[Year]

Frugal innovation in medical devices:

Tackling the shortage in medical devices

due to Covid-19 situation

DESIGN OF A NOVEL PULSE OXIMETER

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Abstract

Frugal innovation is a concept that focuses on effective product and strategy developed to reach a reverse innovative approach. The reverse frugal innovation is a sustainable and cost-effective strategy to target the bottom of pyramid countries and emerging markets. Mainly, the focus is on the limited resources countries with limited budget on their demand side. The current Covid-19 situation created an emergence in shortage of medical equipment, such as, personal protective equipment, masks, ventilators, and pulse oximeters. The large equipment as the ventilator are expensive with nearly £20k for a unit. Researchers at MIT created a 3D printed ventilator following the frugal innovation aspect for a cost of £100. This helped the bottom of pyramid countries to tackle the shortage in their medical equipment in a cost-effective way. In this project, a frugal innovative product development of a pulse oximeter is generated. The pulse oximeter costs between £70 and £100 to be used in hospitals and clinics. The pulse oximeter in this project costs approximately £10 with having the same core functionality of displaying hear rate and oxygen blood level through an Arduino Nano circuitry. The sensory platform relies on photodetector and LED emitters at wavelength range of 640nm to 900nm. The device is designed along with its circuitry diagrams for further implementation. The device tackled the sustainability aspect of frugal innovation as well, where this is attained through the usage of recyclable waste materials, such as, foam and PVC pipes for the shell of the pulse oximeter.

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1 INTRODUCTION

Frugal innovation is a concept created and developed by Carlos Ghosn, former Chairman and CEO of Renault-Nissan. The concept of frugal innovation mainly focuses on cost-effective measures to create new approaches and ideas for low income countries or limited budget customers. The concept has become a strategy with its first publication generated in the Economist magazine in 2010 (Winkler, et al., 2019). Following the article on the frugal innovation, scholars started to increase their interests as the peak of the publication on the topic was reached in 2016 at 31 publications. It was reported in (Michelini, et al., 2018) that the frugal innovation is focusing on the low income groups with an emphasises on the bottom of pyramid countries, such as, Asia and Africa countries.

1.1 AIM

The aim of this project is to design and assess a frugal innovative product to be used in developing countries with focusing on the bottom of pyramid countries as the concept of frugal engineering targets the cost effectivity through the decrease of environmental impact, decrease in resources, and complexity. The project is considering the shortage in medical devices due to the current Covid-19 situation, where a medical device is proposed to solve the shortage in pulse oximeters in a cost-effective approach.

1.2 OBJECTIVES

Attaining the aim of the project requires the attainment of the following objectives:

1) Generate a comprehensive literature review on the frugal engineering and frugal innovation.
2) Discuss the advancement in frugal innovation and its concepts with the current challenges.
3) Propose a problem statement to validate the proposed solution.
4) Create a frugal innovative product to solve the issue of the current shortage in medical devices in a cost-effective way.
5) Discuss and compare the generated solution with the similar available products in the market.

1.3 PROJECT OUTLINE

The project comprises seven chapters, where the first and current one poses the aim objectives, and the background of the frugal innovation. The second chapter tackles a comprehensive literature review on frugal innovation and its sustainability in practice with the possible theoretical frameworks to be applied. The third chapter poses the problem definition and its solution, with showing two possible approaches and selecting the relevant one. The fourth chapter considers the steps to be taken to finalise the project. The fifth chapter presents the analysis and the design of the pulse oximeter. The sixth chapter discusses the design of the oximeter in frugal innovation. Finally, the seventh chapter withdraws the main conclusions and project the further work.

1.4 ETHICS AND SUSTAINABILITY

The sustainability of the project relied under the frugal innovation aspect in lowering the environmental burden and costs of the developed device. Also, the sustainable aspect of the project relies on the targeting of the limited budget customers in delivering them affordable and critical medical device as the pulse oximeter. This device has called a shortage in the current Covid-19 situation. On the social level, the project serves the sustainability in terms of the job creation locally in the bottom of the pyramid countries referring to the simple and affordable resources to develop the device.

From the ethics point of view, the project tackles a theoretical and well-defined approach to generate the current presented design of the pulse oximeter. Also, the standards of testing and design were mentioned following the code of conduct for pulse oximeter used by the manufacturers and suppliers.

2 LITERATURE REVIEW

2.1 INTRODUCTION

In this part of the project, a literature review on the frugal engineering development aspects and frameworks is generated. The literature review focuses on the approaches considered from a frugal engineering perspective with emphasizing on the decrease of costs, design complexity, and increase of usage. Also, the focus in the literature is attempted on the frugal engineering development of products in developed countries. This is referred to the lack of resources in the developed countries and the inability of affording expensive products.

2.2 DISRUPTIVE INNOVATION VS FRUGAL INNOVATION

Emerging countries have been the focus of the market in developing new products in a cost effective way since the emergence of frugal innovation. It was reported that the developed countries have failed to integrate the frugal concept in an efficient way. The issue with the integration is referred to the shortage in resources and the possible environmental burden from the required processing stages. These issues were creating a burden from the conventional approaches in product innovation as well; therefore, urgence for strategies to implement frugal innovation have been emerged recently. (Winkler, et al., 2019) reported the difference between conventional and frugal innovation strategies as illustrated in Figure 2.1.

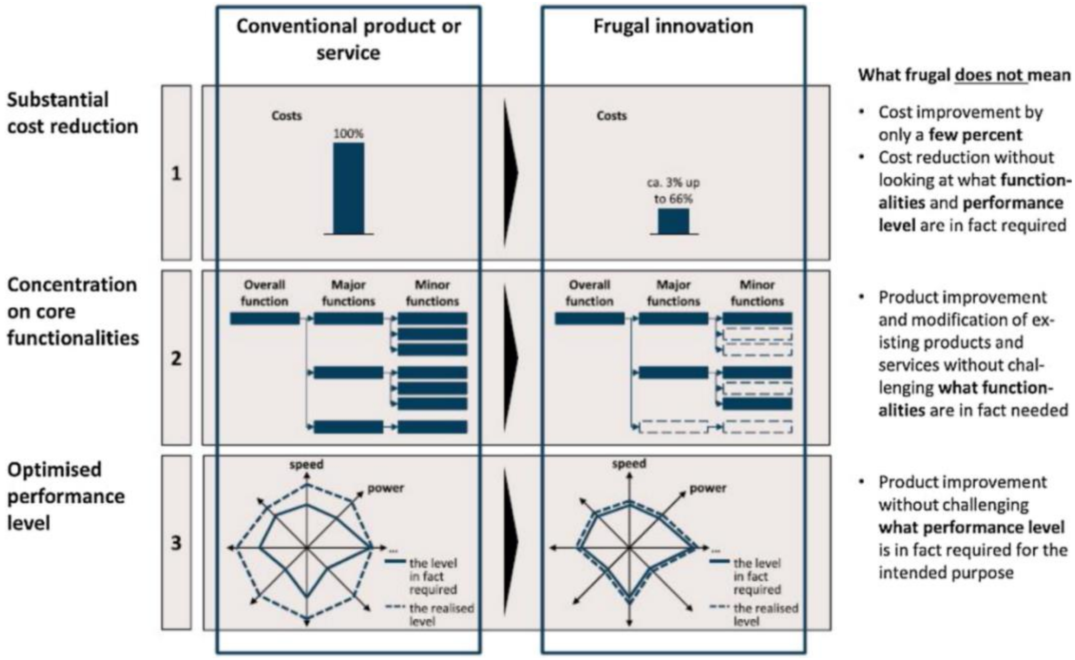

Figure 2.1: Difference between conventional product development and frugal innovation (Winkler, et al., 2019).

Another study by (Albert, 2019) reported that the frugal innovation is categorized as disruptive, where the other way around is not true. This means that the disruptive innovation could not attain the frugal strategy. Also, disruptive innovation could not be attainable by all the masses. The disruptive innovation means that the upgrade of certain products could vary the targeted groups, which is not idea in the developing countries and require more resources. On the other hand, (Zhang, 2018) reported that the frugal innovation and the disruptive one are linked geographically as they integrate the innovation in emerging countries to promote them to a new level known as developed countries. Another study by (Belkadi, et al., 2018) emphasised on the ability of frugal innovation into turning to reverse innovation in developed countries. Following the same concept or approach of the idea discussed earlier, the reverse innovation should be integrated in developed countries and then be integrated in developed markets. Another study argues that in developing markets, the integration of frugal innovation does not have any reverse potential. (Reinhardt, et al., 2018) reported that if the frugal innovation has a potential to be reversed, generates new opportunities to be applied in developed markets.

2.2.1 Customers of frugal innovation

It was mentioned in the previous section that the frugal engineering targets the limited income customers, where an emphasis should be appointed towards these customers in this section. In published paper studies on frugal innovation, researchers focus on the demand side. The output of approaching the demand side was three main streams mentioned in the following (Schleinkofer, et al., 2019):

1) Focusing on the bottom of pyramid customers.
2) Linking between customers behaviour and the advanced economics.
3) Linking between customers behaviour and the sustainability issues (environment-based).

In terms of the first mainstream on the focus on the bottom of pyramid customers, the studies argued on the lack of resources with trying to find new ways to tackle the imposed problems. Another study considered such approach as value addition frugal innovation. In addition, the value addition approach in frugal innovation was argued on fulfill customer needs with an adequate level of quality of the product generated (Malek, et al., 2017). During the analysis of the first mainstream in paper studies, customers always face daily lack of resources, such as, energy, housing, transportation, health, hospitalization, etc. This will lead to the second mainstream in terms of the link between the customers and economic advancements, where this elaborates in the lack of funds to generate the required transformation. Also, the link between the economic advancement is understood in terms of the entrepreneur skills that might be elaborated based on limited capabilities (Basu, et al., 2013). Therefore, frugal innovation is a key aspect of such approach in terms of increasing limited resources usability. The same aspect was discussed in another study focusing on the sustainable issues and challenges faced within the frugal innovation applicability. The sustainability issues and challenges must be discussed in more details which is implied in later sections of the literature review chapter. However, the sustainability issues are related to the business models applied in a frugal innovation environment, where the focus is attained on the maximization of the material usage and their recyclability to limit the burden on environmental impacts. In addition, the link between the frugal innovation from the customer perspective requirements and the sustainable issues was described in (Schleinkofer, et al., 2019) to repurpose the environemnt in emerging markets and scale up the solutions in such markets. The emphasises on the link between the sustainability issues and the economic advancements to the furgal targeted customers increase their caapbility in being more than customers. This means that these customers could be seen as co-manufacturers or producers of the proposed concepts.

2.3 FRUGAL INNOVATION IN SUSTAINABILITY

It was discussion in section 2.2 that the frugal innovation studies have emphasised on the link between sustainability issues and the customers for frugal innovation. Therefore, in this section, an in-depth analysis on the sustainability approach of frugal innovation is attempted. It was reported in (Purohit, et al., 2020) that the usage of material and financial resources should be optimised, where the optimisation objective is set towards the minimisation of their usage. This has a direct effect on the reduction in costs with fulfilling the required innovation needed for the bottom of pyramid countries. In addition, it was reported in (Basu, et al., 2013) that the urge for quality standards should be undertaken in developed countries while applying frugal innovation projects. In another study by (Maturano, et al., 2020), the emphasis on frugal innovation from a sustainable approach resulted in arguing that the focus should be on the core functionalities with an optimisation on performance. Therefore, this is directly affecting the sustainability in terms of the material usage and manufacturing process that decreases the environmental burden (decrease in resource usage).

Sustainability is not an innovative approach, where it was introduced in 1713 by Hans Carl von Carlowitz (Mathew & John, 2016). The same study reported that the sustainability was explained in terms of harvesting at the exact amount of the forest need. The same concept should then be integrated in the frugal innovation, where the UN Commission on Environment and Development took this approach as the basis of their widespread mission. Therefore, in a frugal innovation approach, the sustainability illustrates the creation of an optimised strategy or functionality for the future generations to meet their defined needs. Table 2.1 illustrates three paper studies that emphasised on the sustainability in frugal innovation with focusing on their resultant.

Table 2.1: Main outputs of the sustainability integration in frugal innovation.

References	Output of frugal to support sustainability
(Basu, et al., 2013)	Increase sustainable growth Protect the planet capacity Improve living conditions of BOP Create cost-effective measures for BOP
(Maturano, et al., 2020)	Decrease carbon footprints Ecological ideas inclusion

	Decrease resources usage
(Annala, et al., 2018)	Environmentally friendly solutions Replace undesirable resources Contribute towards sustainability

(Annala, et al., 2018) argued that the replacement of undesirable resources by the required needs has a direct impact on the reduction of the environmental burden from the excessive usage of resources. Therefore, sustainability is a critical feature that should be considered during the creation of a frugal innovative product or strategy. This feature could be considered based on the financial, environmental impact, and social usage optimisation.

2.3.1 Challenges in sustainability features integration in frugal innovation

Since the sustainability is a critical feature of frugal innovation, it has to be applied following certain strategy. Several challenges have been raised throughout such integration, especially, in developing countries and bottom of pyramid targeted customers. Therefore, these challenges are explored in this section to create a road map for the frugal innovation strategy in a sustainable concept. In order to do more with less, frugal innovation should be implemented with optimisation of resources usage. Also, the social and environmental impacts are two of the most challenging aspects in the emerging markets and the bottom of pyramid countries. It was reported in (Ghezzi, 2020) that business models are required to build such optimised strategy to be applied in bottom of pyramid countries. The business models were defined as the innovation that generate significance in core functionalities with reducing the resources costs and environmental impacts. This might create an issue in a frugal innovation approach as not all strategies could be reversed as reported earlier in

(Schleinkofer, et al., 2019). The main challenges in sustainability of frugal innovation were summarized in the following:

1) Maximization of materials and energy usage: the increase in efficiency optimizes the rule of do more and use less.
2) Creation of value from waste: emphasised on the usage of wasted materials or resources from a recyclability perspective. Or, reduction in wastes through optimised processes and materials re-usage.
3) Integrate the concept of sufficiency: optimise the usage of resources for a specific task.
4) Generate scaled up solutions: tackle high cost objects to mimic them in a cost-effective approach. an example of scale-up solutions refers to the ventilator generated in MIT to replaced $20k ventilators due to the Covid-19 situation.

The above mentioned points are challenging in terms of frugal innovation integration in developed countries and the bottom of pyramid targeted customers environment. In addition, the paper studies researched in terms of frugal innovation does not tackle empirically these issues based on the strategies or products created. This means that the sustainability is not taken as a separate well-focused aspect of product generation.

2.4 Definitive strategies towards frugal innovation

In this section of the literature the strategies towards the frugal innovation application are explored in order to address the main aspects of the business models mentioned in section 2.3. This helps in discussing the product innovation proposed in this project at later stages of the report. The approaches and strategies of the researched paper studies focus on the following topics under the umbrella of frugal innovation (Mourtiz, et al., 2016). Table 2.2 addresses these topics along with their description.

Table 2.2: Available strategies in frugal innovation with their description.

Strategies in frugal innovation	Description
Innovation enablers	Focuses on the optimisation of resources for the frugal innovation concepts.
Success factors in frugal innovation	Specific characteristics that enable the development of frugal strategies.
New product development	Produce a frugal product in a cost-effective measure.
Issues in organisations	Fixing strategies to increase the financial aspects of a company.

The strategies in frugal innovation should be taken one at a time, where the development of a new product requires the market research on the available ones to generate a cost-effective one. However, the sustainable aspects could be taken into consideration to optimise the performance from a sustainable point of view. However, all the strategies of frugal innovation are considered as enablers of ecosystems based on a resource constrained aspect. This was reported in (Winterhalter, et al., 2017) referring to definitive concepts in frugal innovation and ecosystem inclusion as mentioned in the following.

1) Closing the gap between the financial and human resources.
2) Increment of the innovation culture in organisations.
3) Proposition of new infrastructure.
4) Minimisation of the failure within the organisations.

Dealing with the above points in a frugal innovation perspective increases the capability of organisations in optimizing their resources towards better usage. This was reported as an essential aspect in strategic development under the sustainability umbrella in organisation. Also, this is essential in terms of the approach towards the targeted bottom of pyramid countries and limited resources customers. The following presents different approaches that have been used in order to integrate the frugal innovation strategies.

2.4.1 Architectural frugal innovation

In terms of the approaches to build a strategy to develop a frugal innovative idea or product, architectural approach was reported in a study by (Lim & Fujimito, 2019). This approach is set to link the existing component of the system that has to be innovated with changing the core functionality to be cost-effective. This approach helps in eliminating all the unnecessary elements that drive the cost up and increase its complexity. However, it was reported in an another study that the standards have to stay the same in terms of applicability to serve in the same scope (Anthony, 2017).

2.4.2 Resources optimisation in frugal innovation

Resources optimisation is another important approach used in frugal innovation, where researchers opted to combine several resources to output the intended frugal innovative aspect. However, the application of such approach requires the consideration of field experience for the process as it could not be planned in advance (West, 2019).

2.4.3 Increment of exploration and research

The increase in exploration of customer needs is another approach of frugal innovation, where the bottom of pyramid countries has limited reaches to organisations and markets. A study reported that this approach is considered as a critical success factor to generate collaborative partnership under the umbrella of frugal innovation (Lu, et al., 2020). In terms of organisations dealing with frugal innovation, the application of such approach increases the maturity of the company in terms of the optimization of the financial resources and services.

2.4.4 Geographical focus in frugal innovation

The geographical focus in frugal innovation intend to user local forces or local organisations in the development of a frugal idea or concept. This has proven an effective method for developing countries to apply frugal innovation projects in terms of research and development (Annala, et al., 2018). It was reported that the focus on local resources in terms of the local needs optimizes the financial resources in terms of the elimination of the costs for research and development as the local companies are well aware of the customers' needs (Numminen & Lund, 2017).

2.5 THEORETICAL FRAMEWORKS AND IMPLEMENTATION OF FRUGAL INNOVATION

The theoretical frameworks in frugal innovation focus on the optimisation of the strategy selection to be pursued by the intended organisation, where a study reported that such aspect is affected by the required growth strategy (Chainsung, 2020). Hence, the following should be assessed for the generation of an optimised strategy or framework:

1) Local needs exploration.
2) Proximity of the organisation to the customer needs.
3) Distance from the intended market.
4) Availability of reverse innovation.

The reverse innovation created an essential feature for the success of cost-effective strategies implementation in emerging markets and developing countries. In addition, the Blue Ocean strategy have been suggested in (Agnihotri, 2014), where an implementation of such strategy was argued to help organisations in looking towards frugal innovation. This is due to the ability to reduce material and resources usages, such as, raw materials. The application of the theoretical frameworks in a frugal innovation perspective refers to the consideration of definitive business models with taking into consideration the sustainability aspects of the application. Therefore, in the following the application of these models is explored.

2.5.1 Application of frameworks in business models

Since the reverse frugal innovation is required to drive successful strategies, several paper studied have mentioned the applicability of these frameworks in terms of certain features described in Table 2.3.

Table 2.3: features of business models and their description in frugal innovation.

Features of business models	Description
Feature 1	Target customers range from BOP to middle-class.
Feature 2	The value proposition focuses mainly on satisfying basic needs
Feature 3	The value proposition focuses mainly on satisfying basic needs
Feature 4	The main revenue model is based on low costs

Feature 5	the value chain is characterized by cooperation, partnerships and NGO involvement
Feature 6	Sustainable business models successfully operated at the BoP build upon local resources and capabilities. Thus, the development of local competencies is a success factor.

The application of these business models based on the features mentioned in Table 2.3 leads to the consideration of the sufficiency in organisation. The sufficiency is directly linked to the sustainability and its challenges in frugal innovation, where its helps in delivering sustainable and optimized resource usage. on the social level, these strategies encourage the customers to make more and do less. Such aspect was defined in several studies on frugal innovation (Basu, et al., 2013) (Lu, et al., 2020) (Annala, et al., 2018). In addition, the promotion of frugal sustainability is driven by the following:

1) Encouraging organisations to find opportunities in local markets.
2) Encouraging companies to vary their mind-sets in terms of their organizational structure and services.
3) Encouraging companies to derive green supply chain approached within their systems.

The application of business models following the criteria mentioned above is challenging (Malek, et al., 2017), where it was reported that barriers have been identified. Table 2.4 illustrates some of these barriers.

Table 2.4: Barriers upon the implementation of frugal innovation strategies.

Barriers	Description
Loosing resources	Application of innovation on a large scale might decrease from the value of the products.
Lack of sufficient research	Generation of institutional deficiencies throughout the strategy implementation.

However, it should be argued that the application of frugal innovation should be discussed in terms of its negative and positive impact on the organisation and the market. On the other hand, the impact should be discussed in terms of the financial and environmental burden occurring on the organizational and market levels.

2.5.2 Theories in frugal innovation

Networking in frugal innovation should be based on theories as reported in (Singh & Das, 2020). The study defined and mentioned two theories illustrated in Table 2.5.

Table 2.5: Theories considered in the application of frugal innovation.

Theory	Description
Resource based theory	Closing the gap between the resources need and availability.

Diffusion theory	Innovation flows from the elite customers drive the costs down for the emerging markets.

However, other studies discussed that the resource based theory is more applicable in the bottom of pyramid countries (Winterhalter, et al., 2017). On the other hand, the studies that mentioned the diffusion theory success, argued that the optimisation should occur on the communication channels between the suppliers. This refers to the logistics channels and their optimizations based on time and costs. In addition, the method of networking in frugal innovation is considered as a theoretical framework that assess the success or failure of the integration. The networking theory focuses on the social class and identities investigation within the locality of the frugal innovation application (Devi & hemant, 2018). Another theory in frugal innovation was reported in (Iva, 2018). This theory deals with the ownership and control schemes applied with the innovation framework. This helps in knowledge transfer between organisations based on legislation for protective measures.

2.6 UNIVERSAL DESIGN IN FRUGAL INNOVATION

As researched in the literature review sections of the report, the cost effective measures are the most mentioned and discussed in frugal innovation. This means that the universal design in any frugal innovation should follow a cost effective measure from the design stage, the environmental consideration, and services. The universal design is a method used to include people in the innovation with eliminating the traditional product. Also, this method helps in defining and eliminating the negative impact of the work environment within the frugal innovation framework to be developed. In addition, the universal design enhances the quality and add value to the available design or product to be assessed. Therefore, the organisation or the designer intended to generate a frugal innovative product is tied to the customers' needs with limited resources availability. This means that the traditional approach of focusing on defined groups should be eliminated. In universal design, a relationship matrix was developed in (Singh & Das, 2020) to generate a successful innovative product based on frugal innovation approach. the relationship matrix is illustrated in Table 2.6.

Table 2.6: Relationship matrix for frugal innovative design and product development.

	Functional	Robust	User-friendly	Growing	Affordable	Local
Equitable						
Flexible in use						
Simple						
Perceptible						
Low tolerance						
Low physical effort						
Size in use						

The matrix shown in Table () illustrates a guidance to assess the frugal innovative product to be developed in any study. Hence, the filling of the matrix refers to three different levels known as follows:

1) Weak.
2) Moderate.
3) Strong.

3 PROBLEM STATEMENT AND SOLUTION PROPOSITION

In this chapter of the thesis, the problem statement is presented in order to generate a frugal innovative product. Hence, in this chapter, two problem statements are generated in order to propose a solution in a cost-effective way which could cut costs dramatically.

3.1 PROBLEM 1

The first problem is referred to the creation or proposition of a medical device to urge the problem occurring due to the current Covid-19 situation. Recently, MIT generated a cost effective ventilators to help the global shortage in ventilators (Minj, 2020). The actual product is illustrated in Figure 3.1.

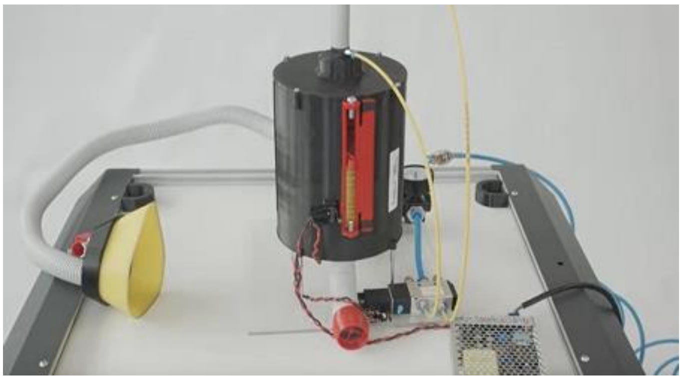

Figure 3.1: 3D printed ventilator generated in MIT (Minj, 2020).

This ventilator is considered as a frugal product based on the cutting of cost from $20k to approximately costing $100. This is considered as a frugal product since the cost is cut dramatically. Referring to Figure 2.1, the frugal does not mean to cut a small fraction of cost. Therefore, this product fills the requirements of a frugal innovative product. The generation of a cost-effective medical device for the current Covid-19 situation is considered as the first problem statement for this project.

3.2 PROBLEM 2

The second problem refers to the extensive usage of materials in shopping trolleys which generates large CO2 emissions. This refers to a frugal engineering aspect from the environmental point of view. In addition, it was found in the literature that the sustainability is an important aspect of frugality in product innovation. Therefore, finding a solution for shopping trolley to reduce the amount of materials used is considered as a frugal innovation aspect. In addition, the reduction of material usage in shopping trolleys could be assessed based on the cost reduction and the environmental burden reduction.

3.3 SOLUTIONS PROPOSITION

3.3.1 Solution 1

The medical devices shortage because of the COvid-19 situation are mentioned by the World Health organisation as follows:

1) Personal protective equipment.
2) Ventilators.
3) Pulse oximeters.
4) Masks.
5) Respirators.

Since the ventilators issue has been solved by the MIT team through creating a cost effective ventilator costing $100 rather than the hospital one costing £20k, another approach is taken to solve the issue of the shortage in medical devices. Therefore, a frugal engineering approach is considered for the pulse oximeters. The pulse oximeters used in hospitals cost approximately between £70 and £100. Designing and creating a pulse oximeter for less than £20 will be considered as a frugal innovative product, where this approach is taken in this dissertation.

The proposed solution is approached using an Arduino-based pulse oximeter using a pulse sensor that costs approximately £4 to £6. This sensor will be connected to a programmable Arduino device that costs between £8 and £12. These are the only devices required to generate a pulse oximeter. The product will generate the design of the circuit, along with the coded required Arduino device and the required connections to generate the frugal innovative product. Also, the dissertation will compare the current available pulse oximeters with the frugal innovative one to show the affordability and the simplicity in the design.

3.3.2 Solution 2

The solution to be addressed for the shopping trolley is the reduction in material (steel) usage with replacing the shopping trolley basket by PET recyclable bags to sustain the required packing during shopping. The study is approached through an analysis of cost and environmental impact comparison between the standard trolley and the trolley with PET bag replacement. Similar solution has been considered with IKEA approach in cutting cost and materials in their trolleys. The benefits from such approach could be considered as follows:

1) Less material usage→ Less processing costs and less material costs.
2) Less space→ Space optimisation of the trolleys area.
3) Usage of recyclable products to increase the product sustainability.

4 METHODOLOGY

4.1 INTRODUCTION

In this chapter, the methodology of project consists of the steps to be taken for the development of the frugal innovative product. The methodology chapter defines the selection process between the proposed ideas as problem statements along with the validation for the selection. The second part of the methodology illustrates the steps considered for design, analysis, and validation of the frugal product development.

4.2 PROBLEM STATEMENT AND SOLUTION SELECTION

In this section, the problem statement and solution selection is validated based on the project description and the better approach to design the frugal innovative product. The ideas proposed in this project are different in their approach and their targeted customers. Hence, Table 4.1 illustrates the main differences between the solutions proposed for the ideas.

Table 4.1: Problem statement and solution aspects of the proposed ideas.

Problem statement and solution	Main aspects
Pulse oximeter for tackling the shortage in medical devices for the current Vovid-19 situation.	• Tackle the shortage in medical devices. • Optimise the cost of pulse oximeters to be affordable for bottom of pyramid countries.

	• Increase simplicity in manufacturing and usage to optimise resources.
Reduction of materials used in shopping trolleys to optimise waste and increase recyclability for environment burden reduction.	• Reduce material waste and optimise the weight of the trolley. • Increase recyclable material usage to protect the environment. • Create an innovative product in terms of frugal innovation. • Optimisation of space usage of shopping trolleys locations.

Following the aspects described in Table 4.1, the project will undergo a frugal innovative product development of the medical devices shortage. A cost-effective pulse oximeter is intended to be generated for the bottom of pyramid countries to fill the gap of medical devices shortage due to the Covid-19 situation. The exclusion of the second idea was based on the lack of resources that validate the generation of such product. Also, the idea was initiated in IKEA with their shopping bag trolleys that decrease the usage of steel in their trolleys' manufacturing process. Figure 4.1 illustrates the IKEA shopping trolley with the PET recyclable bag replacement.

Figure 4.1: IKEA shopping bag trolley (Fixtures, 2020).

Following the argument set in this section, the methodology of the project is focused on the development criteria of the pulse oximeter for bottom of pyramid countries. The product development is set to be a frugal innovative approach that follows the criteria found in several paper studies (Basu, et al., 2013) (Michelini, et al., 2018) (Zhang, 2018):

1) Cost effective product that compete with the current market to be affordable for limited budget customers.
2) Sustainable development of the product with the points mentioned in the following.
3) Optimisation of waste.
4) Try to attempt a reverse innovative product to exclude the disruptive feature.
5) Minimisation of materials usage.
6) Minimisation of footprints generated from the productivity of virgin materials.

Attempting all the features of the frugal innovative approach will be beneficial for the intended product to be competitive in the emerging markets.

4.3 CUSTOMER REQUIREMENTS

In this section, the customer requirements are set for the product. This is a critical feature when designing or generating a new concept for the market. The customer requirements define the main aspect of the design with concise and targeted market. The customer requirements are split into two section mentioned and described in the following.

4.3.1 General requirements

The general requirements of the product focus on the applicability and usage in the market. The intended product is set to be used in hospitals, clinics, and at home. Therefore, the general requirements do not tackle the technical aspect of the product.

4.3.2 Specific requirements

The specific requirements of the product focus on the technicality in designing its core functionality. Also, the specific requirements focus on the parts needed to build it, where they help in scoping its functionality.

4.4 BILL OF MATERIALS

In this section, the bill of materials approach is explained in order to define and validate the cost effectivity of the product. In order to generate the bill of materials of the product, the parts needed should be specified as a resultant from the specific requirements set in section 4.3. Therefore, the results section of the bill of materials should be partitioned intro two sections mentioned in the following.

4.4.1 Parts required

The parts required should fit the specific customer requirements set in section 4.3.2, where they are named along with their functionality.

4.4.2 Costs of parts required

The costs of the parts required to build the intended oximeter should be defined and backed up with references from the sources. In case of a manufacturing cost for certain part of the product, the parts will be not available based on off-the-shelf approach. Therefore, the manufacturing costs should be estimated and explained.

4.5 Circuit design of the oximeter

The pulse oximeter is a device intended to measure the pulse of patients in an continuous way to provide data for doctors and nurses to monitor the status of the patient. Therefore, an electric circuit is required to be designed along with the required connections. This part of the project serves in applying the intended device in real-life as it constructs a guidance for the required connections between the parts.

4.6 Design of the oximeter

The design of the oximeter is another critical part of the frugal innovative product intended in this project, where a software such as Abacus, Autocad, or SolidWorks is used to design the shape and dimensions of the product. This part of the project is critical for the marketing aspect to build the business model for the pulse oximeter as mentioned in (Winterhalter, et al., 2017). The design of the pulse oximeter should be presented in 3D and 2D schematics to help in the design execution process in real-life example.

4.7 SWOT and DFMEA

The SWOT and DFMEA are two important tools to assess the executed frugal innovative product against the customer requirements. This means that the analysis based on the SWOT and DFMEA visualizes the success and failure factors in presenting the device into the intended market. Therefore, it is important to critically assess the specifications of the generated device against the set customer requirements in section 4.3 of this chapter.

5 FRUGAL INNOVATIVE PRODUCT DEVELOPMENT

5.1 INTRODUCTION

In this chapter of the project, the frugal innovative product development plan is executed. In the previous chapter, the steps required for the plan execution were set and defined. Therefore, in this chapter, the output of the plan is defined and validated against current pulse oximeter designs to scope it in a frugal engineering perspective.

5.2 CUSTOMER REQUIREMENTS

It was mentioned in section 4.2 of the methodology that the customer requirements are split into two sections. The general and the specific requirements deal respectively with the broad and technical aspect of the product generation aspects.

5.2.1 General requirements

The general requirements for the pulse oximeter should follow the frugal innovation approach in product development. Figure 5.1 illustrates a sample of the pulse oximeters found in the market.

Figure 5.1: Fingertip pulse oximeters collected from different companies.

The fingertip pulse oximeters research and visualised in Figure 5.1 could be supplied from different companies with difference price ranges and functionality. Hence, the price range of the researched fingertip pulse oximeters is between £40 and £90 (Beurer, 2020) (ChoiceMMed, 2020). The suppliers highlight the main features of these devices and they are mentioned as follows:

1) Display oxygen level through SpO_2.
2) Monitor the heart rate at beats per minute.
3) LED display for easy read to be used at home.

These are the main features of the battery-operated pulse oximeters found in the market. Hence, following the described information on the company's data sheets of the devices, the general requirements of the device could be withdrawn and shown in Table 5.1.

Table 5.1: General requirements of the fingertip pulse oximeter.

General requirements	Description
Cost effective	The device should cost a fraction of the original market price.
Portable	The device should have specific minimal dimensions to be handheld.

Durable	The device should be made of hard enough materials to be durable.
Battery powered	The device should be battery powered by affordable batteries.
Lightweight	The weight of the device should not exceed 350g.

The general requirements of the device are set as a mainstream threshold that could be found in any compact fingertip pulse oximeter in the market. Therefore, the requirements should be addressed specifically referring to its core functionality.

5.2.2 Specific requirements

The specific requirements of the pulse oximeter are defined in this section, where its core functionality is defined. This will lead to a more concise parts and design selection criteria for the intended device. Table 5.2 illustrates the specific requirements with their justifications.

Table 5.2: Specific requirements for the customers with their justification.

Specific requirements	Justification
Power source	Battery powered with AA, AAA, or similar batteries to be portable.
Dimensions	The device should be restricted to no more than 60mmX35mmX35mm.
Cost	The cost should be limited to £15 to accommodate the fraction of the price range of the market.

Materials	Recyclable plastic casing to improve the product sustainability.
Lightweight	The total weight of the parts used for the product generation should be limited to 350g.
Display	The display should be a clear LED display screen to read the required variables.
Sensing platforms	Sensors for generating the heartbeats and the oxygen level in the blood are required.
Usage	Should be easy to use with clip-on automatic application.
Comfortable	The clip on should be comfortable since it will be used for a long time to monitor the patient in real-time.

Following the justification set in Table 5.1, several parts of the pulse oximeter could be generated following the threshold numbers mentioned. However, the core functionality of the pulse oximeter is still not clear, where this should be defined in this section. The definition and justification of the oximeter functionality helps in understanding the required parts to be ordered for the frugal innovative product development. Table 5.3 illustrates the main functions of the device (ItemsCatalogue, 2020).

Table 5.3: Functionality of the pulse oximeter with the requirements.

Functionality	Requirement/Justification
Voltage	Operate at 3V module.
Type of sensing of heartbeat	Photodiode relying on LED emitters at a wavelength range between 600nm and 1000nm.
Type of sensing of oxygen level	Photodiode with high sensitivity (>70%) to absorb the wavelength from the blood.
Battery charging type	Controlled lithium ion to save over charging. 3.6V Li-ion battery cell. Minimum of 4 hours operation time.
Message display	LCD screen with 90X60 pixels. The total area of the screen should not exceed 30mmX25mm.

The functionality assessment of the pulse oximeter refers to the intention of the medical device by measuring the oxygen level in the blood along with the heartbeat. It should be noted that the measurements should be taken from a single point at the fingertip of the patient in order to eliminate any excessive variation in pulse from different body points. It should be noted that the pulse oximeter should follow the specification of the standard of “Medical Device Directive of 91/42/EEC. Also, the device should be tested based on the vibration compliance following IEC 68-2-6/68/2/31.

5.3 BILL OF MATERIALS

The bill of materials helps in addressing the exact total cost of the medical device intended in this project. In addition, the specified bill of materials allows the calculation of the total weight in high accuracy. The calculation of weight would be simply the addition of the parts' specified weight upon research. It should be noted that different components could be used for the same purpose, which means that the weight is approximated at this stage of the project.

5.3.1 Parts required for the pulse oximeter

The parts required for the pulse oximeter should be fitted in the customer requirements sheets illustrated in Table 5.1, 5.2, and 5.3. This means that the parts required have to fall within the specifications set earlier in section 5.2. The parts are partitioned into sections referring to the functionality and the overall design parts of the pulse oximeter. Table 5.4 illustrates the parts required for the production and design of the pulse oximeter.

Table 5.4: Parts for the overall design and core functionality of the oximeter.

Parts for the overall design of the oximeter	
Shell	Made from recyclable material (plastic) manufactured based on the required dimensions.
Display	0.69-inch I2C serial LCD screen.
Clipping mechanism	Manufactured within the shell.
Parts for the core functionality of the device	
Processer	Arduino NANO
Circuit part 1	Capacitor

Circuit part 2	Resistor
Circuit part 3	Wires for connections
Circuit part 4	LED to show the functionality of the device.
Pulse sensor	LED emitter at a wavelength range of 660nm and 940nm.
Oxygen level sensor	Photodiode detector.
Power source	3.6 lithium ion rechargeable battery.

Following the required parts shown in Table 5.4, the parts should be sources and priced in the following section. In addition, the overall parts for the device are defined based on the price of the materials and how they are made. It should be noted that the LCD display could be sourced as an off the shelf part.

5.3.2 Costs of the parts

After the generation of the different parts required for the construction and design of the intended device, the costs could be assessed. Table 5.5 illustrates the required parts with their costs along with the reference of the sourced part for justification purposes.

Table 5.5: Costs of the parts required for the device.

Parts for the overall design of the oximeter			
Part Name	Quantity	Cost	Reference
0.69-inch I2C serial LCD screen.	1	£2.99	(Ebay, 2020)
Parts for the overall design of the oximeter			
Arduino NANO	1	£3.85	(Ebay, 2020)
Capacitor 47nF	1	£0.12	(Mouser, 2020)
Resistor 150Ω	1	£0.1	(Mouser, 2020)
Resistor 180Ω	1	£0.1	(Mouser, 2020)
Resistor 10kΩ	1	£0.1	(Mouser, 2020)
Resistor 100kΩ	1	£0.1	(Mouser, 2020)
AA replaceable battery	2	£0.38	(Ebay, 2020)
Photodiode	1	£1	(Mouser, 2020)
LED emitters	1	£1.2	(Mouser, 2020)
Total Cost		£9.94	

Table 5.5 resulted in the total cost required to buy the parts to generate the pulse oximeter. It should be noted that the design of the shell for the device should be manufactured and could not be bought off the shelf. Buying raw materials and consider a manufacturing process for the shell will drive the cost up. Also, the manufacturing process requires additional costs which will lead to the failure to reach a frugal innovative product development. Therefore, a reliable solution should be addressed for the pulse oximeter. Since the pulse oximeter should be applied at the fingertip of

the patient, a cost effective solution should be considered. The following illustrates the proposed solution.

1) Foam material that could be recycled from any foam based product to insert the circuit in.
2) Recyclable PVC pipe material to be enclosed on top of the foam.

The PVC recycled pipe is rolled on top of a recyclable wasted foam, where Figure 5.2 illustrates the parts needed.

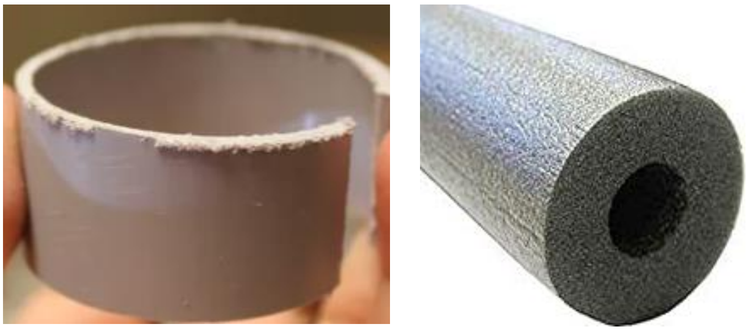

Figure 5.2: Recycled PVC pipe with recycled foam.

The usage of waste PVC pipe along with rolled foam on the inner part to generate the shell of the oximeter affects the sustainability aspect of the frugal innovation product development in this project. Table 5.6 reflects the replacement of the virgin material by the recycled materials.

Table 5.6: Difference between the original and new approach for the pulse oximeter device shell production.

Original plan for the pulse oximeter shell		
Shell material required/part	100g of PET/part	£0.09
Manufacturing costs/part	Injection moulding	£2.5/part
Total cost		£2.59
New plan for the pulse oximeter shell		

Shell	Recycled PVC pipes	-
Manufacturing	-	-
Total cost	[redacted]	-

The usage of recycled material has several positive effects on the frugal innovative product development in this project, where they are mentioned in the following with their description.

1) Reduction of cost by £2.59/part.
2) Increase sustainability aspect by the waste management approach considered for the usage of wasted foam and PVC pipes.
3) Reduction in carbon footprints generated from the production of virgin materials.
4) Reduction in landfilling of the wasted foam and PVC pipes dumped from construction sites.

5.4 CIRCUIT DESIGN OF THE OXIMETER

In this section of the project, the circuit required for the pulse oximeter is designed. It should be noted that the circuit is built referring to three defined parts. The first part refers to the circuit of the photodetector. The second part is the circuit for the LED emitters. Finally, the third part illustrates the circuit design of the Arduino NANO processor with the aforementioned circuits.

Photodiode circuit

The photodiode circuit is set for the detection of the oxygen levels in the blood streaming referring to the pulse at the monitored point in the fingertip. The photodetector is connected to the analogue input of the microprocessor, to the ground, and to the power source (battery). Figure 5.3 illustrates the circuit for the photodetector diode.

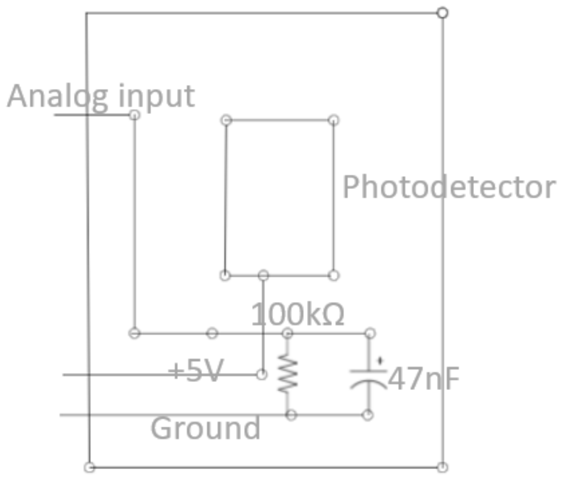

Figure 5.3: Circuit design for the photodetector diode.

LED emitters circuit

The LED emitters circuit is critical in terms of the detection mechanism occurring between the circuit of the oximeter and the fingertip of the patient. The LED emitter refers to the heartbeat detection in time. Figure 5.4 illustrates the LED emitter circuit.

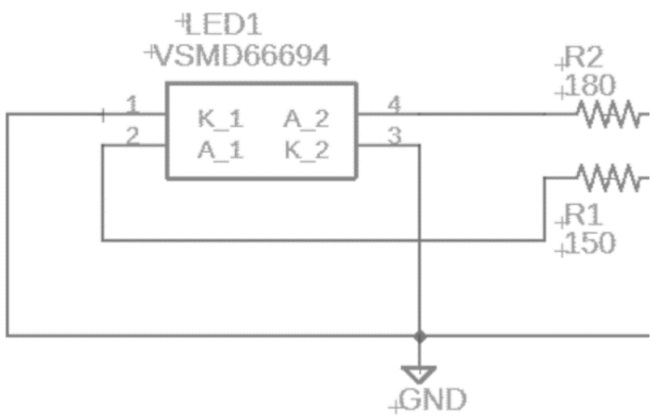

Figure 5.4: Circuit design for the LED emitters design.

Pulse oximeter circuit

The pulse oximeter circuit design is the combination of Figure 5.4 and Figure 5.3 with the Arduino Nano microprocessor. However, the Arduino Nano microprocessor could be illustrated by a circuit design illustration shown in Figure 5.5.

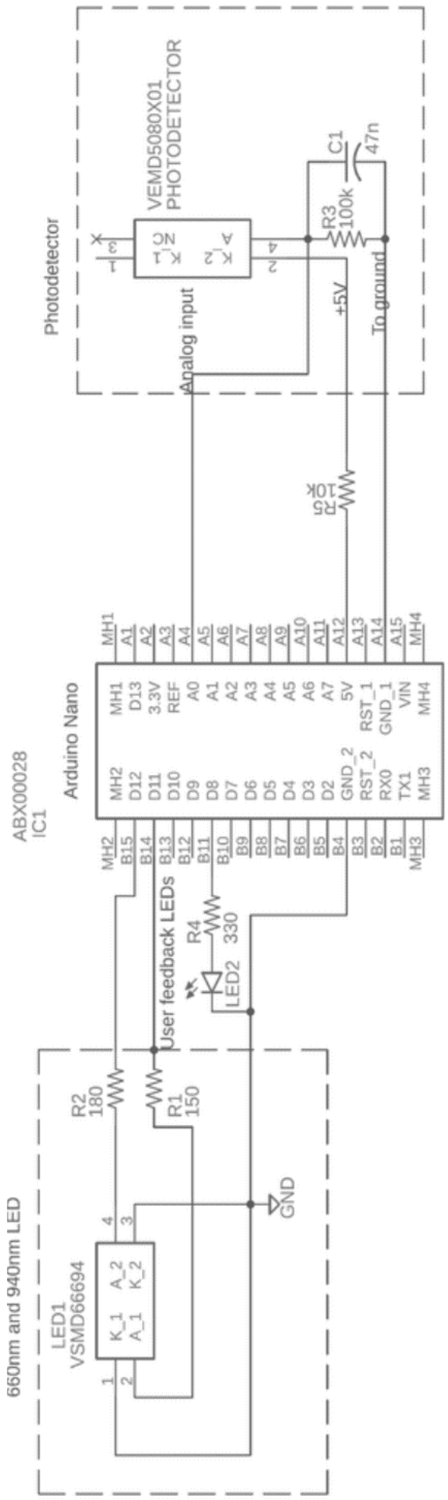

Figure 5.5: Circuit design of the pulse oximeter device.

Following the design of the circuit for the pulse oximeter, this builds grounds for the application in real life. In terms of the implementation with the shell proposed in the same section, the design in section 5.5 will illustrate the implementation. The design implementation will help in addressing the dimensions in 3D and 2D schematics.

5.5 Design of the oximeter

In this section of the report the design is executed using Abacus software to show the dimensions required for each part. This will help in addressing the parts implementation in a tidy box. Hence, the design of the foam integrated in the PVC pipe will be as well executed in this section. For more clarification on how the foam is integrated in the PVC pipe, Figure 5.6 illustrates the designed 3D schematic on Abaqus of the part placed on the fingertip of the patient.

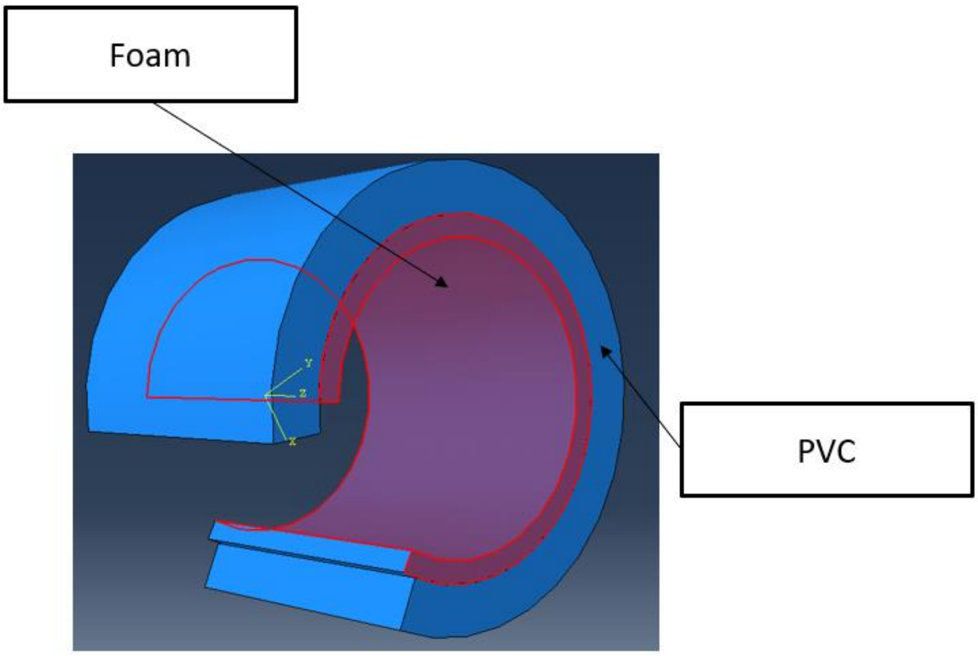

Figure 5.6: 3D schematic of the fingertip part to be inserted on the patient's finger.

Following the design of the fingertip of the pulse oximeter, the intended photodetector and LED transmitters should be implemented in the device to generate the required data.

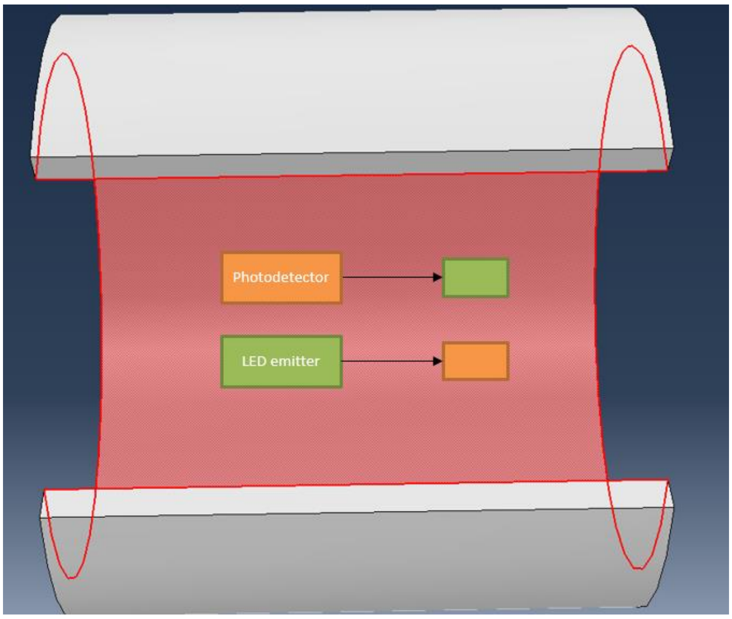

Figure 5.7: Photodetector and LED emitters place on the foam to get the fingertip contact.

Figure 5.7 illustrates the place of the photodetector and the LED emitters to get the pulse and the oxygen level. In this part of the design, the LCD screen should be included to visualise the data, where the LCD screen set in the bill of material was referenced and illustrated in Figure 5.8.

Figure 5.8: I2C battery operated and Arduino compatible LCD screen (Ebay, 2020).

The LCD screen is glued on top of the PVC pipe part set above the foam to provide better fixation. In addition, the opening set in the foam integrated PVC part on the fingertip was set for the LCD screen installation. Figure 5.9 illustrates the schematic of the installation of the LCD screen on the upper part of the fingertip.

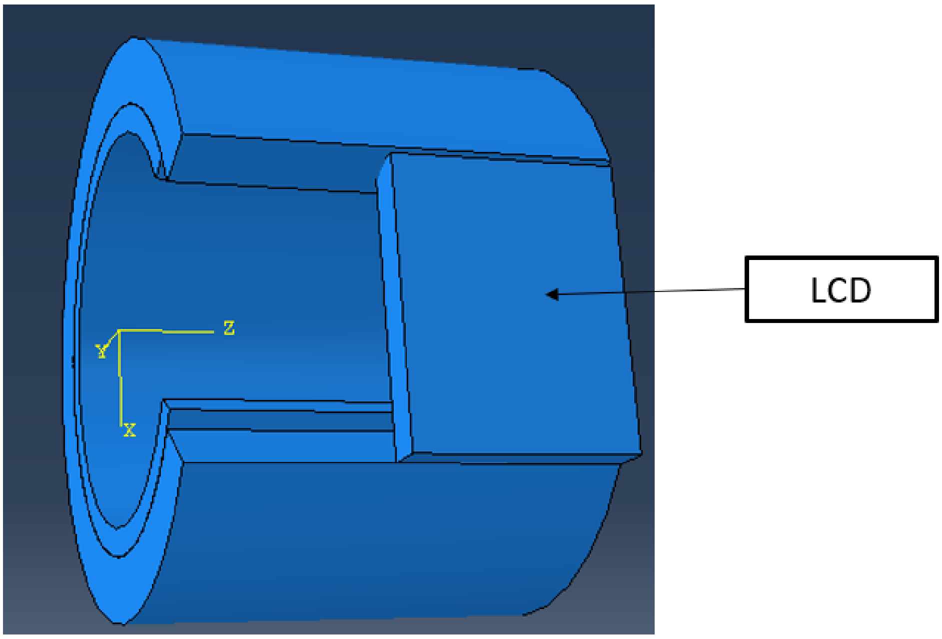

Figure 5.9: LCD installation place on the pulse oximeter.

The position of the LCD screen is idea in terms of the continuous monitoring of the oxygen level and the heartbeat. It should be noted that the bottom part of the foam will be in contact with the fingertip of the patient. In order to illustrate how the fingertip of the patient is set into the foam, Figure 5.10 shows the actual size of the fingertip in terms of the size of the pulse oximeter.

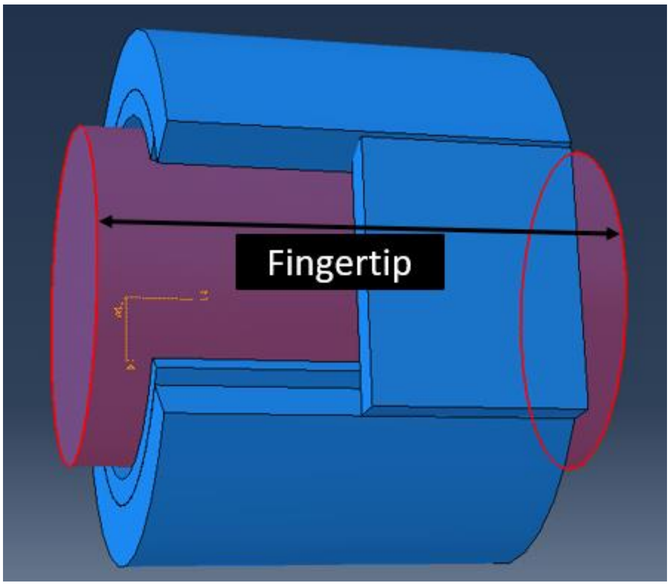

Figure 5.10: Illustration of the fingertip size in scale to the dimensions of the pulse oximeter.

This shows the convenience and the ease to implement of the pulse oximeter on the finger. It should be noted that the red cylinder in Figure 5.10 shows only the fingertip of the patient's finger illustrating the area of contact between the patient part and the oximeter circuit.

5.6 MARKET ANALYSIS OF THE DESIGNED PULSE OXIMETER

In this section of the project, the designed pulse oximeter is analysed based on the market potential to be sold or built for the bottom of pyramid countries. It is noted that the generated pulse oximeter is analysed based on the targeted emerging market with limited resources and limited budget. The total cost of the generated pulse oximeter is less than £10 with the ability to:

1) Monitor the oxygen level in the blood.
2) Monitor the heartbeat of the patient.

In order to analyse the market of the generated pulse oximeter, a SWOT and DMFEA analysis should be applied to explore the strength and weaknesses of such design. In the following the methods are explained along with their applicability on the designed

5.6.1 SWOT analysis

SWOT stands for strength, weakness, opportunity, and threats. It is mainly applied for organisations to assess their position in the market. Also, it was reported that SWOT are used to asses new designs or ideas in terms of their stand point in the market. The SWOT analysis is defined and assessed based on a specific matrix with defined questions to be answered as illustrated in Table 5.7.

Table 5.7: SWOT analysis questions to develop the matrix.

SWOT	Questions to be answered
Strength	In what perspective the part improved the market? What are the unique aspects of the designed part or product?
Weakness	What points could be improved within the designed part? How the resources used could be improved?
Opportunity	What are the advantages shown from the product in a frugal innovation market? How the strength of the device could turn into opportunity?

Threat	What are the threats that can harm the functionality of the device?

The questions mentioned in Table 5.7 should be assessed in terms of the pulse oximeter generated in this project. Therefore, the SWOT matrix could be generated. The following illustrates the generated SWOT matrix for the pulse oximeter.

Strength

- Cost effective: less than £10.
- Sustainable: usage of recyclable material that limits the usage of virgin material for the shell.
- Lightweight and compact in size.
- Could be used in hospitals and from home.
- Well fit in the BoP countries.

Weakness

- Could not come in contact with water.
- Batteries have to be changed on a monthly rate.
- The foam and PVC waste have to be well-sourced

Opportunity

- Could be generated in real-life.
- Affordable for limited budget customers

Threat

- Short circuit from water contact.
- Overheating of the processor.

5.6.2 FMEA

The FMEA stands for failure modes and effects analysis of the pulse oximeter. The FMEA is critical in terms of the generation of a new device or project into the market. The FMEA is a tool to define the risks of failure and rank them based on the following:

1) Severity: defined as the severity of the failure impact, where the failure and its impact should be defined. The severity should be scaled from 1 to 10.
2) Occurrence: defined as the frequency of a failure mode to occur along with scoring it between 1 and 10.
3) Detection: defined as the ability to detect the failure from the parts used to build the pulse oximeter.
4) Risk priority number: the risk priority number of RPN is defined as the overall risk score calculated by the multiplication of the severity, occurrence, and detection. The larger the RPN is, the more attention or alarming situation would be for the defined risk.

Table 5.8: FMEA of the parts creating the pulse oximeter.

Part	Failure mode	Effect	SEV	Cause	OCC	DET	RPN
Microprocessor	Overheat	Stop oximeter	8	Over usage	3	7	216
Battery	Stop	Stop oximeter	8	Empty	6	5	240

Circuit	Short circuit	Overheating	9	Bad usage	4	10	360
LCD	Blank	No data visualization	5	Poor connection	2	10	100

Following the assessed parts in Table 5.8, the overall risk for each failure mode was calculated and the recommended actions to mitigate the risks are mentioned in the following. It should be noted that the overall risk numbers are ranked from the highest to the lowest.

1) Circuit: in order to mitigate the risk of a short circuit, the wires should be wrapped in isolated tape.
2) Battery: replace the used batteries by rechargeable lithium ion batteries.
3) Microprocessor: usage the pulse oximeter for a maximum of 4 hours/day.
4) LCD: make sure the connection and the wiring are set with the correct resistors and capacitors.

The risk mitigations for the frugal innovative product development is assessed in this chapter following the possible failure modes that could occur at the part level. However, more advanced analysis could be applied on the parts and the overall design of the oximeter. In the discussion section of the project, more in depth analysis is discussed in terms of the advanced analysis for the failure modes.

6 Discussion

6.1 Introduction

In this chapter of the thesis, the aspects of the frugal innovative product development are discussed in the light of the developed and designed pulse oximeter. The discussion covers the validation of the idea selection in terms of the medical device emergence because of the current Covid-19 situation. Also, the discussion considers the specifications of the device in terms of their fitting within the frugal innovation approaches researched in the literature review of the report. In addition, the sustainability challenges tackled through the development of the device are discussed. Finally, the development potential of a business model within the available theories of frugal innovation is projected in the light of the generated design on Abacus software.

6.2 Validation of the oximeter selection

The validation of the medical device over the shopping trolley idea refers to the current Covid-19 situation and shortage in medical resources. In addition, the validation of the selection is justified in the light of the effectivity of such device in monitoring the status of the Covid-19 cases. It was reported in (Studman, 2020) that confusions have been raised in terms of the effectivity of the pulse oximeter for Covid-19 patients. However, it was discussed in the same report that the pulse oximeter serves as a diagnostic tool in a general perspective. However, the monitoring of the patient oxygen level in the blood along with their heart rates increases the accuracy of decision-making in clinics as suggested by some doctors of NHS London General Practices. There are no arguments that resulted in a consensus reason to validate the effectivity of pulse oximeter in defining the Covid-19 cases.

6.3 FRUGAL INNOVATION ASPECT AND SUSTAINABILITY OF THE DEVICE

However, in a frugal innovative perspective, the generation of a cost-effective pulse oximeter serves the emerging markets and developing countries referring to the limited budget customers. In addition, a shortage of medical devices has been urged by the World Health Organisation in terms of dealing with the current Covid-19 situation. Also, the pulse oximeter was one of the urged medical devices needed. Hence, the bottom of pyramid countries has already shortage in resources, which was amplified by the current situation of Covid-19. The price range of an effective pulse oximeter used in hospitals and clinics range between £70to £100. The generation of a new device that serves the same function in an affordable price can make a huge difference for the bottom of pyramid countries. An example on the possible difference in cost is illustrated as follows:

If the average price per unit is £80, where 30 hospitals in the bottom of pyramid countries need 200 pulse oximeter each; then, the total cost without logistics would be:

$$Total\ cost = 80 \times 30 \times 200 = £480000$$

Hence, the developed pulse oximeter generated in this project is approximately £10. Therefore, a dramatic cost reduction would occur for the same example.

$$Total\ cost\ of\ the\ current\ design = 10 \times 30 \times 200 = £60000$$

$$Cost\ reduction = 480{,}000 - 60{,}000 = £420{,}000$$

A cost reduction of £420,000 could occur from the usage of the current design generated in the project. It should be noted that another aspect or feature of the frugal innovation in the current design refers to the optimisation of material usage. The shell of the device set at the fingerprint of the patient is made from recyclable materials, which replace the usage of virgin materials. The benefits of this usage reflect the sustainability in all its aspects, such as, social, environmental, and economic.

1) Social: increase the employment rate of the locals referring to the simple design and manufacturing process required for the designed pulse oximeter.
2) Social: reduce the required amount of communication and logistics for a local organisation generation.
3) Social: in case of using the pulse oximeter at home, it offers an ease to use as a plug and play approach.
4) Environmental: decrease the usage of virgin materials which decrease the possible footprints into the environment. This has a direct impact on the Ozon depletion.
5) Environmental: decrease the landfilling of foam and PVC wasted pipes from the construction sites.
6) Economic: thrive towards a green supply chain in using the recyclable materials in the manufacturing process of the device.
7) Economic: decrease costs through optimising the usage of resources and materials.

Also, the sustainability of such device is mentioned as one of the challenges of attaining reverse innovation as was described by (West, 2019). Mainly, the advancement in technology results in a disruptive approach to tackle difference customer groups (Albert, 2019). However, this device was concise to have the same functionality in monitoring the heartbeat and the oxygen level of the patients. This tends to help the frugal innovative product generated in this project to reach the reverse innovative approach of frugal innovation. However, the limitations of such design are emphasised on the design and business model planning discussed in the following section.

6.4 DESIGN AND BUSINESS MODEL OF THE DEVICE

The limitations of the pulse oximeter designed in this thesis refers to the design and business model implementation in the bottom of pyramid countries. In this section these two aspects are discussed in terms of the limitations and the opportunities based on the theories of frugal innovation researched in the literature review chapter.

For the design generated in chapter 5 of the project, it is limited in terms of the rendering and showing the final product with all the detailed connections. This is considered as a limitation in case of a production line implementation. The design generated mainly elaborates on the fingertip of the pulse oximeter with showing the integration of the photodetector diode and the LED emitters. On the other hand, the microprocessor Arduino Nano and the batteries that power the system were not included in the design. This limitation was covered by the full description and analysis of the circuitry parts needed to build it along with the connections between the microprocessor pins and the sensing platforms. Another limitation in the design is referred to the lack of planning in terms of the business model for a frugal innovation full approach. This means that the communication required and logistics to transport and source the products were not emphasised throughout the course of the project. However, the obstacle was attained to be solved through following the roadmap of one of the researched theories of frugal innovation addressed in (Devi & hemant, 2018).

7 CONCLUSIONS AND FURTHER WORK

The conclusions withdrawn from the project are set in bullet points mentioned in the following:

- Frugal innovation focuses on generating a cost effective product or strategy with keeping the same core functionality of the altered one. Hence, in this thesis, the shortage in medical devices due to the current Covid-19 situation was tackled through the design of a cost effective sustainable pulse oximeter.
- The design of the oximeter was validated based on addressing the customer requirements towards limited budget countries. The design was intended to be sold in emerging markets and developing countries on limited budgets.
- The pulse oximeter tackles some of the sustainability challenges addressed in the research, where the optimization of material usage was appointed based on the recycling of waste foam and wasted PVC pipes from construction sites.
- The environmental burden was considered as a part of the frugal innovation in this project following the referring to the reduction in landfilling usually made by construction sites.
- The cost of the designed pulse oximeter was approximately £10 referring to the bill of materials required. In an example of supplying a country with 20 hospitals and 200 units/each, the cost was dropped by £420,000 for the batch. However, logistic costs were not included in the analysis.
- The social aspect of sustainability was attempted to increase the viability of local manufacturing firms to generate the product which tackles the geographic aspect of frugal innovation.

- The circuit diagrams and design on Abacus of the pulse oximeter improved the idea proposition and made it applicable in real life.
- The risks of failures and the opportunity of the device in the emerging markets were assessed based on a SWOT analysis and a quantitative FMEA analysis.
- The main aim of this project was attained by tackling the shortage in medical devices shortage due to the current Covid-19 situation.

In terms of the further work of the project, the following could be tackled:

1) Generate a business model with its strategy to develop the design in emerging markets.
2) Survey bottom of pyramid country to check the validity of the design against current sold products.
3) Generate a theoretical framework to define the limited budget customers in emerging markets to ease the generation and scoping of frugal innovative product development.

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