recently due to COVID-19) and even more than HIV/AIDS. In 2021, 1.6 million people died and 10.6 million people fell ill from TB (WHO, 2022). The disease is an infection caused by the bacteria Mycobacterium tuberculosis and does primarily affect the lungs (CDC, n.d). The disease is mainly prevalent in Low- and middle-income countries (see figure 3.4) which account for 98% of reported TB cases. No effective vaccines are available (WHO, 2012). However, the disease is curable and preventable (WHO, 2022) with free testing and treatment thanks to the StopTB initiative but still the problem persists to a high degree. In the work of preventing TB, it is important to detect tuberculosis at an early stage (Churchyard et al, 2017).

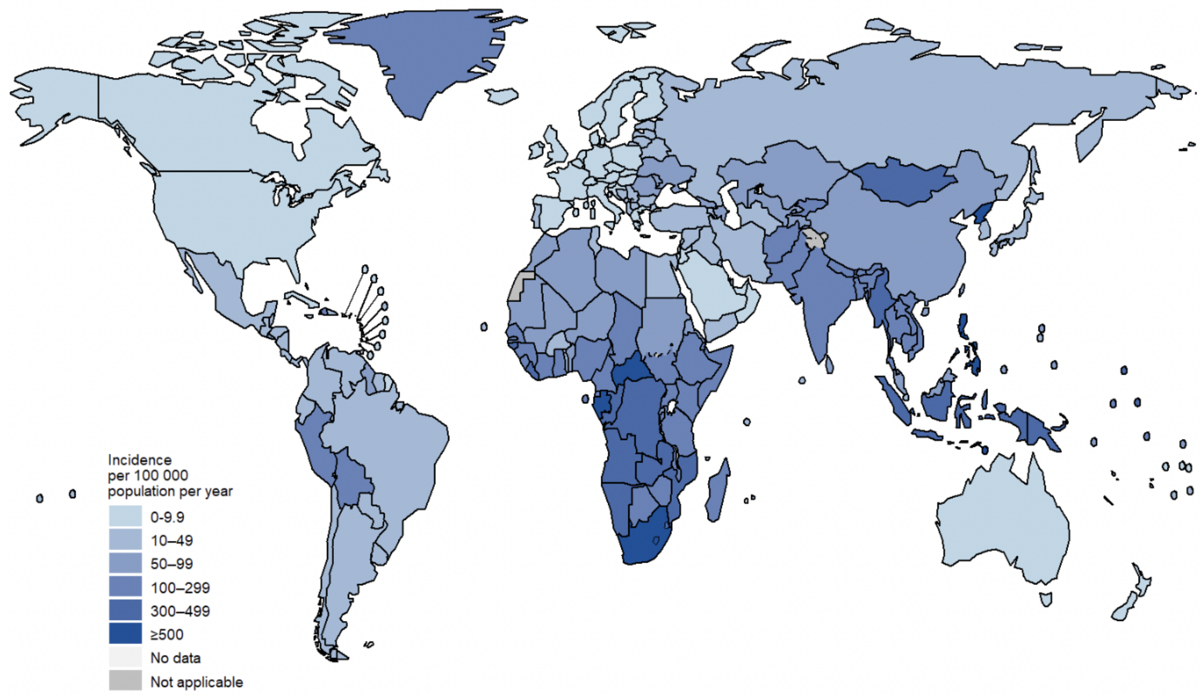


Figure 3.4 World map showing estimated TB incidence in the world year 2020 (WHO, 2021).

Peru is one of the countries in South America with the highest number of TB cases (see figure 3.4). Each year around 27,000 new cases of active disease and 17,000 AFB smear-positive cases are reported. Multidrug-resistant (MDR) TB and extensive-resistant (XDR) TB complicate the prevention and curing activities. In the last two years, Peru has reported more than 1,500 cases of MDR- and 100 cases of XDR-TB (Ministerio de salud Perú, 2022).

Tuberculosis is transmitted through the air, where the bacteria is carried through aerosols, called droplet nuclei in the size of 1-5 micrometres in diameter, and then inhaled (TB does not transmit by surface contact). The infectious aerosols can be generated when a person infected with pulmonary or laryngeal TB disease sneezes, coughs, sings, and shouts or when TB samples are being handled. Factors that enhance the probability of TB being transmitted are a high concentration of infectious droplet nuclei in the air, small rooms with droplets, inadequate ventilation of the room air, causing insufficient dilution or insufficient removal of infectious droplet nuclei. It can also be due to recirculation of air containing infectious nuclei, improper handling procedures of TB specimens that generate infections TB droplet nuclei and positive air pressure in areas like patient rooms and biosafety enclosures causing spread of aerosols to areas outside the safety barrier. TB aerosols can be suspended in the air for several hours and risk that other persons get infected when the droplet nuclei are inhaled (CDC, n.d).

Diagnosing TB using Acid-fast bacilli smear (AFB smear)

In many low-resource settings, the first stage of diagnosing TB is performed in small local laboratories that utilise the AFB smear method (VWS Manual - Preface, 2011). To perform an

AFB smear, tuberculosis sputum needs to be processed onto glass slides, a work that in many settings throughout the developing world is done on an open bench (VWS Manual - Preface, 2011).

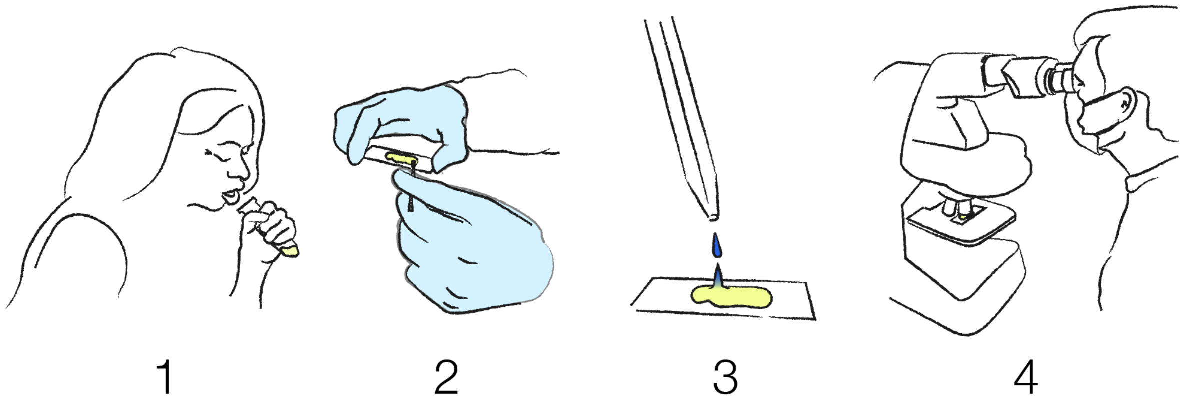
The risk of being infected with TB during work while performing an AFB smear to diagnose tuberculosis is debated. WHO (2012) argues that the process of AFB smear preparation is relatively risk-free and that a biosafety cabinet is not mandatory and that the work safely can be done over an open bench if performed with good microbiological techniques as long as adequate ventilation can be provided. However, some healthcare facilities in resource-constrained settings lack proper mechanical ventilation and natural ventilation through open windows can be limited due to climate (VWS Manual - Preface, 2011). Banada et al. (2010) conclude that any type of sputum manipulation including AFB smear preparation has the potential to generate infectious aerosols. At the TB laboratory in Sahlgrenska, Gothenburg, the guidelines are that the laboratory personnel never open samples outside a biosafety enclosure due to the risks of creating aerosols and the consequences of being infected. The fact that many laboratory guidelines suggest that sputum processing and AFB smear preparation should be performed in a biosafety cabinet and that industrialised countries usually use a biosafety cabinet for this work (Banada et al, 2010), points towards the fact that settings without a biosafety enclosure device for AFB smear preparation are due to what is possible to acquire in relation to available resources rather than what is desired in terms of a proper safety barrier between infectious agents and laboratory personnel.

WHO (2012) argues that AFB smear safely can be performed on an open bench in an adequately ventilated area if appropriate microbiological techniques are used but also states that there is still an increased risk between 0,2 - 10.0 to catch TB for laboratory staff compared to non-laboratory workers (WHO, 2012). WHO states that opening a sputum container and preparing an AFB smear may produce aerosols but that there is little evidence for performing an AFB smear is associated with a measurable risk of acquiring TB infection. They are however highlighting that poor ventilation or illumination, carelessly manipulated specimens, leaking containers and improperly used bench spaces increase the risk of acquiring TB infection. Thus, WHO does not see a biosafety cabinet as an absolute requirement when working with AFB smears as long as the laboratory is adequately ventilated (a directional airflow with 6-12 air changes per hour), which isn’t the case in many of the laboratories visited during this project. However, if adequate ventilation can't be ensured, a ventilated workstation is recommended as a way to create sufficient ventilation for a smaller work area, where the procedures that generate aerosols are performed (WHO, 2012).

AFB smear procedure:

The Acid-fast Bacilli procedure consists of several stages (see figure 3.5) starting with a sputum sample from the patient. The patient coughs up sputum and spits it into a sample container at home or outside the laboratory. The laboratory personnel then opens the sample container in the laboratory and smears out the sputum onto a glass slide. This glass slide is then dried before being processed with certain staining techniques and then finally examined with a microscope to visually count the number of bacteria (APHL, n.d.). The process of opening the sputum container and the smearing process are the activities that risk generating aerosols (WHO, 2012.)

The materials that need to be used for the processes with risk of generating aerosols and thereby are stored inside a biosafety enclosure during work are: glass slides, sputum containers, applicators for sputum (wooden or plastic sticks), trash can, decontamination liquid and maybe a rack for drying the slides.



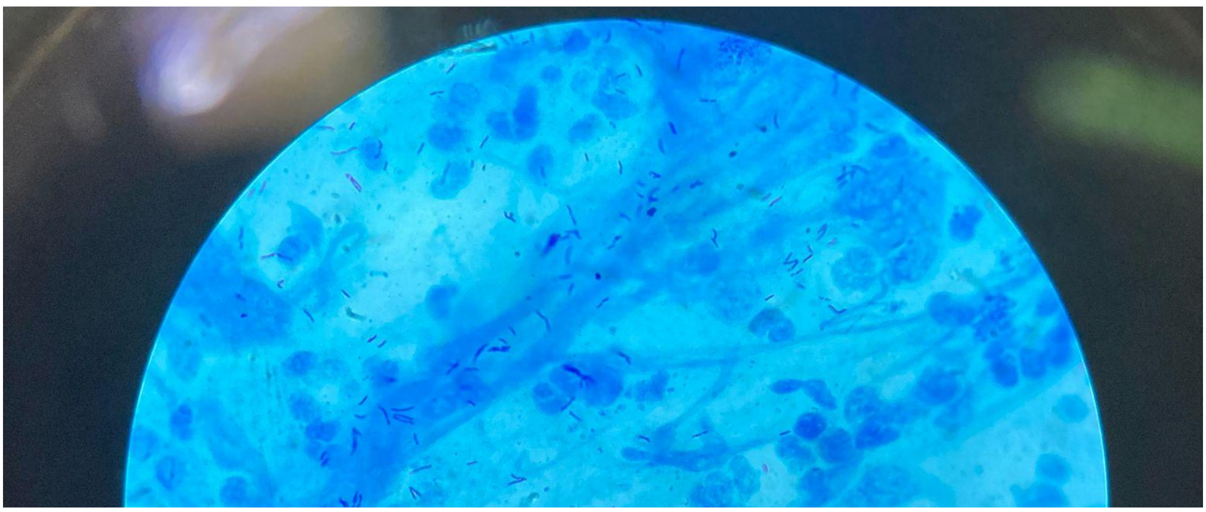


Figure 3.5 Top: Acid-fast Bacilli smear procedure; 1. collecting sputum, 2. smearing on a glass slide, 3. (fixing) Staining 4. examination with a microscope. Bottom: Examination via microscopy (stage 4) at the police laboratory where the FVWS was installed. The darker lines are TB bacterias in the sputum.

Tuberculosis healthcare in Peru

When a person in Peru experiences symptoms of being infected by Tuberculosis, the patient passes several steps. Firstly, when the patient experiences certain symptoms and seeks medical care, they are asked to leave a sputum sample at the local health care centre. This sample is then examined at the health centres with the Acid-fast bacilli smear procedure as described in the previous section. If the sputum sample proves to be positive it is sent forward to a more advanced reference lab with equipment that allows for a more advanced type diagnosis to determine if the infection is sensible for regular medication or if the type of TB is MDR or XDR type which requires a much more complicated treatment. If the patient is diagnosed with a non resistant variant, the patient usually needs to return to the health care centres every day during several months to take the medication, monitored by healthcare personnel to ensure that the medication is taken. If a resistant variant is detected, a much more complicated and protracted treatment is needed including daily injections.

It is noteworthy that the AFB smears are used for each and every one of the TB samples collected. The small health centres that perform the AFB smear as the first step of the diagnosing process are the location where biosafety enclosures and sometimes even controlled ventilation do not exist. In these laboratories, the personnel stand a higher risk of getting infected with tuberculosis every time they go to work.

Figure 3.6 Centro de salud Villa los Reyes, a small health care centre with a TB laboratory without biosafety enclosure in Callao, Lima.

TB laboratories for AFB smear

A laboratory at the smaller local health care centres for the first-in-line diagnosis is often only a room with designated space for performing laboratory work. In many cases, they lack any kind of biosafety enclosure. The AFB smear procedures are performed on open beaches. The ventilation can consist of natural ventilation (only open windows), or mechanical ventilation, i.e electrical fans installed to increase the air exchanges per hour. The laboratory technicians are using personal protective equipment such as face masks, gloves and laboratory clothing.

Figure 3.7 Open bench laboratory at Villa los Reyes, Callao, Lima. Processing area of sputum.

Figure 3.8 Open bench laboratory at Centro de salud Bellavista, Callao, Lima.

Figure 3.9 Open bench laboratory at Centro de salud Marques, Callao, Lima.

Figure 3.10 TB laboratory at National Police laboratory with a malfunctioning (Broken fan, window fallen off) BSC class II. Cost for reparation is over 10 000 USD, including technicians from US etc, according to information from laboratory technicians at the police laboratory.

Biosafety

Biosafety is by WHO, defined as “Containment principles, technologies and practices that are implemented to prevent unintentional exposure to biological agents or their inadvertent release” (WHO, 2020c). This can include different techniques for decontamination, such as the usage of chemical disinfection to inactivate biological agents, the usage of proper personal protective equipment to reduce the likelihood of exposure to biological agents and the usage of proper laboratory equipment such as a biosafety enclosure, eg. a biosafety cabinet. A biological agent can be TB or any other biological agent. It is important to note that good microbiological practices and procedures are an important and necessary aspect to obtain proper biosafety. Human errors, suboptimal laboratory techniques and inaccurate use of equipment have been the roots of most laboratory-associated infections and injuries (WHO, 2020c).

Levels of biosafety in laboratories

Laboratory biosafety is important to decrease the risk of humans being exposed to biological agents that can cause harm, especially for those who work in laboratories. The harm caused can vary from a personal infection to a more severe outbreak. Biosafety enclosures are used in laboratories as a safety barrier between the lab personnel and the biological agent to prevent exposure. Different risks associated with biological agents require different requirements in terms of risk control measures. WHO (2020a) advocates using a risk assessment procedure to determine three levels of risk control measures to handle laboratory biosafety; core requirements, heightened control measures or maximum containment measures (previously BSL4). The American centre for disease control and prevention uses a definition of four biosafety levels, BSL1-4, to define what safety equipment and facility design are required to obtain proper biosafety (CDC, 2021). In laboratories working with TB, the risk level depends on what type of work is performed and biosafety enclosures are often used, generating different safety features for the operator depending on the type of enclosure. The BSC class II, type A2 is the type of BSC, generally recommended for a tuberculosis laboratory, (WHO, 2012). However, WHO advocates a biosafety level in accordance with the risks due to work tasks, and for a laboratory that only works with TB through the AFB smear procedure the risks are seen as low (WHO, 2012), defined as an environment with a low risk of generating infectious aerosols with a low concentration of infectious agents. Therefore are the requirements less demanding in terms of required advanced safety equipment and biosafety enclosures, such as a ventilated workstation or a BSC class I.

Biosafety enclosures

Biosafety enclosures, so-called biosafety cabinets (BSC), isolators, local exhaust ventilators and ventilated workstations (VWS), are biosafety equipment that can be used in laboratories to protect the operator and laboratory environment from infectious aerosols, and can be used as primary containment devices in laboratories (WHO, 2020b). Infectious aerosols can be generated without the laboratory operator's knowledge, due to their small size. This can result in the inhalation of infectious agents (WHO, 2012).

Biosafety enclosures have been shown to be effective in terms of reducing infections caused by laboratory work. A laboratory biosafety enclosure protects the operator by segregating the aerosol-generating work from the rest of the laboratory area through a directional airflow, this hinders infectious agents from being spread outside of the enclosure (WHO, 2020b).

There are different types of containment solutions for the laboratory environment. The BSCs are the most common ones. The main difference between a VWS and a low-level BSC is a HEPA filter. A BSC is filtering exhaust air through the HEPA filter to provide protection for the environment (WHO, 2012) whereas the VWS don’t decontaminate the outlet air. A HEPA filter is a filter that is used to remove particles from the air flowing through the filter. For a HEPA filter to be functional, it is important that it is maintained and replaced when necessary.

Biosafety cabinets

Within the field of biosafety cabinets, there are different categories, each with different purposes, with different functionality in terms of what it protects. The categories are Class I, Class II and Class III (Labconco, 2020).

The class I BSC is an open-fronted cabinet that provides an inward airflow through the front opening in the box. The air then passes through a HEPA filter before being exhausted. BSC class I provides protection for users and the environment but not for the product in the box (WHO, 2020b).

Class II is similar to Class I BSC, with air entering the containment from the open-fronted cabinet. The airflow is then pulled under the work surface, and HEPA-filtered air is circulated towards the work area and then pulled under the work surface. BSC class II protects the user, the environment and the product in the box. BSC class II exists in five types of subclasses (WHO, 2020b).

The class III BSC is a closed box with lower pressure on the inside. The box is provided with HEPA-filtered air. The air passes another HEPA filter for extraction. The work is performed with integrated gloves that separate the user from the work area (WHO, 2020b).

Ventilated workstation

The VWS is a partially open-fronted containment box, similar to BSC class I, providing protection to the user through airflow. They are usually not equipped with a HEPA filter for the exhaust air (WHO, 2020b).

Containment isolators

Isolators are similar to class III BSCs in the sense that operators are separated completely from the work area, they do however differ in construction and materials, leading to different uses as they can for example be more portable than BSCs (WHO, 2020b).

Flexible film isolators

Flexible film isolators often consist of a frame suspending a flexible transparent film that makes up the barrier between the inside and the outside atmosphere. These isolators work with a negative internal pressure achieved through extraction. Both intake and extraction air are filtered, allowing the exhaust to be discharged within the laboratory. The flexible characteristic allows the isolator to work at a lesser negative pressure than class III BSCs as the pressure is not affected as much when operators insert or move their hands. However flexible film isolators are more susceptible to damage than class III BSCs.

Flexible film isolators are flexible and can consist of small glove box-type designs, and much larger enclosures that contain eg. laboratory equipment or animal cages. Flexible film isolators can come into use in many different and difficult conditions (WHO, 2020b).

Unventilated isolators

If the risk of aerosols is very low, simple unventilated film isolators in the shape of pods or tents may offer good physical protection both from the agent and disinfectants used, it is however worth emphasising that safe working practices are very important (WHO, 2020b).

Workstation

The fact that laboratories in resource-constrained contexts with a BSC or other types of primary containment devices often lack validation and maintenance (Ventilated workstation manual for AFB smear microscopy, 2011), the risk of working in a workstation - i.e a ventilated primary containment device with malfunctioning ventilation is present and can pose an increased risk for the operators.

Open bench

The fact that laboratory work in many healthcare facilities in resource-scarce environments is performed on an open bench without a primary containment device (fig 3.7 - 3.10) should be highlighted due to its high prevalence, even though an open bench in no way can be argued to be a primary containment device.

Benchmark biosafety enclosures

To get an overview of some examples of more affordable and simple solutions for biosafety cabinets and ventilated workstations, compared to the more complex and expensive BSC Class II, a few devices relevant to this project are briefly described below. First, a BSC Class II is presented to get an understanding of the product that generally is advocated for TB laboratories that are performing procedures related to a higher risk than the AFB smear procedure. Then, two products with a performance level enough for AFB smear will be presented to show the differences in price and complexity.

BSC Class II Nuaire

A BSC class II is, as mentioned, used for more demanding laboratory work where there is a need for clean air inside the cabinet to protect the work that's performed as well as the operator. This results in a more complex product. The cabinet that can be seen in figure 3.11 is a cabinet with space for two operators. The cabinets are expensive and require more expertise for maintenance. These types of BSC's Generally cost above ten thousand US dollars and up to several tens of thousand US dollars.

Figure 3.11 BSC class II from Nuaire. In operation (left), front view (right).

BIOBase Class II, 1 person

A BIOBase class II for one person can be found in Lima, it is sold by vendors on the street called Avenida de Emancipación in Lima, this street is full of companies specialised in medical equipment. The cost is around 14300 soles (ca 3730 US dollars, 2 Dec 2022). The equipment is manufactured and imported from China.

Figure: 3.12 Biobase BSC class 2 at the Mi Perú health centre, Lima

Flow Sciences 2' Ventilated Enclosure, With Hood Filter Blower

The small ventilated enclosure for one person from flow science is a small acrylic enclosure equipped with a filter and fan box. The enclosure is almost entirely constructed of acrylic and has the properties of a BSC class 1. The cost is US$3,195 plus packing and shipping from the United States.

Ventilated Workstation Germfree

The ventilated workstation developed as a joint work by several actors, including CDC, and manufactured by Germfree is a open-source design product designed for AFB smear in resource-constrained contexts.This product was developed specifically for the peripheral level of healthcare where HEPA filter cabinets and other types of BSC are not feasible or suitable. The ventilated workstation is designed to be more affordable and require less maintenance than conventional BSCs. The plans and manufacturing instructions for the ventilated workstation have been made publicly available to allow qualified manufacturers to produce it. The design requires the use of higher-grade materials such as stainless steel, as well as an exhaust duct and extractor fan. However, it is designed to include as few components as possible and to be robust. The design has been validated to function properly, entailing a safe work environment for AFB smear preparation and sample manipulations that inactivate sputum specimens like done for GeneXpert MTB/RIF Assay from Cepheid (CDC, 2010). Produced by Germfree in the USA, it sells for US$4,110, excluding freight costs from the USA.

Figure 3.13 The Ventilated workstation for AFB-smear preparation (enhanced from ventilated workstation manual, CDC, 2010)

Air decontamination methods

To prevent TB from transmitting to humans, infectious droplets nuclei must be prevented from being inhaled which can be done through both reducing the creation of aerosols, deactivation of the bacteria or through removing the bacteria from the air, i.e separation of aerosols and humans. There are in general only two accepted methods for decontaminated air from TB aerosols. Filters and ultraviolet light (UV-C) are both methods proven to be efficient when it comes to decontaminating air containing infectious aerosols of TB (Lee, 2016).

HEPA filter

A HEPA filter (high-efficiency particulate absorbing filter) is a filter that is designed to remove 99,97% of the particles down to a very small size, usually 0,3 micrometre (Lee, 2016). The contaminated air is passed through the filter and the infectious particles are gathered in the filter medium, resulting in the outlet air being clean and safe. The HEPA filter requires that the contaminated air is controlled via e.g. a biosafety enclosure and a duct to control that the air flows through the filter.

UV-C radiation

UV germicidal radiation (UV-C) is a light with a wavelength of 254 nm. UV-C radiation can be used to kill or inactivate airborne microorganisms including tuberculosis aerosols. The dose required to inactivate TB is estimated to be between 576 μWs/cm^2 and 1080 μWs/cm^2. Within healthcare, three types of installation of UV-C light to inactivate microorganisms, including TB are used. UV-C lamps can be installed in ducts to sterilise the air flowing, in the room air recirculation unit and lastly as an upper-room irradiation unit emitting radiation to the top of the room air, constantly sterilising the air that naturally circulates in the room. Exposure to UV-C breaks down the cell of the infectious agent and kills it or eliminates its possibility to replicate. However, exposure to UV-C radiation can also be harmful to humans, so caution should be taken when working and installing UV-C to avoid overexposure (CDC, 2009).

Conclusions tuberculosis & biosafety

We conclude that the need for a biosafety enclosure with the functionality of a ventilated workstation or a BSC class I, depending on the context of each individual lab, exists in Peru. An enclosure for those laboratories that lack biosafety cabinets should meet the needs and requirements for the AFB smear procedure since it is those laboratories that lack the desired equipment.

Many solutions exist today but they are all relatively expensive and or require engagement with companies outside Peru. This barrier to acquisition due to obtuse bureaucracy and even corruption shows the importance of designing a solution tailored for Lima and Peru. Not because solutions with an adopted functionality do not exist on the market, but rather due to them not being successfully taken in use in more resource-constrained settings like for the smaller healthcare centres in Peru.

Clarifying the architecture of a biosafety enclosure system

We conclude the general product architecture of a biosafety enclosure as a device that can be more or less complex, but to demystify the product in regards to functionality it is a system/product that uses airflow to protect the operator. It has a function that we can break down into a number of parts, visualised in figure 3.14. The parts can be:

- A workspace separating infectious aerosols from the surrounding work environment.
- A device (most commonly a fan) that creates an airflow.
- A safe outlet of the contaminated air to protect the people that risk coming in contact with the exhaust air. Could be via a sterilisation device that makes the extracted air safe once again, or by a duct transporting the air to a safer outlet spot. These two can also be combined.

The design may also contain any number of smaller components that make the product suitable for its specific purpose, eg. a lamp to illuminate the work surface or a power outlet for use of equipment within the workstation.

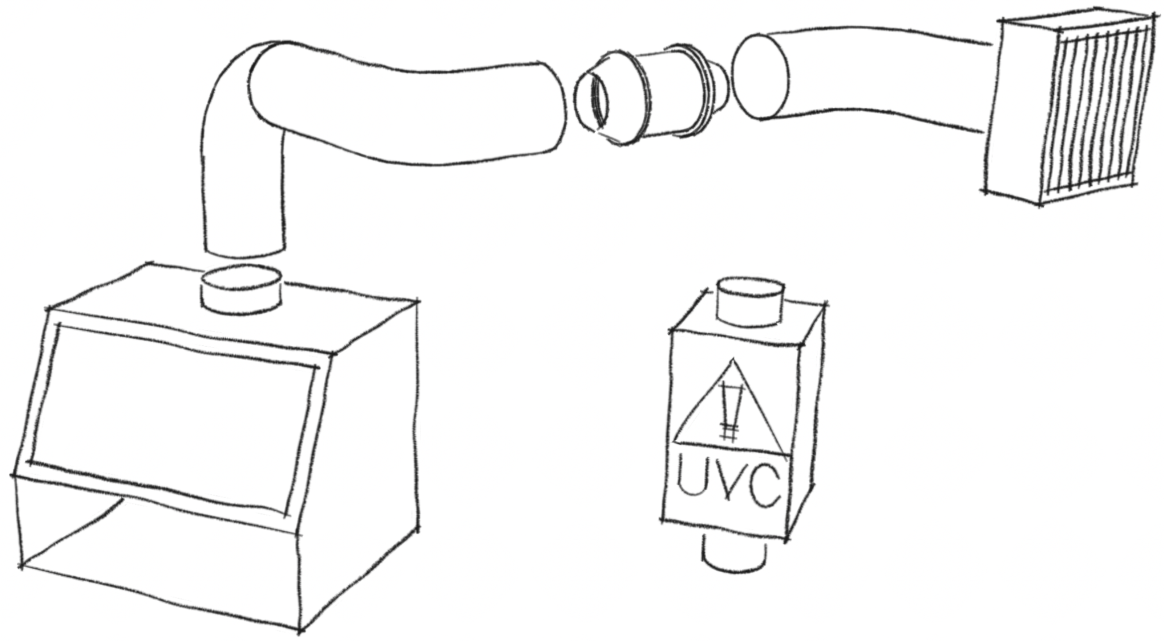


Figure 3.14 Some of the components that can make up a biosafety enclosure system, the enclosure itself (left), the ductwork, an electric fan (middle), a microbiological filter (right), and a germicidal UVC-lamp unit (bottom).

The Frugal Ventilated Workstation (FVWS)

With the relevant background information now presented, a description will follow that elaborates on the final design result in a technical fashion. This is to clarify what is part of the design so that this is better understood during the following sections that will describe why the design ended up the way it did, what design decisions that were taken and how this all relates to FD. This section will describe the design in detail regarding dimensions, materials, manufacturing, technical performance etc.

Figure 3.15 The Frugal ventilated workstation; a frugally designed ventilated workstation developed specifically for front-line AFB smear tuberculosis diagnosis.

Specifications

Enclosure dimensions (height/width/depth)	60/75/53 cm
Work surface dimensions (width/depth)	70/50 cm
Enclosure weight	11,95 kg
Package dimensions (height/width/depth)	10/80/60 cm
Intended flow rate and velocity	260 m^3/h & 0,45 m/s
Duct outlet	150 mm
Approximate price of system during case study	1500 PEN (slightly less than 400 dollars)

The enclosure

The Frugal ventilated workstation is an acrylic biosafety enclosure consisting of five permanent panels that make up the base, sides and top of the enclosure. These panels are the main contributors to the structural integrity of the product. In addition, there is a window assembly which is removable using small toggles. The window assembly is also important for the structural integrity of the enclosure but removable for cleaning. Lastly, the internal baffle, the damper assembly, and the exhaust are three vital parts that contribute to the enclosure's functionality, facilitating a controlled and protective airflow through the enclosure. The integrated damper in particular allows the enclosure to be used together with a wide range of fans that may be found in different contexts, without requiring additional components to control the airflow, or tampering with electronics to throttle fans.

As the product architecture consists mainly of panels, it allows the enclosure to be transported by one person as a flat package to be assembled in the lab. The base and backside of the enclosure are produced in white opaque acrylic so as to allow the operator to work with a non-distracting work surface and backdrop, regardless of the quality of the surface that the enclosure is placed in front or on top of. The remaining panels are made from clear acrylic in order to allow as much light as possible to enter the enclosure from the outside, diminishing the need for an integrated work light in addition to the illumination that already exists in the laboratories. The panels are made in varying thicknesses depending on their function and position. Strategically placed folds are used to increase the rigidity of the thinner panels such as the window assembly and the internal baffle.

The thickness of the base and back panels are 4mm, the top panel is 5mm and the sides are 6mm. The baffle and window are both 3mm and utilise a fold to increase their rigidity.

These nine parts/assemblies (figure 3.16) are what constitute the design. In order to make it into a functional biosafety enclosure, a blower/fan and a duct need to be attached in order to create the protective airflow and to send the contaminated air off to a safe space. These components are not included in the design as the requirements on these will differ for each implementation in each lab. No universal solution has been found for these parts and many possible alternatives exist.

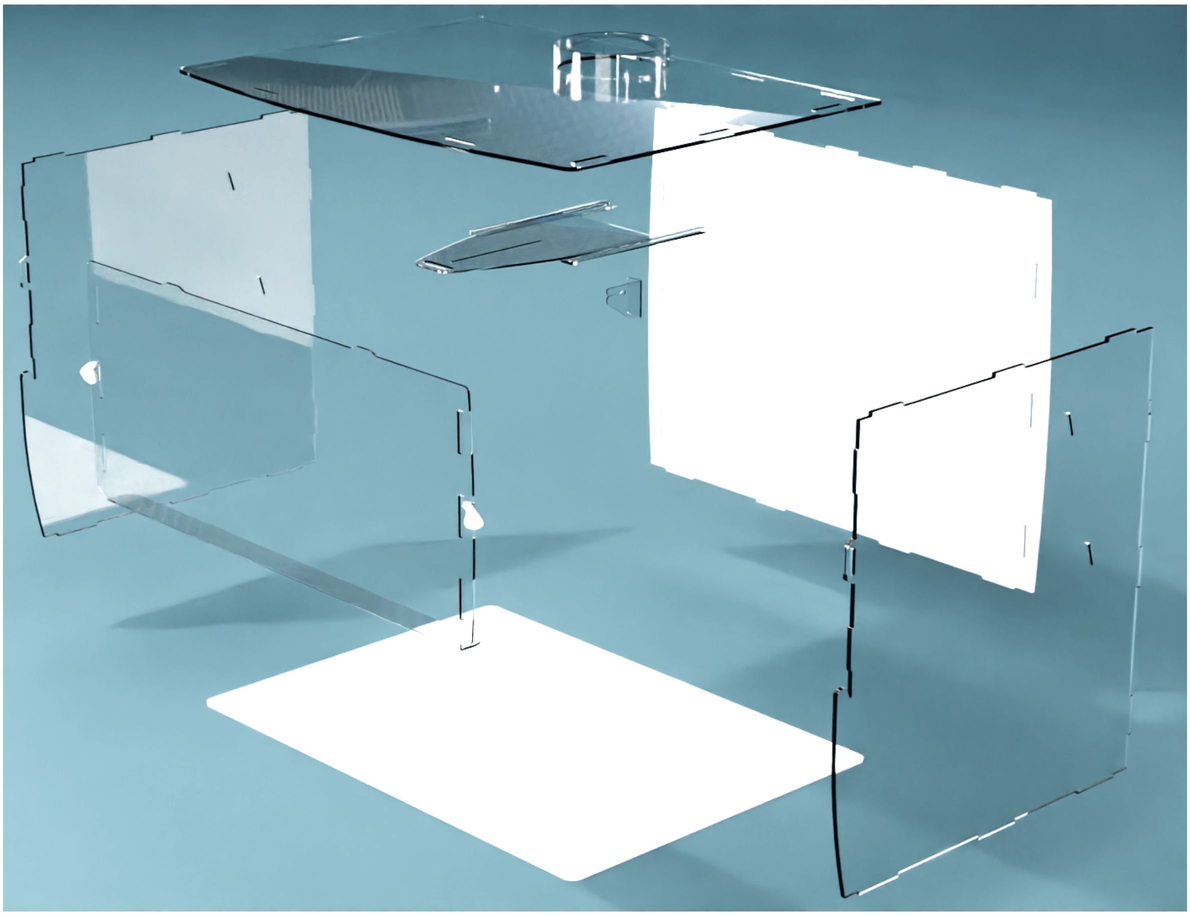


Figure 3.16 The parts and assemblies that make up the FVWS

Airflow

The performance of the airflow was verified using a grid of measuring points spanning the enclosure's entry, in accordance with the WHO Laboratory biosafety manual (WHO, 2020b). Further observations of turbulence around the edges of the enclosure entry were done using smoke. The result of a total of 74 measurements across these 24 points can be seen in figure 3.17 below. All averages as well as all of the underlying individual measurements were within the +-20% range that is acceptable, represented by the dotted lines.

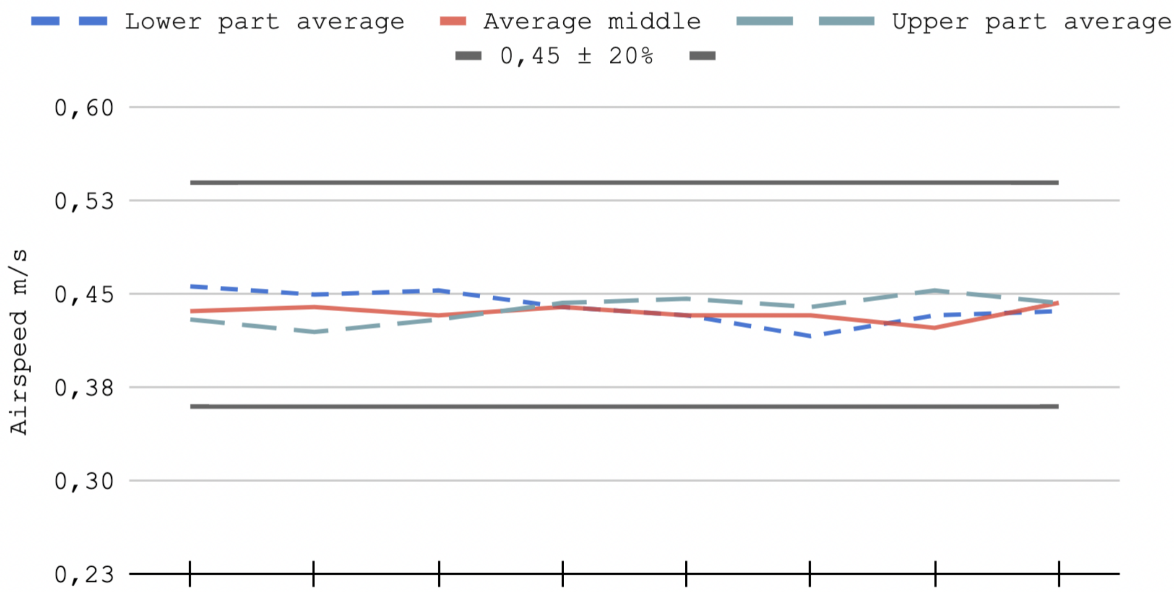


Figure 3.17 The measured airflow characteristics of the FVWS, The figure represents the average values of three series for a total of 74 measurements.

To get more detailed information about how the testing was performed to achieve and verify the airflow as shown above see appendix D “FVWS Manual”

Optional disinfection modules

The FVWS is designed for safe AFB smear processing by extracting contaminated air and sending it off to a safe outlet. Though this is likely sufficient for most if not all settings in order to meet the WHO biosafety guidelines for this type of work, other factors such as regulations, wishes and even stigmas may come into play and make extra safety measures necessary in order to achieve implementation. These disinfection modules are in a similarity to the FVWS adapted to what is available in the context and known to be efficient in removing or deactivating tuberculosis. The modules that can be added are filter and/or UV-C light modules.

All different types of sterilisation functions add complexity to a design and therefore also risks of brake downs. If a sterilisation unit is to be added to the biosafety system, caution needs to be taken when choosing what type of disinfection module and in what context. It is important to make sure that adding a disinfection module does not lead to increased risk-taking and an irresponsible placement of outlet air etc. Relying on disinfection modules for creating a safe outlet of air brings requirements of rigorous control measures of the disinfection modules. If the system is implemented in a context where there is a risk of these control actions and related maintenance and reparations being overlooked, it is beneficial to not add modules that will risk the whole function of the system if the disinfection module fails. Such an example would be adding a filter. A filter is a part that after time will decrease in functionality of letting air flow through the filter. If there is no possibility that the filter will be changed over time, the system should be installed in a way that makes it possible to remove the filter, or preferably totally avoid installing a filter from the beginning and still maintain a safe outlet of air. Thus, a robust system will be dependent on what possibilities of maintenance there are and the impact a lack of maintenance will have on a system's ability to maintain a safe work environment for operators as well as the risk for people surrounding the system. A robust system in a resource-constrained environment is likely less complex.

UV-C sterilisation unit

UV-C light tubes can be placed inside the duct or preferably inside an additional box that allows maintenance of the light tubes. The dimensioning of the light needs to be done separately for each laboratory to ensure that the bacteria will be exposed to a sufficient dose of UV-C radiation. This can be calculated with the intensity of the UV-C light and the exposure time. The advantage of UV-C light is that if they break down, and the system is installed in a manner that would not put people at risk due to the placement of the outlet air, the main functionality of the biosafety enclosure will still be fulfilled. Since UV-C light is harmful to humans, it is important that it is installed in a manner that safely shields humans from the radiation. It is also recommended to install it in a manner that ensures that the UV radiation starts when the FVWS starts. If adding a UV-C unit, it is preferably added at the suction side of the fan since it will generate more safety if a leak occurs.

An example of how a UV-C unit can be implemented in the FVWS system is covered in appendix A “Prototype installation”

Filter unit

A filter can be placed somewhere between the outlet from the FVWS and the final outlet of the air to the outside environment. A filter that has the ability to collect particles within the particle size of the TB bacteria (1-5 microns) must be chosen. When adding a filter into the system, regular control measures must be performed, to monitor the condition of the filter and replace it when it is not letting a sufficient amount of air pass the filter, leading to a drop of airflow and decreased safety functionality of the FVWS, which puts the operator in risk. In a context where this can't be ensured, the filter should either not be added or, it should be added in a way that allows it to be removed without replacement without reducing the functionality of the enclosure. Therefore, should the filter holder be designed so it allows the removal of the filter and/or place it outside of the laboratory, close to the safe outlet spot. Some cabin filters for cars have sufficient quality to collect the tuberculosis particles and could be found for a much lower price than HEPA filters.

An example of how a filter unit can be implemented in the FVWS system is covered in appendix A “Prototype installation”

Setting up the FVWS system

The FVWS is transported as a flat pack. When it is to be assembled, the base panel is placed in the intended working location and the sides are placed on top using the tenons to guide their placement. The panels are designed so that they can only be assembled the correct way. After the sides are placed/inserted into the base, the baffle can be inserted inside the enclosure.

Finally, the top is placed over the three upright sides locking it all together. The window assembly is stood on the slots in each of the side panels of the enclosure and then tilted in to join with the tenons of these side panels. The top panel is lifted in the middle to make it flex enough for the tenons of the window assembly to seat properly in the corresponding slots in the top panel. This secures the window to the enclosure and the toggles can now be used to lock the window in place. The construction of the window assembly with tenons and slots that lock into the enclosure allows the construction to be made thinner and lighter while maintaining rigidity. The construction is designed so that the FVWS will securely maintain its structure without the use of adhesives or fasteners. However, to increase the rigidity of the product it should be fixed together with double sided tape or silicone. The tape/silicon essentially transforms the five main panels into one large piece which greatly benefits the rigidity of the enclosure.

Included in the construction is a yarn holder that is glued or taped with double-sided tape onto the back of the FVWS, 1 dm under the air outlet through the top panel. On the holder is a yarn added that indicates proper functionality through the air flow lifting the yarn, thereby indicating that the fan is operating and generating an airflow.

The fan and ductwork

When the FVWS is assembled in its intended location, the ductwork and fan can be put in place. The ductwork can be constructed with many different materials. Smoother surfaces and bends in the ductwork might allow the choice of a more frugal and less powerful fan. The configuration of the ductwork and blower must allow the system to produce an airspeed in the entry of the enclosure of no less than 0,45 m/s. Being able to exceed this airspeed is ok as this can be adjusted with the integrated damper, however, it should, in this case, be considered if a more frugal configuration with less performance is possible.

Choosing the fan is depending on what fan that can be acquired and what airflow it can generate in the system. The required properties of the blower will vary depending on the used duct size, length of the ductwork and type of fan. There are an endless number of options that can be used. However, some guiding numbers can be used when searching for an available fan. To obtain an air speed of 0,45 m/s, the fan must be able to move at least 250 cubic metres of air per hour. Naturally, a too powerful fan should be used rather than one that is not strong enough, the airspeed is adjusted accordingly.

To get a first indication of the suitable size of the fan, look at the pictures of the project's prototype installation, see appendix A “Prototype installation”

Prototype installation characteristics, affecting blower choice:

- Ca length of duct: 4,5 m
- Duct diameter: 150mm
- Type of duct: Aluminium, small ribbed, bendable.
- Nr of 90° in ductwork: 5
- Sufficient blower: S&P TD 350, with a power of 30 W

Calibration of the FVWS

The system is calibrated with an anemometer that can measure speeds between 0 and 1 m/s. With the blower running at the intended speed, the damper is adjusted until an average wind speed of 0,45 m/s is measured at the entry of the FVWS.

During the case study, it became apparent that wind speed testing equipment was desired but too expensive, for this reason, a swing vane anemometer that could be produced by the same manufacturer as the enclosure was developed. The anemometer uses vanes made from aluminium foil of around 35-40 grams/m2. These vanes are manufactured by the user with a small deep drawing press that comes with the product. The anemometer does not produce measurements in decimal numbers, but it gives the user a clear indication of whether or not the workstation is functioning within acceptable limits.

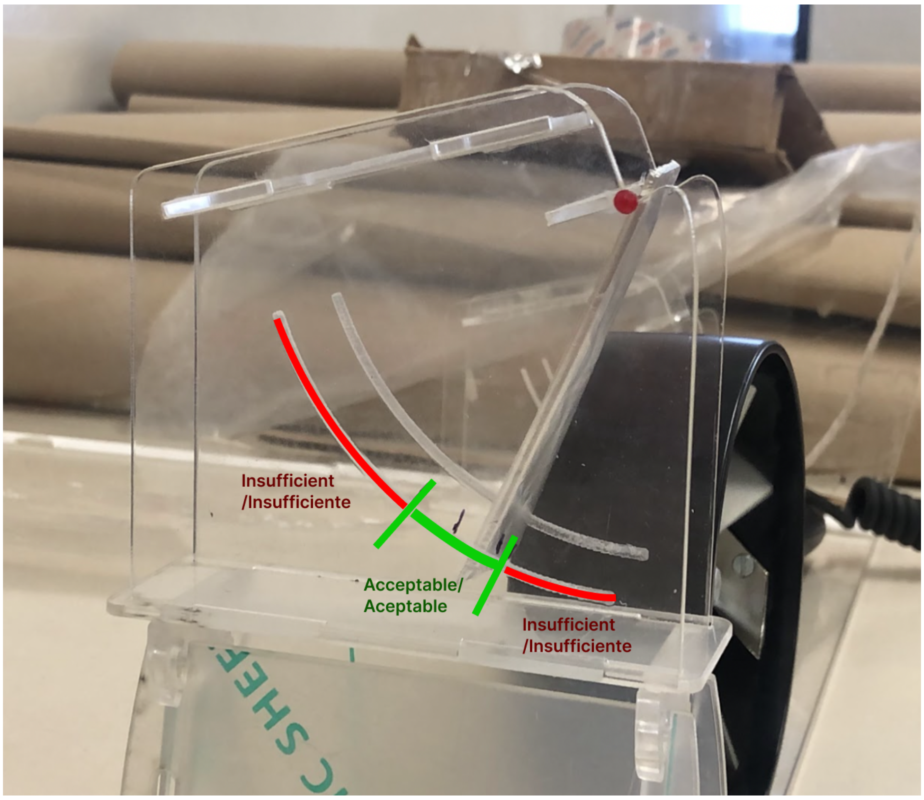


Figure 3.18 Testing of the frugal acrylic anemometer prototype, verifying using digital anemometer in the background, the aluminium vane hangs on a needle in the frame.

Manufacturing of the Frugal ventilated workstation

The FVWS is designed to rely on as few suppliers as possible and is therefore completely (apart from three fasteners) constructed from laser-cut acrylic sheets. The manufacturing starts with the 3D model of the enclosure and from this model, 2D plans are extracted and then vectorised. The vectorised plans are used by the CNC laser cutter to cut out the different panels and pieces of the design. This process is briefly visualised in figure 3.19 below.

When the pieces have been cut out, the baffle and the window are folded by being heated and then bent and held in place while cooling. The damper assembly is glued to the top panel. Apart from this, the laser-cut pieces require very little finishing work, if any. The pieces are test fitted and then they are ready for packaging and transportation to the customer for the final assembly.

The process of acquiring this product in Lima, Peru, can be quick and easy. This process is described in detail in the FVWS manual (appendix D), where you can find information about specific suppliers, and more recommendations.

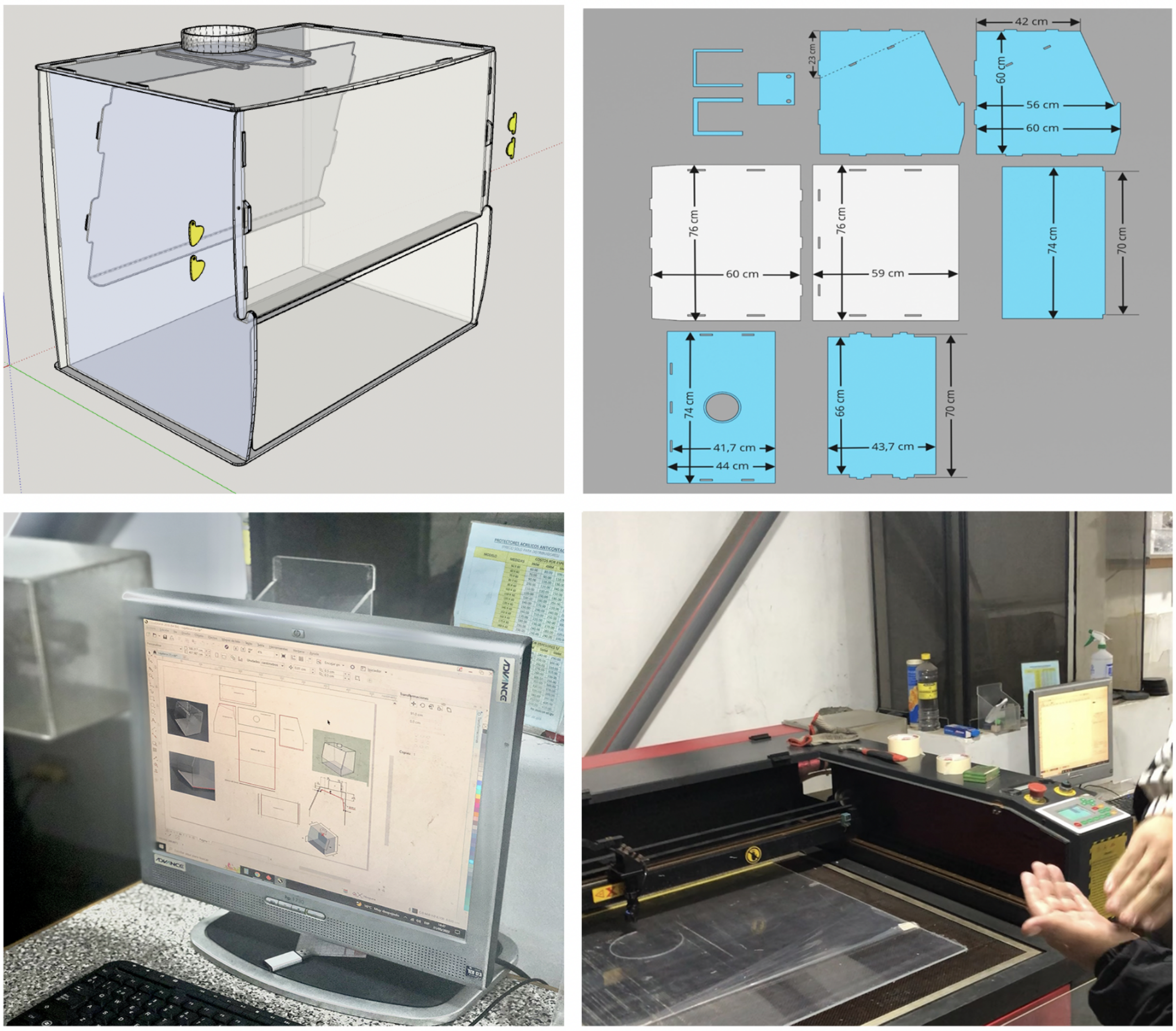


Figure 3.19 The process of taking a 3D model and making it into a laser-cut physical product

The Frugal Design process of the case study

In accordance with the aim of this thesis, the following sections will emphasise and explain how FD has influenced the design process and what learnings that can be drawn from the process of the case study. This will be done by describing and discussing, through four phases, the process and the actions taken. The four phases the process has been divided into are: 1. exploratory research phase set to understand the problem and to determine the intention of the project, 2. an exploratory phase, with a focus on exploring the development detail context to identify needs, requirements and possibilities, 3. an iterative phase to develop ideas and concepts with a big focus on prototypes, and finally 4. an evaluating phase focused on implementing the solution and evaluating it in the real context. For each of the four phases, we will bring up the aspects that were affected by the FD approach or that in a particularly interesting manner contrasted a regular design process (based on the design thinking process described in chapter two of this thesis). These aspects will be discussed for each phase in order to explain what worked and what did not work when applying the FD theory, as well as some challenges a frugal designer might encounter, and hopefully how to overcome them.

The product development process in its four phases is visualised in figure 3.20, and described in further detail in each of the four phases. From chapter 2, we concluded and set out to follow a regular design process and when possible utilise the FD factors when possible within the actions taken and methods when possible. Further on to utilise and test the tools proposed to obtain the FD characteristics and work with local resources and use them as constraints to the ideation phase.

The process figure shows what is essentially a regular design thinking process with additional actions that are specific to FD. These frugal actions have affected the preparation for and the outcome of all four phases. The activities that were directly affected by the FD approach are highlighted with yellow and pink in the figure, where yellow indicates a direct use of the FD factors concluded in chapter 2, whereas the pink activities indicate an influence of the FD factors or usage of other tools also concluded in chapter two. One should note that while the figure may look like a sequential road from idea to finished design, in actuality the product development has been an iterative process and many of the activities seen in the figure may in fact have taken place simultaneously, repeatedly, or sequentially. The figure is constructed not as a chronological representation, but instead as a visualisation of which activities and what information facilitated the next step towards a finished design.

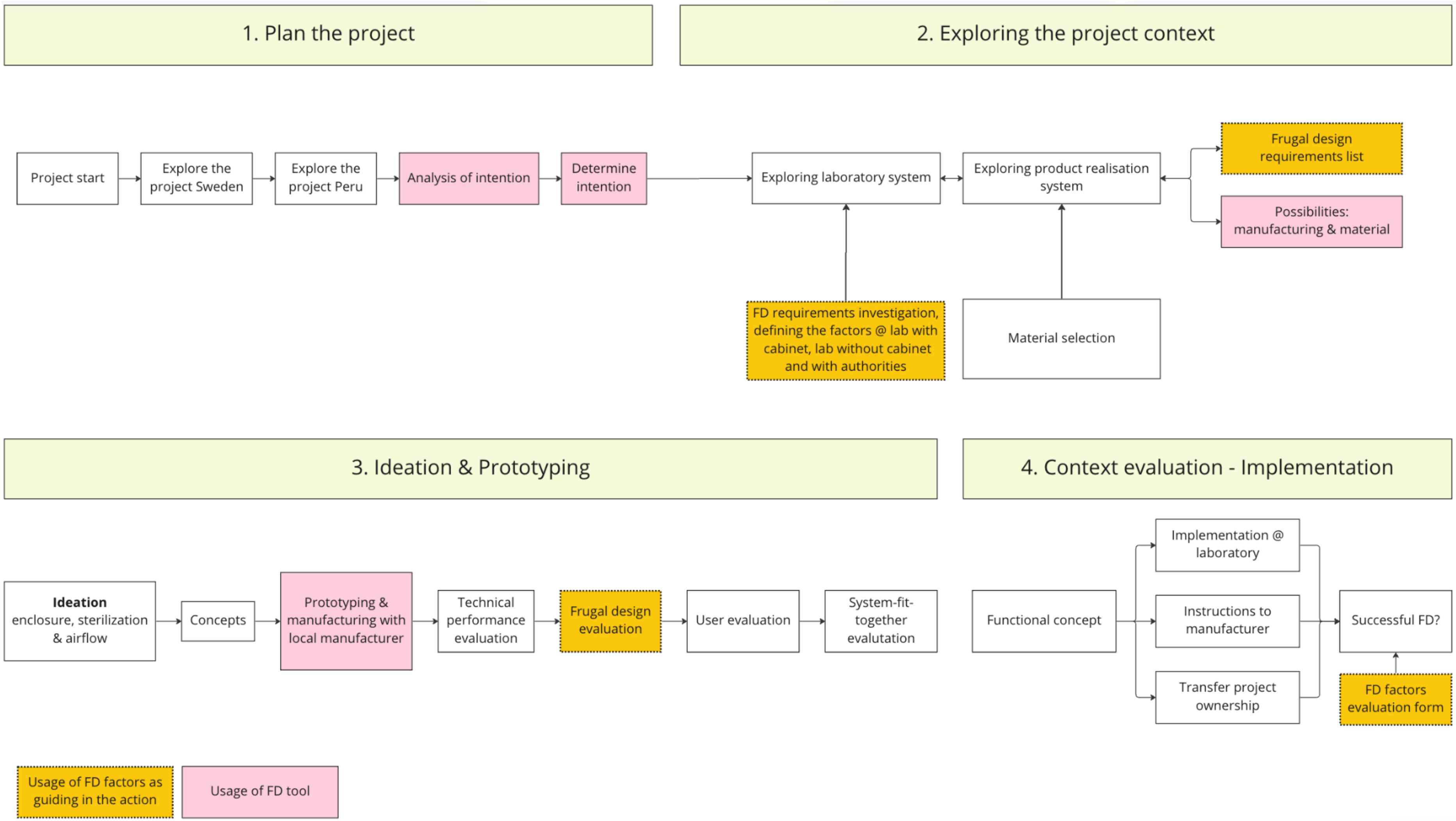


Figure 3.20 Process description of the phases. Yellow and pink boxes indicate activities with differences from a regular design process. Yellow boxes: usage of FD factors. Pink boxes: usage of FD tool

Phase 1: Planning the project

Figure 3.21 Health centre Villa los Reyes, Callao. In this lab there is no biosafety enclosure

During phase 1, the work circulated around exploring the problem and determining the intention of the project as would have been the case within regular design as well. This included deciding broadly what was to be designed, in terms of what type of product and for whom. The activities that were directly affected and performed in a different way due to the FD process are indicated in figure 3.22 with yellow and pink boxes, where yellow boxes indicate usage of FD factors and pink boxes usage of FD tools. The main sequence of activities still follows a regular design process with an initial exploration of the project to determine the project's intention. What differs is rather the way to do this, where the FD has had an impact on the execution of these activities. These differences will be described thoroughly below and further discussed at the end of phase 1.

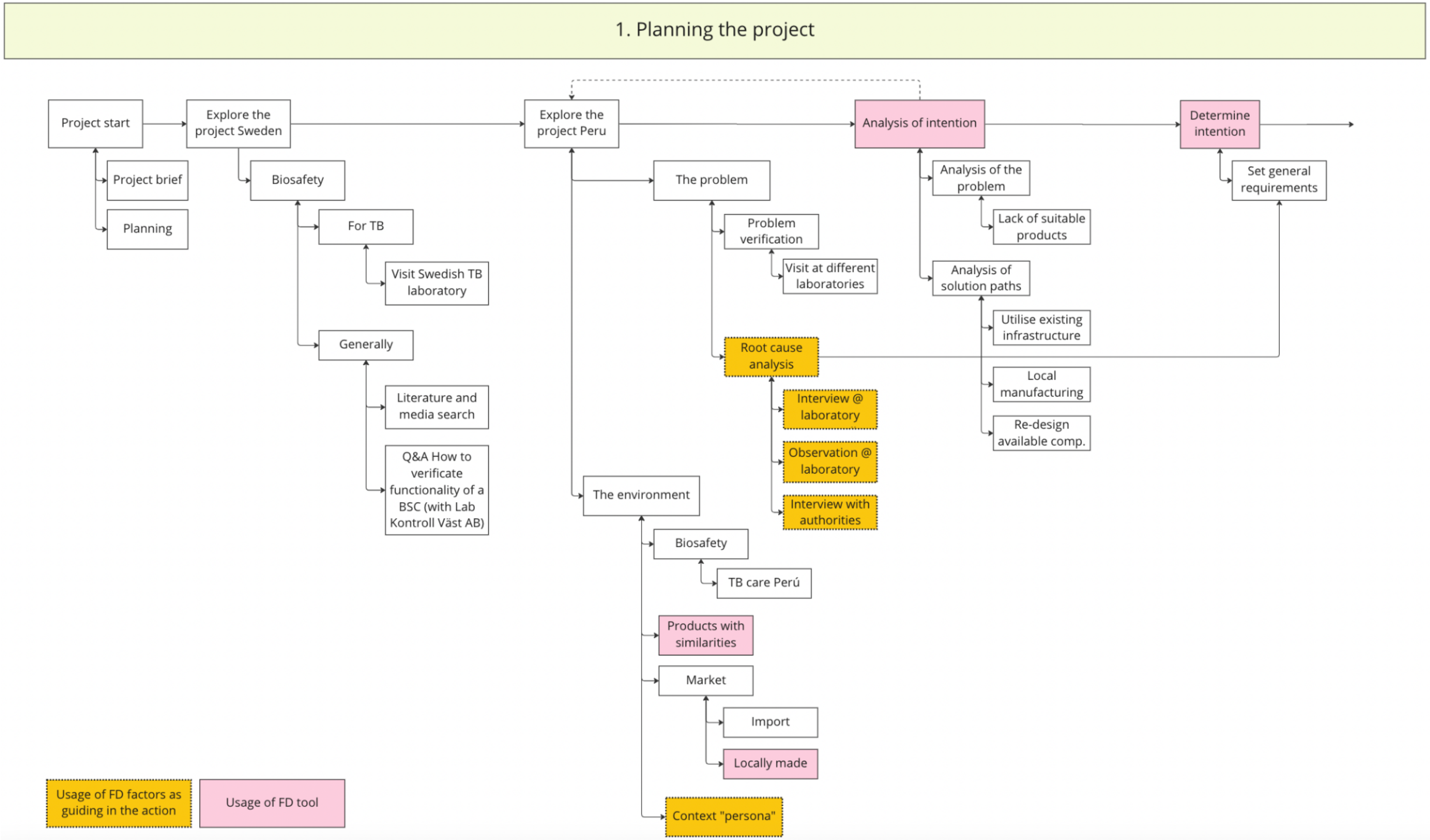


Figure 3.22 Process description of phase 1; Planning the project. Yellow and pink boxes indicate activities with differences from a regular design process. Yellow boxes: usage of FD factors. Pink boxes: usage of FD tools

Understanding the problem and barriers through the use of Frugal Design factors

The first step of activities was to explore and validate the problem picture we had received. To familiarise ourselves with the area, TB care and biosafety were investigated. This was done through visits to laboratories with interviews and observations, through speaking with experts on biosafety validation and certification, TB laboratory personnel and through literature studies. This work was all begun in Sweden and then, in accordance with the frugal approach, the rest of the work was carried out close to the source, immersing ourselves in the context, which included moving from Sweden to Lima for one year. In the project context the problem could be verified through interviews and observations at several health centres in different areas of Peru, mainly in and around Lima.

To get to know the context in a structured way, “context personas” were created, mapping characteristics that are context-specific in relation to the FD factors and other important factors that would affect the design. This was an attempt to in a structured way think of the context and how it could affect the design outcome. However, it was not used much as a formal design tool after an increased understanding of the context was reached.

Once embedded in the context, it soon became apparent that the brief was quite accurate as several health centres performed TB diagnosis work through the AFB smear process without controlled ventilation, putting operators at risk and causing discomfort and fear. As the problem was now validated, the next step was to try to figure out the hindrance, and the root causes of why there are laboratories that lack the desired equipment of biosafety enclosures. The question “why no BSC?” was constantly present during the different actions taken in phase one. This was however not an easy question to answer and unsurprisingly it offered a multifaceted answer. The FD approach came to aid in this uncertain situation as it offered a new point of view with certain stated angles of inquiry. The FD factors were used to form questions both for interviews and observations (see appendix B), that would cover all possible barriers that would likely not be brought up in more conventional investigations. For example, one line of questioning regarding accessibility and affordability led to two interviewees describing one hindrance being that of failing bureaucracy and even corruption. The interviewees mentioned frequent organisational changes within the public sector, arduous paperwork, and the real fear of losing one's job or worse if accidentally involved in a corrupt acquisition process. These are uncommon types of issues to involve in the design of a product, but in this case, these insights prompted ideas with the very frugal characteristic of avoiding institutional issues. For example, allowing the lab personnel to buy the product not only through official channels but also by utilising the lab's monthly budget for office supplies to pay for the product in parts. This is just one example where the frugal approach resulted in innovative and different ideas than what would have resulted from a more conventional design process.

The extensive insights stemming from this work were used to map the root causes in manageable portions in order to see the whole system of barriers more clearly, see figure 3.23. All individual problem areas that played a role in the system were categorised in relation to the

FD factors to see what need each root cause could be transformed to and dealt with through the design work. The other root causes that needed to be addressed through outside interventions with less connection to the actual product development could thereby be understood. This created a “Frugal understanding” of the problems, helping out in adapting a FD mindset for the whole product system. In the figure, the use of the FD factors shows a way to understand the underlying problems with all pieces of the wheel that need to be addressed in some way if the wheel is to spin, i.e for a solution to overcome the hindrance. Even if the solution of this project can’t bridge all the gaps, the solution must facilitate other solutions that address problem areas within the wheel as proficiently as possible to avoid the solution being designed in a manner that obstructs other solutions that need to coexist with this project's end solution. For example, if training is to be implemented for a successful biosafety system, a cabinet must have a design that is reconcilable with the available knowledge and resources that could be utilised for the training.

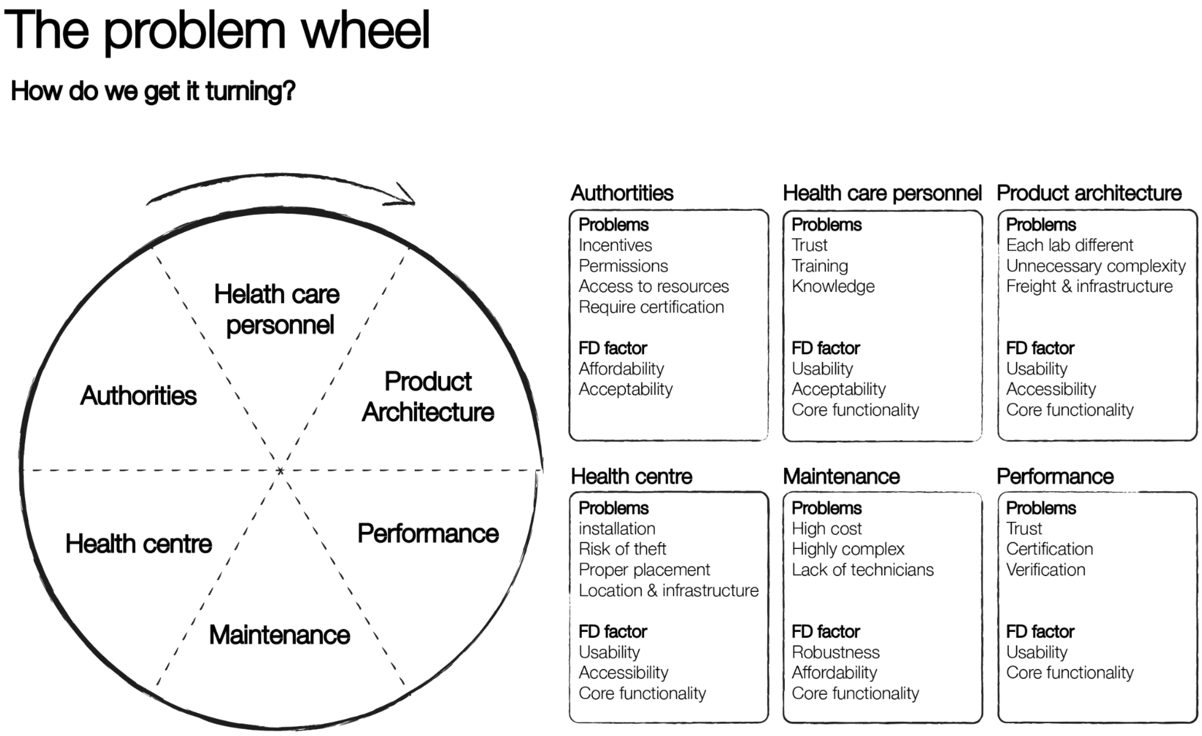


Figure 3.23 The problem wheel. Root cause analysis of the most prominent factors and issues in the context.

Immersion in the context - Exploring paths to a solution

With a verified problem, and a fundamental understanding of the underlying causes of the problem, attention was directed towards possible paths to a solution. Using the suggested FD tool of *utilising existing resources*, the context was evaluated in order to see if any pre-fabricated resources held any potential of being utilised as a solution. This part of our frugal approach brought attention to the very wide sector of small-scale manufacturing businesses that exist in Lima. There are numerous trades and craftspeople on every street in certain neighbourhoods of the city. These local manufacturers specialise in various materials, many of which, due to their properties could be suitable for biosafety enclosures, such as glass, melamine wood board, steel, acrylic plastics and more. Utilising this know-how and designing a new product built on the manufacturing techniques already practised by these local manufacturers could create a robust manufacturing system that would benefit many of the FD factors as well as make the realisation of this project more likely.

Determine the intention

At a point in the project where it was necessary to determine what was needed and what could be done, i.e determine our intention, the choice was done frugally. We wanted to continue with a path that utilised not only the available resources in terms of eg. material resources in Lima, but we also wanted to proceed with a path that would most effectively utilise the resources the project team had to offer, the know-how and skills that would make this project happen. This had a big effect on the project as this limited the time of development and implementation to one year, affecting partnership possibilities, and restricting the possible solution space.

Knowing that the solution space was limited to the resources and capabilities of the project, we needed to further define what those capabilities were. One tool that helped us choose which way to go was the well-established concept of control hierarchy when dealing with hazards in the workplace. This model, provided by The US National Institute for Occupational Safety and Health (NIOSH) (figure 3.24), describes what actions are more effective and desirable in order to protect personnel. When diagnosing tuberculosis samples, the hazard is the task, thus the two most preferred methods of hazard control are ruled out. We can not eliminate the sample because then we will not be able to diagnose it, and we can of course not substitute the sample as then the diagnosis would not tell us anything about the actual patient's health state. Thus the most preferable method of hazard control, in this case, is to isolate the personnel and the hazard from one another.

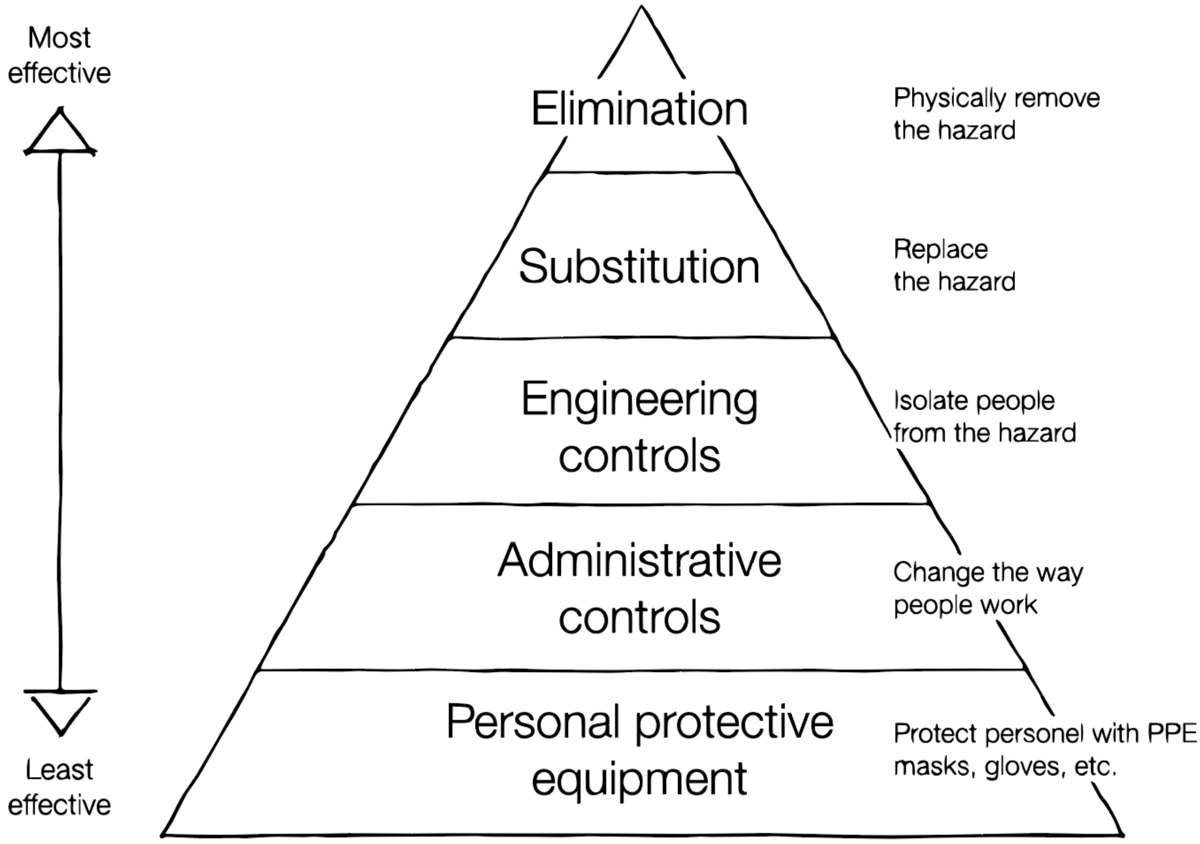


Figure 3.24. The hierarchy of controls when protecting personnel from hazards (adapted from NIOSH, 2022)

We had now defined the intent in regard to the project's resources and capabilities, the most preferable type of solution according to the control hierarchy, and by reflecting on the effects these choices would have. Thus, the most reasonable choice was to confine the solution space to containing quite conventional products since we then would have resources to verify proper functionality through prototyping and tests. Furthermore, the root cause analysis didn't show that the main hindrance had anything to do with the concept of a biosafety enclosure as it is known today, but rather that the solution could benefit from using the same generic knowledge of how a biosafety enclosure works. We concluded this to be the most frugal path towards a design that could function and fulfil all FD factors in relation to the resources that the project and context possessed.

Similarly, the focus on utilising local, small-scale partnerships for the manufacturing and letting these manufacturing methods and techniques guide us in coming phases was a decision based on accessible resources. We considered this a more frugal way of creating a product that had a real chance to reach implementation and a self-sustaining business model. This was a presumption based on the fact that this isn’t a product that is likely to be sold in large volumes and therefore can’t rely on big manufacturing batches to lower the price for the end customers. Utilising local manufacturing was also advocated to be used as a tool when designing frugally, and hence, logically to do also in this project.

The final intention was ultimately stated as:
Design a frugal physical biosafety enclosure with a function level in accordance to a VWS or a BSC class 1 that protects the user from dangerous aerosols through the use of directional airflow, specifically meant for small existing laboratories working with the AFB smear procedure. Thus, a product that is possible to install in an already existing laboratory, using the existing interior and requires as little need for reconstruction as possible. Further on to develop the enclosure with and for established small-scale manufacturers in order to benefit from their know-how and manufacturing techniques to increase prototype-ability, development speed, robustness, affordability, accessibility and other aspects of importance to the final solution and to ensure a possible future manufacturing.

Discussion phase 1

As we can see in the flow diagram for the process (figure 3.22), many of the actions taken did not have anything specific to do with FD, but rather followed a regular design process as described in chapter two of this thesis. The actions within the process that are influenced by the FD factors are contrasting a conventional process by immersion much further in the context as well as widening the field of interest for the product system. A regular design process would be more likely to focus solely on needs and requirements around the user to create an understanding sufficient for determining the intention.

The focus on early exploration of available resources, products and production was very useful for the project. It was a quick way to get to know the context, what type of products and materials that were accessible, as well as what was produced locally and what was imported. This information helped us form an intention for the project that was in accordance with what could be realistically achieved with the resources the project possessed, arguably a more frugal intention. The information also formed the foundation for the exploratory work in phase two when the possibilities for local manufacturing were examined in depth.

Adopting a frugal mindset

The actions during phase 1 affected by the FD approach played a role in creating a frugal mindset which was perceived as important for the FD process. Especially the context persona and the way of using the FD factors for the root cause analysis sparked the Frugal mindset.

Context persona

The context persona as a formalised way for creating the understanding of the context by using the FD factors was a great way to see the spectrum of the FD factors in relation to the surrounding characteristics affecting a design scope. This created the base for the frugal mindset. Without the understanding of the context in relation to the FD factors, the frugal mindset would have missed its base and therefore the possibility to understand what defines a FD in the context of Lima, Peru. The context persona was also especially useful to collect early requirements and insights of the context that together with the root cause analysis could act as a basis for the general requirements needed to determine the intention. Therefore, we think it is advantageable to do these kinds of investigations early in a FD project.

Root cause analysis

Using the FD factors as a tool for extracting data for our root cause was a structured way to explore the problem area. The relation between the factors and each problem made it easier to understand all problem areas as smaller portions. This also helped in creating the Frugal mindset, when all problems were reflected upon and related to the FD factors.

The problem wheel (fig. 3.23) shows the construction and functionality of the enclosure as only a small part of the puzzle that a solution must solve. Some aspects, such as training, are also important factors for a successful implementation. A FD biosafety enclosure can't feasibly overcome all barriers for implementation solely through the physical product itself. The solution must therefore make sure to facilitate the resolution of these other non-product barriers through other means. If not all of these problem areas are solved, the overall goal to create a safer work environment for the laboratory personnel will not be achieved, not directly nor over time. We would like to argue that utilising the FD factors to search for these root causes helps create insights regarding non-product barriers and an understanding of requirements for other stakeholders than the end users. Without the FD approach, we believe we would have seen several of these barriers only when first trying to implement the more or less fully developed design, likely causing a reworking of the design that would be resource expensive as well as missing the chance to understand the root causes as a part of our frugal mindset. Therefore, the FD approach makes not only the product more frugal but also the development process.

Phase 2: Searching for possibilities - Constraining the solution space

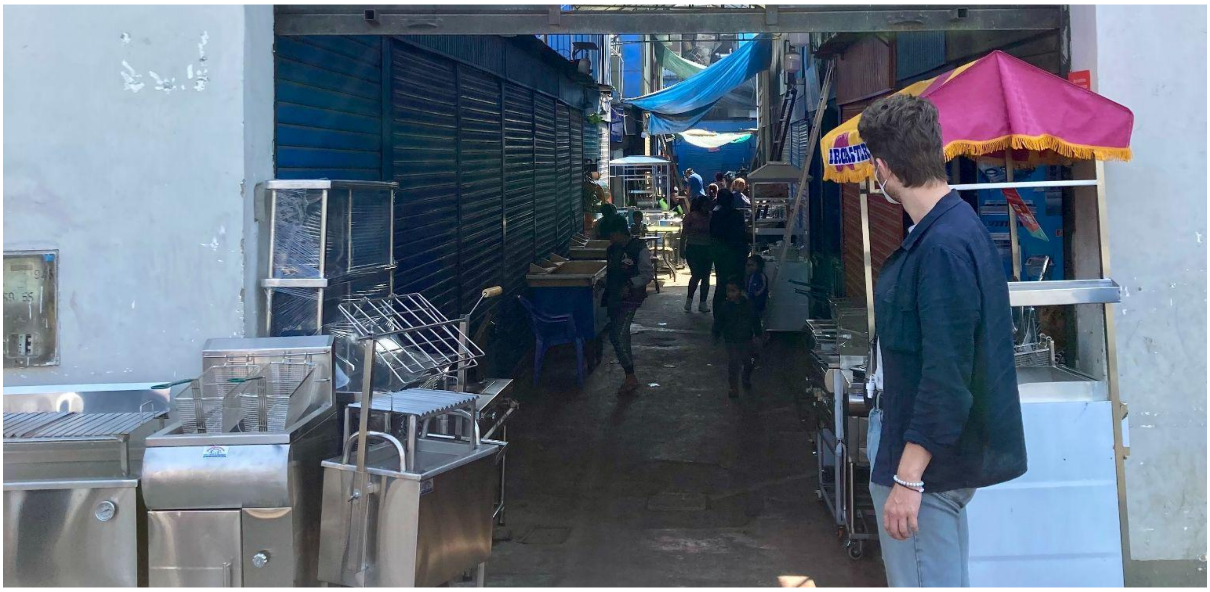


Figure 3.25 The metal workshop district. Here you can find craftspeople who will build you whatever you would like.

In phase two, the focus was set on users and their work (see figure 3.26). The process contained several elements of a regular design process. First deep diving into the user system to the user needs and then converting these needs into a requirement list. However, phase two also contained an element of searching for possibilities in regards to available material and manufacturing that was suitable for a biosafety enclosure and in line with the general requirements stated in phase one. Included in the search for possibilities was also identification of technical guidelines for the construction and functionality. In this work, the VWS (described in background - biosafety), its manufacturing-, validation- and user guide was identified. The guide provided a starting point containing important design considerations from a technical perspective. With the data from the VWS guide focus could directly be directed to learn how a VWS could be materialised in Lima as a way to speed up the innovation process and to generate a test platform where important characteristics for a biosafety enclosure, such as airflow and system robustness could be examined. Therefore, the first prototypes follow the same shape and measurements as the original VWS, even though manufactured with different techniques and materials.

One of the more prominent differences in phase two from a regular design process was the use of the FD factors for data collection. Another prominent difference was the search for local manufacturing and resources to constrain the allowed solution space for the ideation phase.

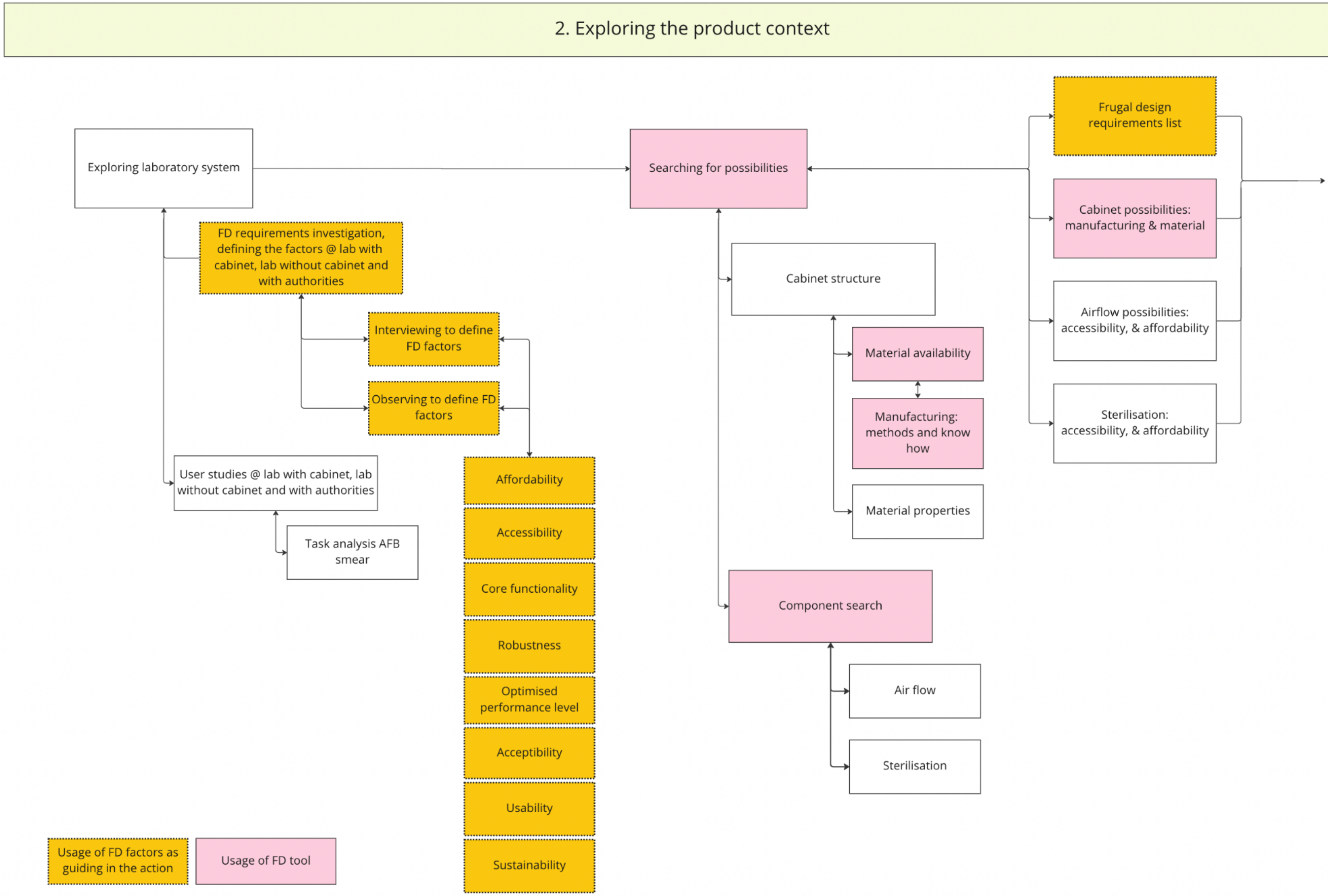


Figure 3.26 Process description of phase 2; exploring the product context. Yellow and pink boxes indicate activities with differences from a regular design process. Yellow boxes: usage of FD factors. Pink boxes: usage of FD tools

Using Frugal Design factors to search for requirements

In order to find needs and requirements corresponding to each FD factor, interviews and observations at laboratories with and without biosafety cabinets, as well as with authorities that play a role in the acquisition process were executed. To find the FD requirements, each FD factor acted as an open category for requirements that needed to be investigated, and studies continued until a level of saturation had been reached for every factor. The interviews and observations were structured into questions about the problems related to each FD factor. Eg. What defines accessibility of a biosafety enclosure in the given context? What problems were connected to accessibility of this kind of product? This generated answers and requirements, for e.g, that it was expensive and difficult to access testing and verification of cabinets due to a shortage of technicians doing this work, thus, decision makers decided not to acquire biosafety enclosures if there was no possibility to later test and verify the functionality. This illuminated the need to include verification and test functions in the cabinet itself. Appendix B shows a few examples of how FD factors were used in observation- and interview templates during the case study.

Examining the FD factors of optimised performance level and core functionality led to questioning the required size for the work surface, addressed through interviews and observations including a full size mock-up, see figure 3.27, (as a normal method in a design project), for investigating and defining the perceived workspace needed and what equipment used and activities that was performed during work to determine the minimum required size of the work surface.

It quickly became apparent that the economical resources were a problem that users and managers perceived as a main barrier for the acquisition of BSC's for the small health centre labs. In addition to this there were also statements that indicated that decision makers were either partly unable or unwilling to make such investments. This caused much effort during this phase to be directed towards the aim of finding the affordable price, not derived from the production cost but rather derived from the price that the labs or those responsible for the acquisition could feasibly pay. In contrast to questions regarding the material, or how to think about logistics and manufacturing, the FD approach struggled in catalysing and mediating the thought process when it came to the issue of extracting the affordable price and in finding the institutional barriers.

Forming a Frugal requirements list

The FD factors were used as a guiding light in the creation of the requirement list. The requirement list started empty with the eight FD factors that needed to be filled, then during the work through interviews and observations, requirements were added for each FD factor and thereby showing if or not all FD factors were looked at and addressed in terms of related requirements. This made the FD factors act more or less as the overarching requirements, and the underlying requirements functioned as limits or definitions of each FD requirement. Working in this manner showed where knowledge gaps in relation to the FD factors existed and where further investigation was required.

Figure 3.27 Determining the required size for the workspace using an adjustable mockup, questioning the required space for the intended work, thus determining the optimised performance level.

Limiting the solution space through searching for possibilities

Through using the requirements of suitable materials for biosafety enclosures and reflecting upon the adherence to the FD requirements, all the possibilities that could be utilised for realising a design concept, such as materials and products that were suitable for a biosafety enclosure system were observed and searched for. The local markets were scoured for equipment intended for biosafety, as well as other types of equipment possible to re-fit for this project's need. In some cases, similarities could be seen between the architecture of biosafety enclosures and other products used and produced in Lima. The application of the frugal approach with focus on Accessibility with tools like local manufacturing generated ideas for utilising locally available resources in the form of ready-made components or products that could serve for the purposes of the project. The other solution alternative, to produce a completely new product through utilising locally available materials and manufacturing know-how was perceived as more feasible due to the need for adjusted and tailored measurements to obtain certain technical characteristics needed for a biosafety enclosure. However, the observations of locally manufactured products with similar architecture were used to identify the manufacturers to see if they were a possible resource to engage in new production.

Available and proper manufacturing, materials, and components, all necessary for the product system, and crucial for taking a design from concept to an implemented product, together created the boundaries for the solution space (see figure 3.28). Several matches of available possibilities between these three aspects were found in Lima which gave us different solutions spaces that could be explored during the ideation process.

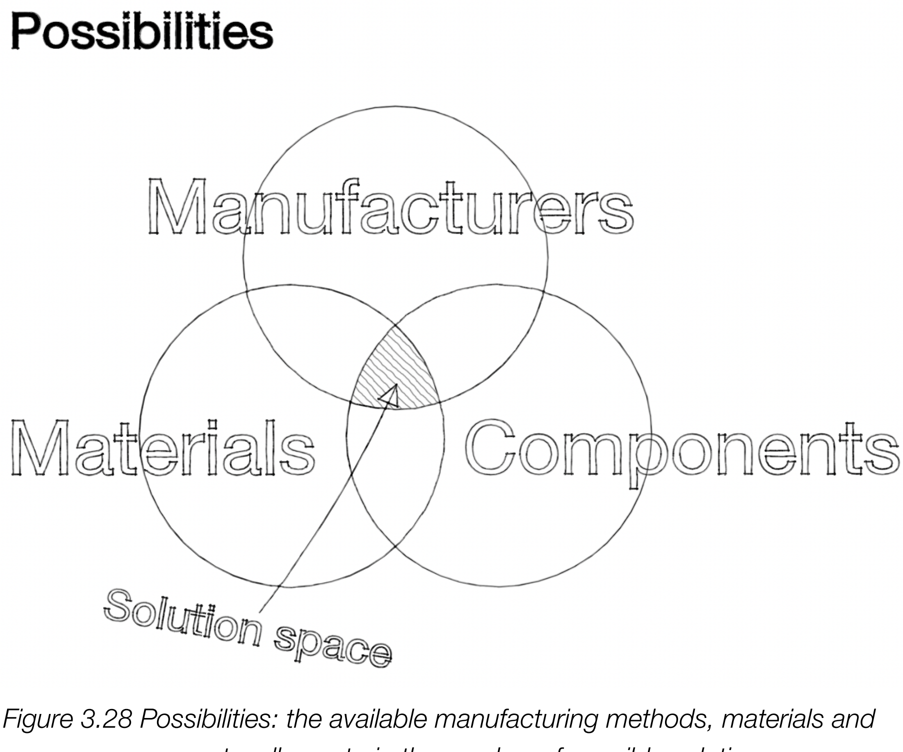


Figure 3.28 Possibilities: the available manufacturing methods, materials and components, all constrain the number of possible solutions.

Material and manufacturing focus

The material requirements set on a biosafety enclosure are of course numerous, one example is that it must withstand the daily use of certain sterilising chemicals. This prompted an investigation into which locally available materials had the appropriate properties for use within biosafety. Initial investigation led us to stainless steel as a material. This was greatly affected by the frugal approach as stainless steel production was widely used in the Lima context, for example in the stalls used by vendors to sell food and drinks in the streets of the city. The widespread use of stainless steel as a material indicated to us, among other advantages, that there was a good availability of the materials and manufacturers. Another locally available production method was laser-cut acrylics. Products manufactured in this material were easy to find throughout the city and acrylic plastic also showed many beneficial characteristics, for example, the chemical resistance mentioned earlier.

Figure 3.29 The food stalls that street vendors use throughout the city bear some resemblance to a biosafety enclosure

Figure 3.30 Acrylics workshop where customers can order Of-the-shelf designs, or submit their own for production

In a case like this, the FD approach had a big influence not only on why these materials were examined but also how the decision was made between them. For example, the fact that an acrylic enclosure will allow light to enter from all sides and therefore allow a reduction of the number of components by excluding a lamp from the design, and thereby increase the Affordability and Robustness, is one reason why it likely would be a more frugal choice than stainless steel. Omitting an internal light from the design might seem like a small economical saving, but it is one design aspect that has the potential to achieve small but important improvements of the adherence to the FD factors. It reduces the number of parts that may break, simplifies transportation, and removes an additional supplier from the equation making the production more simple, robust and accessible.

Component Focus

The focus on a design that utilised available manufacturing technologies was intended to generate an easily accessible product. This was a particularly useful approach when trying to source an affordable enclosure as these were not readily available. However, other components that would come to form part of the design (as shown in figure 3.31) proved more available. It was a question of considering what path would be the most frugal option, producing these components according to our own design, or sourcing them off the shelf. One example of this was the fan which was one type of component where sourcing it ready-made turned out to be a frugal option, rather than trying to ideate a new frugal option for creating an airflow. To this list of off-the-shelf products, we can also add a duct, filters, lights, UV sterilisation, rubber seals, etc. all depending on the design. Some of the main challenges were to find a reliable supply of the component, and a component that did the job without overperforming.

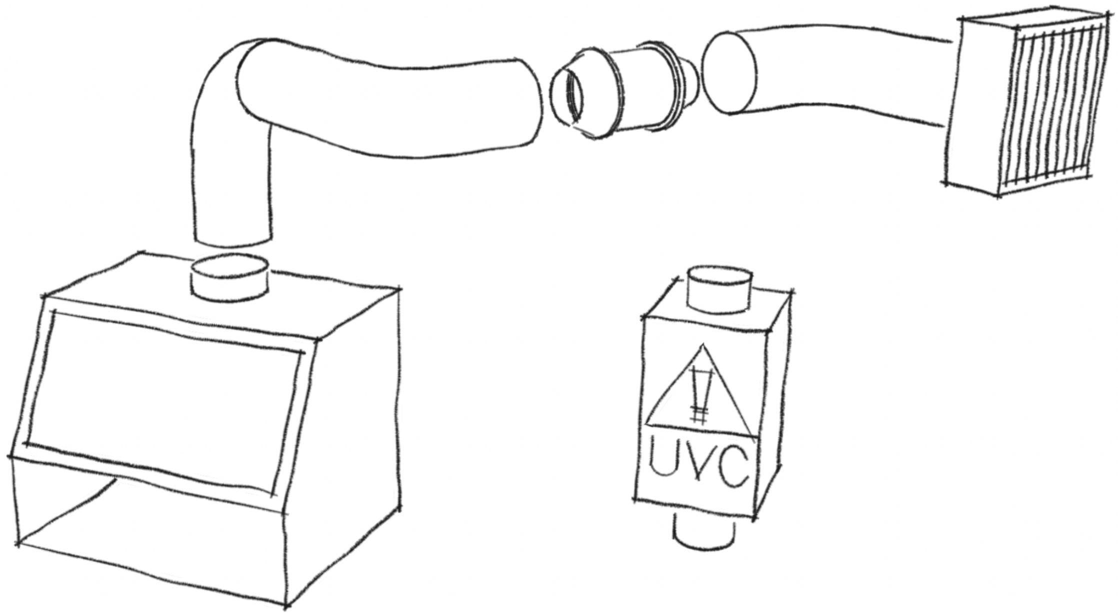


Figure 3.31 Some of the components that could make up a biosafety enclosure system, the enclosure itself (left), the ductwork, an electric fan (middle), a microbiological filter (right), and a germicidal UVC-lamp unit (bottom).

Discussion phase 2

During phase 2, we can see one of the clearest deviations from a regular design process, when the possibilities are mapped in an early stage to form a basis of options that constrains the ideation space. This is of course something that affected this project enormously. This part can also be seen as a way of finding requirements from the context. I.e, the FD process still mainly relies on the sequence of a regular design process.

Utilising the FD factors to find and set requirements - how did it work?

The main methods for the user studies were as mentioned conventional methods such as interviews and observations. Even though the methods are conventional, the incorporation of the FD changed how the interviews and observations were prepared and structured, giving eight clear topics for discussion.

The use of FD factors for observations did not allow the observer to answer many of the questions of what “defined” the FD factors in the context. However, it was helpful in creating a Frugal mindset during the visits to the health centres. We argue that it is a helpful tool to remind the observer of the factors during observations early on in the design process when requirements still are to be gathered, and that this is part of a Frugal mindset.

Using the FD factors as guidance in the creation of interview templates was a very helpful tool for directing the user studies toward topics of importance to the FD process. This helped us ask the right questions and always keep the work on the frugal path. It was also useful to group the questions after each label of a factor to make it clear if enough data to answer what was important for each factor was gathered. The question is if the guidance also obstructed the open probing that sometimes can be necessary to get to know the real problems or needs. The FD factors are very open and comprehensive, which is why we think that the risk of missing important information is fairly small. It is also worth noting that using the FD factors for investigating the user needs does not exclude the usage of any question or investigation that is not explicitly about a FD factor.

The issue of affordability

A biosafety enclosure within a public health care system in Peru is a product that is a part of a complex system with many stakeholders and a lot of bureaucracy. In this system, the end user of the biosafety enclosure is not the one responsible for acquiring the equipment. Users may not even have the possibility to affect the decision to acquire new equipment. Getting in contact with the person responsible for the acquisition of laboratory equipment turned out to be very difficult, and discussing prices even more so. This made the work of defining affordability very difficult and instead of finding out what price was perceived as affordable, market investigation of prices for similar products was used to guide the definition of Affordability. This, however, had the downside that it could only tell us what was affordable in the labs that had biosafety enclosures, not what was affordable in the labs that did not have enclosures. Perhaps a more efficient way to find an answer would have been the creation of a physical product for use as a mediating object in the discussion of Affordability, hopefully giving an understanding of whether or not the product is cheap enough. Additionally, Not being able to define the price led to a more complicated balance between the 8 FD factors. The ideal state would be to be able to define all factors precisely and thereby align the solution in regards to that. However, when Affordability can’t be defined, the designer has to aim for as low cost as possible. This affects the process to be much more of a balancing act between cost and other factors, such as robustness.

One can discuss if the parameter of Affordability can actually be allowed to remain unknown. If the product is designed to achieve all the well-defined requirements within the other factors such as Robustness, Core functionality, Acceptability etc, and with the affordability as unknown, theoretically, the product will then be as frugal as possible if it is developed to be as cheap as possible while meeting all other defined requirements. If at this point the product still isn’t affordable, the question arises if it is at all possible to fully achieve a FD of the specified product in the specified context.

Frugal Design helping to set requirements

The choice of grouping all requirements that were set for the product under each FD factor and thereby utilising the factors as general requirements and then letting the found needs rather act as limits and embodiment of each general requirement was a great way to structure the FD process at this stage and can be a recommended way to work.

Importance of acceptability

Requirements on sterilisation of the outlet air turned out to be dependent on both technical requirements, i.e if the outlet air needs to be sterilised, but also on acceptability of the product regarding the trust of the functionality and to solutions attractiveness for the managers to acquire. Thus, important for a successful FD is also product acceptance.

Searching for and utilising possibilities - advantages and disadvantages

Advantages with creating a solution that embraces the conditions within the context was perceived as a method that gave the ideation and its outcomes (solutions) a chance of creating long-term impact without constant interaction and support from us as designers and project owners. This would mean that the solution holds a better chance to succeed being a self-sustaining system that could continue to function and grow over time. Working with what could be identified confined the solution space to only include material and manufacturing that would be a realisable product, before even starting the ideation process. This also made the transition to prototyping a fast effective move since we early knew the boundaries for the prototyping to make it efficient.

A possible disadvantage with first mapping the possibilities and then founding the ideation on this would be the risk of missing other opportunities, perhaps our judgement of what is possible is too restrictive. In a city with the overwhelming size of Lima, the work of mapping all possibilities must be seen as an endless task. The number of possibilities for creating a biosafety enclosure would therefore be too numerous to completely exhaust. It is likely that this approach has excluded us from possibilities that exist but which we haven’t identified and therefore excluded from the later ideation process. It is arguably a suitable approach in a very resource-constraining and limited setting, where the possibilities can be quickly mapped. The truth is that while it may be interesting, the work situation in the laboratories will not improve if a lot of time and effort is invested to come up with a design that has absolutely no possibility to be realised. If one or several facilitators of a possible solution such as the manufacturing, know-how or logistics is hard to find or implement, the ability to utilise that possibility is not certain.

When working with FD in a context with fewer resource constraints, it is maybe better to keep the solution space open for longer, and not look too deep into what possibilities there are in the context since they are so vast. For example, in a context with a well-functioning infrastructure, it is arguably so that a locally connected approach isn't always the best option. Thus, in the first stage of a FD venture, the designer should pay focus on which constraints the context entails, this would be what defines the possibilities to bring forward to the ideation phase, or whether to not constrain ideation at all or with arbitrary constraints.

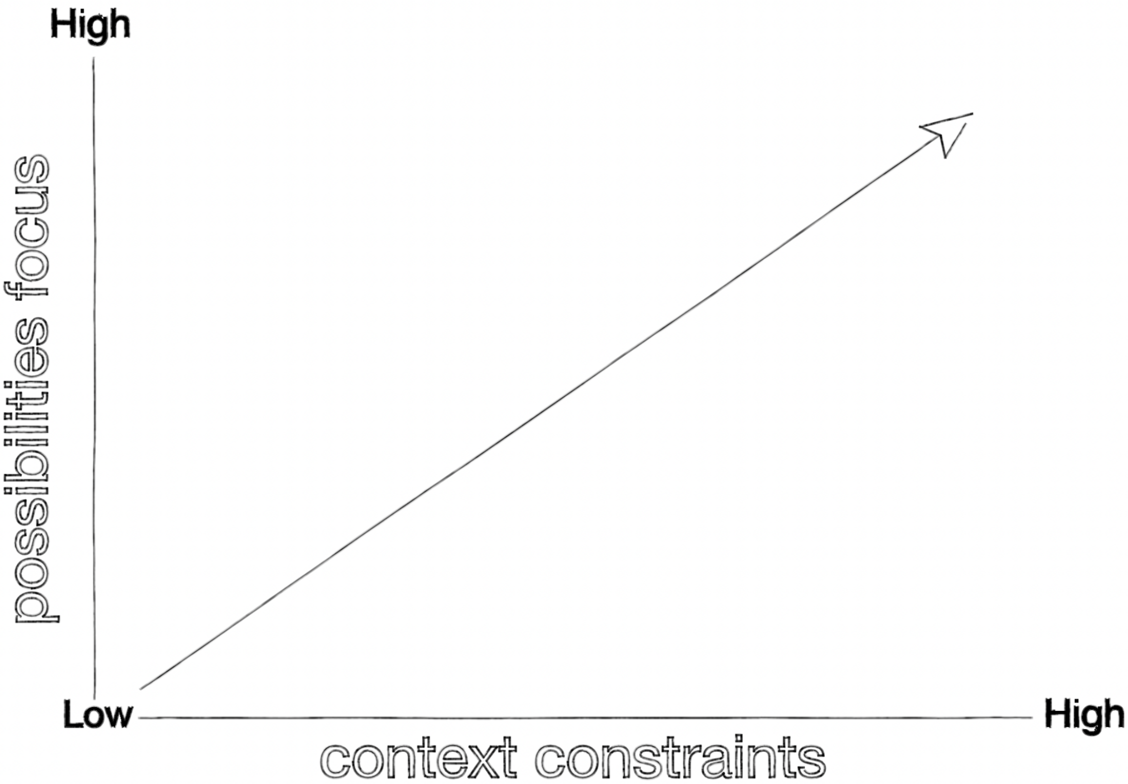


Figure 3.32 When constraints are high, a designer must focus more on what is possible. In non-constrained contexts, the designer doesn't need to pay as much attention to this.

Phase 3: Ideation, prototyping and evaluation

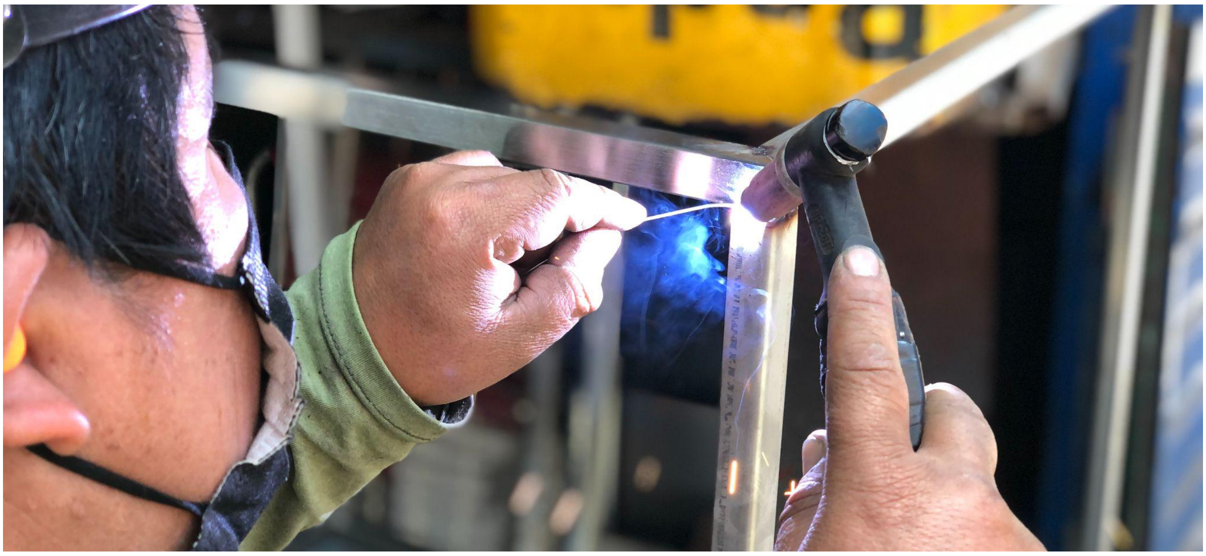


Figure 3.33 Welder in the metal district constructing a prototype out of steel

The sequence of activities, prototyping and evaluation, in phase 3 ideation followed a regular design process, see figure 3.34, but the way to execute each activity differed. The ideation process, instead of being totally open, was constrained by the defined solution space. The idea generation focused on three main areas: concepts for an enclosure, concepts for how to create an airflow, and concepts for how to make sure that the contaminated air did not harm anyone. The idea generation led to two main concepts based on stainless steel and acrylic, two different materials where possible manufacturing and know-how were identified.

The prototyping was directly performed through the manufacturers instead of in-house prototyping. This anchored the design in reality and gave the possibility to evaluate and iterate directly towards a concept aligned with a functional manufacturing. Results from the prototyping and adherence to the FD factors formed the conclusion that the acrylic concept was the most frugal option.

Within the evaluation process, the new process activity of concept evaluation, the FD evaluation matrix (appendix C) developed during this project differed from regular evaluation methods. The matrix was used at each design iteration to evaluate how the product addressed the FD factors and to reflect upon what could be improved at each stage. This work mostly revolved around the enclosure itself, but frugal considerations were also relevant for the duct and fan assembly, and the “optional” sterilisation assemblies such as filters and germicidal UV lights.

During phase 3, the entire Frugal ventilated workstation system could be tested and evaluated for the first time in a controlled environment to prepare it for phase 4, the implementation.

3. Ideation, prototyping & evaluation

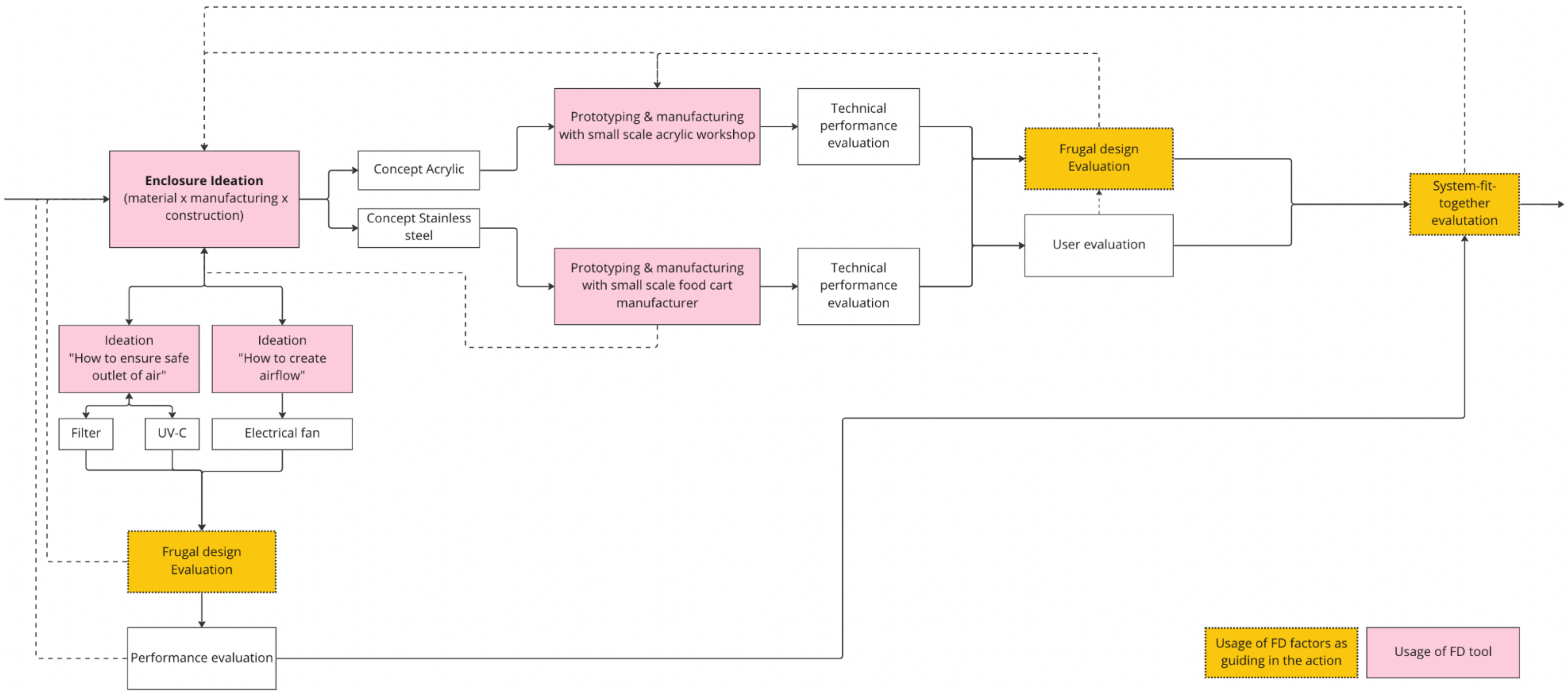


Figure 3.34 Process description of phase 3; Ideation, prototyping & evaluation. Yellow and pink boxes indicate activities with differences from a regular design process. Yellow boxes: usage of FD factors. Pink boxes: usage of FD tools

Ideation moderated by possibilities or constraints

The ideation process focused mainly on creating ideas and concepts of how the biosafety enclosure was to be designed to best utilise the local possibilities of manufacturing, know-how and appropriate materials for this kind of product to meet the FD requirements and the factors of the root cause analysis. In addition to this, the biosafety enclosure was to be designed to make it compatible with the other components that may be needed, such as filters and UV sterilisation.

The ideation methodology could be recognised in regards to ideation tools, but the idea generation, prototyping and iterations of concepts were greatly guided by the materials and manufacturing methods identified in phase 2. This resulted in ideas that were within the solution space of what was possible to realise. This more restricted outcome of concepts due to the constrained ideation removed the need for a later adaptation of the concept to the manufacturing, which otherwise would have been necessary.

Reducing the number of suppliers

The frugal approach, and particularly the Accessibility factor and experiences from working within the context, inspired a new tool that focuses on reducing the number of suppliers. This meant designing the biosafety enclosure in a manner that reduced the number of suppliers that needed to be involved. As an example, instead of fitting an off-the-shelf metal latch on the biosafety enclosure to keep the lid closed, a new design was developed that used only the abilities and resources that were available to the manufacturer of the cabinet itself. Using only one manufacturer reduced dependency on other suppliers which was seen as a way to increase the robustness of the production since only one supplier would be needed to make repairs or supply spare parts. It is also an established principle that the use of only one material is a good way to avoid stress concentrations and points of increased wear, making the product more robust in that sense as well. This became a new way to constrain the ideation space even more when it was possible.

Utilising previous work as a start point for the construction

As a starting point for the construction, from a technical performing perspective, as mentioned in phase two, the previous work with the VWS was identified as a great possibility from which much knowledge and design recommendations were extracted. This generated a quick transition from requirements to a functional prototype that worked as a test platform, verifying functionality, and where new ideas and concepts could be quickly tested. The low focus of generating an innovative new construction as the first iteration was based on the perception that the physical appearance of the product itself held few critical problems. Instead, contextual factors such as availability of material, manufacturing and maintenance acted as greater barriers to successful implementation and held a bigger risk of ruining the possibilities of reaching an implementable and self-sustaining product. Starting our work on the basis of the VWS resulted in the first prototype sharing many of the properties of a VWS, but manufactured with new materials and techniques which can be seen in figure 3.35. To utilise previous knowledge and constructions was also seen as FD in terms of utilising available resources, as a tool for several FD factors.

Prototyping through manufacturers

During the beginning of phase two, a strategy of prototyping with the manufacturers was used. The intention revolved more around learning about what material and manufacturer that was most promising, rather than the exact construction of the enclosure, as mentioned, the open source design of the CDC Ventilated Workstation was utilised to speed up the learnings from the manufacturers.

The early development of prototypes through collaboration with possible manufacturers meant that their know-how of the materials and manufacturing techniques forced the concepts to align with what was possible in reality, saving time and other resources from being spent on dead-end ideas, ideas that would later have shown to be too complicated or expensive to produce using their techniques. This approach also allowed us to quickly learn about the manufacturing technique, its strengths and its limitations, allowing iterations and re-designs with full innovation height, exploring what was possible within the manufacturing method. It was a give-and-take interchange between the designers and the manufacturers that took place directly instead of first creating concepts that later had to be redesigned to adapt to what was possible from the manufacturer's perspective. Thus the product and the production method both developed in parallel, discoveries or improvements of one would immediately lead to a change of the other. This close collaboration made it possible to challenge the manufacturer's perception of what could be created, bringing in new ways of utilising the materials and techniques that were already established. This was especially true for the acrylic concept, where new ways of utilising the manufacturing possibilities were discovered and evaluated together with the manufacturer

This co-design had several positive implications and brought several advantages in relation to the FD factors:

Robustness: The product was assured to be designed in a way that suited the manufacturer's methods and that benefited from their know-how as well as meet the manufacturer's acceptance of how the product was designed avoiding inappropriate design that the manufacturer knew would decrease the robustness.

Affordability: The utilisation of small-scale manufacturing and the manufacturing techniques suitable for small number batches generated a good understanding of the manufacturing cost and how to lower it most effectively, including the manufacturer's margin. This made it possible to evaluate what factors and changes in the design that would lower the cost of the product and benefit the Affordability, often without having to manufacture a new prototype which saved resources during development. For example, the thickness or size of an acrylic sheet could easily be changed in the design plans, the new price could then be inquired from the manufacturer, and with the information about the price, combined with the understanding of the material properties, it was possible to evaluate whether or not a major change in the construction could reduce cost while still maintaining robustness, and if such an effort was worth it.

Aesthetics: As the co-design approach granted a good understanding of the manufacturing and material characteristics, factors affecting the end user's acceptance of the aesthetics that a manufacturing method or design entailed, could be evaluated early on in the ideation and conceptualization process.

Sustainability: The work conditions surrounding a manufacturing method would be hard to evaluate and get insight into without visiting and working together with the manufacturer. This made it possible to learn early about the whole process, where certain manufacturers or manufacturing techniques could be excluded as a suitable option if it entailed problematic conditions.

Optimised performance level: Via constant discussion with the craftsmen, it was possible to challenge the material usage and dimensions of the product.

Usability: By working with the manufacturer from the start, the plans and models of the product were adapted into something that the manufacturer could easily understand and use.

Core functionality: Last but perhaps most important, working closely with the manufacturer ensured that the product could become reality.

Evaluation using the Frugal Design factors

As ideas, concepts and prototypes were developed, a structured method for evaluation in a frugal manner was needed, which is why the FD concept evaluation matrix was created (appendix C). The matrix, built on the eight FD factors, was designed to clarify core problems and to keep track of strategies to overcome the problems for each factor. This basically reminds the designers of the goal and methods to reach it. For each design iteration, the design was questioned in relation to each FD factor. With a critical FD view of the design, possible improvements were ideated for each factor. This helped break down the concept and its adherence to FD in smaller portions which made it easier to bring forward improvements. For each iteration and factor, changes and used FD tools were recorded.

Figure 3.35 illustrates a timeline of acrylic prototypes that were developed and iterated using the FD evaluation matrix. The four prototypes all fulfil the same core functionality, allowing a laboratory worker to perform AFB smear safely, however, the earlier prototypes are lacking in other aspects. The pros and cons of each prototype in the figure shows how the design could be improved for all 8 FD factors, even affordability, without worsening sometimes contradictory factors such as core functionality or robustness. The FD factor evaluation form helped illuminate all the pros & cons of the prototypes and thus advance towards the final iteration.

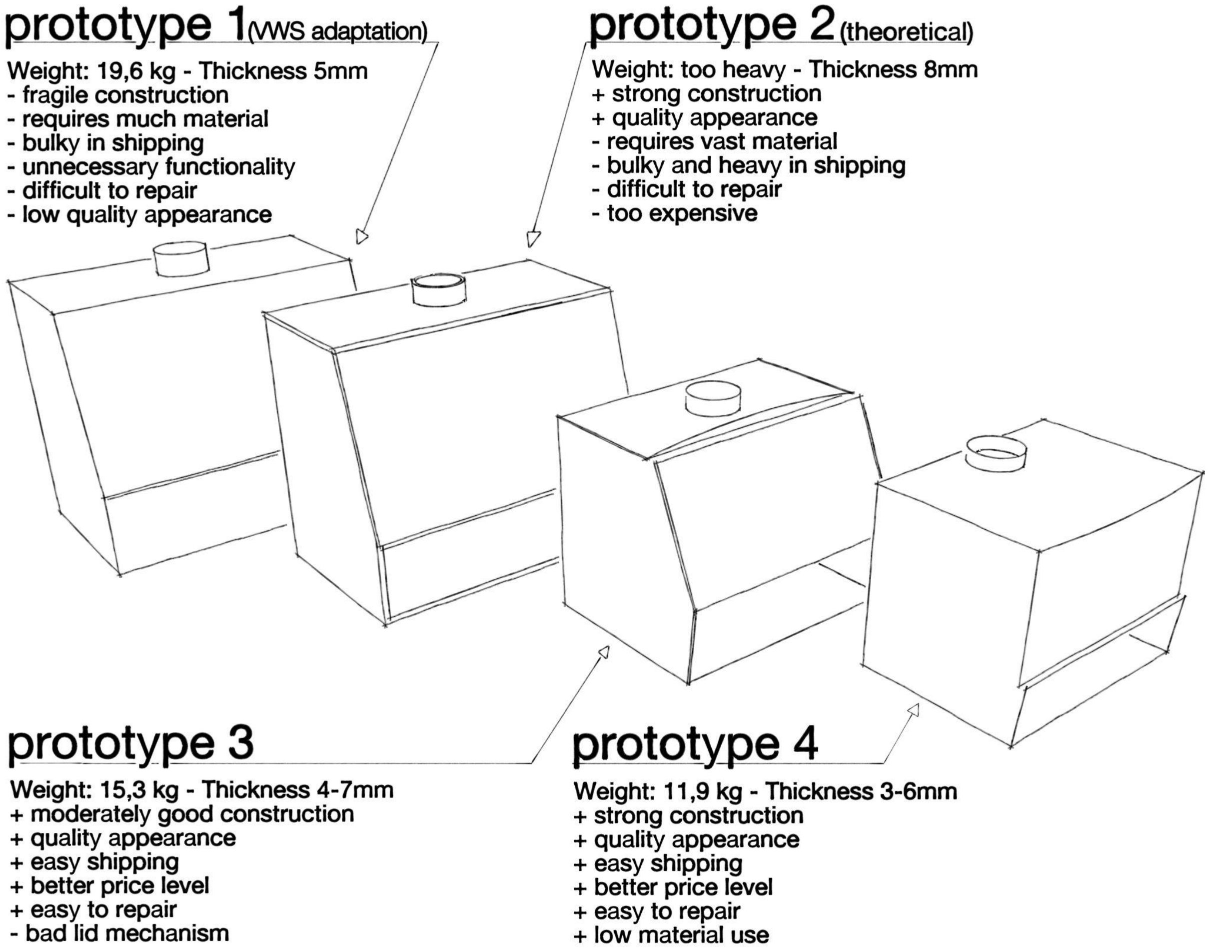


Figure 3.35 Four iterations of the acrylic concept and how the Frugal Design evaluation matrix brought insufficiencies of the designs to light.

Size optimization

One tool for FD that was extracted from the literature was that of reducing size. As this project revolves around a physical product, the optimisation of the size of the enclosure proved one big factor in reduced material consumption, which in turn has several frugal benefits. Conventional biosafety cabinets are large machines and their size is necessary for certain types of work. However, when the Ventilated Workstation was developed specifically for the AFB smear process, they reduced the size of the cabinet to half the size of many conventional cabinets. During this project, the needed size for a biosafety enclosure was once again questioned and evaluated using observations with mockups and interviews. This resulted in the size of the final design being even smaller than the original VWS (fig. 3.35 & 3.36), and a product that was more affordable and easier to transport among other benefits, but still entailing its Core functionality.

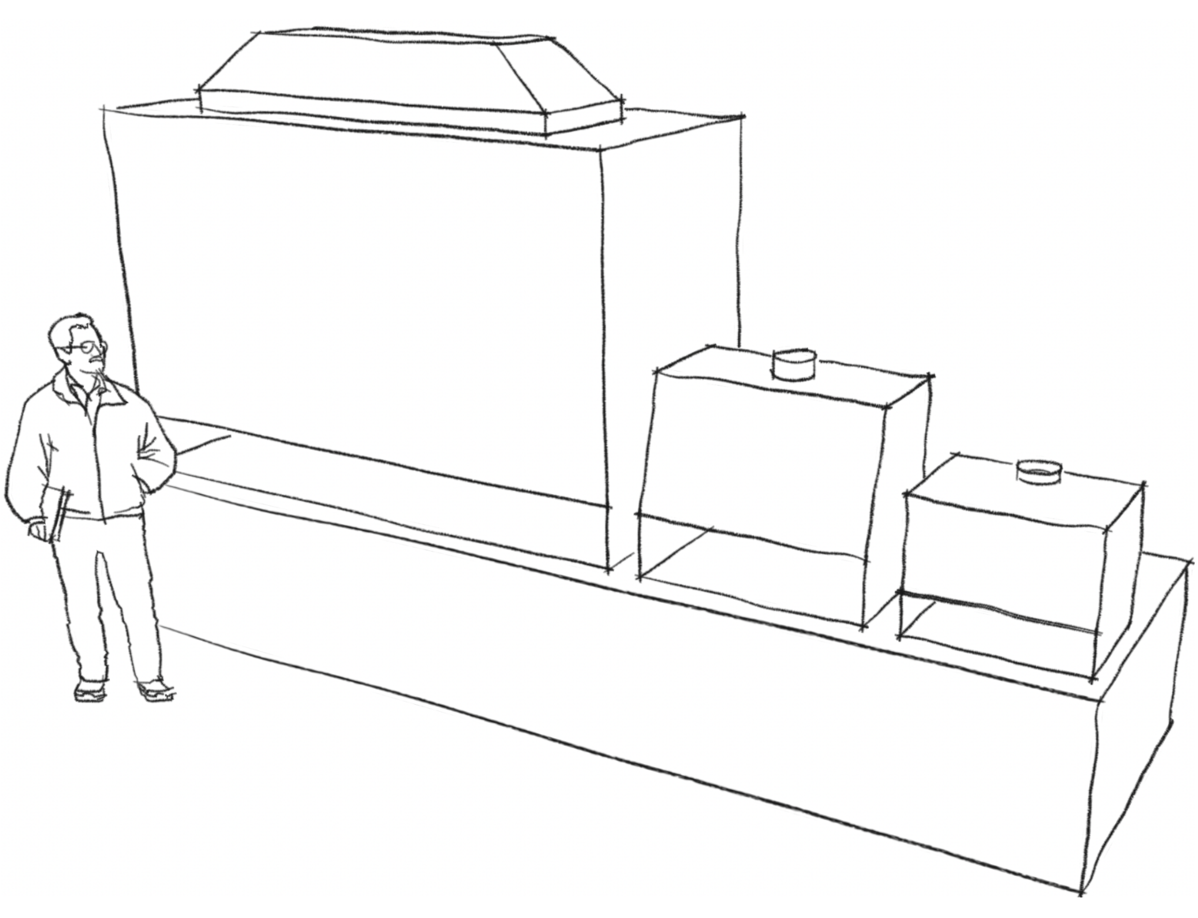


Figure 3.36 Size comparison between different designs, Nuaire two-person BSC class II (left), Germfree ventilated workstation (middle), FVWS (right). Note that the design on the left is intended for more tasks than just the AFB smear which may justify the bigger size.

Addressing the root cause analysis

As mentioned earlier, the design of the biosafety enclosure cannot solve all problems that cause the current biosafety situation at many laboratories. However, all the problem areas of the root cause analysis (figure 3.23) were addressed in some shape or form by the design. Whether it regards the training of lab personnel or adding a microbiological filter to please decision-makers, the solution has been designed to not contradict any root cause, but rather facilitate a solution. For the healthcare personnel, the solution had to include feedback functions that, in an easily understandable way, could verify and communicate a sufficient airflow maintaining a safety barrier. However, this had to be done in a manner that followed conventional training and test principles to not exclude existing resources and instructions from the existing health care system, which otherwise would have confused and required enormous changes in training principles. As for the authorities, the possibility to include sterilisation units where guarded even though it from a functionality aspect, in most cases, isn't necessary. This is to make the product obtain functions that can release responsibility and therefore being vital for succeeding with an implementation including a purchase phase including managers signing the purchasing order. However, since a sterilisation unit will add costs and increase complexity making the system less robust, it wasn't included as a standard part of the system.

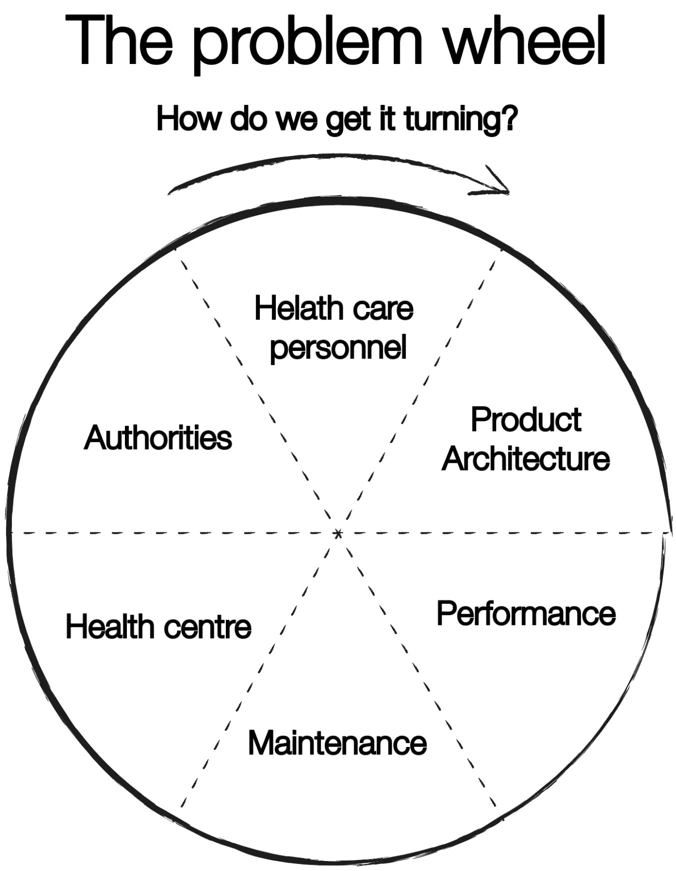


Figure 3.37 While all identified problems may not be solved by the design itself, the design must not counteract the identified problems eventual solutions

Adherence to the Frugal Design factors

After several iterations using the FD factor evaluation matrix, the final product adhered to the FD factors in several ways. The different characteristics related to each FD factor is presented below to demonstrate the adherence to each factor, proving the product design as FD.

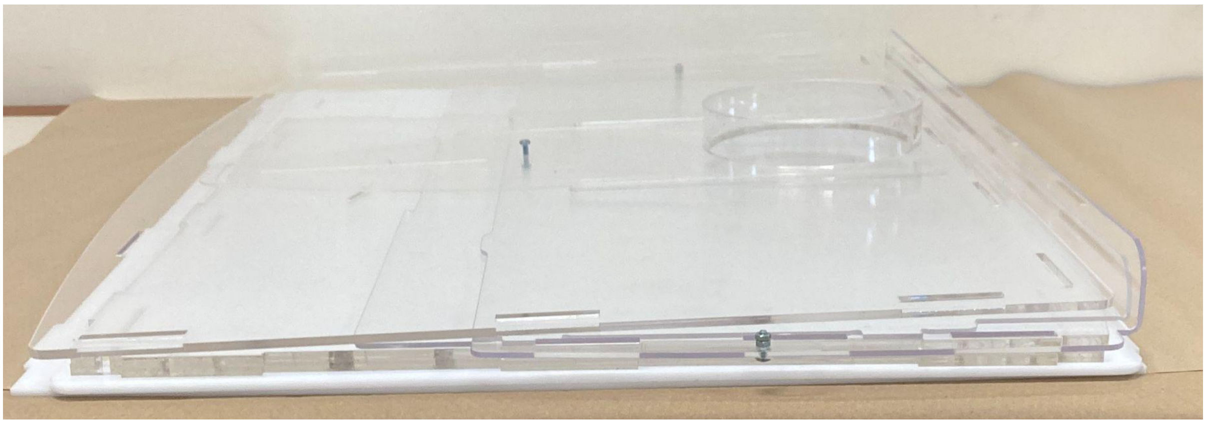


Figure 3.38 The FVWS as a flat package before being assembled, manifesting the frugality of the product in several manners.

Core functionality:

- Designed specifically for the AFB-smear process, nothing else.
- Removed conventional functions that are not needed, for example, an adjustable window, electrical outlets, integrated faucet etc.
- Reduced size according to the need for tools and workspace
- Integrated damper assembly to allow the enclosure to function with various fans
- Low complexity construction allows the product to be manufactured and implemented in contexts where conventional BSC´s are normally not found.

Affordability:

- Produced locally by established manufacturing avoids expensive shipping and import costs.
- Small-scale manufacturing method without the need for large batch sizes does not tie up resources on the manufacturer's shelves, with no need for storing products.
- The use of widely available material that does not need to be imported and shipped specifically for this application reduces cost.
- Modular design radically reduces shipment size and lowers the shipment cost of the product.
- Cheaper to repair as individual panels can be replaced as opposed to the whole unit.
- Reduced size consuming less material and therefore lowering the costs.
- Reduced material thickness due to improved construction reduce consumed material and therefore lowering the costs
- Produced with transparent material eliminates the need of additional light
- The choice of manufacturing method provides the possibility to integrate the airflow damper in the construction of the enclosure, without much additional work.
- Full system costs around 1500 soles = ca. 400 dollars. Which is much less than several similar products, ex. The ventilated workstation for around 3500 dollars not including the shipping costs.

Accessibility:

- Production in Lima makes the buying and transport process easier in this context.
- Open source design and plans make the product producible in any context with laser cutters and acrylic sheets
- Use materials and knowledge that are available in the context.
- Production method potentially allows the use of other materials
- One supplier makes everything, reducing need of contact with several suppliers
- Reduced size makes it easy to transport
- Modular design allows for transport of a flat, more easy handled package.

Optimised performance level:

- Work area optimised to a smaller area.
- Optimised height of the enclosure, optimised for performed work (lower material consumption)
- New design allows thinner material thickness.
- Good balance between affordability, material use, robustness and transportability.

Robustness:

- Design and material are used to their strengths to obtain robustness and reparability.
- Local manufacturing and know-how allows local accessible repair.
- The need for only one supplier increases the robustness of production, making it easier to find the right supplier for providing the spare parts.
- Open source and “CAD file centred” design lowers dependency on a specific supplier, many other manufacturers can also be used.
- Few components with little complexity reduce the number of failure points.
- Acryl - resistant against relevant chemicals and scratches.

Aesthetics:

- Material with good aesthetic robustness due to characteristics of Acrylic.
- Manufacturing method that provides high accuracy without increasing costs allows for an aesthetically detailed design creating a sense of a “real product” without risking affordability.

Sustainability:

- Reduced size and thickness reduces the material use.
- Acrylic is a recyclable material.
- Containing only one type of material, the FVWS can easily be recycled.
- Easy to repair due to modularity and local manufacturing.
- Acceptable working conditions for the chosen type of manufacturing.

Usability:

- Removing unnecessary parts reduces misuse.
- Instruct through design with panels a design that denies a faulty assembly.
- Indicator of airflow in operators field of view
- White base - Better work area

Discussion phase 3

The work in phase three was containing the same elements and activities that would have been seen in a regular design process. The biggest difference was rather the base for this work, formed in phase two, which affected the outcome more than the actual doing. However, within each activity was the FD approach affecting a lot.

Ideation moderated by possibilities

FD from the practitioner's perspective seems to be about designing through both the user needs AND the limitations that define the context. The limitations used to guide the process makes FD very focused on design for implementation. To achieve this, FD seems to be heavily dependent on early prototyping specifically in close cooperation with a possible manufacturer. Only then can the true possibilities and limitations be revealed. This makes it possible to learn about the product from a manufacturing- and an implementation perspective. Constraining the ideation to available resources was perceived as a way to make it easier to focus on the design possibilities within that certain manufacturing and material scope. With a fully open ideation space, it is likely that it would have been harder to focus the development to fully make use of the design possibilities provided by one certain manufacturing technique or material. This became clear when working with the acrylic and laser cutting as manufacturing methods. With the solution space locked to these parameters, we could fully explore and create innovation with as little need for disadvantageous trade-offs as possible. It is possible that this is an important element of the FD process for creating innovative solutions and to decrease the need for problematic trade-offs.

Reducing number of suppliers

One FD tool that has been discovered during this project is that of reducing suppliers for production. As the enclosure is part of a system, it has been necessary to find various components from different suppliers and locations in order to combine these into a functioning system, and it has become obvious that each time a new actor is involved, every time new materials or components are to be joined with another, and every time a craftsman has to work with something they are not used to, the need for resources increases, the complexity of managing the contacts and the manufacturing increases, it takes more time and the result is not always as good. By designing the product so that it can be produced by one single manufacturer, we increase the producibility, make the product more affordable and of higher quality, and increase the robustness of both the product and the production. This of course also changes the solution space according to which and how many suppliers you limit development to.

Utilising available manufacturers - prototyping with manufacturers

Utilising available manufacturing and co-designing through joint development of prototypes guarded the feasibility of every design iteration, ensuring the final concept was not only functional from a conceptual perspective but directly from the manufacturer's perspective. We argue that this is an important tool for FD when working in a resource-constrained context, it helps create products that are possible to realise, and also makes the process faster and less resource demanding.

Could "manufacturer prototyping" benefit projects that are not about FD?
In this case, small-scale manufacturing has been utilised together with a design and manufacturing process that didn't require any investment to be able to create real, functional prototypes. This granted several benefits. The question is if an early co-development with the manufacturer would lead to the same advantages in a context possessing more resources or for a development project focusing on more radical innovation. One risk could be that early collaboration with a manufacturer would limit the innovation space too much. However, if done at the right stage in a design project, preferably when a promising concept and a suitable material have been identified, the benefits we saw from prototyping with the manufacturer should be applicable also for design projects in resource abundant contexts. The deciding factor is maybe to what extent the project focuses on conceptual radical design or on creating a quicker, directly implementable design.

Evaluating concepts iteratively with the Frugal Design factors

Using the FD evaluation matrix was a great way to evolve the design with regards to every FD factor, ensuring each FD aspect of the design was evaluated for each step of prototyping. It is notable (and perhaps obvious) that these frugal factors can contradict one another, for example, a reduction of thickness may benefit affordability but reduce robustness and acceptance of the product appearance. The challenge is to succeed with the trade-off between the factors to not decrease the value of the product. This can be difficult when data is lacking regarding certain requirements such as in this case study when size/functionality requirements came to contradict affordability requirements. We could quite easily and confidently determine a minimum size for the enclosure so as to not inhibit the lab technician's ability to perform the work. However, we had a harder time setting the limits for Affordability, and answering what an affordable price could be. But by keeping all the factors in mind using a FD mindset and the FD evaluation matrix, and through high focus and much diligence, we were able to improve on all factors as we iterated the design (figure 3.35). It was, for example, possible to reduce cost, and also improve robustness from the early prototypes. The stage where the factors are in balance, and where benefiting one factor may lead to worsening of the other can be argued to be when design is more or less finished and the highest level of frugality is reached.

The challenge of how to define Affordability brings attention to another discussion. What is affordable is a question that is hard to answer for a customer, especially in a system where the end user and the purchaser are not the same people. Instead of feeling the necessity to define Affordability clearly, we believe that user studies and market research could be used to form a brief understanding of how to define Affordability in the context, and then move to a physical prototype early. The prototype can then be used to test the business offer quickly to determine Affordability or not. Only then can a real understanding of Affordability be achieved. This lies in accordance with many start-ups theories of using a minimum viable product to quickly test the business offer in reality.

Another way to address the issue of Affordability (that was used in this case study), is to get a rough estimate of what is affordable, and then focus on meeting the requirements of the other factors that are more well-defined. Then, while developing the product, the designer should continuously just keep pushing the price lower where possible. When working in this way, the product should become as affordable as possible as long as the requirements of other factors are well understood and adhered to.

The Frugal mindset

During the evaluation phase and the iterations of the product, the Frugal mindset was very useful to always direct the iterations in a more frugal direction through constantly small changes that improved the adherence to the FD factors. Even though the evaluation process was formalised by the evaluation matrix, the improvements of the product were done with an open and implicit understanding of what could improve frugality, due to our Frugal mindset. For example, the Frugal mindset resulted in the new tool of reducing the number of involved suppliers, trying to adapt the design to only make use of the benefits of one manufacturer's possibilities.

The Frugal mindset is what is present during the whole project and we argue that this is very important for succeeding when utilising FD since it affects how we gather information, ideate and iterate the product. To create a Frugal mindset, we have constantly reminded ourselves about the aim of using the FD factors. What this entails can be hard to clearly describe in a fashion that is applicable to many contexts, but what we want to emphasise is that designers should formalise what the FD factors mean in the context they are working in. During this case study it could, for example, be something as simple as putting the FD factors on post-its on the wall over the work desk, reminding us to reflect on these, sparking a Frugal mindset.

Phase 4: Context evaluation & Implementation

Figure 3.39 Microbiologist performing her work inside the FVWS

With a functional product, the focus in phase four was set on context evaluation and implementation (figure 3.40), to see how and if the biosafety enclosure could work satisfactorily in its intended setting, preferably in a self-sustaining manner. The work included three main focus areas: Installation in a laboratory, generalisation of manufacturing, and transfer of project ownership. The installation and the evaluation with users of the biosafety enclosure are what would be expected to be done in a regular design project. It's mainly the evaluation of the user's perception of adherence to the FD factors that could be said to differ from what a designer usually would do. However, the work included activities to develop the future of the FVWS, which might not be included in a regular design process, even though it of course has to be done for all products.

The laboratory implementation was done in order to learn about hurdles such as for example logistics, user opinions and the process of setting up the system etc. The manufacturer aspect regarded such things as the making of plans, models and manuals that could be distributed in order to allow others to produce and use the product. Finally, the transfer of project ownership was done to create awareness and communicate important information such as who could manufacture the product, where a manual that can be found online etc was conducted to try to make the product self-sustaining, through local entrepreneurship and awareness.

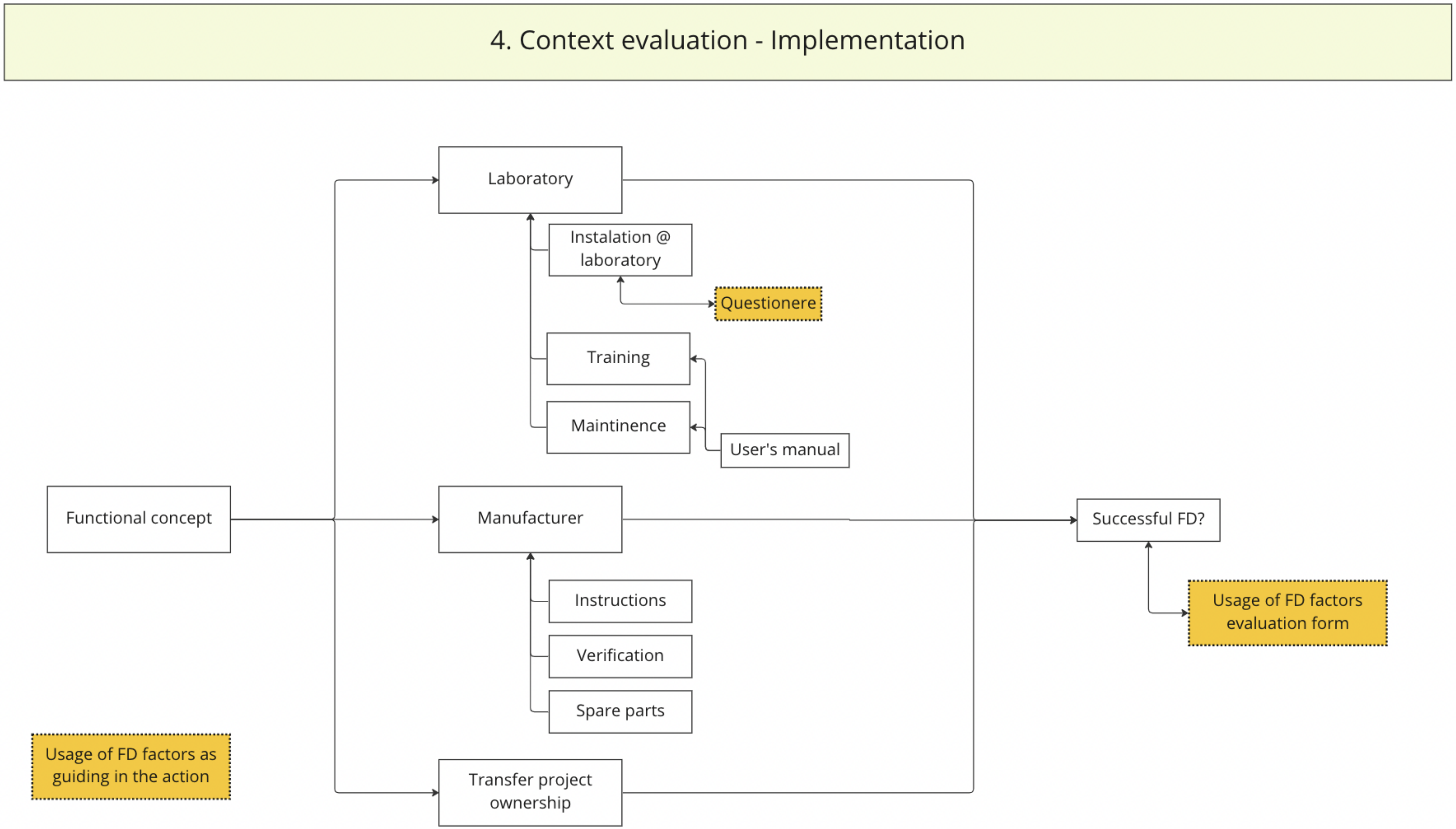


Figure 3.40 Process description of phase 4; context evaluation and implementation. Yellow (dotted stroke) boxes indicate activities with differences from a regular design process through the usage of FD factors.

Installation of the biosafety enclosure at a laboratory for design verification

To learn and evaluate how the product works in a laboratory under real work settings, the FVWS together with a filter unit and a germicidal UV-C unit was installed in a TB laboratory at the Luis N. Sáenz police hospital in Lima (figure 3.41). In this lab, the personnel were previously working with a completely dysfunctional cabinet, which ensured that this implementation would result in improved safety for the operators. The implementation was done at a later stage of the project than what is normal due to the fact that the biosafety enclosure is a piece of safety equipment where the performance of the solution had to be verified and rigorously tested before implementation. The installation tested the functionality of usage in relation to daily laboratory work rather than the protective functionality which had been tested earlier. The implementation also served as the first real-world prototype of how the product was set up, entailing mountings in walls, holes in windows, and creating inlets for air into the lab in order to achieve a controlled airflow. This gave us the first real indications of how frugal the entire system was to implement and not only the FD characteristics and functionality of the enclosure itself.

The installation of the FVWS required a sterilisation unit (UV-C or Filter) to be accepted and to avoid the fear of reprisals for the personnel. The installation of sterilisation units was a question of product acceptability rather than a Core functionality. The acceptance of the product relied on the responsibility aspect of installing safety equipment.

Figure 3.41 Introducing the FVWS after installation (left), first use, preparing glass slides for examination in microscopy to diagnosing sputum samples for TB (right).

Evaluation of the usage of the FVWS and the adherence to FD

To evaluate how the FVWS was perceived by the laboratory workers, a questionnaire, see appendix B, was used together with unstructured interviews to get the user's perspective of the enclosure and if it was perceived as a FD or not. The questionnaires and questions were designed to cover how safety was perceived, how the work environment was affected, and specific characteristics that were heavily affected by the design, such as size, light intensity and perceived robustness. The laboratory personnel were also asked to regularly take photos of the FVWS and send them via the mobile message-app WhatsApp to make it possible to evaluate how the enclosure was used and if any usage that wasn't foreseen occurred.

Users manual

The initial user studies performed in phase one and two, as well as the evaluation of the usage and the user's perception and opinions of the biosafety enclosure system showed the importance of the possibility to show that the cabinet is working properly, both in theory and in reality. This was to please authorities that may ask for documentation that shows that the enclosure works but also for the operator's own trust in the equipment. Therefore, the Frugal ventilated workstation manual was created (see appendix D).

Evaluation of the installation process

The installation served as the first "prototype" of a product installation. As could be expected, this brought up new issues. It was obvious that the system as it was constructed for the first implementation would not allow just anyone to do the implementation. Special tools that you may not find at a laboratory (especially in a low-resource context) and knowledge that can't be assumed to be held by the laboratory personnel were required, meaning that the lab personnel were not likely to be able to order the components and do the installation themselves.

Installation manual

To make future installations easier for anyone to undertake, an installation manual was created, (see appendix D). The guide also included some guidelines for choosing a fan, building ducting etc. to give a future user a solid base of important and helpful information to succeed with installing the whole system of the biosafety enclosure. This was of course done with a heavy influence from the context in Lima as we wanted to include information on exactly where certain components could be found, and which manufacturer could be approached.

Introducing an anemometer

During the implementation at the Police lab, personnel asked for some sort of a test unit, a way for the laboratory personnel themselves to show that the product was working. This verified the initial indications from the root cause analysis, pointing towards this being an important problem to address. A swing vane anemometer was developed and designed to be produced by the same manufacturer to ensure accessibility. The anemometer was included in the user's manual and the product was introduced and left to the operators to ensure that confidence in the functionality could be maintained.

Figure 3.42 Old dysfunctional cabinet (top), in the progress of setting up the first iteration of the FVWS for real-world use (bottom)

Implementation for manufacturing

When entering phase four, the FVWS design was technically producible by any manufacturer in possession of acrylic sheets and a laser cutter. In order to make this product as realisable as possible, the plans for the enclosure were drafted in several digital formats in both 2D and 3D, to allow manufacturers with different workflows to adopt the production.

FVWS manual

To deal with the information transfer of important knowledge to future manufacturers, a short manufacturer's manual, including necessary drawings, was created to make sure that a manufacturer would understand which design aspects were uncompromisable and why. For example, the toggles that lock the window in place may be manufactured in any colour, however, the base and back of the enclosure should be produced in a neutral light colour in order to act as a good, non-distracting work surface.

The FVWS manual, and other useful entities such as the 3D model, have been made available online and are accessible on the "FVWS repository" using the link or QR code below, The manual is also appended to this thesis in appendix D.

https://drive.google.com/drive/folders/11RK_pyjwNZXB98emu3b3dufYtUryyU1x?usp=sharing

Figure 3.43 The FVWS repository, relevant files and manual for anyone interested in the FVWS

Transfer of knowledge and sense of ownership to ensure continuation

In an attempt to transfer the sense of ownership of the project including the possibility to produce the product, the manufacturing & user manual (figure 3.44) was sent to manufacturers, laboratories and managers within the healthcare system. Transferring knowledge to IFHAD was also seen as important since they have a long-term engagement with TB care in several parts of Peru and the world and therefore get in touch with several contexts in need of the FVWS as well as managers with the possibility to acquire the product. To make the information easier to spread, all materials were also made available online using a QR code (as seen in figure 3.43). This code was included in the manual and printed as a sticker together with the project team's contact details. The sticker was added to the already installed FVWS to provide necessary information to anyone who would find the product interesting.

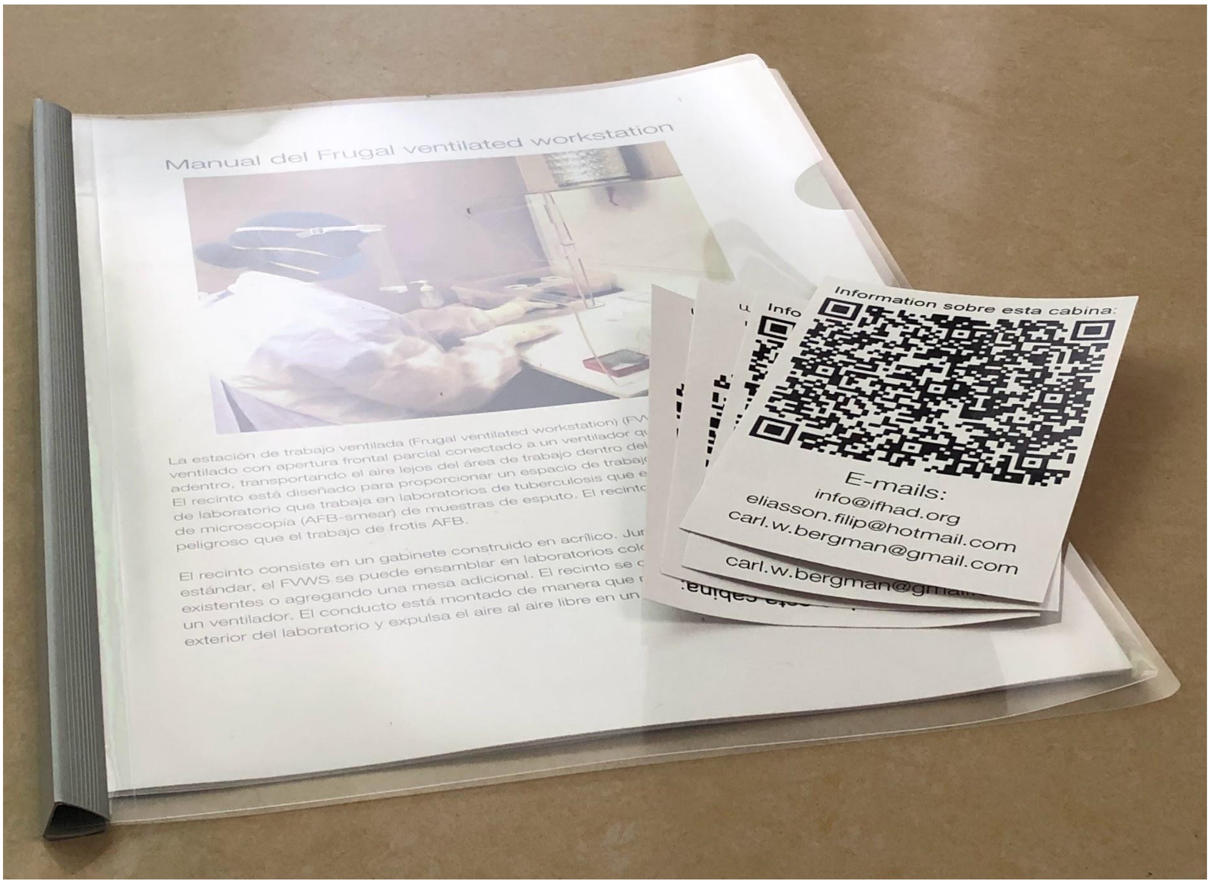


Figure 3.44 Manual and sticker that were used to spread information about the design

Discussion phase 4

The last phase of this development project mostly included activities that normally aren't included in what is considered the design process. Of course, this work must be done for all product development projects, but what makes FD differ is that it might be here that many of the critical factors answering if the design was successful or not are revealed. This phase made it obvious why a successful FD of a biosafety enclosure must also contain the installation process and not only the design of the enclosure itself.

The importance of a wide definition of Core functionality

The installation at the Police lab and their expressed desire to possess a verification unit that could give them the chance to by them self verify the functionality of the FVWS, but also to be able to demonstrate for managers that require documentation of a proper airflow shows the importance of having a broad definition of what a core functionality could be. This need was expressed in the early user studies, and then verified in the installation phase since the first part of the installation only included the FVWS and the function indicating yarn which was perceived as not enough for convincing managers that the FVWS do contribute to a safer work environment.

Core functionality vs. acceptability

The installation process demonstrates the important balance act between acceptability and core functionality. Even though the inclusion of sterilisation units wasn't required from a perspective of core functionality i.e a biosafety perspective, the question of responsibility and the view of what a biosafety system should contain made it obvious that acceptability of a product is as important as the actual functionality. If the product isn't accepted as a proper product, it will never be implemented and create any larger impact. The importance of acceptability shows in this case the relationship to the FD factor Aesthetics which also is a factor that is required to meet the requirements of the user's acceptability.

Importance of a Frugal installation process

One could reflect on whether the design of the product should be changed to make installation easier, eg. a standalone fan/filter box that does not need wiring or mounting on walls etc., or if the design should include installation by the manufacturer. This is a question that we have not been able to fully answer during the time available to the project. The product system could benefit from further work in this area.

Discussion Case study - Is the FVWS actually Frugal?

To start answering this question and to make a later argument about the utility of FD, we would like to illuminate all the beneficial properties of the FVWS design, that the FD approach has helped us to develop.

The benefits of the new design

The FVWS is a much more economical product than comparable alternatives, the price of less than 1500 Soles (≈400 dollars) is one tenth of the cost of the cheapest alternative that we could find that was commercially available ("BIOBASE", figure 3.12), even excluding the installation cost for these alternatives (which would likely not be insignificant). This is important as the cost aspect has been the number one concern voiced by many interviewees. This is relevant for the manufacturer, the decision makers and for the end user.

One reason for this lowered cost is size reduction, which has also provided several other benefits. The size of the FVWS has been dramatically reduced (compared to other cabinets, including the relatively small VWS from germfree, figure 3.13) to only accommodate the AFB-smear work. Apart from making the product more economical, this has greatly reduced the material usage in production, making it more sustainable. It is also noteworthy that the material used is 100% recyclable. The smaller size also makes the product more sturdy, both in terms of expression and feel for the end user, as well as in terms of actual durability and longevity. Another fact that becomes apparent after visiting several AFB-smear labs is that larger biosafety cabinets simply will not fit in many of the small rooms that are allocated as labs for this work, making a smaller solution the only solution that is implementable in these cases.

The smaller size makes the design lighter and easier to transport. The transportation is also greatly benefited by the product modular construction, making it shippable as a flat package. The modularity also makes the product easier and more economical to repair as single pieces can easily be exchanged if it is dysfunctional. Note that the pieces are designed to only fit together in one manner, making assembly a very simple process.

The ease of assembly is also thanks to the finger-joint type construction, and this construction coupled with the CNC manufacturing process results in a product with low tolerances and thus a reliable and reproducible quality. The manufacturing itself is economical and easy for the manufacturer, including only two manual steps in the process, the rest being done by the computer, allowing the manufacturer to work on other jobs. The fact that the product uses only one material and manufacturing technology allows a base level workshop with only one speciality (laser cutting) to produce the design. This means that the financial social benefits of the work can be directly put to use at the base of society, without losses through hierarchy and management of large corporations. The local small scale manufacturing also makes the producer more approachable for the user, both due to geographical closeness and due to the fact that the user can contact a person instead of a corporation, this all also makes the product more repairable, and perhaps more importantly, it makes the product be in tune with contextual preferences, visual norms, and other aspects that are important for acceptance.

Not only does the product utilise local production, but it is also constructed in one single material that is also widely available in the context. This makes the production more reliable as dependencies are reduced, and the product becomes more durable as a single material reduces wear and risk for damages around stress concentrations in the design.

The material itself (acrylic plastic a.k.a. Polymethylmethacrylat, PMMA), is recyclable, but most importantly for this product, transparent. This is a great advantage of this product as it negates the need for an integrated light in the enclosure, making the product more robust and economical. The transparency also means that if extra light is needed, it can be added outside the enclosure in the form of a desk lamp, or a mobile phone lying on top of the cabinet, meaning that no changes need to be made to the product to solve the problem. Note that the acrylic panels on the bottom and the back are not transparent. This is done in order to cover the often dirty and damaged countertops with a work surface that is easy to clean and not distracting.

The materials transparency along with removal of all unnecessary functions and parts results in a product that is easier to understand as it hides nothing from the user. The lowered complexity also adds further to robustness & affordability.

What do the users think?

After installation, use and revisit, including interview, observation and questionnaire, we can conclude that the users are happy with the product and find it a great aid in their work. The following comments were made by users regarding the product's effect on the users work situation and feeling of safety. It concisely puts our own situation into perspective, and makes it well worth all our investment.

"We are very satisfied, now we can work at ease"

"It is a great help "

(translated from spanish)

We would like to note that despite the users being satisfied with the product, two suggestions for improvement came up in the feedback. The users suggested making the window more inclined back into the cabinet to allow the users to observe their work more closely. They also suggested adding a light to the design. This feedback was encouraging as we have considered both these additions/functions, and come to the conclusion that these improvements in functionality are possible, but not necessary, as confirmed by the users satisfaction. These two improvements were omitted from the design as this granted many other benefits as described in the previous section.

So is the new design frugal?

The development of the FVWS has resulted in an open-source design that is manufacturable in all places where laser cutting technology and acrylic sheets are available. The implementation at the Police hospital TB laboratory, including questionnaire, observation and interview, showed that from the end user's perspective, which is a very important piece of the puzzle to “get the wheel turning” (figure 3.23), the FVWS is a successful FD. It is a vastly more affordable product that meets the user's requirements while making their work situation safer. The enclosure is also easier and less costly to maintain and repair. However, it is more difficult to say if the FVWS is a successful FD from an overall perspective. For example, though the design has been implemented, this has been done with a lot of support from the design team, and we have not yet been able to ensure that this product will be adopted and used widely. We have many reasons to believe that this is possible, but not even the fact that it is possible means that it is a success. Something that could benefit the product system, ease implementation and thus facilitate the success of the FVWS as a FD, would be further design work focused on the installation of the product, as the design of the installation has not been iterated during the case study.

From a FD perspective, it is only a success if it is widely implemented in the laboratories where it is needed. More time is needed to see if the stakeholders that are now engaged with the product, and that stand to gain from its use, can continue the implementation journey. If the production continues, if awareness is raised and if the local stakeholders continue to act for implementation, then we can say that a truly successful FD has been obtained.

Even though the design is adapted to many of the identified problems surrounding the topic, public health is a bureaucratic field and the hindrance to overcoming these barriers might be too high for being able to solve without interventions from a third actor, like an NGO that could operate and economically finance the implementation. Even if this is the case, we argue that the design is a more suitable one than the ones that so far have been available, since the cost is lower and the possibility to maintain the functionality over time should be higher due to the close connection to the context.

It's arguably so that the FVWS bears a better chance to succeed with implementation at a larger scale compared to alternatives due to its adherence to the FD factors. The fact that the enclosure at this stage is ready to be produced, installed and used makes it a useful resource and a great advancement in the work for better the biosafety situation in the laboratories that lack a biosafety enclosure in Lima and possibly other parts of Peru and the world.

It is our hope and desire that the design of the FVWS will come to further use than what we have been able to achieve during this project. That it will benefit work safety in more resource-constrained laboratories in Peru and possibly other countries and contexts as well. Therefore the information about how to manufacture the FVWS, including drawings is made available through this report, (see Figure 3.43 and appendix D), free for everyone to use. We encourage everyone that finds the design useful to freely use it.

Conclusions Case study

This case study has been used to investigate the design approach FD through testing its theory through practical work in a case study with the two aims of increasing the knowledge of FD and developing a biosafety enclosure that can be used within the Peruvian health care, where the desired protective equipment for the diagnosis of TB through the AFB smear method is lacking.

The case study has generated a design of a biosafety enclosure for resource-constrained TB laboratories called the Frugal ventilated workstation, which is technically verified, manufactured and installed in a TB laboratory in Lima, Peru. Further, practical experience from and learnings of the FD approach could help to characterise and explain how it could be used and performed.

We can briefly conclude the activities and outcome from the case study as follows:

We set out to do

- Overall follow a regular design process
- Utilise the FD factors to guide regular methods and activities
- When suitable, utilise, for each FD factor, proposed tools
- Work at the site to get full context understanding
- Focus heavily on reducing the need for resources
- Develop a biosafety enclosure adapted for resource-constrained laboratories

We did

- Followed a regular design process in terms of general phases and types of activities (except the ideation process)
- Made use of FD factors in all phases and in several methods
- Created a Frugal mindset defined by the FD factors
- Learned about which factors and other aspects of FD that worked and which did not

There were difficulties

- Defining Affordability
- Usage of a FD pricing model due to difficulties with defining Affordability.
- Working with specifically the environmental aspect of sustainability
- Using usability as a FD factor.
- Obtain a fully frugal installation process for the FVWS.

We achieved:

- A Frugal biosafety enclosure design adapted to the Peruvian context.
- Successfully installed the biosafety enclosure in a TB laboratory in Lima, proving its functionality.
- New FD tools.
- Experience from the FD approach.

4. Discussion - Frugal Design

The stated overall goal of this thesis is to perform research through design to gain a deeper understanding of FD and to further develop the approach as util for designers. In this discussion, we will try to sum up the project in its entirety in order to reach this goal by joining the theory with the learnings from the case study. In doing this, we can determine what parts of the theory functioned well and which did not, as well as highlight the completely new learnings that originated from the practical work of the case study. The synthesis of theoretical and practical learnings will lead to a revised view of FD and how the approach should be practised, as well as some further questions that could aid in further research and development of the FD approach.

To understand what FD is, it can help to see it in relation to general design thinking where FD is one of many sub-approaches of the whole field of design where the different approaches act as helping hands for designers (symbolically described in figure 4.0) as different toolboxes that can help designers develop products that adhere to the searched aim. In common for all these toolboxes is a general way of processing a problem and iteratively, through investigating the reality, developing a proper solution for its context.

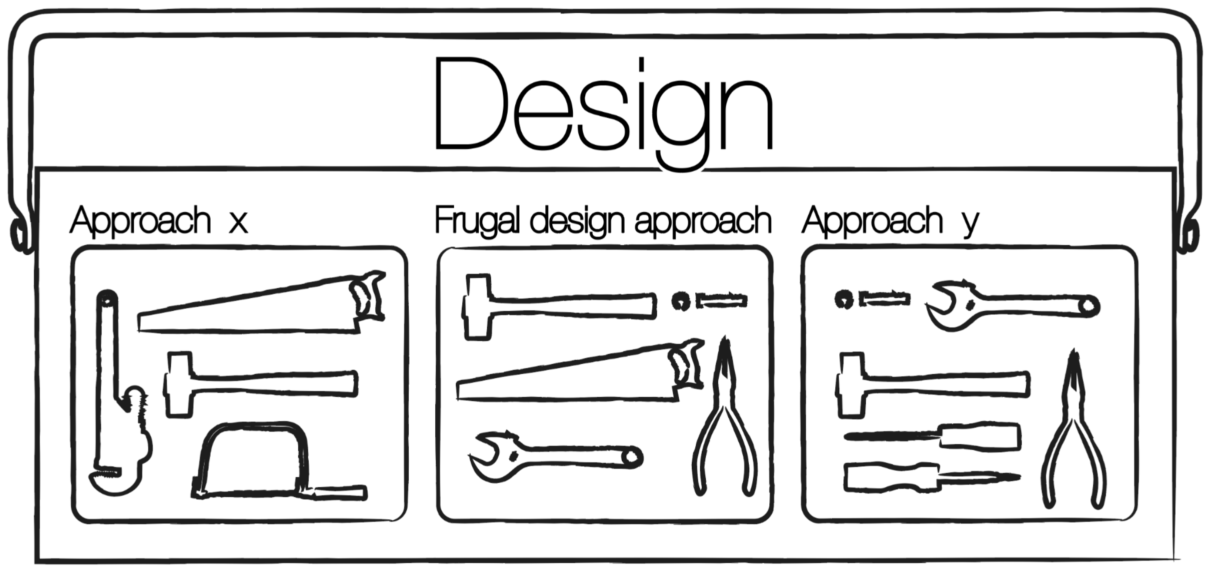


Figure 4.1 Frugal Design - One of many sub-approaches in the design universe, sharing characteristics and tools but each with its own set of strengths

Within the field of design, there are approaches, as exemplified earlier, that are more or less similar to FD in its definition, aim or processes while there are other approaches that differ more. However, utilising a particular design approach is seldom the goal itself for a designer, but rather a help in the work of designing new products. It is therefore the designer's own responsibility to explore and utilise the design approach they think is most suitable for the intended project, whether it is FD or not.

FD has in this work proved helpful for developing products that reduce resource consumption and increase the implementation ability of functionality in complex contexts, defined by resource constraints. Our FD framework in chapter two was built around eight FD factors and several process considerations which were concluded from theory. This framework was put into practice and tested in the case study. We will now discuss how the framework and the tools fared during the case study and suggest a new FD framework including the FD factors defining FD and a process model including process elements, proved important for the FD process.

The Frugal Design factors

The FD factors are the core of FD, and the most important element. Their characteristics are what define a FD product. Thus, it is through them we can say if a certain design is a successful FD or not. Further on, the FD factors are used in a variated way within the FD process to aid the development into a frugal direction. These factors, therefore, have a wide and important impact on the final outcome. Due to their importance, they should be carefully chosen to not limit the approach to a certain type of context or environment. Therefore, will all factors be discussed individually further down with the knowledge from the previous theory and new knowledge gained from the case study to determine which should be included both from the perspective of a proper definition of FD and from the perspective of their usefulness in the FD process.

As shown in the case study, the FD factors can give an angle of approach when trying to understand the context, examine root causes and find requirements, making sure that all perspectives are taken into account when examining the problem, and guide the work in a frugal direction. Typical design activities like interviews, observations and concept evaluation can gain from the involvement of the factors in the process of creating FD. This aligns with much of the theory that advocates for a general implementation of the FD factors in all parts of the design work, like Bolaños (2013) suggests using the factors to narrow down ideas or Santiago et al. (2019) propose using them as means of reflection.

The FD factors also play a crucial role in creating a FD mindset, which in the case study, was shown to affect the whole process in a not so concrete, but yet effective and important way. Similar to how Soni & Krishna (2013) & Pradel & Adkins (2014) points out the Frugal mindset as important for the designer to succeed with the FD design work, the case study also showed the importance of the FD factors as guiding in the design work and that the FD factors aid in the process of creating this mindset, especially for a new practitioner. The fuzzy nature of a mindset is the reason for the importance of a concrete starting point when forming a Frugal mindset. The factors help with creating the boundaries for the mindset, defining what factors to understand and align to due to the FD factors defining the FD outcome.

With a general understanding of the importance of the FD factor as a joint element of FD, all the factors concluded from chapter two, and used in the case study are discussed separately below to elaborate on which are to be retained and which are to be changed or discarded.

Affordability

Definition: The user in need of a certain function has sufficient resources to acquire and use the design providing that certain function.
Tools: use local manufacturing, utilise available resources (material, financial and institutional), decrease the number of parts to reduce complexity, reduce the size, reduce material consumption, aim for modular design and prototype early together with promising manufacturers.

Affordability has been one of the most prominent aspects of FD in the literature, and it is no surprise that the importance of cost has been emphasised by users and decision-makers in the case study as well. Affordability is obviously an important factor to achieve a good frugal product. The challenge has been to uncover the affordable price point. If the intended client, in need of the design, also has the resources to acquire and use a product, then the design is affordable. If a designer doesn't know how much a client can feasibly pay for a product, the designer will not know when to stop making the design more economical which is problematic as the price of the design is likely to always be somewhat conflicting with other important aspects such as the performance or robustness of the design.

While the question of affordability was one of the most prominent in the literature, proposals for methods of research and defining what level of the cost was perceived as affordable were not very common, and those that were proposed were valid for critique. Thus, during the case study, we were not able to greatly benefit from the literature in this regard. Instead, the work of achieving affordability was focused more on cost reduction, which was also a common characteristic to use for defining FD. Despite these hardships, it was obvious during the case study that affordability was important to several of the stakeholders and the factor was important for guiding the frugal mindset. Cost reduction on the other hand does not serve a purpose by itself. Cost reduction is relevant for FD since it entails affordability for the users but affordability does explain the true purpose of the factor. Therefore do we still argue that Affordability is to be considered a FD factor even though it is most likely to be achieved through cost reduction. We can see that the area of FD could benefit from further research into tools that could help determine affordability in a given context and product category.

Accessibility

Definition: The design is practically accessible for the user/customer. This means that the user must be able to easily acquire the product in terms of buying, shipping etc.
Tools: Use locally available resources (manufacturing, material and institutional), minimise stakeholders involved (manufacturers, material and component supply etc.), aim for modular design and minimise included materials.

Accessibility can imply anything from avoiding imported goods to a product that is accessible online on every smartphone. Regardless of how it materialises, the factor of Accessibility cemented its place among the FD factors during the case study. In the context of the case study, problems with the accessibility of not only the product but also maintenance and spare parts were obvious. The definition of accessibility had a big impact on the design process which materialised in the choice of the manufacturer, the materials and the know-how which were all accessible right away. The view of accessibility in the theory was a bit sprawling, but unity about the importance of the possibility to access the product to achieve a successful frugal product between the theory and practical learnings from the case study makes us conclude Accessibility is an FD factor.

Core functionality

Definition: The design consists of only the core functions that fulfil the necessary and important needs of the user, no “nice-to-have” features are included.
Tools: reduce complexity, simplification.

Core functionality has been found to be of great importance for FD, both in the literature and during the case study. By not exceeding the inclusion of functions as often done in conventional design to create competitiveness and satisfaction, the factor of core functionality guards frugality and brings several benefits such as reduced resource consumption and reduced robustness when the number of failure points is reduced. This way of working with functionality free space for innovation in the search for adherence to the other factors. Consequently, it is important not only for the definition of FD but also for it to let the designer focus on the other factors, which might require space for an innovative solution. Core functionality will continue to stand as an important factor for FD.

Optimised performance level

Definition: The performance of the design is in equilibrium with the core functionality. The functionality should be able to perform “just enough”, rather than “a little extra”. This means lowering the margins.
Tools: reduce the size, and reduce material consumption.

While core functionality is a binary characteristic (either the product does what is needed or it does not), the optimised performance level for these core functions is more complex. The performance level is a factor that is likely to suffer when eg. materials selection and manufacturing technologies are encroached upon due to resource scarcity. Or on the contrary, a very high-performance level might risk detrimental effects on the affordability of the product. This is why the factor is called ***optimised*** performance level. Higher is not necessarily better, at least not when striving for a frugal product. Being able to confidently decide which performance level is suitable will facilitate the creation of requirements and limits for these, and free up the designer to focus on achieving other factors of the design. During the case study, this meant an approach consisting of learning what trade-off in performance level was acceptable to the users and then working from there. For example, the users needed a work area inside the FVWS, however, when optimising the area of what was needed to perform the work, it was possible to decrease the area from the starting point of the VWS. The Optimised performance level should be kept as a FD factor since it helps the designer to critically understand and assess the core functionality.

Robustness

Definition: Robustness means durability over time. The product withstands wear and tear and is easily repairable when needed.
Tools: reduce complexity, utilise local know-how, local resources and local manufacturing, minimise involved few suppliers of material, components and activities, aim for modular design, and abstain from mixing materials.

Robustness was the subject of interesting discussions in chapter two, and more interesting considerations arose during the case study, eg. is the product more robust if it is easier to repair? or if it is less likely to need repair? A dictionary may give a clear definition and meaning of the word robustness, but to a designer that strives for FD that will survive long use while also balancing the other necessary factors of FD, the answer is not as simple. The answer is also likely to be different in each context the designer faces. The tools to achieve robustness will also be different depending on the type of product, as it could be anything from a bridge to a computer program. The tools we will present will have been influenced by the physical nature of the case study. Even though robustness can be achieved in many different ways, the importance of Robustness for a product with the aim of making functionality available in the short and long terms is extremely important and is one of the factors that clearly differentiate FD from other cost-focused design approaches such as Jugaad innovation or Low-Cost innovation. Therefore is it important to maintain Robustness as a FD factor defining the FD approach.

Aesthetics → Acceptability

Definition: The design is accepted by the user. This can entail both aesthetic aspects as well as customs, values and culture.
Tools: aim for visual appeal and trustworthy impression, guard functionality level to not be perceived as not provoking, utilise pride of local manufacturing.

The importance of aesthetics was brought up as an FD criterion by a few of the literary sources and the relevance of the factor was also confirmed during the case study. While not the factor that consumed the most time or attention, it was apparent that it mattered to the end user and to decision-makers. What also became apparent was that other aspects that were important for the users to accept the product kept ending up in this category during our work, despite not necessarily having to do with aesthetics. This is why we quite quickly stopped considering the factor as aesthetics and instead started working with it as the factor of acceptability. This worked well and we propose that acceptability should be considered a FD factor instead of aesthetics, and let aesthetics be included within the concept of acceptability. This also helps the designer to understand what level of aesthetics to strive for. The requested aesthetics for a FD product isn't about creating the most aesthetically pleasing product, it's about achieving a, from the perspective of the user, acceptable aesthetic appearance.

Sustainability

Definition: The product, manufacturing and use must be sustainable. This includes both social and environmental sustainability.
Tools: Reduce all costs, strive for resource-saving, engage only with acceptable working conditions, reflect upon material selection, abstain from material mixing, aim for modular design, and reduce material consumption.

Sustainability was added as a FD factor in chapter two and even though the case study showed some difficulties with how sustainability was utilised as a FD factor, we still argue that it should be a part of the FD factors. It would be irresponsible to exclude it since it is common in theory to use sustainability as an argument for why FD is important to adopt. It is additionally not so that sustainability necessarily is achieved by the rest of the factors. As an example, there are no other factors that hinder the usage of toxic materials. Therefore, is it logical to include sustainability as its own factor, guarding that sustainability isn't only a consequence of reduced material consumption but without a focus on other sustainability factors. The case study also showed the importance of considering social sustainability in terms of work conditions etc. when working in a resource-constrained context where less safety equipment is in use and more questionable working conditions could be found. To not unconsciously be a part of supporting this, also social sustainability should be considered within the factor of sustainability, in accordance with how Bolaños (2013) also defines the concept of sustainability and argues it to be important for FD.

Usability

During this project several insights and design ideas have revolved around usability (making it impossible to assemble the product incorrectly for example). Usability is a super important factor to address if a product is to be valuable to the user, regardless of whether you are doing FD or more conventional UCD. Usability was added as a FD factor in chapter two, to test if it was applicable since it bears such importance for successful design. The theory pointed out it more as a consequence of FD. However, unlike many of the other factors of FD, in the case study, the usability factor did not change anything about the design work as it is already so heavily incorporated into the design thinking of designing successful products. We argue that usability is important, but that it is not helpful to consider it a frugal factor as this lessens focus on the factors that are there specifically for frugality. We will remove usability from the list of FD factors as we believe that this will focus the FD tool more on its specific purpose, and rest assured that usability will not be forgotten in the overarching UCD.

Frugal Design tools - Ways to obtain adherence to the FD factors

In addition to the FD factors, several tools were proposed in the literature and tested in the case study. The case study work also led to the conception and development of a few more of these FD tools. The tools are many times closely related to the factors and many of them were in the theory proposed as defining characteristics of FD. The reason why we argue that they rather are a possible route to obtaining the FD characteristics is that they are very context-dependent and that they are not necessarily useful for all contexts. The theory argues that FD is important to adopt also in contexts that aren't limited by resource scarcity. In that case, it is important that the FD factors are chosen to be general. Therefore do many of these proposed definitions of FD serve better as tools that can, but are not required to be used to obtain the FD factors.

It's important to emphasise that there is no inherent value in using the specific tools presented below, but their only purpose is to have an effect on the FD factors. The tools presented have in the setting of the case study been proven to be useful for one or several FD factors. They may prove less useful in another context that is not subject to the same type of resource scarcity. However, we will cover each of the tools regarding their performance and perks, in hopes that these will prove useful in future projects. The tools can also help a new FD practitioner to understand the approach and ways to achieve FD.

Validating the tools from the theory

The tools presented here are all previously presented in the theory to varying degrees and then utilised in the case study.

Local manufacturing

Serves: Affordability, Accessibility, Robustness, and Acceptability.
Local manufacturing is an example of a tool that is well suited for the type of context where the case study was done. In such a context, where infrastructure and shipping systems are expensive and/or unreliable, local manufacturing has increased the affordability and accessibility of the design by cutting freight costs, getting rid of import fees, and minimising transport. Local manufacturing has also benefited the product's robustness in the sense that spare parts and repair know-how for this particular design is locally available. Finally, it has also strengthened acceptability as the manufacturer's techniques and thus product appearance is already present in the context.

In order to show how these tools are context and solutions specific we can take the example of LifeStraw (VF, 2011). As described in chapter two, LifeStraw is an affordable solution for clean drinking water, but the product requires advanced production technologies, this means that it is not a product that will be produced and used in the same location. The local manufacturing tool is not helpful for such a product. Keep in mind that this context dependence is a factor for applicability as we cover the rest of the tools.

Utilising available resources

Serves: Affordability, Accessibility, and Robustness.
The use of available materials was commonly brought up in the theory and was a very helpful tool in the case study. The final result and many of its most beneficial characteristics originate from the fact that the material and other design choices were very much based on resource availability, whether it be financial, material, technological etc.

Decreasing number of parts and complexity

Serves: Affordability, Core functionality and Robustness
Reducing complexity, for example by reducing the number of parts to a product, was suggested as a way to improve usability in theory. We agree that it may be one way to reach better usability, but we also saw many other benefits from reducing the complexity as well. In the case study, the reduction of complexity led to a lower cost, higher accessibility and better robustness of the design.

Size reduction

Serves: Affordability, Optimised performance level, Robustness and Sustainability.
A few authors in the theory chapter mentioned size reduction as a tool to achieve FD. Size reduction turned out to be an efficient tool and for our type of product one of the best potentials for improvement in relation to the decreased resource consumption and thereby affordability and optimised performance level, robustness, and sustainability. The tools' high benefits may be dependent on the design's physical nature, however, it is not very hard to imagine how it could be interpreted in a helpful manner eg. for a digital product.

Reducing material consumption

Serves: Affordability and Sustainability
Reducing material consumption is stated in theory as a way to benefit the design’s sustainability and affordability. During the case study, this focus on the reduction of material consumption in all stages of the product's life (from development to production and use) all functioned well, and this particular tool allowed the product to also be more producible and transportable. Sometimes it was good to be reminded about the possibility to reduce material consumption, which in our case mostly manifested through decreasing the material thickness as the re-design improved the design and allowed for more and more decrease of the thickness of acrylic sheets. .

Modularity

Serves: Affordability, Accessibility, Sustainability and Robustness
One of the theory sources suggested modularity, specifically for the prototyping stage in order to make product development less resource intensive. While we had some use of modularity in this sense, mitigating the need for an entirely new prototype each time we made a new design iteration, modularity led to many benefits when it was also incorporated into the final design, making it more robust, affordable, accessible and sustainable due to increased possibility to repairs

Cost reduction

Serves: Affordability
Reduction of the cost was suggested in different forms in the theory. While we were not designing to meet a set strict budget, or by trying to cut prices to a percentage of comparable products as suggested, during the case study we found that a general focus in the back of the head to always think of the cost of each decision, even just briefly, helped us maintain a grounded and pragmatic solution space, leading more quickly to a finished design. Thus, saving resources.

Visual appeal (local aesthetic preference)

Serves: Accessibility
The importance of visually appealing products was emphasised by several authors in the theory. Even though no distinct tools were possible to derive, Brem et al. (2020) suggested local aesthetic values as a characteristic of FD. This was interpreted as a suggestion to evaluate the aesthetics of the context and especially within the same product category as the intended design, to gain knowledge and inspiration of what aesthetics that is perceived as acceptable in the local context. For the case study, it was difficult to get any concrete data on acceptable aesthetics. This was likely due to the product category. However, the tool gave us indications of symbolics and aesthetics creating pride which could increase the acceptance of a product.

New tools

In addition to the tools that were proposed during the theoretical work and later tested in the case study, another set of tools was found and developed independently from the literature. These are detailed below and may prove useful in future frugal ventures.

Prototyping early with promising manufacturers

Serves: Affordability
In earlier projects, we have produced prototypes and developed designs internally and then periodically or only at the end of the development process, approached a manufacturer in order for them to produce the more or less final design, with changes made to facilitate the use of their manufacturing technologies. However, in this case, the early focus on available materials and manufacturing technologies lead us to encounters with the potential local manufacturers quite early on. We decided to utilise these manufacturers not only for the final design but for every prototype along the way. This meant that we were very quickly able to advance from the idea to the finished design while always adhering to what was possible to produce, negating the need for a redesign of a refined design at the end of the process. Another factor is that this cooperation built a relationship and commitment with the manufacturer. Early prototyping with the manufacturer is something that we strongly advocate for future projects as long as it does not inhibit innovation.

Reducing the number of suppliers

Serves: Affordability, Robustness and Accessibility.
During the case study, our focus on robustness and affordability lead us more and more towards trying to utilise the strengths of only one supplier or manufacturing method, instead of using multiple suppliers. This has resulted in more agile/nimble product development as there was no dependency on, or need for finding a middle ground between suppliers. Apart from making the development process less costly and faster, the final product has seen benefits to robustness, both structurally and regarding the supply of the product, and to affordability and accessibility, with fewer resources being needed in the supply chain with the lead and production times being decreased.

Using fewer types of materials

Serves: Robustness, Accessibility and Sustainability.
As mentioned, the case study work led us to try and reduce the number of suppliers, this type of thinking and the benefits from this led us to also consider the benefits of reducing the number of materials used by that supplier as well. The procurement, management and storage of materials for the production of our design are thus simplified. The design can also be optimised for the material properties of that single material, making it more robust by avoiding compromises within the design and making it easier to steer clear of structural deficiencies such as stress concentrations. This characteristic is also relevant for the aspect of sustainability, as products that are not made of mixed materials are easier to recycle or repurpose.

The process of Frugal Design - How is it done?

Even though much has been written about FD and how it is characterised, little in the theory could be extracted about the FD process. Several FD process elements such as the importance of being at the site, identification and utilisation of local resources, a focus on cost reduction, a new pricing model and constant usage of the FD factors were proposed. Few concrete models explaining the FD process were found but several similarities with the foundation of design thinking and the design process indicated that FD also relies on a regular design process. The concluded view of the FD process was brought to the case study to test and learn in practice how FD is practised.

The case study verified the utility and importance of several of the proposed process elements and rejected a few. The case study could also verify the relation between FD and a generic design process and we still argue that this is where the FD process is anchored. However, some unique FD process elements that differentiate FD approach from what could be expected from a generic design process were discovered or further elaborated from the theory. In figure 4.2, we propose a new model of the FD process where the similarities to a generic design process could be noticed but also elements unique to the FD process.

The model (figure 4.2) contains three main phases: Determine *intention*, *Determine requirements* and *Ideation & evaluation.* These are expected to take place in every design process and could be recognised from the model of the design process by Wikberg-Nilsson et. al (2015), see figure 2.4. The differences between a regular process and the FD process could be found within these phases with effect on how and what type of activity that is performed. During the first phase, *Determine intention,* do a frugal designer focusing more on getting to know the context and what defines the FD factors in the given context. The second phase, *Determine requirements*, is the one that differs most, where also the type of methods and activities differs. In the work of determining requirements, the incorporation of the two elements that we call "Identifying suitable possibilities" and "constraining the ideation space" takes place. This is when the designer makes sure to develop a realisable design. The third phase is again relying on well-known methods and activities but within the constraints defined by phase two. In phase three there is also a need for handling trade-offs in a typical way for FD. Taking place during the whole design process is the adoption and usage of a frugal mindset and a usage of the FD factors.

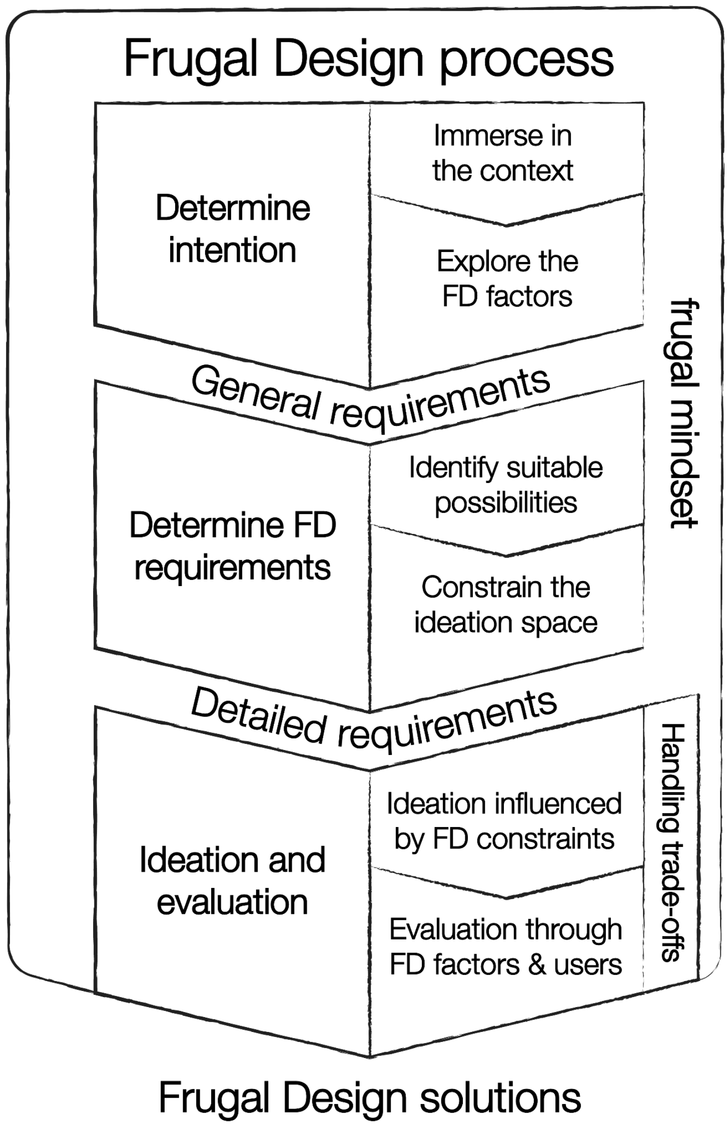


Figure 4.2 The Frugal Design process

Frugal Design process elements

All FD process elements are general in the sense that they don't rely on a certain context. However, they will most certainly generate very different input and boundaries to the design process in different contexts. Thus, also here, we argue for the need of only including process elements that are general. All FD process elements will be discussed in detail down below to give a more deep understanding of how to incorporate these in the design process since it is at this stage much of the previous theory has haltered.

Immersion in the context

In accordance with the theory's emphasis on the need for immersion in the context, the case study showed the importance of this process element. It is when the designer deep dive into the context and explores not only the problem area but the whole environment where the problem exists that a full understanding of what defines the FD factors and thereby a FD could be achieved. Therefore, the designer must first immerse in the context to be able to start reflecting upon and exploring the FD factors. With a deep understanding of the context, the exploration and understanding of paths towards a solution can be performed and achieved which is key in determining the intention. Without understanding the characteristics of a context, including its limits and possibilities, it will be impossible to determine a viable intention.

The case study showed us that, as opposed to the user-centred design, the user was not the sole number one priority. Instead, it has become obvious that FD is a very context-dependent design approach adopting or even utilising much of the resources or constraints present. Exemplified with our solution of a biosafety enclosure, we argue that it is a FD for the Peruvian context but put into another context, the whole product may fail if there are no usable acrylic manufacturers available. Several of the reasons why the design ended up as it did is directly connected to what was possible to acquire and achieve in Lima. Therefore is it reasonable to say that FD is a context-dependent design approach and to undertake such a venture, the designer needs to start the journey by being present and immersed in the context.

Utilising the FD factors

To utilise the FD factors as a process element was one of the proposed methods where the theory was most in agreement. But how and where in the process that FD should have an influence wasn’t expressed in total unity among the sources. Different suggestions were presented and the conclusion was to see it as a general process element and try to use it whenever it was found useful. The case study could confirm the usefulness of utilising the FD factors within the design work. They worked especially well for being incorporated into regular design activities such as user research and requirement listing. The FD factors also played a key role in the formation of a frugal mindset, especially at the beginning of the process where all the factors were used as a base for reflection. The conclusion is that the FD factors shall be present and incorporated from the beginning of the design process to the end where they are found useful in the design work and in accordance with the process figure 4.2.

Identifying possibilities and constraining the ideation space

The, by theory, advocated focus on identifying and utilising locally available resources had a big impact on the outcome of the case study. It showed that this way of work does not affect the general design process but highly affects the ideation process since it limits the designer's solution space with more factors than only user requirements.

To ensure that the ideation process generates concepts that hold a better chance to be fully realisable and implementable solutions, the ideas and concepts should rely on what we know as resources that conform to the FD factors and requirements. They must in particular be accessible and affordable. Therefore the designer should identify the possibilities in terms of resources that are required for a certain solution path, a path that shows promise in the specified context. With these possibilities identified the designer should constrain the ideation of the next phase, to only utilise these known possibilities in the creation of concepts.

We argue that this is one of the biggest differences between FD and a regular design process and that it requires a new activity in the phase of determination of needs and requirements. As can be seen in fig 4.2, the identification of possibilities stands as a new activity that needs to be done in the same phase as when the user needs and requirements are explored and determined.

The process of identifying or determining the constraints for the ideation focused around identifying resources that were seen as possibilities. I.e the determined constraints were based on real identified context characteristics such as material and manufacturing availability. Ramdorai & Herstatt (2015) instead suggested using arbitrary constraints as a way to spur innovation. What implications more arbitrary constraints would have on a design is hard to say since this project has focused on constraining through what is accessible but it is an interesting concept since, as discussed in chapter 3, phase 3, the difficulties with identifying possibilities in a context that does not suffer from resource constraints might be harder. The focus on accessible resources has ensured product accessibility and possibly also generated a more effective design process by avoiding concepts that hold no chance of being realisable. The case study also made clear that the introduction of constraints generated new perspectives, which spurred innovativeness. We would however like to note that these constraints could have detrimental implications if they are set arbitrarily.

Adopting and using a Frugal mindset

The development of the FVWS has shown the importance of adopting a Frugal mindset that can follow the designer during the whole design process. In theory the Frugal mindset was brought up as a part of the FD process. Soni & Krishnan (2013) argues that FD includes a Frugal mindset and Pradel and Adkins (2014) point out the importance of adopting a FD mindset as a part of the FD process. However, a clear description of what a Frugal mindset is, and how it affects the design work isn't presented. Our Frugal mindset had an effect on most design decisions and especially during the identification of possibilities, when exploring the context. To explain what it is, in an attempt to formalise a fuzzy topic, it can simply be explained as an understanding of the FD factors and the implications they have on the design together with a constant strive for reduction of resource consumption, regardless of the type of resource, including cost reduction. To explain how to create this mindset, we argue that the formalised FD factors are efficient for creating and adapting to the Frugal mindset since it is what defines a FD. All the way from the beginning of a project, the context and the environment can be explored by these factors, charging the mindset with a frugal understanding of the boundaries for the project scope. Add to this a desire, almost an eagerness, to reduce unnecessary resource consumption. To live with the FD factors, always processing their meaning and implications for the given context is how we successfully created our Frugal mindset.

In relation to how to create this mindset, the importance of using the FD factors from the beginning of the project is important to emphasise. Trying to reflect upon and define the FD factors early in a project, for example as in the case study, through a context persona that defines in relation to the context is a good way to create a foundation for the Frugal mindset.

To conclude, we argue that creating a Frugal mindset, by utilising the FD factors while being at the site in the context is an important part of the process of creating successful FD.

Handle trade-offs

All types of design work are full of trade-offs to balance the requirements. FD can sometimes be referred to in a bit of a glorified manner without acknowledging the necessity of trade-offs. To exemplify, this quote from Singh & Das (2020) "The concept of frugal innovation is to create low-cost products without compromising the functionality, usability and performance of the product" demonstrates what we believe is a slightly reality-detached perspective. As seen in the case study, for example Affordability often ended up a bit contradictory with Robustness. In reality, FD contains trade-offs where all these characteristics brought up by Singh & Das seldom are possible to fully achieve without trade-offs in between them.

The experience from the case study is rather in accordance with Lecomte & Blanco (2015), which put forward the perspective of FD always being a trade-off, especially between core functionality and affordability, calling a successful trade-off "good-enough". A situation in a context with few, and expensive alternatives for local manufacturing would likely end up in a trade-off between Robustness and Affordability. This state of good-enough might be the state of the FVWS where the iterations had increased the Affordability without decreasing the Robustness. Is worth noting that the iterations of the FVWS actually created better and better adherence to all the FD factors in accordance with Singh & Das' idea of doing everything better. The trade-off took place when the affordability was as low as possible without compromising the other factors too much. However, it is clear that the FVWS would have been even more robust if not handling trade-offs between Robustness and Affordability. Thus, it is possible to achieve good adherence to all FD factors. When the product has reached a state of good-enough, then more harmful trade-offs occur, which should be avoided. Therefore we advocate to balance the factors between each other until a good enough state is obtained.

If any of the factors is to be perceived as more important than the other needs to be further investigated before a possible ranking between the FD factors can be determined. If a ranking could be decided, that could possibly make the process of trade-offs easier for the designer.

Evaluate with the Frugal Design factors - a FD evaluation matrix

The FD evaluation matrix as a process element was specifically developed for the evaluation of each design iteration during the case study and was based on the FD factors. For each concept and each iteration, the design was critically evaluated in relation to each FD factor to answer if there was room for any improvement and how these improvements could be materialised.

The matrix helped us as designers to view our product from different perspectives, consider deficiencies, and see opportunities that may not have been obvious otherwise. This is the most concrete way in which the Frugal mindset materialised process-wise, ensuring that we maintain focus on the factors and don't forget aspects that are important in the context at hand.

The evaluation matrix wasn't proposed previously as a formal process element but since many of the authors argued to incorporate the FD factors in the design process, it is not a fully new idea. However, we argue that it is advantageous to let the FD evaluation matrix be a formal part of the FD process since it is so important for the work in improving the design towards a FD.

Frugal Design - what does it entail, what is the effect?

FD is an approach that focuses on the user in a context and on what's possible to achieve in relation to the context, rather than only focusing on the users and their needs. This creates ideas and concepts that are adapted to the requirements of a wider group of stakeholders. All of the FD factors, especially the factor of Core functionality, cut out wishes and desires that aren't absolutely key for the intended functionality. This means that the designer actively excludes some of the user's wishes to be able to achieve a true FD. This shows the core of FD, its aim of making a solution available for a user in the most resource-effective way possible. This was demonstrated by the implementation of the FVWS, where the users after evaluating the FVWS expressed possible improvements of the enclosure, which had been actively opted out since they were not considered as core functionalities and that the users despite this were very satisfied with the product.

How this restrictive perspective on what is necessary to include in the design affects the user, is not discussed much in the theory. We would like to comment on this topic that it is important to learn from the case study, and accept that some wishes and desires can not, and should not be fulfilled. This may sometimes lead to disappointment from the user's perspective, but it may also be the only way to implement a solution. It is important for a future frugal designer to be aware of this aspect of FD, the users will not always be perfectly satisfied with the design.

With a good understanding of the FD factors and how they are defined, the relation between them can be described to help demonstrate the ultimate purpose of FD. Figure 4.3, shows what we believe to be the consequences or effects of each factor. When reflecting upon these effects, eventually we can see that they all lead towards one final goal: a solution that, in every aspect, makes a valuable function available to the user. For each of the tools pertaining to the FD factors the same can be said. Each specific tool affects one or several FD factors, but ultimately, they serve the same ultimate purpose.

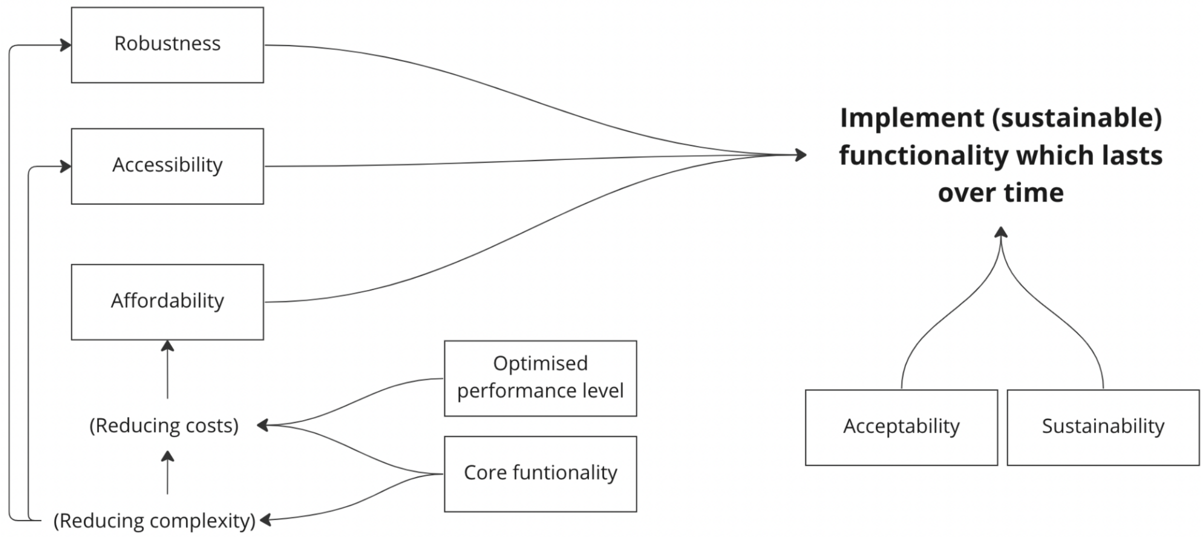


Figure 4.3 The relation between the FD factors demonstrates the ultimate effect of FD.

The effect of FD as presented above demonstrates the benefit the design approach can have, why it likely is a more useful approach if the biggest problem is to succeed in achieving the implementation of certain functionality. Since the effect of FD is an implemented functionality it is obvious that the design approach requires a specified context. All the aspects that relate to the FD factors are also very context dependent and could not be determined without a specific context with specific users. This is reflected in the FVWS solution, which to a high extent is perceived as frugal due to the accessibility of the acrylic cutter manufacturing technique. If this was not accessible, the FVWS could not be produced, and thereby not acquired, and thus wouldn't be a FD. As such we can only confidently say that the functionality of the FVWS bears a good chance to be implemented and used over time in the context of Lima and Peru.

In a context where it isn't a challenge to succeed with the implementation like in Peru and other resource constrained contexts, the consequence might instead manifest itself with a more affordable solution than other products on the market since many of the actions also leads to a reduced resource consumption, and therefore reduced costs.

The designer's responsibility to reflect upon and choose a proper strategy

As we argue that the main goal of the FD approach is to make a valuable function available to the user, we would like to emphasise that the road to this goal is not what makes the product a FD. In our case study, we ended up utilising local manufacturing and materials. This served the aim of creating a stand-alone and self-sustaining production system and business opportunity, without the need for further interventions from an outside context. Another possible design strategy could for example have been to involve an international NGO to distribute and implement the product. In that case, FD could also have been utilised. No option should be ruled out because of preconceptions about what is frugal or not. Instead, the designer needs to reflect, consider the FD factors, and decide which strategy is most likely to reliably give the users the most value.

There are interesting questions to how FD materialises and how the FD process functions when working with a different strategy as described above. This is one example of further research that could be valuable to the development of FD, especially since FD is brought up in theory as a design approach that holds high potential, also for contexts that are not so resource constrained.

Ethics

The philanthropic aspect of this project has been a driving force behind its initiation and execution. However, it is also clear to us that this project, its topics and the way it has been executed, bring other ethical considerations to light. This section will delve into these ethical questions and provide an examination of the potential implications of the project, as it is important to consider both the positive and negative effects of this thesis in order to aid future research to be executed in a responsible and ethical manner.

Ethics of Frugal Design

This project has several times been balancing between functionality and cost which is a trade-off typical for FD. The question is if it is ethically correct to design a product that is not 100% safe and instead aims for good enough, especially when it comes to safety equipment. This makes the discussion of what is ethically correct more nuanced but just as hard for the designer. If a choice has to be made between a good enough product that is cheap enough to be implemented, or a product that is too expensive but perfectly safe, what is the right call? The answer we lean towards is perhaps obvious considering the content of this thesis. We believe in creating something that is good enough, since it has the best chance of implementation, and thus, a positive impact. But we still think the question is well worth considering from an ethical perspective.

When working in a resource-scarce context with fewer regulations or less compliance with regulations, we have noticed that there is a risk that a design will utilise manufacturing methods that entail a work situation that isn't acceptable in a more developed context. How to handle this situation isn’t obvious. Of course, if the manufacturing method entails work conditions that are very bad, it should be avoided. But, when do we consider the work environment as too bad? In the case study, the workshop where our manufacturer worked with CNC lasers to produce our design, the ventilation is one example of what would most likely be judged as insufficient in Sweden. But how do you as a designer make the decision of selecting another type of work environment if that will lead to a less successful product with less chance to create a positive impact. It is the FD equivalent of “the trolley problem” (figure 4.4). Is it better to inactively allow a bad work situation to go on, or is it better to actively improve the situation, but use another bad work situation to do so?

In our case, this choice was not so hard to make, as we had no problem working with the manufacturer in the acrylics workshop ourselves. But imagining a work situation that is so bad that you would not tolerate it yourself, we believe it could be a difficult choice to stop development and abandon a promising concept. Even this topic contains trade-offs, however, in a less pleasant manner. However, with these reflections in mind, it is likely that it is possible to avoid most unpleasant situations and the reflection of what to watch out for would be easier.

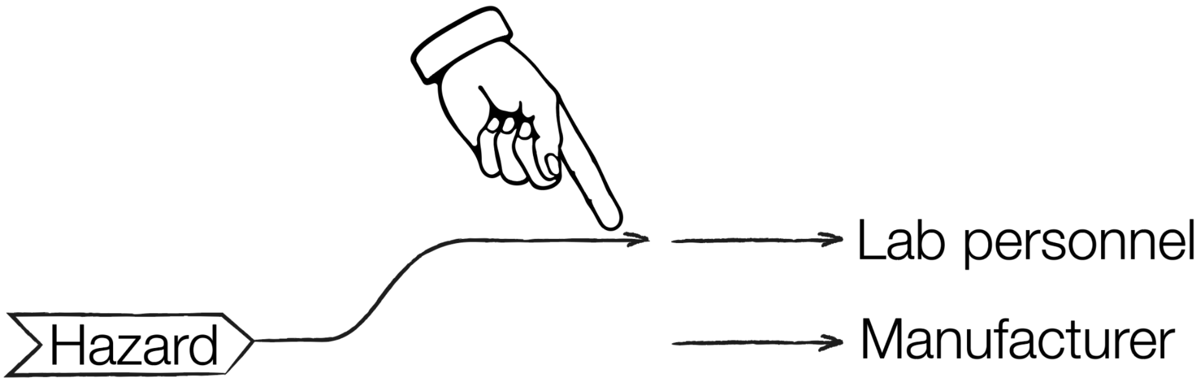


Figure 4.4 What is the right call? an inactive choice to not "take advantage" of the manufacturer, or an active choice to help the lab personnel

Ethics of this project

Ethical considerations of the project and how it was executed are presented below.

CO2 emissions

The choice to execute this master thesis as a research-through-design project in Peru brings up several questions about ethics, an obvious one is the fact that we flew on a plane around the world to perform a project that we did not need to do. However, this is a sustainability consideration that can be seen as trivial in comparison to others. It is also easy to argue that the project contributes to a safer work environment for healthcare personnel fighting against the global spread of TB and that this is of huge importance and may justify the carbon emissions.

Swedes coming to save Peru

A more difficult consideration is the aspect of being a Swedish engineering student in Peru. It could be seen as a presumption that we can do something that national resources here in Peru cannot. Is it not naive to think that we can come and contribute to development in a context we know almost nothing about in advance? We justify our work here by acknowledging that every person has something to bring to the table. We believe we can contribute to something good in Peru, just like we believe that a Peruvian would be able to contribute in Sweden. The fact that this project and this development have not been done before confirms this, justifying our presence in this context. However, the project would have benefited in several ways, and been more ethical, if the project could have involved collaboration with local students, maybe planning this thesis as a cross-cultural design project instead of working alone as we have done. This is a consideration that we missed, and a shortcoming of the project.

Language barriers

The risk of miscommunication with the participants in the case study has been a concern throughout the entire process, particularly at the start when our poor Spanish abilities limited the complexity of our user studies. We have questioned the ethics of advancing with a design project without certainty of a full understanding of the users. However, our ability to gather necessary information from other sources to create a design that ensures user safety, and our improved Spanish proficiency over time, as well as the fact that we have financially invested in this project ourselves and not the users, leads us to believe that the risk of negative consequences due to miscommunication is minimal.

Including or not including sterilisation unit

The decision to not include a sterilisation unit as standard in the design was based on the balancing between the risk related to the AFB-smear process and the negative implications such systems would have on the adherence to the FD factors, likely decreasing the chances for the FVWS to be implemented in the future. We concluded that sterilisation units aren't needed due to what's argued from WHO. However, it is unlikely that a laboratory handling TB, regardless of process method, in Sweden would install a biosafety enclosure without a sterilisation unit. So who are we to come here and argue that some safety barriers aren't necessary here? Even though it can be questionable to not include it, we still argue that in total the exclusion of sterilisation units will increase the probability of implementation of the FVWS and thereby increase the biosafety.

Possible consequences of this thesis

Developing frugal safety equipment that is more affordable, but limited in its ability, has the potential to make safety equipment more widely available to a larger population, which is good. However, there is a risk that this more economical equipment, designed for resource-constrained contexts, may also be purchased in less resource-constrained contexts where better equipment is available, solely for the purpose of cost savings. This could potentially compromise the safety of these better-funded labs.

Our intention to make safety equipment more accessible and affordable to those who need it most is meant to be for good. However, we can see and consider the potential negative consequences of this type of work. It is possible to imagine one impact of this type of approach on the safety culture in general as safety culture is built much upon trust in the equipment.

Cheaper equipment could lead to users feeling a lack of respect for the product and its purpose, ultimately compromising the safety culture. It may also change user perception of what a biosafety workplace is, that it is not so special. This is not our intention.

Another aspect that relates to the product's limited abilities is that we cannot control what users will do with this publicly available design, if another lab eg. decides to have this design manufactured to then use it for processing of TB cultures (a much more dangerous and contagious medium than sputum samples, for which the FVWS is inadequate), this could have terrible consequences. To do this safely the design would have to be developed further.

Sustainability of Frugal Design

In design theory, FD is often brought up as a sustainable design approach that will lead to better products and less environmental impact, Frugal innovation has also been described in terms of a tool to give resource-constrained people of emerging markets the chance to consume affordable products. But from an environmental perspective, can the production of new products, and increased availability to the masses, really be congruent with sustainability? This will consume more resources than not consuming new products at all. This is a perspective seldom brought up in relation to sustainability and FD.

In contrast to the tool "local production" which streamlines our design process by making it more prototype-able and producible, a corresponding sustainability tool such as "use recyclable materials" does not have the same level of impact. While this type of tool could drive innovation and influence the design, in this particular context, plexiglass which is technically a 100% recyclable material, is not being recycled, making its recyclability irrelevant. An alternative approach would be to use a tool that emphasises "using a material that is recyclable in the context." This would have set hard demands on us and of course, resulted in an interesting outcome. However our design already uses less material than comparable products and produces little waste during production, and if we continue to add more environmental aspects to our design process, the solution space becomes more limited, and at some point, it would become restrictive in a negative sense, and risk leading to an unfinished project, which would be very wasteful. The right call in this situation is not obvious, but we acknowledge that we have not fully addressed all aspects of environmental sustainability with the design of the FVWS.

Critique of Frugal Design

During this project, some areas and views of FD that have been present in theory and in practice have been open for critique. This is presented below.

Questioning the innovativeness of FD

As the FD approach prioritises affordability and resource efficiency, some argue that this approach may limit the potential for innovation and the development of really novel solutions. It is possible to imagine that the focus on repurposing and adapting existing knowledge and technologies, rather than creating new ones, may limit our ability to think outside the box and generate truly innovative solutions. Additionally, the constraints on resources and cost may discourage a designer from experimentation and risk-taking, which may be key for driving innovation. We however also think it is important to note that the FD approach can drive innovation, by pushing the boundaries of what is possible with limited resources and encouraging creativity to find new solutions as we have done with the FVWS. Finally, we want to point out that we do not argue only for the use of FD, there are many design approaches, suited for different objectives.

Well-performed user-centred design should take these factors into consideration even though they are not emphasised as in the FD process.

Is FD too focused on physical design?

We have done this development project in order to research and improve the FD approach in a very general manner, and we have argued that the approach can be used for any number of design tasks. However, we are not oblivious to the fact that the theory and ourselves have had a high focus on physical designs. This has been a recurring topic of discussion in our little design team for months. We have eg. thought of applications for the FD factors in the digital realm, but we are very willing to admit that the FD approach has not been proven to work beyond physical design, at least not to our knowledge. This highlights a highly interesting area for further research on FD.

Limitations in the result

The results from this project have several limitations, both in regards to the product developed but also in relation to what limitations the research of the FD approach itself entails. These limitations will be presented below.

The effect of the nature of TB and health care

The nature of this case study limited the access to the end users and the possibility to perform exhaustive observations of the work. Both due to the difficulties with getting access to the laboratories, as well as the risk of working in an unventilated laboratory while TB samples were processed. Our experiences from earlier design projects allow us to definitively say that simulations and interviews cannot substitute real world observations. The implicit knowledge of the users that comes into practice during their work is something that they cannot convey to anyone outside of a real world scenario. We accept this, as well as the fact that it is not appropriate for us to be working continuously under hazardous biosafety conditions, for which the lab personnel have training. The question is if more observations would have led to an impact on the design? We would have learned more information without doubt, but would that information have taken us in another direction? We do not know. We want to clarify that we have been present and observed work under real world circumstances, but not to the extent that we would normally. This has been a limitation of this project

Developed in Lima, extrapolation to other regions

The FVWS has been designed in Lima, but with the goal of being useful in other parts of Peru and the world as well. This has been done by focusing on what's available in Lima (and likely other large cities) and adapting the design to be easily transportable. However, focusing on the area around Lima risks creating a product that does not meet user requirements or context requirements that may exist in other regions. For example, the FVWS requires access to electricity. If there are other regions where this access is limited, the solution won't be implementable as it is today, and this is just one example. Therefore, we can not be fully sure that the design is suitable for other contexts than Lima.

5. Conclusion

FD is an approach to design that many find promising. Previous theories on the FD approach have however been lacking aspects that are important for the design practitioner, particularly in regards to the process of FD. As such, through our theoretical and practical work, we have concluded that FD is a relevant design approach. It is a design approach that is contextual dependent, and that can help designers deliver valuable and lasting functionality to more users, especially in resource-constrained contexts. FD will make it easier for designers who are not familiar with the challenges of such contexts to adapt and successfully design for these segments. With our new knowledge we have been able to develop the approach further, describing what FD is and how it can be implemented, as well as the risks and pitfalls that should be avoided. Finally, we have condensed our learnings into a FD framework consisting of a process model that describes how to apply the 7 FD factors, and a set of tools that can be used to achieve these factors. Our framework is available below as figure 5.1. More in depth discussion of the contents of the framework illustrated in the figure can be found in section 4 of this thesis.

RQ1: What is Frugal Design?

Our work has led us to define FD by seven FD factors. A product that adheres to all these factors for a certain context is, by our definition, a FD. These seven factors are Affordability, Accessibility, Core functionality, Optimised performance level, Robustness, Acceptability and not least Sustainability. A product that adheres these seven factors will be characterised by its ability to be implementable, and sustainably bring lasting functionality to the users. This makes FD particularly useful in design projects where contextual factors make it difficult to successfully realise a design concept

RQ2: How can Frugal Design be utilised by designers?

One result of this project is a FD framework designed to help design practitioners in their execution of the approach. Before detailing the framework further we would like to emphasise that the process is NOT the goal of FD, the solution, its characteristics and potential to impact are what it is really about.

The FD framework

Below you can see figure 5.1 that briefly describes the framework we have developed for the FD approach. The FD framework (and execution) revolves around the seven FD factors. These factors are to be continuously observed and reflected upon during the FD project, creating what we call a Frugal mindset (detailed in section 4 “Adopting and using a Frugal mindset”). The framework includes a FD tool set that we have found useful in addressing the FD factors. The tools and factors are useful in the FD process as illustrated in figure 5.1.

The FD process revolves around deeply immersing in the context and determining which solution strategy will create lasting value for the users in it. Then examining and detailing the constraint and possibilities pertaining to the FD factors under these circumstances, in order to use these conventional hindrances to instead facilitate and katalyse ideation in a more constricted solution space. By this point a FD mindset should be well developed for the context. This and the FD factors are used to evaluate the solution together with the user.

TOOLS

Use local manufacturing
Serves: Affordability, Accessibility, Robustness & Acceptability

Utilise available resources
Serves: Affordability, Accessibility, and Robustness

Decrease numbers of parts & reduce complexity
Serves: Affordability, Core functionality and Robustness

Reduce size
Serves: Affordability, Optimised performance level, Robustness & Sustainability

Reduce material consumption
Serves: Affordability and Sustainability

Implement modularity
Serves: Affordability, Accessibility, Sustainability & Robustness

Always consider cost reduction
Serves: Affordability

Follow contextual aesthetic preference & norm
Serves: Accessibility

Prototype early together with manufacturers
Serves: Affordability

Reduce the number of suppliers
Serves: Affordability, Robustness and Accessibility

Use as few types of materials as possible
Serves: Robustness, Accessibility and Sustainability

FACTORS

Affordability
The intended user has sufficient resources to acquire and use the design

Accessibility
The design is practically accessible for the user or customer. The user must be able to easily acquire the product in terms of buying, shipping etc.

Core functionality
The design consists of only the core functions that fulfill the necessary and important needs of the user, no "nice-to-have" features are included

Optimised performance level
The performance of the design is in equilibrium with the core functionality. The functionality should be performed "just well enough", rather than "a little extra"

Robustness
Robustness means durability over time. The product withstand wear and tear and is easy to repair

Acceptability
The design is accepted by the user, entail aesthetic aspects as well as customs, values and culture

Sustainability
The product, manufacturing and use must be sustainable. This includes both social, environmental and financial sustainability

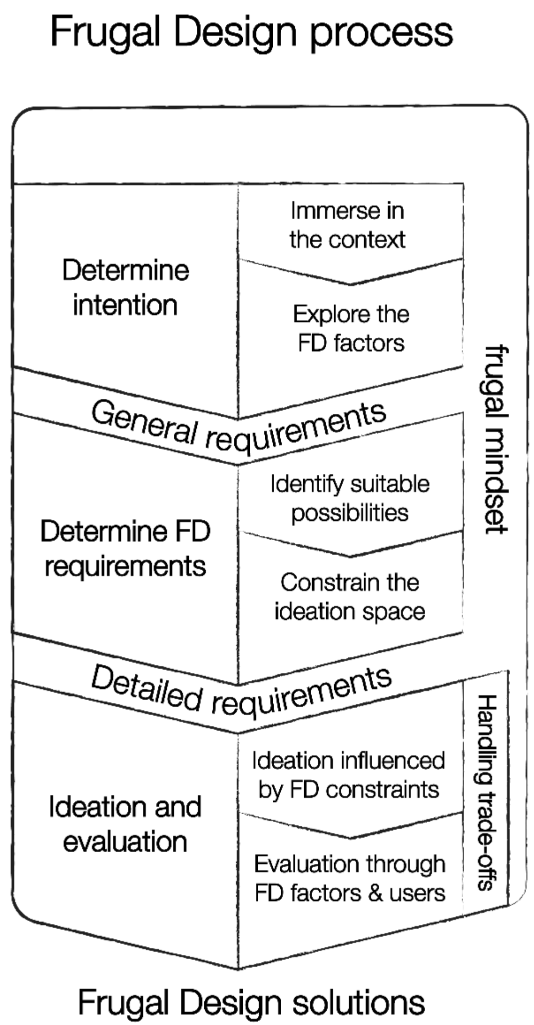


Figure 5.1 The Frugal design framework

Further research

During the work investigating FD as a design approach, several interesting questions have been revealed that were not possible to answer through this work. These questions can be used as a basis when engaging in further research of FD. The most interesting questions are brought up below.

Frugal Design beyond a resource constrained setting?

FD is by some argued to be beneficial for all types of settings. However, most examples in theory are from resource constrained settings. This project and the learnings also originate from a somewhat resource constrained context. How FD works in a less resource scarce environment is therefore not answered by this project. The field of FD would benefit from further research of how FD performs in contexts not defined by resource constraint. In the context of the case study, FD was utilising context specific constraints. It has been suggested to utilise arbitrary constraints as a method for FD and it is possible that it could be how FD is embodied in a less resource constrained context. However, to our knowledge this is not yet tested. The whole topic of FD in a less resource constrained setting should be further investigated. Preferably through another case study to get insight about how it is done in practice. One suggestion would be to use the FD framework concluded in this work for a case study in a new type of context to verify or develop if FD or the proposed framework could be argued to be general for all context, or only fitting for resource constrained settings.

The development of affordability

During the case study, it became evident that the topic of affordability offered several challenges, particularly in terms of how affordability is defined. There is a need for research to develop FD so that it can better help designers address their design's affordability within a specific context. This research could for example include the innovation of tools to determine affordability, or the identification of contextual factors that may influence the affordability. Additionally, it may be valuable to consider the perspectives of different stakeholders, such as manufacturers, consumers, and specifically decision makers, to gain a more comprehensive understanding of how they view affordability.

Frugal Design beyond the physical realm?

Examples of FD brought up in theory, and previous attempts to test FD in practice, have to our knowledge all revolved around different types of physical products. Since the FD approach has not been proven to work beyond physical design, (to our knowledge), we believe it would be valuable to attempt another type of design project to see if FD could bring benefits also for digital design for example.

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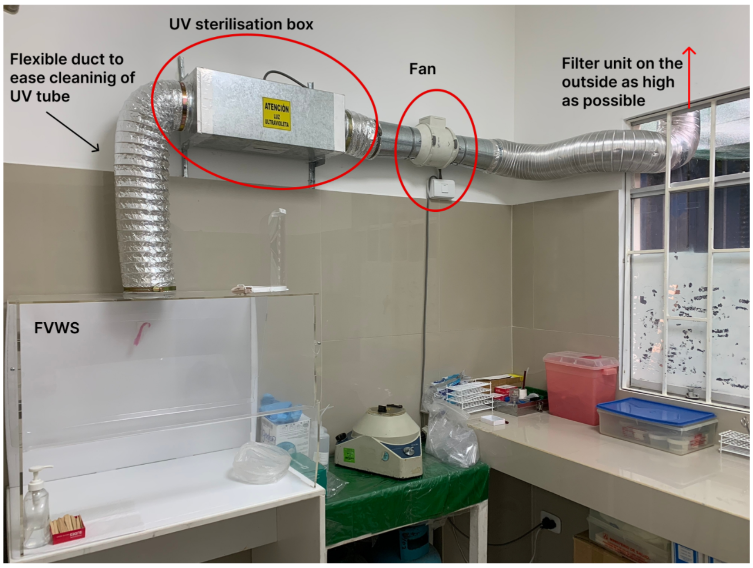
7. Appendices

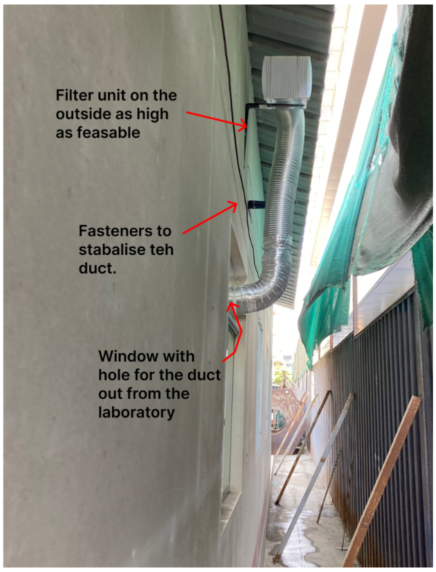
List of appendix:

A. Prototype installation
B. FD interview and observation templates
C. FD evaluation matrix
D. FVWS Manual
    a. Introduction
    b. Installation Manual
    c. User's Manual
    d. Manufacturers manual

Appendix A - Prototype installation

Appendix A shows detailed information of the first installation of the FVWS in a real TB laboratory. Detailed images of the other components making up the system are demonstrated as well, and how these are put together to make it a fully functional system. By examining the installation, a reference point for the fan choice is obtained, comparing the duct length and nr of 90 degree duct bends.





The image above demonstrates how the installation was made in the police laboratory. The FVWS can be seen down to the left. From the FVWS follows a soft duct, leading to the UV-sterilisation box. The UV-box is placed as early as practical and most importantly on the suction side of the fan. This decreases the consequences if a leak would appear in the duct on the outlet side of the fan. From the UV-box the duct leads into the fan and then out through an acrylic sheet, tailored to the size of the old window opening with a hole for the duct. Lastly the duct leads out and upwards as far as feasible to ensure dilution of outlet air. The electrical switch is placed under the fan and the cable is connected to the closest power outlet. A vent was added in the door to the laboratory room in order to create a good flow of air from one end of the room towards the enclosure.

Prototype installation characteristics, affecting blower choice:

- Ca length of duct: 4,5 m
- Duct diameter: 150mm
- Type of duct: Aluminium, small ribbed, bendable.
- Nr of 90° in ductwork: 5
- Sufficient blower: S&P TD 350, with a power of 30 W

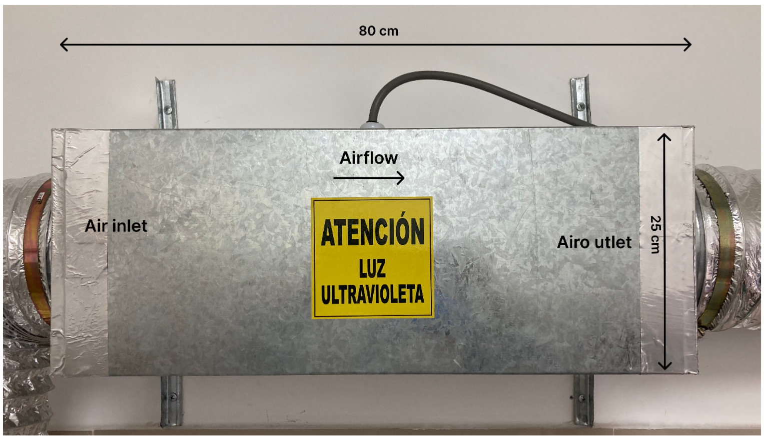
The filter unit

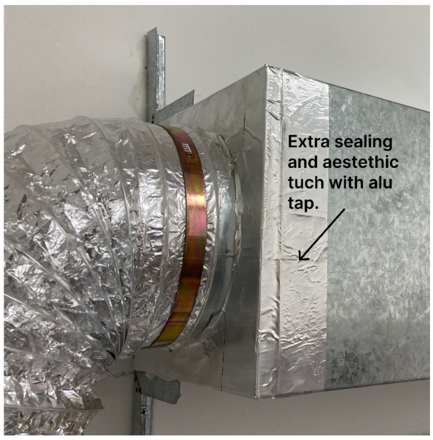
The filter unit was made from prefabricated ventilation parts and particle filters for car compartments. The filter was attached on the ventilation box with steel wire and the whole unit was attached to the end point of the duct system, on the outside of the building as high as possible to secure efficient dilution or ventilated air. See where the filter unit was attached to the duct on the image above.

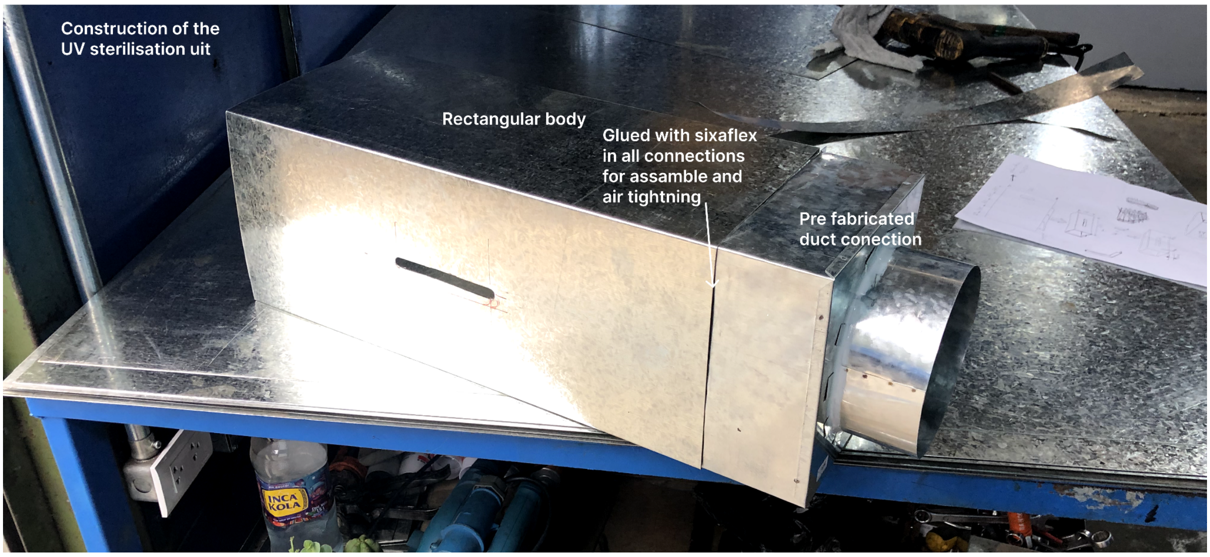

UV-C box

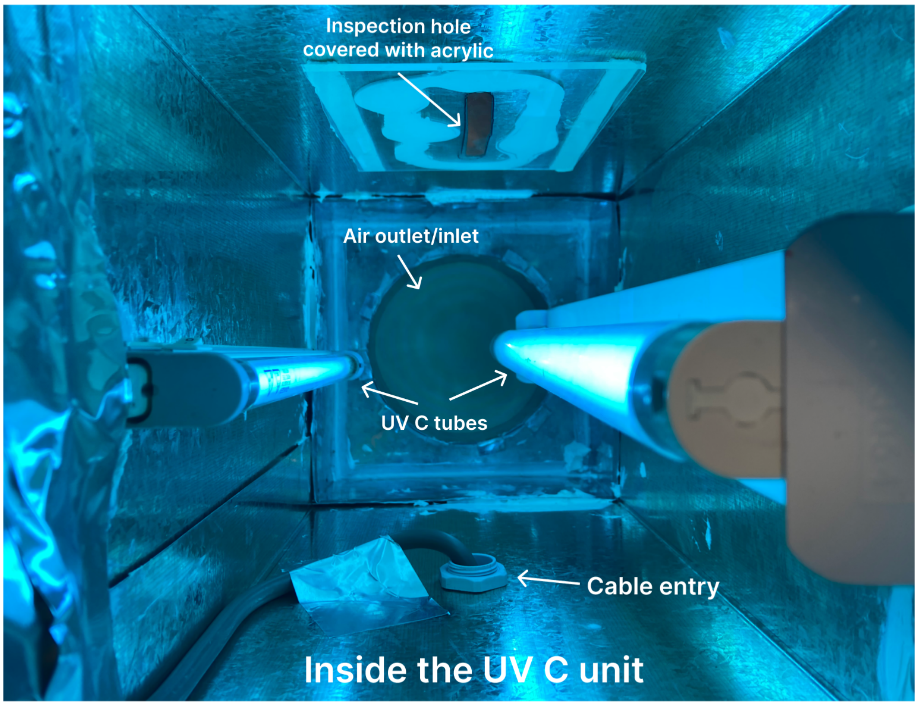
An example of how a UVC sterilisation unit can be implemented in the FVWS system can be seen in the pictures above. The construction of the unit itself can be seen below as inspiration of how a UV C unit can be shaped.

The UV C sterilisation unit was designed from parts that could be quickly accessed. This included two prefabricated duct connections like the one used for the filter unit and a rectangular bent tube. The tube was adopted with one inspection hole that admitted easy control of functionality of the UV C tubes. The inspection hole was covered with acrylic plastic that is efficient in blocking the hazardous UV C radiation but allows visual inspection of the light. The other hole was for cable entry.









The dose required to inactivate TB is estimated to be between 576 μWs/cm^2 and 1080 μWs/cm^2 (CDC, 2009). Basing our calculations on this we were able to use a UV-metre to form the following table giving some examples of lengths of UV-units in relation to different air speeds.

UV box data							
	UV exposure (mW/cm2)	**Exposure time (seconds)**		**Lengt of UV unit (meters)**			
		for		at theoretical lowest speed		at measured highest speed	
		low dose	high dose	length for low dose	High dose	length for low dose	High dose
Worst exposure location	2000	0,288	0,525	0,510	0,930	0,864	1,575
Average exposure location	3400	0,169	0,309	0,128	0,233	0,508	0,926

Reference:

CDC, (2009)., Environmental control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal irradiation Guidelines for Healthcare Settings, https://www.cdc.gov/niosh/docs/2009-105/default.html

Appendix B - FD interview and observation templates

This appendix includes interview templates, observation templates and questionnaires with incorporated FD factors into the structure. They demonstrate how the FD factors were used to structure these activities in the works towards defining the factors.

FD Interview template lab personnel

The interviewee

- Name?
- Job title?
- How long have you worked here?

Your job

- How many people work here?
- Do you all do the same type of work?
- How often do you work? 5-6 days a week?
- Describe what you do
  - What constitutes a day's work?
    - Sample handling?
    - Sample processing?
      - Diagnosing?
    - Cleaning?
    - Anything else?

The context

- The location
  - How would you describe this workplace
    - A lab?

                - A room for receiving patients?
                - Storage room for samples?
                - Something else?
            - What type of facility is this lab part of?
                - Hospital?
                - Health centre?
                - University?
                - Other?
            - In what place is the facility situated
                - Which village, town or city?
                - Rural or Urban?

Labs without cabinet

- Why is there no cabinet here?
    - Core functionality: What functions do you need in order for a Biosafety Cabinet to be suitable for work here?
        - Why do you need this?
        - What requirements do you have for the tools that you buy?
            - Are there standards or certifications that you need to follow?
    - Affordability: who decides which tools and equipment should be bought for this lab?
        - What can new equipment cost, what can you afford?
    - Accessibility
        - Do you ever get new equipment?
            - Through which channels or stores?
        - Are there problems with getting new equipment?
            - due to bureaucracy?
            - due to economic resources?
            - due to limiting logistics? Bad roads, expensive shipping? etc.

        - Can you easily get spare parts when needed?
        - Can you get a hold of workers to do repairs of your facilities and equipment?
- Optimised performance level
    - What size is required for the AFB smear work?
- Robustness: Do the tools and equipment you use usually work well?
    - Are your tools reliable?
    - What usually breaks down?
    - Are there problems with any of the following:
        - Moisture?
        - Corrosion?
        - Power outages?
- Usability: How do you want to manipulate, read and use equipment
- Aesthetics: What makes a product look professional
    - Do you perceive the equipment in this lab as safe? Reliable?
    - What makes a piece of equipment look reliable?
    - What makes a piece of equipment look safe?
    - Does the safety equipment in the lab give a feeling of safety?
- Sustainability
    - What is important for a sustainable usage

Observations laboratories - checklist with 8 factors

Location:
Type of laboratory:
(hospital, centro de salud etc.)

- Core functionality
  - Can we observe any core functionalities that differ from the biosafety cabinet in the lab at IFHAD or at the core functionalities at VWS?
  - How is the cabinet used? Can we extract core functionalities from there?
- Affordability
  - What other equipment is there that can hint about affordability?
  - Is the other equipment new or refurbished?
  - The condition of the existing equipment

- Accessibility
  - Does the location entail any demands on core functionalities to reach accessibility? (like roads, altitude, and possibilities for transportation)
  - Where is the available equipment from? Much imported or locally produced?

- Optimised performance level
  - In places where there exists a BSC, are there signs of optimised performance level?
- Robustness
  - What factors are defining the context? Dust, moisture, cleanness?
  - Electricity. Is it a reliable electricity network?
  - Materials that seem proper/improper for the context?
  - Other equipment. Signs of what constitutes a robust design in the context?
- Usability
  - Are there any generic models that seem to be consistent?
- Aesthetics
  - What is the accepted aesthetics? Any signs? Compared to other equipment. Take photos → do a "mood board" of aesthetics in the contexts
- Sustainability
  - Is there something that should be avoided?

Notes:

Questionnaire implementation Lima VWS

The Police lab - Questions to ask before and after implementation

In terms of your current biosafety cabina, how satisfied are you overall?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of safety, how satisfied do you feel with your sense of safety while working with the cabina?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of the size of the cabina, are you satisfied?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of placement of the cabina, are you satisfied?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of the work environment, are you satisfied with the noise of the cabina?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of the work environment, are you satisfied with the light in the cabina?
Circle the phrase that best indicates your opinion:

Very dissatisfied   Fairly dissatisfied   Neither satisfied nor dissatisfied   Fairly satisfied   Totally satisfied

Please use a few words to explain why:

In terms of your current biosafety cabina, is there anything else that we should know about?
Please use a few words to explain:

Is the Lima VWS frugal?

<u>What we want to know:</u>

- Is the product frugal?
- What problems do they perceive in their work situation?
- What could be better with the cabinet?
- How did the mounting of the cabinet work?
- Are there any functions that they miss?

<u>Affordability</u>

The cabina cost around 1000-1500 sol. How affordable would you rate that cost for your workplace? (1-5)

Very expensive 1 2 3 4 5 Very affordable

Please use a few words to explain why:

<u>Accessibility</u>

The cabinet can be bought from acrílico Perú, a company that is situated in the centre of Lima . How easy would it be to get your lab to buy the cabina so that you can use it for your work?

Would never be bought 1 2 3 4 5 Very likely that it could be bought

Please use a few words to explain why:

<u>Robustness</u>

Do you think that this product would break easily or not?

Yes it will likely break 1 2 3 4 5 This product is robust

Please use a few words to explain why:

<u>Acceptability</u>

How appealing do you find the aesthetics of the cabina?

Not appealing 1 2 3 4 5 Very appealing

<u>Usability</u>

Can you perform your work tasks in the cabina? Do you find the cabina limiting in any way?

Very limiting for my work 1 2 3 4 5 It does not affect my work negatively

<u>Core functionality</u>

Does this solution allow you to perform all the tasks that are required of you?

Not at all 1 2 3 4 5 Yes I can do everything I need to do

<u>Optimised performance level</u>

Can you perform your work in an efficient way?

Worse than before 1 2 3 4 5 Better than before

<u>Core functionality</u>

Are there any functions or functionality that you miss and would strongly wish the cabinet to have?

Appendix C - Frugal design evaluation matrix

This appendix shows the evaluation matrix how it looked during the case study. This in particular includes the notes from the evaluation of the third prototype to give an picture to how to fill in the matrix

	Identified core problems	Strategy	Design / Concept	Problems with the design/concept	Possible improvement	Tools
Affordability	To expensive to buy To expensive with maintenance	Local and already established production Small scale production cheap, available material Modular reduced size	Smaller than prototype 2. thinner material “Finger” construction + wedges less light needed due to transparency	Maybe not cheap enough	reduce material thickness,change colour etc.	Identify what products exist locally produced and where the production methods can be used to produce a BSC. critically assess the material margins eg. thickness
Accessibility	A lot of bureaucracy leads to difficulties with buying equipment	Ease the buying process through production in Lima, Use materials and knowledge that are available in the context. one supplier Smaller and easier to transport	Locally produced WVS → no import process → Easier to reach Easier to ship due to modularity and size	nobody knows that this design exists tube could be a problem, but easy to fix for the user	Awareness packaging solution for safer shipping	Local production and knowhow
Core functionality	Create an airflow within the limits. Disinfection of outlet	Design the product to be used only for AFB-smear	Less advanced lid with wedges	Does not indicate airflow No liquid safety barrier	Liquid barrier	critically assess the necessity of a function be weary of

	air?? Yes or No? Other solutions often include unnecessary? possibilities to close the box					nice-to-haves
Usability	No clear indications as to when the cabinet works" properly	Remove unnecessary parts. instruct through design (denial of faulty assembly)	only possible to assemble in the correct fashion damper easier to reach Easier to use lid Easy to transport assembled like a puzzle, not technical	Does not indicate airflow	Light might be needed	reduce complexity/ number of parts
Robustness	Products are not aligned with availability of test and maintenance personnel.	Choose design and material to obtain robustness and reparability Local manufacturing and know-how One supplier one material?	Modular few glued parts reduced stress concentrations reduced size optimised tenon placement	stress concentration in the bottom corner of the lid?	look over if more wedges are needed and where look over any possible stress concentrations	one supplier local manufacturing
Aesthetics	no problem	Look after signs how existing equipment looks material with good aesthetic	White base and background make a nice impression	Not a problem, but it does not look as good the previous design according to	perhaps work with the shape of the window or other parts	

		robustness	Straight front design for better structure	us this is necessary for better structural stability		
Sustainability	Use of plastic What glue/resin? How to recycle Acrylic?	reducing size	Prototype 3 is about 55% of the size of a VWS, and 83% of the last prototype	material that is hard to recycle	To investigate: if it is possible to use 3 mm in back and bottom.	material minimization
Optimised performance level	Innificient perf level on the VWS	align with need	enough thick, suitable fan, enough size	The fan is too strong. Less tick sheets → more insatiable (obs test with tape first)	Tape/glue parts together	material minimization

Appendix D - The Frugal ventilated workstation Manual

The Acrylic Frugal ventilated workstation (FVWS) is a partial front open ventilated work space connected to a fan creating an inward airflow, transporting air away from the work area inside the enclosure out from the laboratory. The enclosure is designed to provide a safer workspace for laboratory personnel working in tuberculosis laboratories that are involved in microscopy work (AFB smear) of sputum samples. The enclosure should not be used for anything more dangerous than AFB-smear work.

The enclosure consists of a cabinet constructed of acrylic. Together with a fan and standard ductwork, the FVWS can be assembled in laboratories by placing the cabinet onto already existing benches or adding an additional table. The enclosure is then connected with a duct and a fan. The duct is mounted so that it moves the air from the FVWS to the outside of the laboratory and exhausts the air out to the open air in a location where there are no people.

The enclosure is designed modularly so that it is easy to manufacture, transport and repair. The FVWS is produced in transparent acrylic and white to allow surrounding light to enter the enclosure, reducing the need for an exterior light source. Through local manufacturing, it gets accessible and easier to repair with good accessibility to spare parts if necessary. The front window can be opened and removed for cleaning the inside of the cabinet. The design includes a damper that is used to regulate the airflow to the desired level of 0,45 m/s.

Included with the drawings of the enclosure is a swing vane anemometer that lets the laboratory personnel set up, calibrate and continuously verify the airflow.

The design of the FVWS is a work done as a collaboration between the research group IFHAD (Innovation for health and development)/IPSYD (innovación por salud y desarollo) and the master engineers students Carl Wingren Bergman and Filip Eliasson.

Contact details:
IFHAD: www.ifhad.org, Carlton Evans, Carlton.Evans@IFHAD.org
Filip Eliasson: eliasson.filip@hotmail.com
Carl Wingren Bergman: carl.w.bergman@gmail.com

Properties

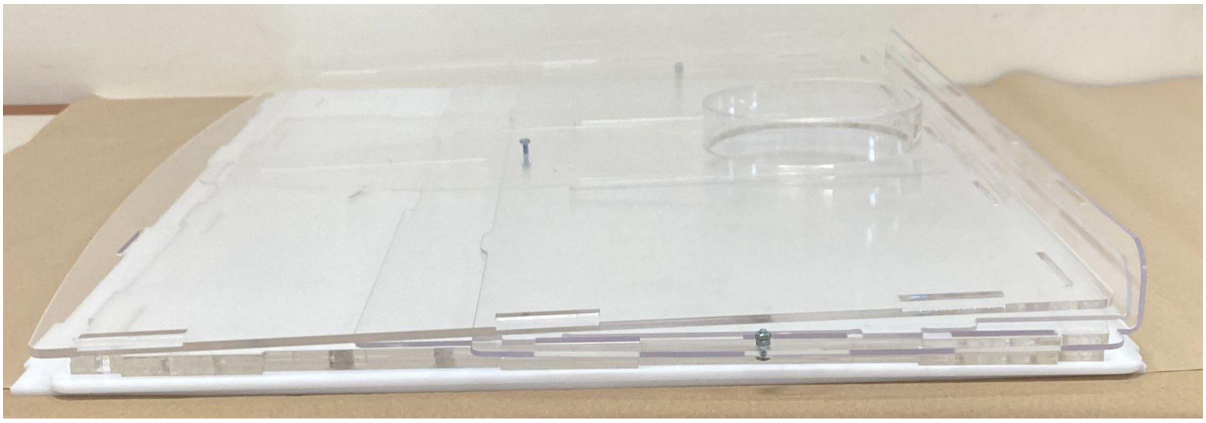


Figure 1. FVWS before assembly

Specifications

Cabinet dimensions (height/width/depth)	60/75/53 cm
Work surface dimensions (width/depth)	70/50 cm
Cabinet Weight	11,95 kg
Package dimensions (height/width/depth)	10/80/60 cm
Intended flow rate and velocity	260 m^3/h & 0,45 m/s
Duct outlet	150 mm
Approximate price of the system during case study	1500 PEN (slightly less than 400 dollars)

Airflow

If appropriately installed, the FVWS maintains a stable and laminar airflow of 0,45 m/s in the opening of the cabinet, with no more than 20% deviation in accordance with what is recommended by WHO Laboratory biosafety manual (Laboratory biosafety manual, 4th edition: Biological safety cabinets and other primary containment devices, https://www.who.int/publications/i/item/9789240011335?sequence=1&isAllowed=y)

The airflow properties of the FVWS have been tested through a grid of 8x3 measuring points on the upper, middle and lower levels of the opening of the cabinet. The figure below indicates the measuring points (the intersections in the grid), as well as the average results from three series of measurements for a total of 74 measurements. None of the underlying measurements were outside of the acceptable ± 20% span, i.e. all measurements were between 0,36 - 0,54 m/s.

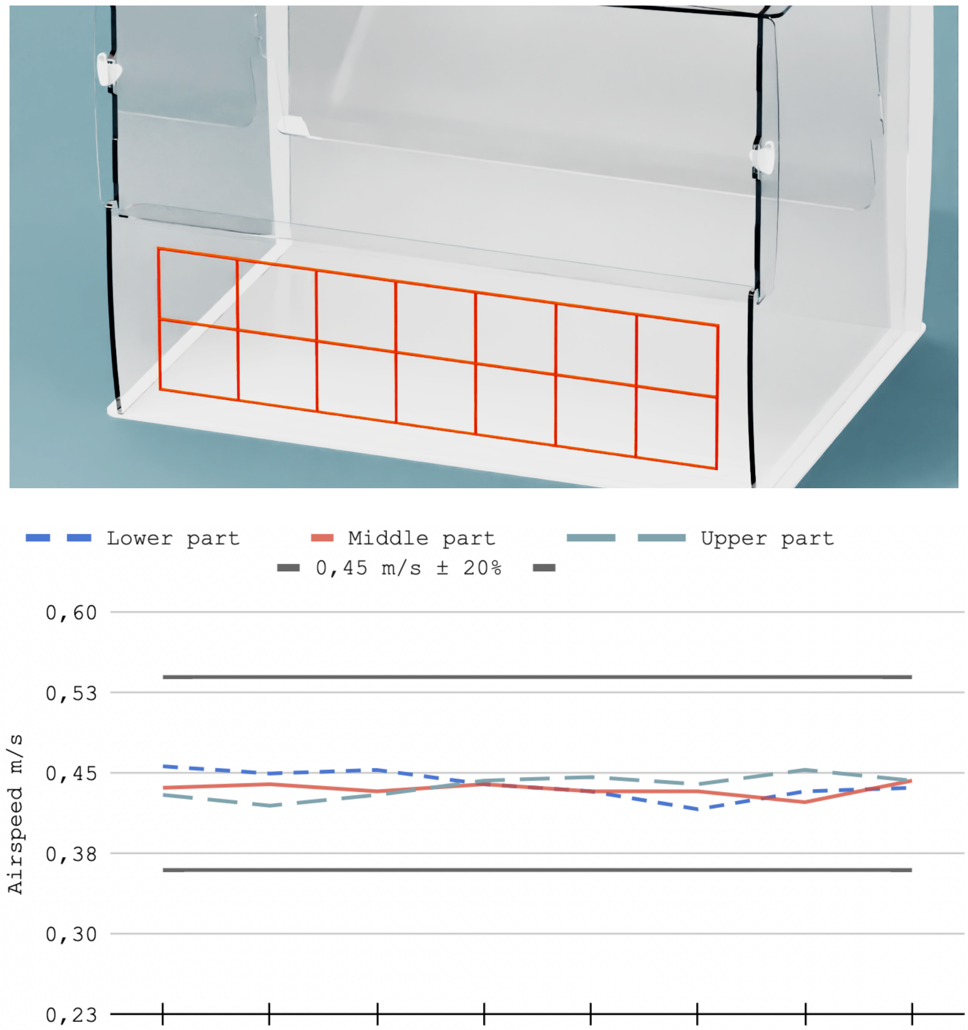


Figure 2. The measuring grid and the average results

Acquiring process

The FVWS is an open-source design, free for everyone to use. The 3D models, drawings etc can be found in the FVWS repository at this link https://drive.google.com/drive/folders/11RK_pyjwNZXB98emu3b3dufYtUryyU1x?usp=sharing, or via scanning the QR code below. With the data files, a workshop (preferably an acrylic workshop) possessing a laser cutter machine and acrylic sheets can easily cut out the panels the FVWS built from.

FVWS repository
All information about the FVWS

In Lima, there are several companies working with acrylic and that can manufacture the FVWS if they are provided with the drawings and files available in the FVWS repository (QR code above). Below are some recommended manufacturers that have been helpful in producing the first FVWS, Note that no manufacturer has any responsibility for the design or technical performance of the FVWS. They are only helpful in the physical manufacturing of the product:

For producing the acrylic cabinet
Acrílicos Perú LBM
https://acrilicosperu.com/
Whatsapp +51 943 558 735

For the installation, a window with a hole for the duct will often be added in order to let the air out outside. An acrylic window that can replace an already existing window with a hole for the duct can easily be customised at any acrylic workshops.

For the fan and other electrical components

The FVWS needs a fan and a duct to move the air to a safe place, together with wiring and an electric switch to make it easy to operate. In Lima, both new and used fans can be acquired in several places and by several companies. The electronic market in the area of Urb Lima Industrial is a market where several new and used fans can be acquired. Maintenance and repair of fans can also be done in this place: Centro comercial Nuevo centro Paruro

Centro comercial
Nuevo centro Paruro

To build a duct and make any special connections, In Lima, there are many companies that can do this professionally. One example is:

For the duct and any other help with installation

Corporación Frio Temp Soluciones S.A.C.
friotempsedano@gmail.com
Whatsapp +51 987014342

Installation Manual

The FVWS should be installed in accordance with recommendations and guidelines from the laboratory biosafety manual provided by WHO Laboratory biosafety manual (Laboratory biosafety manual, 4th edition: Biological safety cabinets and other primary containment devices, https://www.who.int/publications/i/item/9789240011335?sequence=1&isAllowed=y). It is recommended to read the Biosafety manual before installing the FVWS. Further information about TB and biosafety can be found in the TB manual:

SP version of the TB manual:
https://www.who.int/es/publications/i/item/9789241504638

ENG version of the TB manual:
https://www.who.int/publications/i/item/9789241504638

Further useful information for how to install a ventilated workstation can be found in the *VWS manual for AFB smear*, where a previous work with designing a ventilated workstation, led by CDC, is brought up together with installation considerations. These considerations can be found very useful also for the FVWS.

ENG version of the *VWS manual for AFB smear*:
https://www.stoptb.org/file/10517/download

(All the documents can also be found as PDF in the FVWS repository)

Assembly

The assembly of the FVWS is done at the laboratory when the exact location is determined in accordance with WHO guidelines mentioned above. The assembly can be done by anyone. A video of the assembly sequence can be found at the FVWS repository. The process is described below:

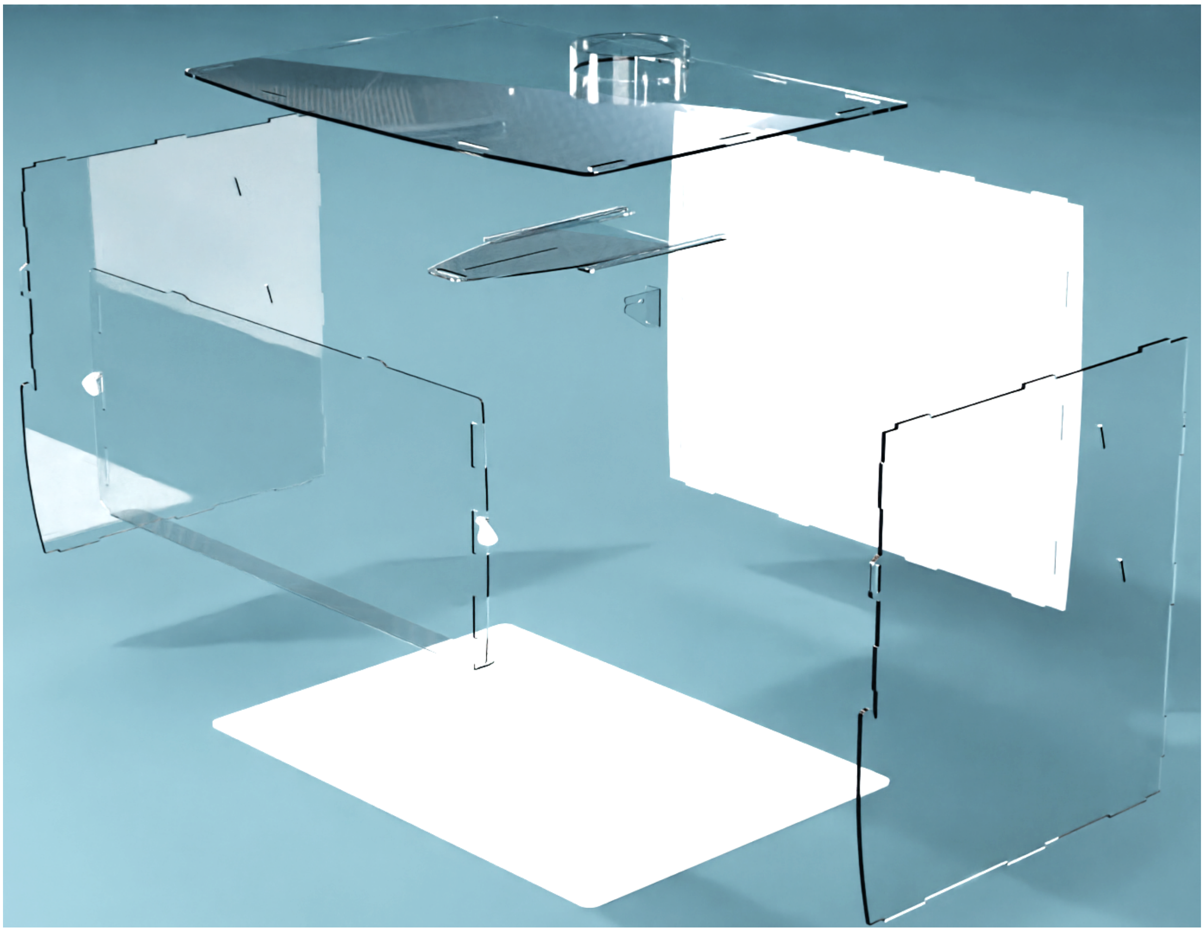


Figure 3. the parts and assemblies of the FVWS

1. **Setting up the FVWS (a job for two people)**
    a. The FVWS can be placed on an existing bench or on an additional table
    b. Place the bottom panel on the area where the cabinet is intended to stay. Prepare sealing material (double-sided tape or silicone). If using double-sided tape, prepare all sides where the acrylic sheet is to meet another sheet, with tape. If using silicone, secure all panels and joinings when the whole FVWS is mounted.
    c. Tape or glue the yarn holder to the middle of the back piece
    d. Mount the FVWS by first placing the back panel in the holes in the base panel. Then, place the side panels without attaching the holes from the back panel into the side panels (to make room for the baffle to be inserted). Insert the baffle and push the side panels together. Attach the back panel to the side panels. Secure

the construction by placing the top panel on top of the side panels and the back panel.

e. Secure and seal all panels with double-sided tape or silicone (or similar).
f. Palace the front panel (window) by putting it on the hooks in the side panels, fastening it by lifting the top panel to let the fingers in the window attach in the holes in the top panel.
g. Lastly, fasten the FVWS by attaching double-sided tape under the bottom panel to make sure that the cabinet doesn't move while working in it.

2. Connect the cabinet to a duct and a fan

a. Place the fan as close to where the duct is leaving the building as possible (eg. via a window), or better yet outside.
b. Attach a duct between the fan and the enclosure, fastening it on the walls if needed.
c. Lead the duct well out in the open air, away from people.

How an installation of the system can look like:

Note that the duct is passing through a window out from the laboratory to open air.

Choosing fan

Choosing the fan is depending on what fan that can be required and what airflow it can generate in the system. The required properties of the fan will vary depending on the length and diameter of the duct used. There are an endless number of options that can be used. However, some guiding numbers can be used when searching for an available fan. To obtain an air speed of 0,45 m/s, the fan must be able to move at least 260 m/3 of air per hour.

To get an indication of the suitable size of the fan, you can compare a future installation to this project's installation, giving a quick indication of a sufficient size of the fan.

Installation characteristics of the test installation of this project, affecting fan choice:

- Estimated length of duct: 4,5 m
- Duct diameter: 150mm
- Type of duct: Aluminum, small ribbed, bendable.
- Number of 90° turns in ductwork: 5
- Sufficient blower: S&P TD 350, with a power of 30 W

Longer and narrower ducts need a more powerful fan.

Calibration

When a fan, strong enough to create at least 0,45 m/s inflow into the FVWS (preferably capable of more) is acquired and installed the enclosure and its airflow need to be calibrated. This is done with the built-in damper on the inside of the top panel of the FVWS, see figure 4.

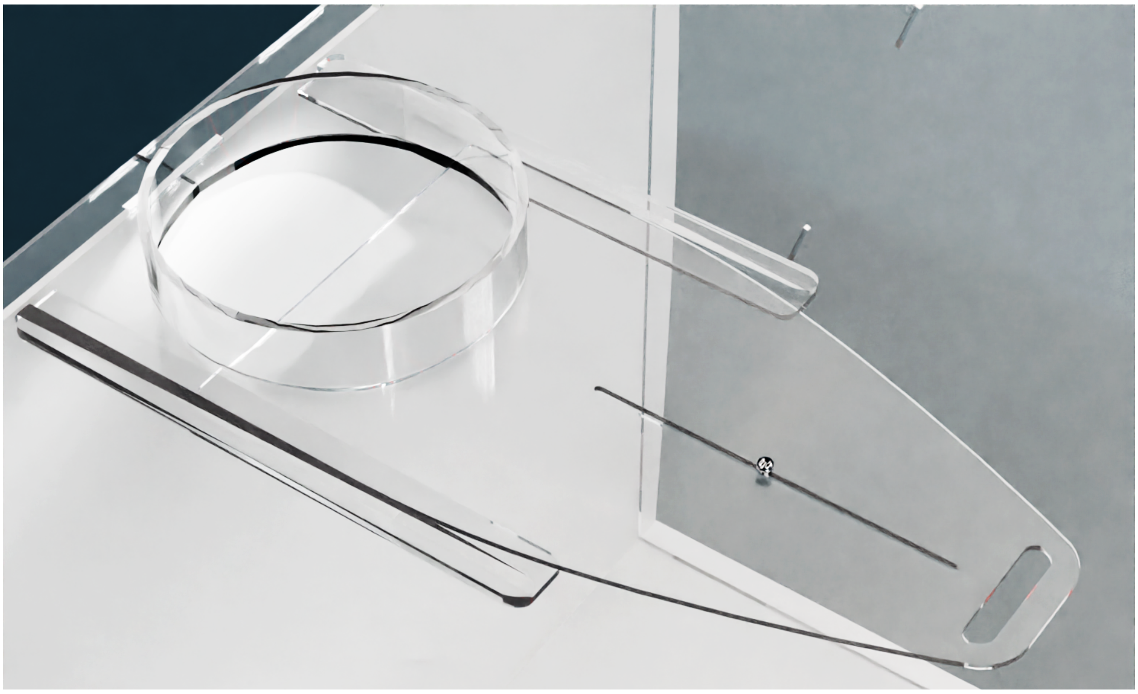


Figure 4. The integrated damper is used to regulate the airflow to 0,45 m/s

To calibrate the cabinet, an anemometer is needed. If no digital anemometer is accessible, the swing vane anemometer that comes with the design can be used, see figure 5.

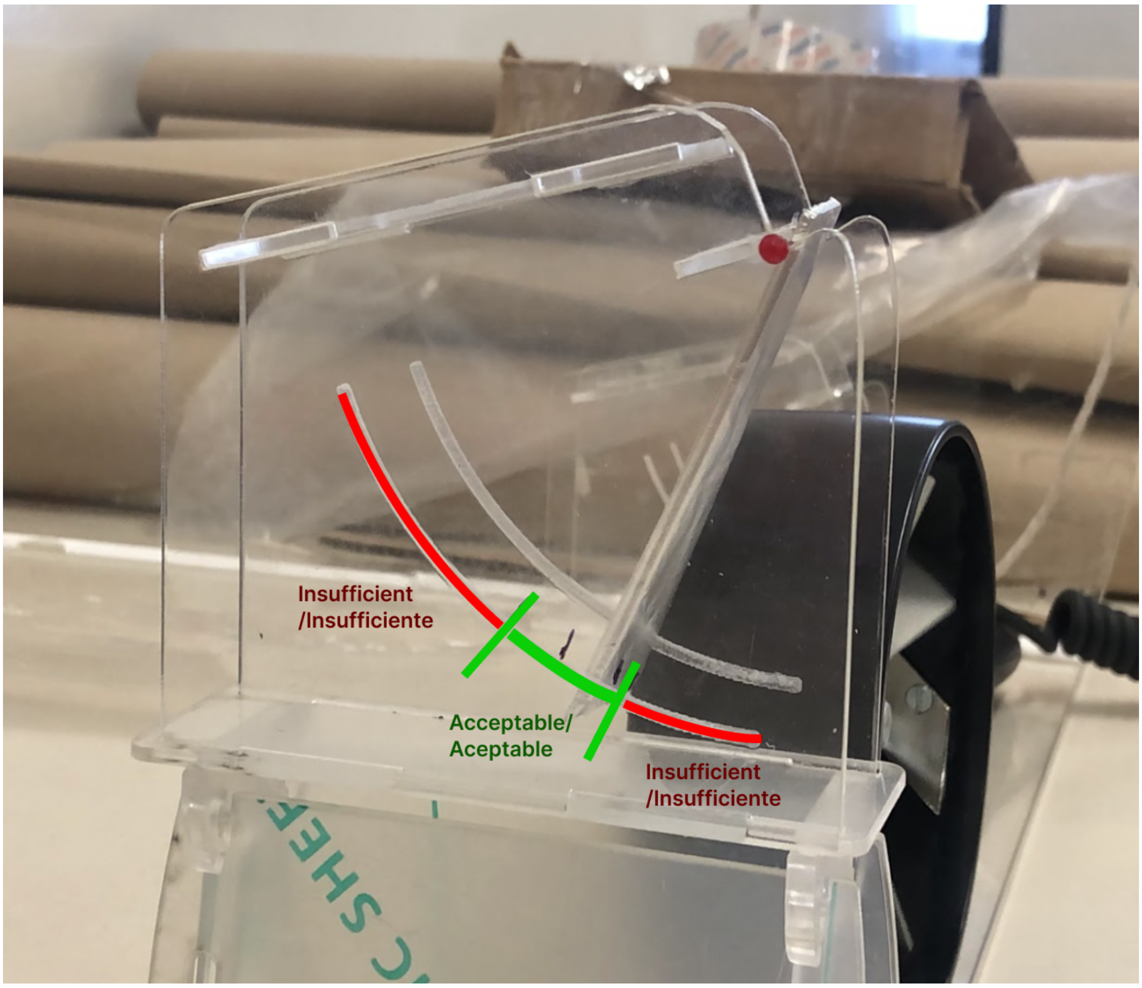


Figure 5. The anemometer uses an aluminium foil vane to indicate if the airflow is good

To calibrate:

1. Start the fan and let it run for a few minutes
2. Place the anemometer in the middle of the front opening of the FVWS
3. Adjust the damper inside the FVWS, by sliding it back and forth. Start with the damper fully open and close it slowly in small steps until the anemometer shows 0,45 m/s on average over time.
4. When the airflow is correct, screw down the secure screw from the top of the FVWS to secure the placement of the damper.

User's Manual

General
As with all biosafety work, proper biosafety procedures are more important than any biosafety cabinet or other safety equipment that could be provided. The FVWS will perform safely only in combination with good microbiological practice and procedures. A practitioner should be knowledgeable about this and read for example the laboratory biosafety manual, produced by the WHO. The purpose of the FVWS is to increase the safety and work environment for laboratory workers preparing sputum smears for AFB smears.

The FVWS shall be connected to a fan that should be running at all times when the cabinet is in use as well as before starting to work as well as some time after work has been performed in accordance with instructions from WHO in the laboratory biosafety manual.

As the air from the enclosure will be ejected from the building, usually via a window, the windows at the side of the room should be kept closed so any contaminated air cannot reverse back in through the window.

The colouration of samples is not recommended to be performed inside of the enclosure since it risks making the window and other parts of the cabinet dirty and discoloured.

Start and stop the FWVS

1. Switch on the fan and let it run for a few minutes before working
2. Check the airflow
    a. The yarn should be flowing and indicating a proper airflow.
    b. Every once in a while you can using an anemometer (swing vane or digital)
3. When finished with the work, let the FVWS run for a few minutes before shutting down the fan.

Working in the FVWS

The work practices in the FVWS should be in accordance with guidelines of how to work in a biosafety cabinet from WHO. Make sure to not block the open space for the airflow in the back of the cabinet.

Cleaning the FVWS

The FVWS can be cleaned with all chemicals that do not damage acrylic plastic (PolyMethyl MethAcrylate or PMMA). The chemicals alcohol, bleach and Vesphene are tested and can be used without danger.

Validation

Continuously airflow check

The FVWS is equipped with a yarn holder, this yarn continually indicates the airflow. The yarn is placed under the outlet in the top panel, at the eye height of the operator. While running the fan, the yarn should be flowing, pointing upwards, see figure 6. If the yarn is not moving like normal, the FVWS may not be operating as intended and air speed measurement should be done.

Figure 6. The yarn (circled in red) indicates if there is an airflow in the cabinet. Left: The yarn is hanging down indicating no or insufficient airflow. Right: The yarn is standing up indicating an airflow.

Inflow velocity

To validate the inflow velocity, an anemometer needs to be used. A digital or swing vane anemometer (included in the drawings).

Place the anemometer in the middle of the front opening and let it run for a minute. Check the average measurement and make sure that it is within the approved limit (0,45 m/s +/- 20%). If the included swing vane anemometer is used, the scale demonstrates an area that corresponds to +/- 20%. Monitor the anemometer from the side for a minute. The aluminum vane should be inside the area of an acceptable airflow, see figure 5. If the airflow check does show that there isn't a sufficient airflow, the damper needs to be adjusted or the duct and outlet need to be controlled for obstructions (clogged filter if installed etc)

Making more swing vanes for the anemometer
The swing vanes for the anemometer are created from aluminium foil of a weight between 35-45 grams/m2. These vanes are manufactured by the user with a small deep drawing press that comes with the product (figure 7). The vanes are suspended in the anemometer using a sewing pin.

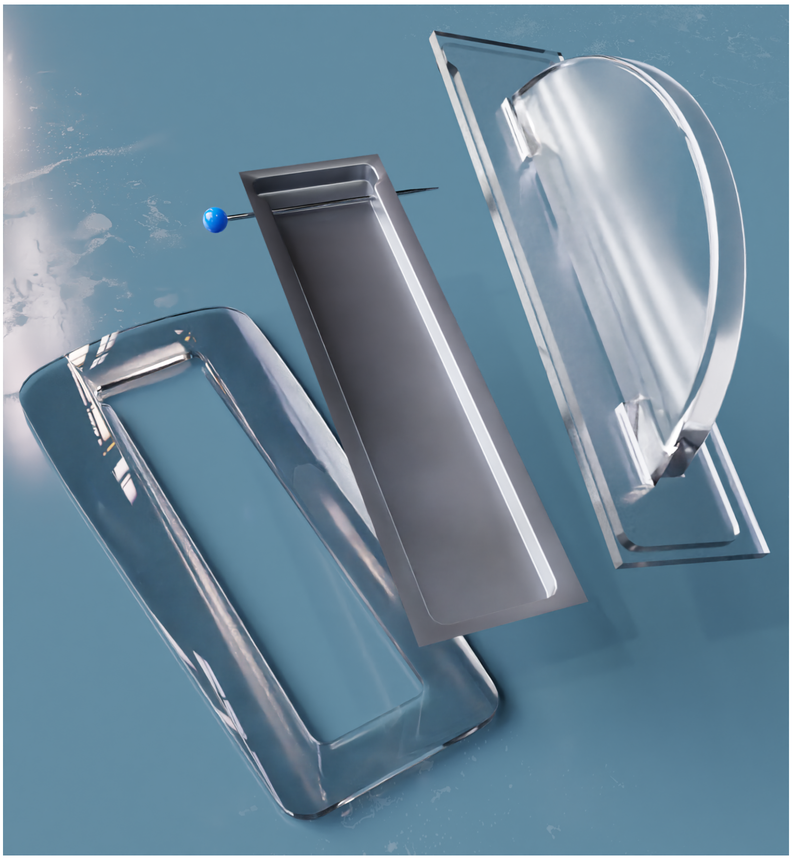


Figure 7. The swing vane press

Maintenance

The FVWS is designed to need as little maintenance as possible. Regular cleaning and airflow control measurements are the only required maintenance.

Cleaning: The cleaning should be performed using chemicals that do not affect acrylic negatively. Usage of alcohol, bleach and Vesphene has been tested and does not damage the FVWS.

Repairs
If any part of the FVWS gets damaged and needs to be changed, only the part that is damaged needs to be replaced. Contact the manufacturer and ask for just the desired part, which can be cut alone. If parts are exchanged, the calibration process should be done again.

Manufacturer's manual

This manual provides any manufacturer with the needed information for producing the FVWS and the included swing vane anemometer.

Material

The FVWS and the anemometer are manufactured in different thicknesses of acrylic sheets in two colours; transparent and white (back panel and bottom). The transparent panels are letting light into the FVWS and the white panels ensure a good work surface without seeing the bench or wall where the FVWS is placed. All types of transparent sheet material of the specified thicknesses, that can withstand chemicals used in the laboratory, and that can be cut in a laser cutter could also be used. Eg. Polycarbonate would be a possible candidate. Check the 3D-files on the FVWS repository (figure 9) for more information of the thickness of each part.

Parts

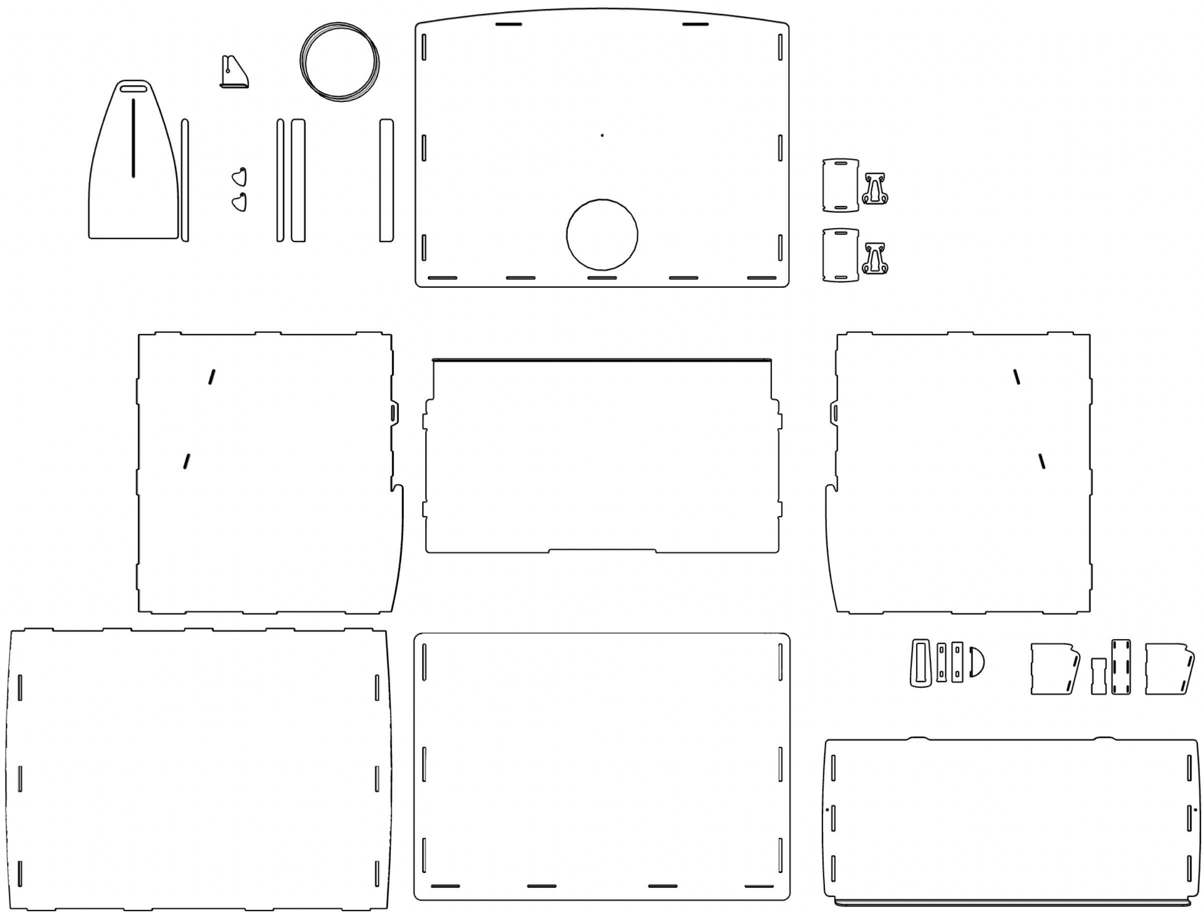


Figure 8. The parts that make up the FVWS and the anemometer, these drawings are available at the FVWS repository

FVWS repository
All information about the FVWS

https://drive.google.com/drive/folders/11RK_pyjwNZXB98emu3b3dufYtUryyU1x?usp=sharing

Figure 9. QR code to the FVWS repository

Important considerations

- If the fingers and holes joining the panels together are not cut precisely, do not force them together. Use a file to adjust the cuttings so that they fit together without difficulties. Forcing them together can make the acrylic crack.

- The round outlet of the cabinet is heat treated and then bent together to a circular form. If this possibility doesn’t exist, adding another type of tube and attaching it with glue will work as well.

- If the thickness of an acrylic is limited, the panels can be made thicker. If this is done, the holes in the related panel must also be changed to accommodate the bigger thickness

- The bottom and back panel of the cabinet should be made out of white acrylic, or other colour that will not distract from the work in the cabinet

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