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Integration of Computer Aided Design and Engineering (CAD/E) Principles for Development of a Face Shield Concept to Protect Against the COVID-19 Virus

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Abstract: *The COVID-19 pandemic has exponentially developed over the past two years into the most prominent crisis that humanity has encountered regarding the stark danger posed to the health and well-being of the everyday citizen. As such, a multitude of safety measures have both been mandated and heavily advised by the governments of the world in a desperate attempt to reduce infection and mortality rates. No method has been more strongly encouraged than the wearing of personal protective equipment (PPE) when coming into human contact, by virtue of the adornment of face masks and face shields. This paper investigates the integration of computer-aided design and engineering (CAD/E) principles for the development of a face shield concept to protect against the COVID-19 virus. The study was orchestrated through the use of the SolidWorks software in generating CAD concepts, employment of the SolidWorks Sustainability tool to evaluate the most viable concept's lifecycle environmental effects, and the subsequent material redesign of this concept within the sustainability tool to reduce its adverse inflictions on nature. Due to the exceedingly high number of persons using face shields in today's society to protect against this virus, waste levels upon disposal are equally immense. This paper is to describe the development of the CAD/E concept through the major avenues of sustainability and environmental conservation, and provides an opportunity for sanitation and engineering companies alike to explore a niche in this increasingly expanding market.*

Keywords: *COVID-19, PPE, face shield, CAD/E, sustainability*

1. Introduction

The first cases of the Coronavirus disease 19, a.k.a. COVID-19, were recorded in Wuhan, China between late November and early December 2019, and has quickly become a widespread, vastly prominent health crisis in most countries around the world (Mohan and Nambiar, 2020). Only four months later, on March 11th, 2020, the World Health Organisation (WHO) officially declared COVID-19 as a pandemic, the first of such declarations since the announcement of the H1N1 pandemic flu in 2010 (Liu et al., 2020). The COVID-19 virus was determined to have originated in bats and is primarily transmitted among humans through direct or close contact with infected persons who expel saliva and other respiratory secretions while speaking or coughing. The disease is highly contagious and although most infected persons remain asymptomatic or experience mild flu symptoms, more severe inflictions such as breathlessness, fatigue, coughing, pneumonia and even death have occurred among elderly, immunocompromised and co-morbid victims (Mohan and Nambiar, 2020). The Center for Disease Control and Prevention (CDC), since the inception of the virus, has highly recommended taking the following preventative measures: maintaining social distancing, staying at home unless absolutely necessary, frequent sanitisation and disinfection via handwashing (Probst et al., 2020), and most importantly, covering the mouth and nasal cavity via face masks and face shields (Gostin et al., 2020). Despite these measures, as of early January 2022, there have been over three hundred million reported COVID-19 cases including over five million deaths globally (Schaverien and Bengali, 2022). Naturally, there has been an extremely high demand for face masks and face shields on the global market and consequentially, engineering and sanitisation companies in countries, such as Taiwan (Worby and Chang, 2020) have desperately increased these design, development, and production level of these products to meet the high priority needs of the average citizen.

These engineering enterprises, like many others as technology has advanced throughout the years, have employed the use of computers to exploit the vast possibilities in the design and development of products through generating virtual models [computer-aided design a.k.a. CAD], and conducting testing, as well as simulation exercises of these models [computer-aided engineering a.k.a CAE] (Kontogeorgis et al., 2022). Product design teams have coordinated the use of integrated CAD/E principles to correct hindrances early in the development process that would have otherwise given rise to wasted time and money should they have been detected later using traditional methods. One such method is the reduction of cost and improvement of sustainability performances [reduction of a product's adverse lifecycle environmental impacts] in the early phases of the development process (Schöggl et al., 2017). Engineering simulations indicative of CAE principles have been increasingly used for sustainable product development by identifying how a product can be redesigned and subsequently prototyped in a more efficient, less iterated manner in an effort to reduce material wastage, non-renewable energy usage and scrap rates among others (Hanna, 2019).

This paper involves the development of a face shield concept to protect against the COVID-19 virus by integrating these CAD/E principles such as product modelling and sustainability analysis within the SolidWorks design and the SolidWorks Sustainability programs respectively. It underlines the combination of customer requirements and existing product data to serve as the foundation to generate CAD models of the face shield product, while the CAE sustainability tool is used to identify material and/or geometric alterations to these models that can be made to decrease the projected, adverse environmental impacts over the course of the product's lifecycle.

2. Literature Review

2.1 The Impacts of the COVID-19 Pandemic

The most recent pandemic to which the world has been exposed, i.e., the coronavirus disease 19 more commonly known as COVID-19, has heavily disrupted the normal proceedings of the everyday citizen, commercial businesses, and large enterprises in a variety of ways since its inception in late 2019 (Sampath et al., 2021).

Expectedly, this highly infectious, respiratory disease has impacted the health and well-being of many infected persons across the world, presenting itself through a large number of asymptomatic cases, mostly mild symptomatic cases in healthy persons [fever, loss of taste or smell, cough], more serious symptomatic cases in elderly and immunocompromised persons [severe body pains, shortness of breath, pneumonia], and fatal cases [average mortality rate of ≈ 5%] (Plapp, 2020).

Due to the incapacitation and/or deaths of an ever-increasing number of infected persons, the global economy, i.e., the world's driving workforce, has progressively dwindled (Haleem et al., 2020). With various travel and gathering restrictions being set in place whereby the working citizen was confined to his / her home, the global supply and demand chain has taken a major hit. Manufacturing, transport, and distribution of goods and services around the world have been severely limited and as such, many households and businesses have seen a drastic decrease in their regular income (Xiong, 2020).

Apart from the serious health and economic distress that the world has experienced due to the COVID-19 disease, there have also been massive social changes put in place by governments and health officials alike for the purpose of preventing infections, as well as limiting the spread of infections. These social changes come in the form of highly advised and/or mandatory preventative measures (Bashir et al., 2020), including quarantining, frequent disinfection and sanitisation, social distancing, and the wearing of face masks and face shields among other methods (Güner et al., 2020). These drastic changes in society have indeed affected the normal flow of everyday life for the average person whether he/she has been infected or uninfected. However, looking at the sustained effects of the physical aspects and confinements, the COVID-19 pandemic has been associated with a high level of mental and psychological distress, making the effects of the pandemic an international public health priority (Xiong, 2020).

2.2 The Face Shield as a COVID-19 Preventative Measure

The use of face shields as a method to limit the COVID-19 disease has been heavily discussed and proven as a highly effective way to not only prevent wearers from being infected, but by extension, to help reduce massive spikes in cases which forces government bodies to enforce strict lockdowns and severe socioeconomic restrictions. The usage of these shields is even more vital for high-risk professions such as school teachers, health care workers, emergency services personnel, and transport workers due to their increased level of human contact in their daily work schedule (Wain and Sleat, 2020).

Consequently, a number of companies have designed, developed, produced, and distributed their unique face shields into the market. For example, the ZShield company has developed their respective product known as the ZShield Wrap Face Shield that extends upward from the neck area to above the forehead region (Kellogg, 2021). It is said to be comfortably worn even on a 16-hour flight and is justified in the fact that because it wraps around your neck, there is no pressure on the skull which can cause pain, indentations, and headaches after prolonged use. Besides, NoCry is another company in manufacturing work and safety gear and has released its own face shield called the NoCry Flip-Up Face Shield (Kellogg, 2021). This style of product has a similar fastening method to most other face shields on the market, but it excels in both comfort and adjustability owing to its anti-slip padding and adjustable band features, respectively.

2.3 The Integration of CAD/E Principles in Product Design and Development

As technology has advanced, it has become more evident in the manufacturing engineering field that product concept models can be more easily analysed, adjusted, and exploited by implementing computer-aided design and engineering [CAD/E] principles (Chowdary et al., 2019) to elevate the development process as opposed to conventional methods of overly repetitive, iterative analysis of physical prototypes. In addition, it has been observed through trial that the integration of these CAD/E tools in these design and development processes is effective in improving a product's sustainability, assembly efficiency, and performance value whilst ensuring that unit cost and manufacturing ease are held to a minimal level (Chowdary et al. 2019).

An example of these principles in the product development field lies within the use of CAD/E tools to produce a virtual, optimised model of a lawnmower blade that would be able to emit lower noise during use, as opposed to the traditional lawnmower blade (Gokool and Chowdary, 2017). It must be noted that the integration of these tools allowed for efficient prototyping of the blade via a Fused Deposition Modelling (FDM) machine.

Another application of these CAD/E tools in product design and development is the development of a tennis ball retriever concept. It is highlighted that CAD tools would enable the engineer to make design corrections and modifications early in the design process (Chowdary and Phillips, 2014), rather than wasting precious time and resources on recognising these errors and potential improvements upon analysing the physical prototype much later.

2.4 CAD/E and Additive Manufacturing in the Design and Development of Face Shields

As the COVID-19 pandemic rapidly escalates, the high demand for medical protective equipment such as face shields has spurred on various enterprises and organisations to design and produce these products at a very high rate. This, however, requires the combination of CAD/E product modelling and analysis, and additive manufacturing [AM], i.e., 3D printing, to meet the desperate demands of the consumers during these times (Celik et al. 2020). This is confirmed as studies show that when CAD/E tools and additive manufacturing are combined in a product development process in comparison to traditional methods, supply time has a reduction of 98% and replacement time is reduced by 46% on average (Remache-Vinueza et al., 2021).

Various stakeholders at the University of Washington have used these techniques to 3D print face shields to protect against the COVID-19 disease in March 2020. It was designed with three connecting parts in mind: cradle, transparent shield, and elastic band. It was the intention of the university to develop these face shields quickly (Donohue et al. 2020), therefore it can be understood that by developing a virtual model using CAD/E principles and linking it to a viable 3D printer, the production count of a COVID-19 shield can be very high in response to the shortages of medical equipment coupled with the high demand of face shield PPE around the world during this pandemic (Nande 2020).

3. Research Methodology

The research methodology is displayed in Figure 1 and highlights the steps taken to arrive at the desired results for this product design and development process of a face shield concept for COVID-19 protection using CAD/E principles. The study is divided into seven distinct stages which are orchestrated using a variety of tools and techniques that are evident in most product design and development processes. These stages were performed incrementally and not in a simultaneous manner, as described by the flow of the methodology indicator in Figure 1.

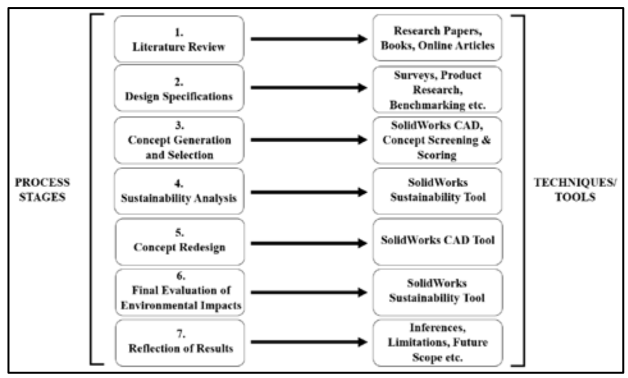


Figure 1. Research Methodology

The first stage involves developing a literature review that contains important information that will inform the reader about the background of pandemics, the impacts of the current COVID-19 pandemic, how face shields specifically are being developed and used as an effective preventative method, the integration of CAD/E tools in modern product development, and how these tools are being utilised alongside additive manufacturing to develop face shields.

The second stage entails how an ideal product specifications list would be obtained by employing two methods: distributing questionnaires and/or conducting interviews to viable customers to gain an understanding of what they would like to see included in a COVID-19 face shield, and by doing secondary research on existing face shields in the industry to analyse their specifications so that a framework can be envisioned of promising features and dimensional data that would prove useful for the proposed product. Using the results of these two methods and by utilising various design tools (e.g., competitive bench marking, needs analysis, and design metrics), an ideal product design specifications list can be constructed.

The third stage, concept generation and selection, begins by incorporating the design specifications list to generate design concepts in the SolidWorks CAD software for the face shield that differ in geometry, features, and materials to give a wider perspective on what may be the most ideal option. This most viable concept will be chosen via two design criteria, i.e., concept screening and concept scoring respectively, whereby the few initial concepts are narrowed down into the most suitable option for further development, according to which one is projected to satisfy the customer's needs the most whilst promoting the highest level of performance.

The fourth stage expounds upon the selection of the most suitable concept by subjecting it to a SolidWorks Sustainability Analysis, whereby each component of the chosen face shield concept is examined to divulge their expected, adverse environmental impacts over the course of their lifecycle from manufacture to disposal. These impacts include carbon footprint, non-renewable energy output, acid acidification and water eutrophication. To reduce these effects, a material and/or geometrical change would be made to as many parts where possible, diminishing the overall negative environmental impacts of the entire product. This redesign performed in the SolidWorks CAD modelling package is the premise of the fifth stage.

The sixth stage simply involves a final evaluation of the redesigned concept's projected environmental effects in the SolidWorks Sustainability tool to confirm that the updated model is sufficient for progression into further development (various analysis methods, tests, and prototyping, etc.).

The seventh and final stage embodies a reflection on the results obtained during the product's design and development process with particular attention to how the decisions made were effective in achieving the end goal, limitations that were encountered, recommendations that could further improve this product in future endeavours, or any other similar products in which the enterprise may want to invest and develop, and a scope for future research/and or work into progressing this project past the conceptual level.

4. Case Study

4.1 Case Description

The main component that will be discussed and analysed in this study is the design and development of a face shield concept to protect against infection from the COVID-19 virus, integrating CAD/E tools and product design criteria into the process to achieve the desired results.

4.2 CAD Modelling of Design Concepts

Upon generation of the product specifications list using a similar research and analysis method to that conducted by Chowdary and Kanchan (2013), the foundation for concept creation was established. A brief summary of the design steps taken to arrive at the design generation process from the conceptual stage is shown through:

1. *Research* – Questionnaires and/or interviews conducted to gather client need information (primary research); existing product research and supporting literature via books, and online resources, etc. (secondary research)
2. *Needs Analysis* – Research data on customer needs are transcribed, listed, and categorised according to their respective component, and assigned a degree of importance with respect to the overall design of the shield concept. This assists the designer in understanding the design foundation of the concepts in order to satisfy the customer needs and provide its intended use.
3. *Matrix Analysis* – The secondary research done on existing products is collated and the major features are listed in a matrix format. The designer chooses 5 existing products with sufficient product information and each chosen feature is mapped onto each product where appropriate. Each feature's percentage representation among the existing products was summated at the end to determine the most vital features for the intended design concepts.
4. *Design Metrics and Competitive Benchmarking* - The results of the matrix and needs analysis methods were now used in conjunction to develop a list of design metrics that would be useful for the shield concept, along with their own relative importance levels, list of needs that they intend to address based on the needs analysis, and their respective units of measurement. Utilising this design metrics list and the list of five existing products that were analysed as part of the product research, a competitive benchmarking table was now generated. This method of analysis uses the quantitative design specifications obtained from each of the existing products' manufacturer models and maps them onto the respective design metrics where possible, as a means of comparison among the different models.
5. *Design Specifications List* – The results of the competitive bench marking allow the designer to examine the most ideal quantitative design specifications for the intended concepts, and along with their respective units, a design specifications list can be generated which provides the numerical foundation to begin creating alternative designs in a chosen design software. Often, these specifications are denoted by a range rather than a solitary value, and this facilitates freedom in design.

Hence, three (3) alternative design concepts for the COVID-19 face shield were constructed in the SolidWorks program. These designs comprised of varying combinations of features and functions according to structured morphological charts. These charts were devised according to the identified problems and subproblems that naturally arise at this stage. The systematic embodiment of the face shield requirements have been obtained through research. This can be directly implemented as fundamentals of design. Figure 2 shows a distinct combination/iteration of the morphological chart that encompasses the main design features that are to be included in the first concept, i.e., Concept 1.

These major aspects were then integrated into the design of this concept using the SolidWorks CAD package. It must be noted that although the original creativity of the designer was and should always be encouraged, these main features alongside any further additions adhered closely to the restraints of the product design specifications list within all three concepts.

Although the second and third design concepts followed similar structured procedures, they were representative of unique combinations of features and geometrical compositions to ensure that a wider range of performance capabilities and/or satisfaction of customer requirements is covered for consideration. The isometric views of each design concept can be seen in Figure 3.

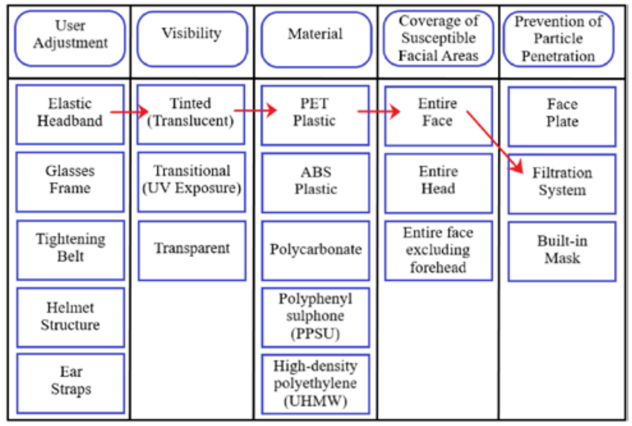
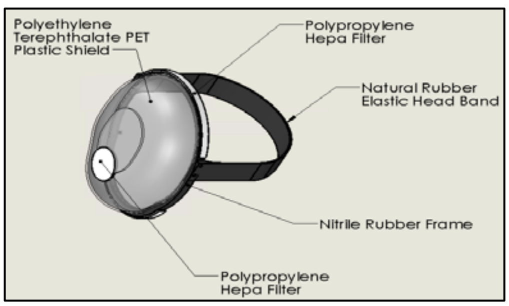


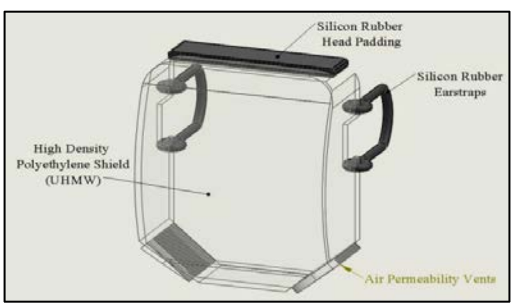
Figure 2. Morphological Chart for Concept-1

(a) Design Concept 1



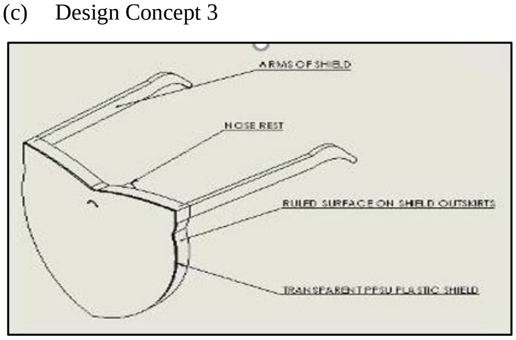
Main Design Features –
- User Adjustment: Elastic Headband
- Visibility: Tinted (Translucent)
- Material: PET Plastic
- Coverage of Susceptible Facial Areas: Entire Face
- Prevention of Particle Penetration: Filtration System

(b) Design Concept 2



Main Design Features –
- User Adjustment: Rubber Ear Straps
- Visibility: Transparent
- Material: Ultra High Molecular Weight Polyethylene (UHMW)
- Coverage of Susceptible Facial Areas: Entire Face
- Prevention of Particle Penetration: Face Plate

(c) Design Concept 3



Main Design Features –
- User Adjustment: Glasses Frame
- Visibility: Transparent
- Material: Polyphenyl Sulphone (PPSU) Plastic
- Coverage of Susceptible Facial Areas: Entire Face Excluding Forehead
- Prevention of Particle Penetration: Face Plate

Figure 3. Isometric Views of CAD Face Shield Concepts

4.3 Selection of the Concepts

4.3.1 Concept Screening

After the three face shield concepts were generated and fully defined, they were then subjected to a concept screening design criteria method, as described in detail by Satria et al. (2018). These three concepts were utilised along with a reference face shield. This reference was selected from the five products already analysed from previously conducted product research, hence the Jackson Medical Face Shield XC was designated as the control variable of this screening method. The method was hence carried out and the results were inputted into a matrix (see Tables 1 and 2).

Table 1. Concept Screening Matrix

	Concept 1	Concept 2	Reference	Concept 3
Prevention of Particle Penetration	+	0	0	0
User Adjustment	-	-	0	-
Visibility	-	0	0	0
Material	0	-	0	+
Coverage of Susceptible Facial Areas	0	0	0	-
Sum +'s	1	0	0	1
Sum -'s	2	2	0	2
Sum 0's	2	3	5	2
Net Score	-1	-2	0	-1
Continue?	Yes	No	No	Yes

Table 2. Concept Screening Legend

Symbol/Item	Definition
+	Indicates that for that particular concept, the associated feature is considered to be more suitable than that belonging to the reference product.
-	indicates that for that particular concept, the associated feature is considered to be less suitable than that belonging to the reference product.

Upon understanding the definition and application of the matrix symbols for this screening method (Satria et al., 2018), it was revealed that design concepts 1 and 3 shared the same highest net score in comparison to the reference score. They would have to be moved on to a different design criteria method (i.e., concept scoring). This would determine the most suitable concept for further analysis and testing.

4.3.2 Concept Scoring

The concept scoring method is similar in principle to the screening method in that it examines the performance of the two remaining designs against the reference product. However, in this case there exists a different rating system as explained by Satria et al. (2018), in addition to a weight percentage and weighted score system (Xiao et al., 2007) that contribute to the final determination of the most viable face shield concept. Its results were arranged into a matrix, as displayed in Table 3.

Ultimately, when the weight percentages and ratings were multiplied and the net scores for each concept were summated, it was determined that concept 1 was the most viable face shield concept for which the design team can engage in further analysis, testing, prototyping, and iteration processes. This chosen concept can be considered now as the final design and can be seen in more detail via the manufacturing drawing seen in Figure 4.

Table 3. Concept Scoring Matrix

	Weight	Concept 1		Concept 3	
		Rating	Weighted Score	Rating	Weighted Score
Prevention of Particle Penetration	30%	5	1.5	3	0.9
User Adjustment	10%	2	0.2	1	0.1
Visibility	20%	2	0.4	3	0.6
Material	10%	3	0.3	4	0.4
Coverage of Susceptible Facial Areas	30%	3	0.9	2	0.6
	Total Score	3.3		2.6	
	Rank	1		2	
	Continue ?	Yes		No	

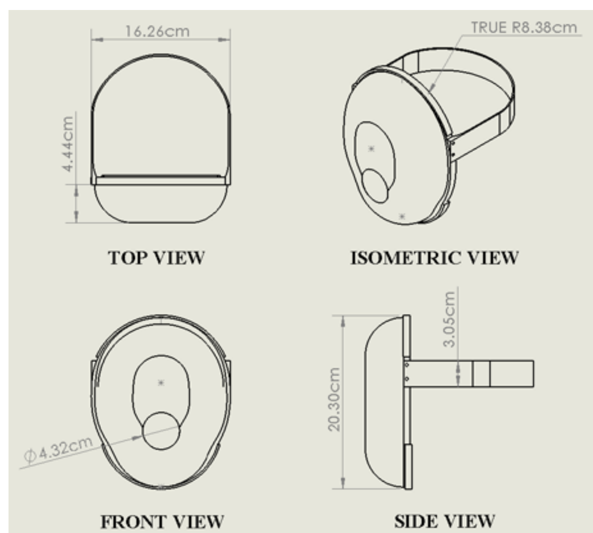


Figure 4. Manufacturing Drawing Display of Final Design

4.4 Sustainability Analysis, Redesign, and Evaluation of Environmental Effects

A SolidWorks Sustainability study was run on each constituent part of the selected face shield concept [Concept-1] to identify its projected output of adverse environmental impacts over the course of its life cycle, which involves processes such as raw material extraction, manufacturing, transport, usage, and disposal.

The SolidWorks sustainability tool analyses each part's material, weight, and geometric makeup to project what levels of carbon footprint, non-renewable energy consumption, acid acidification and water eutrophication will occur as a collective result of these processes.

Upon completion of the analysis for each part of the shield concept, a sustainability report was generated for the face shield assembly to understand the concept's projected environmental impacts as presently constructed. Material changes were made to each part where possible to reduce these projected effects and improve the sustainability of each component, while the performance value of the parts is not compromised in a substantial manner.

As per viewing of the modified design concept in Figure 5 as compared to its original version displayed in Figure 3, the elastic headband's material was changed from natural rubber to styrene-butadiene rubber (SBR). Also, the filters' material was changed from polypropylene (PP) to very low-density polyethylene (LDPE), and the concept's frame was switched from nitrile rubber (NBR) to SBR.

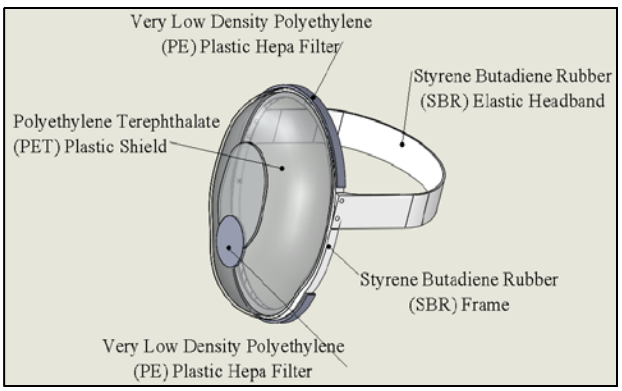


Figure 5. Modified Concept 1 after Introduction of Sustainability Methodology

Upon making these changes, apart from the PET shield, the net environmental effects of each part were significantly reduced and by extension, the entire shield assembly's sustainability was improved, and a new sustainability report was hence generated to examine these reduced environmental effects. It must be noted that the plastic materials selected for the final shield design before and after the sustainability analysis are not very high density as compared to low-porosity, high molecular dense plastics. These choices were made owing to factors such as lower procurement and consequent production costs, lower overall weight for user comfortability, and in this case, lesser lifecycle environmental effects. Since we have now obtained a sustainability report each for the original design concept and the modified design concept, their four major environmental impacts can be viewed diagrammatically in Figures 6 and 7, respectively.

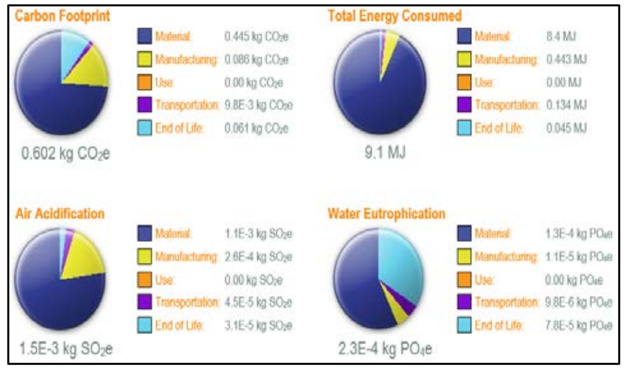


Figure 6. Environmental Impacts for Original Concept 1

Figure 7. Environmental Impacts for Modified Concept 1

Regarding the individual categories of environmental impacts and computing the respective differences shown in the figures above, the modified concept generated a 0.203 kg CO_2e (kilograms of carbon dioxide emissions) drop with respect to the carbon footprint, a 1.3 MJ decrease in non-renewable energy consumption, a 7.0 x 10-4 kg SO_2e (kilograms of Sulphur dioxide emissions) decrease with respect to air acidification levels and finally an 8.0 x 10-5 kg PO_4e (kilograms of phosphate emissions) drop in water eutrophication levels.

5. Reflection of Results

Throughout the development of the face shield concept to protect against the COVID-19 virus, important CAD/E principles were employed alongside specific product design and development tools to procure a viable framework for this product that would benefit a sanitisation or engineering company should they choose to expound upon manufacturing and market distribution activities.

The product development tools of market and product research, design metrics, benchmarking, and even concept screening and scoring were all utilised for this process.

They have incrementally progressed the project from gathering the source data to scientifically determining the most suitable face shield concept for its intended protection requirements from the COVID-19 virus. As per most processes of these types, these principles were conducted early in the development process to ensure that fundamental design errors are not incurred so that precious time and money are not wasted on unnecessary repairs. While the use of these tools is sound, the design team can gain greater understanding of what customers may expect using these face shields by exploring a wider sample size of questionnaire/interview respondents during market research. Furthermore, more in-depth product research on COVID-19 specific face shields could be conducted to generate more refined product design specifications.

The SolidWorks design software was used in creating 3D CAD models of three different shield concepts, hence engaging a wide scope and variety of the established design specifications. This program allowed the user to virtually design these concepts with accurate geometrical coordinates and material compositions. Also, this method saved a substantial amount of time and spared the greater probability of human error while exploiting this CAD program as opposed to conducting physical drawings. However, the concepts could also be generated in more manufacturing-oriented CAD programs such as Mastercam whereby the virtual concepts can be more easily linked to their possible machining and drilling processes.

In terms of the CAE principles employed in this study, the SolidWorks Sustainability tool was effectively used to examine the most viable concept's impact on the environment and to ascertain what material changes can be made to reduce these negative impacts while ensuring that the shield's performance capabilities were not compromised. A product will always contribute to adverse environmental effects over the course of its lifecycle processes whether it be extraction of raw materials, manufacturing, or disposal, but in light of the imminent effects of climate change around the world, improving the sustainability of any manufacturing company's commodities should be a vital task. Other than analysing the sustainability of this shield concept, its total projected cost could also be computed in the SolidWorks Costing tool to improve the value of the study. Additionally, the SolidWorks Simulation package can be deployed in analysing the concept's endurance, durability, and other performance characteristics.

6. Conclusion

This case study was successfully conducted for the integration of computer-aided design and engineering [CAD/E] principles for development of a face shield concept to protect against the COVID-19 by employing a systematic series of steps aligned with standard protocol evident in product design and development projects across society by engineering companies globally.

A few limitations did arise throughout the ordeal for developing the viable shield concept. Firstly, due to the social restrictions of the pandemic, market research was limited to a smaller than desired number of participants. The simulations and designs were conducted using the SolidWorks 2017 version of the software, equipped with lesser available and underdeveloped CAE packages.

Moreover, with many unknown virus variants and anomalies, there lies a scope for entrepreneurs to be encouraged to fine-tune the proposed concept-1 in terms of embedding strict industry standards to manufacture face shields that guarantee 100% protection. The work in this direction is in-progress at the authors' workplace.

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