Engineering Journal issn: 0125-8281

Article

Developing an Easy-to-Maintain UV Sanitizer Cabinet for Safe and Efficient Disinfection and Improved Hygiene Practices

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Abstract. In day-to-day life, people constantly come in contact with pathogens such as bacteria and fungi that can negatively impact human health, causing skin infections and foot-related issues. The aim of this research is to create an easy-to-maintain consumer level product utilizing UV-C to efficiently and effectively disinfect everyday household items to improve hygiene and general quality of life with a shortened time spent, less human labor required. Key design concepts are 'minimal-design platform' to keep things minimal and streamlined – highlighting uncomplicated forms plus having been made simpler, and 'design for maintainability' to achieve effective building's performance - system functions in relation to designated criteria, easy-to-maintain, easy-to-access, convenient, and embracing a healthy lifestyle. Besides, the optional mobile application is added to the system for assisting users as a remote communication. The modules are adaptably made to future requirements while maintaining a stable usage cost throughout the building's design life. For protecting users from UVC radiation leakage or emitted out from the cabinet (0 UVC leakage in the unit of mW/cm^2 measuring by UVC light meter), the polycarbonate sheet is applied as a cover. The efficiency of UV sanitizer cabinet can be evaluated via structural performance (the maximum load that can be supported by rotary table is 1 kg.), bacterial culture test (the number of colonies decrease significantly to < 5%), and reliability of system (99.47%).

Keywords: Health-related product, product design and development, fault tree analysis, UV sanitizer, controlling system, UVC light meter.

ENGINEERING JOURNAL Volume 27 Issue 4
Received 23 November 2022
Accepted 24 March 2023
Published 30 April 2023
Online at https://engj.org/
DOI:10.4186/ej.2023.27.4.1

1. Introduction

Nowadays, there are many pathogens that can affect our health including bacteria and fungi. Bacteria can cause many skin infections, but fungi are the main cause of feet itching, scaling, redness of foot, and infection. Unexpectedly, everyday objects have bacterial - there are germy things we touch every day; cellphone, remote control, computer keyboard, headphone, toothbrush holder, dish sponge, anything in the office, money, purse, shopping carts, soap dispensers, kitchen towel, socks, and shoes [1]. From the study of collected on footwear, the large numbers of bacteria both on the bottom and inside of shoes have been found, averaging 421,000 units of bacteria on the outside of the shoes, and 2,887 on the in-side part [2]. The tests were run in the dark room, around 12% of bacteria were alive and able to reproduce. For the exposed to the daylight room, only 6.8% of bacteria and 6.1% of bacteria exposed to UV light were viable [3]. UV emitted from the sun can effectively killing bacteria by destroying the molecular bonds that hold their DNA together. However, if germs are in hidden places, UV light can only kill the germs that contacts directly.

Generally, applying a disinfectant spray out-side the shoes can kill some germs, the disinfectant sprays usually have a direct effect on only disinfect non-porous surfaces. Another method is about applying an antifungal spray to the inside part of the shoes; this can kill many fungi, such as athlete's foot - it is a fungal skin infection that usually begins between the toes. It is commonly found in people whose feet have become very sweaty while confined within tight-fitting shoes [4]. Foot odor is not a serious problem compared to the other disease issues mentioned earlier; however, feet that smell bad can be a nuisance and a potential embarrassment in some situations. According to the National Foot Health Assessment conducted for the institute for preventive foot health by the NPD Group, saying that 16% of adults age 21 and older (about 36 million of US people) have experienced foot odor and this is equally common in men and women [5]. Foot odor is fairly common, especially among people who are very active or whose feet tend to sweat. Sweat itself is odorless; nevertheless, it creates the opportunity for certain bacteria to grow, producing odorous substances.

With a fast-paced society nowadays, people tend to neglect taking care of their daily stuffs – e.g., they do not wash their shoes regularly. The simplest way is to let the shoes sit in the sun to kill germs and bacteria, since the sunlight will get rid of shoe odor. With this classic method, by placing the shoes in direct sunlight for 2 hours or longer, the problem can be solved; however, applying UV light from sunlight cannot be applied in some situations like in the rainy day, or the dusty day. The unprotected exposure to the sun's ultraviolet (UV) rays can cause damage to the skin or surface of the product that contains sensitive materials (the chemical/synthetic materials); the quality of that item starts and turns to degradation mode or malfunction.

From the effects of social media on disinfection issue, for shortening the process, using chemical cleaning products has been introduce and become popular. However, these cleaning products cannot clean off completely and it might leave some chemical (harmful) residues from the fact that, after using in surface cleaning, and independent of whatever chemical ingredients are used to apply, the detergent molecules remain chemically unchanged [6]. These can cause some serious health problems.

Therefore, it would be better to apply UV light that is more effective than chemical disinfection processes because it can destroy all viruses and bacteria in a wide range.

2. Literature Review

This section can be classified into two main issues, the environmental health issue(s), and how to solve them. The details of each will be explained in the following subsections.

2.1. Environmental Survey

In general, the environmental health issue(s) consists of three categories: *health impacts*, *air quality*, and *water and sanitation*. Due to COVID-19 pandemic situation plus PM2.5 crisis, the researchers have tried to find way for collecting data about "environmental survey" directly from the target customers by launching a set of questionnaires via digital platforms. More and specific details reported as in percentage value were extracted from the famous articles researched and reported by the organizations and groups of researchers [7-11]. The results from these sources were then integrated properly to help the design team to understand the levels of concern people where the considerations have been mentioned around topics like air pollution, hazardous substances, and climate change. Besides, these answers can assist the team in better educating people on vital issues related to the patterns of air, waste, water, and weather they have faced during the day or usually met. The environmental survey can link to the hidden issue of infection found in the area of interest; for example, there is a study about pathogens brought in from work, school, and public transportation, which tells that work place, school, and public transportation are a great place for sharing bacteria and viruses approximated 400 times more germs than the amount found on a standard toilet seat [12].

Moreover, according to World Health Organization [7-8], HFMD spreads mainly in children, who are under five years old, because they are more likely to be susceptible to infection by these viruses. An environment survey in nursery care and elementary school in 2017 demonstrates the incidences of HFMD in Thailand are increasing to be 41.62 and 41.83 per 100,000 people in Mahasarakham province respectively [9-10]. Those pathogens can lead to the common contagious disease that is hand, foot, and mouth disease (HFMD) caused by touching the surface of things that contain multiple stereotypes of enteroviruses (EVs). Moreover, for the recent popular disease, in March 2018, WHO updated the cryptococcal disease in HIV-infected adults, adolescents and children [11]. Cryptococcosis is a disease caused by fungi from the genus Cryptococcus that infect humans, usually by inhalation of the fungus.

2.2. Disinfection Methods

Many technologies and devices are available for versatile purposes in a single unit of the product. Due to the different experiences of humans, the difficulty for product designers is about how to make the product suit for all customers with easy-to-access concept like universal design concept. Most people want to have good sanitation and hygiene with environmental-friendly platform, because no dangerous or toxic chemicals are left in the storage space or handling. The key point of UV-C light is about disinfecting bacteria, viruses, and fungi with a high-performance function that effectively operates as a single entity. Destroying the molecular bonds that hold their DNA together as their germicidal range of UV is within 200-280 nm. Simply saying that ultraviolet germicidal irradiation (UVGI) is applied where the electro-magnetic radiation uses short-wavelength ultraviolet (UV-C) light to kill or inactivate microorganisms by destroying nucleic acids and disrupting their DNA and leaving them unable to perform vital cellular functions. Therefore, the cell that cannot reproduce is considered dead - no longer living. It is unable to multiply to infectious numbers within a host.

In summary, the suitable range of UV is Ultraviolet Light-Emitting Diodes (UV-C LED) lamps that emit UV light at selectable wavelengths between 255 and 280 nm. The UV-C provides radiation that might not be suitable and safe enough for the limited space. It can be harmful to skin, and it causes an impact on skin cancer risk [13], directly interfacing with UV-C for a long period should be avoided. For protection issues, materials such as glass (but not quartz glass) or most clear plastics have been introduced, and it is possible to observe a UV-C system through a window safely.

For cleaning stuffs or disinfecting process with the traditional styles, some people apply UV from sunlight or use chemical disinfectants like vinegar to kill the bacteria and pathogens. With the traditional method for disinfection via using acetic acid (i.e., white vinegar). It can tackle some type of bacteria, E. coli and other "gram-negative" bacteria. The special benefits obtained from the acid in vinegar are crossing the bacteria's cell membrane and releasing the number of protons, which causes the cell to die [14]. However, applying vinegar disinfectant causes unpleasant according to its chemical compound, and the acid property might destroy the surface or physical property of an object when the synthetic material is applied.

3. Research Background

In this research, design factors are required to achieve the objective that leads to the final model of the product, which can both satisfy customer demand and balance between production and cost. Design factors can be categorized into six main sections as follows.

3.1. Customer's Perception and Requirement

According to this modern society, people try not to waste their time on unnecessary task. Automatic devices have been played as one of the vital solutions for supporting this issue. However, they have no chance to prove or verify by testing whether the advertised products suit them well with less maintenance cost. Some evidence, normally, is shown via good-looking images and short VDO clips representing the brand identity and value via words and actions from the famous influencers. For self-confidence people, they are highly ambitious and believe in research documents or real-world evidence with conscious. This group of people is recorded to be the major pattern of downtown (metropolitan area) life.

The key reason for selecting the area or region of interest as a metropolitan area to start the research on design and development of a new product is that the characteristic of this area is the core city that acts as the primary hub of the area. There are many development platforms found; the business industries to drive the economic development of the area with providing a good educational system, and implementation of infrastructure to serve the inhabitants such as transportation, and housing utilities. Moreover, self-confidence people are considered as the major group who are living in a large city.

The perception of self-confidence people in the health-related products is all about trust where the strengths and weakness of the products can be well revealed by themselves. They have tried to set realistic expectations and goals and communicate assertively. They think the health issues can be properly solved and handled according to the basic research that is the systematic study directed toward understanding of the fundamental aspects of situation and of detectable facts without imaging the specific applications towards processes or products in mind.

The products should be created under a well-proof platform with reliable sources. For the customer perception of UV sanitizer products, they are to cope with disinfection and unpleasant smell. Besides, price is the key factor that has a direct effect on purchasing decision. For this reason, various prices and interesting promotions of UV sanitizers are posted on many websites. In or to increase the selling volume and satisfy customers' requirements, launching a product with an affordable price might be the choice. The affordable price can be considered as a price lower than that charged for high income countries, and which normally covers the manufacturing costs plus a reasonable margin to help ensure the commercial sustainability of the product.

3.2. Maintaining Hygiene and Sanitation at Home

Most people want to have good sanitation and hygiene. Foot hygiene is one of the most important factors for a good hygienic lifestyle. Feet are part of the body that we use every day from when we wake up, shower, or go out for work. For foot hygiene, this can be seen as an indicator of general hygiene. The moist bacteria and fungus breeding environment created within shoes is something most people try to ignore. The resulting odor is another concern matter that people need to consider and focus. Putting the shoes in the washing machine is not always an option; thus, using an ultraviolet (UV) shoe sanitizer is the alternative way.

This style of sanitizer uses ultraviolet light to kill the bacteria and fungus that create foot odor and uncomfortable condition. Besides, this design of the UV sanitizer can be added with more features to apply with more various purposes. Currently, a portable hand-held UV sanitizer is introduced as an alternatively perfect addition to the closet referring to the traditional methods. Applying the general disinfection methods with direct sunlight, which is the natural source of UV or even chemical disinfectant products, can disinfect many species of bacteria and eliminate odors [15]. However, the application of sunlight is not thoroughly getting through all places of the object, and according to the EWG study saying that 53% of chemical disinfectant products are contained with lung harmful ingredients [16], as mentioned earlier in the previous section.

In order to minimize the negative effects of chemical disinfection methods, studying about the existing ideas and concepts plus key considerations about how to kill shoe germs by using a shoe sanitizer [17-18], can reveal the hidden view and perception of the design team (at the initial stage of concept development) to clearly create a virtual model of the alternative function(s) and structure of UV sanitizer unit. From the related works, the easy-to-access methods for sanitizing stuffs are disclosed where users can operate the system easily. The design team must develop a system that is easy to maintain. The developed platform must enable better cleaning of stuff through multi-functional capabilities with less human labor required. This can be an alternative way to tremendously enhance the people's lifestyle.

The expected direction of the obtained result is about the selling price of the product, which should be affordable to the target customers (20-60 years old). In 2022, the average monthly income per person in Thailand was approximately 16,700 THB (472 USD); thus, for a family of four – it was around 66,800 THB (1,888 USD). The proposed UV sanitizer cabinet is aimed to support both personal and household services, the expected price of this developed product should not be more than 3,300 THB (93 USD) per unit – less than or equal to 5% of the average monthly income per family. However, from the summary about cost of living in Bangkok, Thailand, a family of four estimated monthly costs are 78,099.2 THB (2,205 USD) without rent where a single person estimated monthly costs are 21,875.9 THB (618 USD) without rent [19-20]. This developed product might be considered as an optional item applied for supporting for the customers to disinfect everyday stuffs, and the UV sanitizer product can be classified into "safety need" level.

3.3. Reliability of UV's Disinfection Mechanism

There are some antibiotic resistant bacteria that cannot be disinfected by using typical method. UV light disinfection can be applied for killing pathogens without immunity, due to the effective method of dry physical process. According to National Tanning Training Institute, UVC light, which has a wavelength of between 266 to 279 nanometers [21], which is highly competent at killing bacteria and viruses by destroying the molecular bonds that hold their DNA together. UV is more effective than chemical disinfection processes at destroying a wide range of viruses. Moreover, UV-C also provides residue free disinfection, so there is no concern over dangerous residues that need to be wiped down or neutralized after the disinfection occurs. Therefore, UV disinfection technologies [22-24] are environmental-friendly platforms since there is no dangerous or toxic chemicals left in the storage space or handling. However, the amount of UV and time spent for killing germs or fungi on the outer surfaces of different type/ size/ and physical objects will be taken into consideration and need to be studied to define or suggest the end user of a product or service for the safety purpose. Moreover, the structure performance of UV sanitizer equipment should be taken into consideration at the final stage of a design platform for checking whether the resources necessary to design and construct a building have been used effectively for supporting people to live longer and healthier lives, preventing illness, and promoting physical and mental well-being.

3.4. Key Addressed Issues for Selecting UVC for the Proposed Design

The addressed issues can be classified into three points. *For the first issue*, the proper range of UV-light wavelength, which is suitable for killing hand foot mouth disease (virus), flu virus (virus), athlete's foot disease (fungi), and Escherichia coli (abbreviated as E. coli, bacteria, is selected. Thus, from the illustrated diagram (Fig. 1), the Ultraviolet Light-Emitting Diodes (UV-C LED) lamps emitting wavelengths between 255 and 280 nm is the choice [25-27].

For the second issue, to support the limited space, the proper UV protection covers or shields should be provided since the UV-C provides radiation might not be safe enough for the small room [26]– a usually small room is used for storing things (such as clothing, towels, or dishes). Materials such as glass (but not quartz glass) or most clear plastics have been introduced for protection issues.

For the third issue, since the UV-C can be harmful to skin and cause an impact on skin cancer risk [13], the testers or users must avoid direct UV-C emitted for a long period. Thus, it is possible to observe a UV-C system through a window safely. The optional idea is about applying a control system that provides the timers or counters to function the UV-C light during disinfection and adds smartphone-linked application, these might be useful.

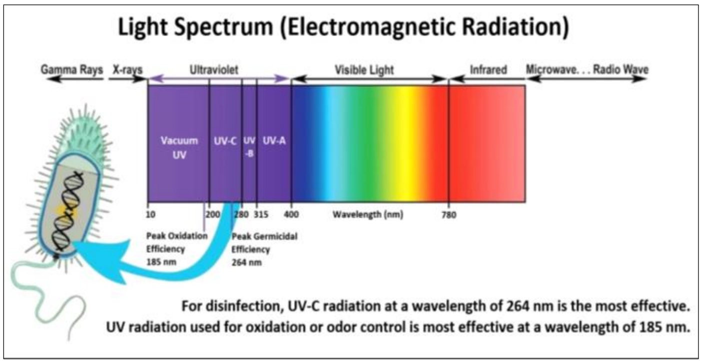


Fig. 1. The spectrum of light [28].

3.5. Research Scopes and Limitations

- *Types of UV Light*

UV-C LED or Germicidal lamp (UVGI) is applied in this study for supporting the design stage Since UVC-LED can be found easily in the market and this UVC-LED also has ability of wavelength that can kill bacteria and germs. Germicidal lamp is used with low-pressure mercury, which can release radiation at 254 nanometers [29].

- *Covering*

Polycarbonate (PC) is used as a cover. According to the material selection platform of SpecialChem, polycarbonates are a very special class of engineering thermoplastic, which has high impact strength, high dimensional stability, and very good in heat resistant [30-31]. PC is commonly used for plastic lenses in eyewear, medical devices, and automotive components. When sunlight falls onto polycarbonate, the polycarbonate molecules can absorb energy of certain wavelengths in the UV range. However, the polycarbonate resins are not suitable for long-term exposure to UV radiation. To overcome this primary resin, we can add UV stabilizers to help protect the material from the effects of exposure to the Sun. UV stabilizers in plastics usually act by absorbing the UV radiation preferentially and dissipating the energy as low-level heat [32].

- *Categories of application*

This product can be applied with various types of objects, which are utensils, shoes, small bags, and hats, or other everyday objects that need to be sterilized. The concepts of "just-one-touch" plus "easy-to-use" convenience appliance are applied in this research.

- *Limit size of the product*

Reducing the storage space of the product is the key consideration of the new design where the UV cabinet must be compact, and it should provide enough UV light. For the size of the box, the standard size of footwear is the key consideration in order to facilitate all the users.

3.6. Data Collection and Analysis

In order to achieve the objective of this research, where the disinfection time and germs need to be reduced, the research background and problem statements must start first. The customer experiences on how to clean the everyday stuff plus customer perceptions on disinfection bacteria, virus, and fungi by using technologies were studied and analyzed. Data collection method with questionnaires via online platform was applied to determine the important parameters, which are the famous or the most frequent traditional method that people are using for disinfection, disinfection time, and the expected price that is suitable for the target customers.

There were 268 questionnaire participants who took part in answering via Google form. From the questionnaire results, most of the participants are in the range of age 30-60, which is considered as 51.5%, and other range of age included under 16, 16-20, 21-29, and over 60 are around 0.4 %, 6.3 %, 33.2% and 8.6%, respectively.

Most of the participants are of working age and got the highest percentage of salary in the range of 20,000-50,000 per month. For the questions about "Disinfection with traditional methods", most participants (47.4%) disinfected bacteria or germs of their stuffs by sunray, around 36.6% decided to use disinfectant liquid (chemical cleaning products), and the use of superheated steam (or boiling) cleaning was reported as 14.9%.

Presented in Table 1 are the percentage of responses obtained from 268 target customers where the key point is revealed about the frequency of cleaning or disinfecting their shoes, hat blanket, mobile phone, plate utensils, and others. The results can be applied as the supportive information for the design stage to identify the matching method(s) that might be fitted to the customer's behavior and requirement where the hidden issues can be revealed like they have not much time for cleaning their stuffs and they have decided to manage this task as "once a month" instead of performing as daily routine.

The results showed that 39.6% of participants disinfect bacteria or germs of their stuff once a month, 32.1% once a week, 19.8% 2-3 times a week, 5.2% every day and never disinfect bacteria or germs of their stuff 3.4%. In the participants' feelings, they think that their traditional way cannot kill all kinds of pathogens.

DOI:10.4186/ej.2023.27.4.1

Table 1. Results of customer's experience on how often they disinfect bacteria or germs of their stuffs.

Time	Percentage of responses
Everyday	5.2%
Once a week	32.1%
2-3 times a week	19.8%
Once a month	39.6%
Never	3.3%

The key reason for not performing cleaning tasks every day or every time after using is "time-consuming process". Since per one disinfecting their stuff activity, it is mostly more than 1 hour, and their satisfaction is at a moderate level, which means that they feel like doing this too often might not necessary.

Besides, most of the participants clean their sensitive stuff that cannot be washed by dry-wash, sunbath, and send to the shop. The third part of the questionnaire compares the performance between three traditional methods, which are disinfected by sunray, using disinfectant liquid, and using steam or boiling. Most people answer that being disinfected by sunray makes the color fade, using disinfectant liquid and steam or boil can damage stuff's surface. Most of the participants know that different types of material should be used with different kinds of disinfection methods, and most of them answer that the three traditional methods can eliminate unpleasant smells at a moderate level. In the fourth part base on "disinfection with UV sanitizer".

Most of the participants have never experienced UV sanitizer products (64.4% of respondents) before but they think that UV sanitizer can be applied as an alternative way for disinfecting their stuff (60.7% of respondents). The customers are open-minded to learn and experience the new technology of health-related products. The alternative design of UV sanitizer product might support their life in the future, to disinfect the bacteria and germs in their daily life and give better health. After obtaining the results from the questionnaire, the conceptual design of the UV sanitizer cabinet has been created.

As most of the respondents said that they want the UV sanitizer to have a suitable size, remote control, and safe for human health. Designing UV sanitizer with the wood box might be the good way for supporting environmental-friendly platform and less toxic-material required where a rotary table is provided inside for letting the object being exposed with UV light properly in 360 degrees. In addition to the questionnaire results, our group decided to add additional functions to the primary model to create a new design that will be more convenient for the user. The requirements of the target customers were translated to be the UV Sanitizer design, factors affecting the UV product are considered and classified into three groups: dimension of appliance, mechanism, and material of each part.

According to the research objective where the storage space of the appliance is to be reduced for supporting small-to-medium accommodations, the main frame and structure of UV sanitizer (cabinet) should be designed with compact while providing enough light to disinfect the germs. In this proposed design, the Arduino program is applied to facilitate the customer when setting the disinfection time via using control panel (4x4 keypad), or even using Blynk (mobile phone application) to be a remote control. This research applied the knowledge about materials for selecting the suitable material for individual part with lowest cost possible. Moreover, considering the quality of the material for each part can extend the life cycle of the UV cabinet while preventing some risk factors that might affect human health.

Presented in the next section are the key concept of product design and development (PDD) for systematically classifying a new product development with proper sequence and preventing some hidden issues that might have a direct effect on the user's health. In order to accomplish PDD, five phases are identified: concept development, system-level design, detailed design, testing and refinement, and production ramp-up. The overall phases required for accomplishing this new design, five phases are expressed as shown below in Figure 2.

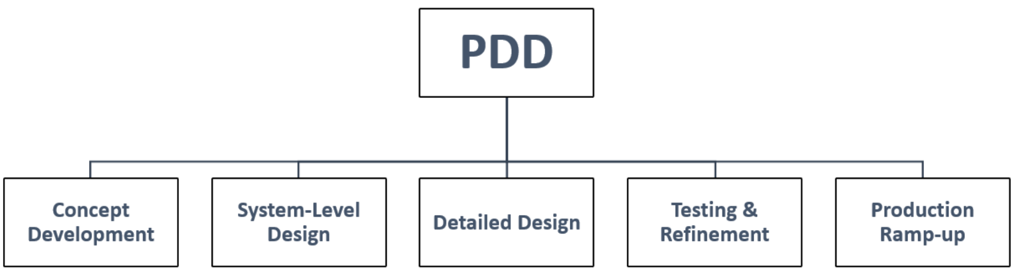


Fig. 2. Five phases of PDD for creating new design of UV sanitizer cabinet.

However, for the last phase – production ramp-up, which is about a term used in economics and business to describe an increase in a firm's production ahead of anticipated increases in product demand, will not be explained in detail. Some guidelines and recommendations about UV sanitizer cabinet will be mentioned in this phase for supporting a further study.

4. Phase 1: Concept Development

Presented in this section are the concept development – phase 1 of product development and Design (PDD). Two main topics are mentioned and discussed for creating a new alternative design for the UV sanitizer cabinet.; *key design* consideration, and *concept of 3Fs approach*.

4.1. Key Design Consideration

According to the questionnaire results combined with the references model, a new prototype design that is more innovative than the existing products could be developed. Compare and adapt the good things from the existing product, with additional functions that could be added to the primary model, with a proper engineering point of view. The dimensions of the proposed prototype are roughly 35.5x43.2x53.4 (unit is in "cm"), the expected design can be inferred that it should be roughly around this size as well. Since the material used for these product references are *Polycarbonate (PC)*, *Aluminum Profile*, *ABS plastic*, and *Acrylic*. According to the data obtained from the questionnaire, the answers of 268 participants are considered to discussed and analyzed for the *Product Characteristic* (Table 2) and *Customer Emotional Requirement* (Table 3) below.

Table 2. Product Characteristics and Definitions.

Product Characteristics	Definitions
Quadrilateral	UV sanitizer cabinet has a quadrilateral shape.
Round	Rotary table has a round shape.
Rotating *(Rotary table)*	Using Arduino to drive the motor to rotate the rotary table.
Various alternative	UV sanitizer can disinfect with and without rotary table.
Normal *(Polycarbonate Plastic)*	The quality of the material is ordinary.
Normal *(Aluminum Profiles)*	The quality of Aluminum Profile is strong enough to use for a box structure.

Table 3. Customer Emotional Requirement and Definitions.

Customer Emotional Requirements	Definitions
Affordable	UV sanitizer cabinet should be sold with reasonable price.
Good Hygiene	UVGI light can disinfect pathogens.
Safe	The plastic cover can provide high quality and specific property to protect human from UV radiation.
Lightweight	The materials used for making a cabinet are polymer-based platforms, which can be carried by a person.
Easy-to-access technology	UV sanitizer cabinet can be functioned quickly and remotely by the controlling panel via mobile application.
Convenient	Components are "standard parts" that are easily found in the markets. Users can fix or replace the failed part(s) easily.

4.2. Concept of 3Fs Approach

The research of interest for this UV sanitizer box prototype is the functional use of the UV sanitizer box. As the aforementioned ideas for UV sanitizer in this research will concern with "*Affordable and accessibility*" issue was the critical point for the new design to be survived in the competitive market. To emphasize its functional use, the three main components details and functions will be mentioned in each section. The design embodies the 3F approach, form (shape, size, dimension, mass, weight, and other visual parameters that uniquely distinguish a part), fit (the ability of a part to physically interface with, connect to, or become an integral part of another part) and function (the action or actions that a part is designed to perform) as shown in Table 4 and Fig. 3. Table 5 are the key components required for creating UV cabinet. The expected design would likely be kept compact and lightweight; accessibility for users and additional functions will be included for multipurpose use.

DOI:10.4186/ej.2023.27.4.1

Table 4. 3Fs Concept.

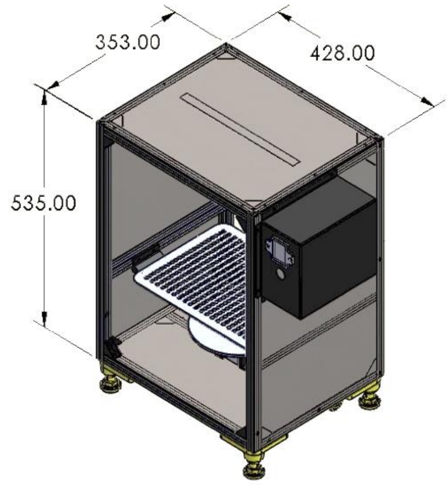
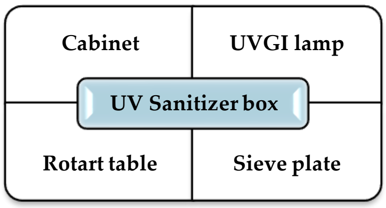
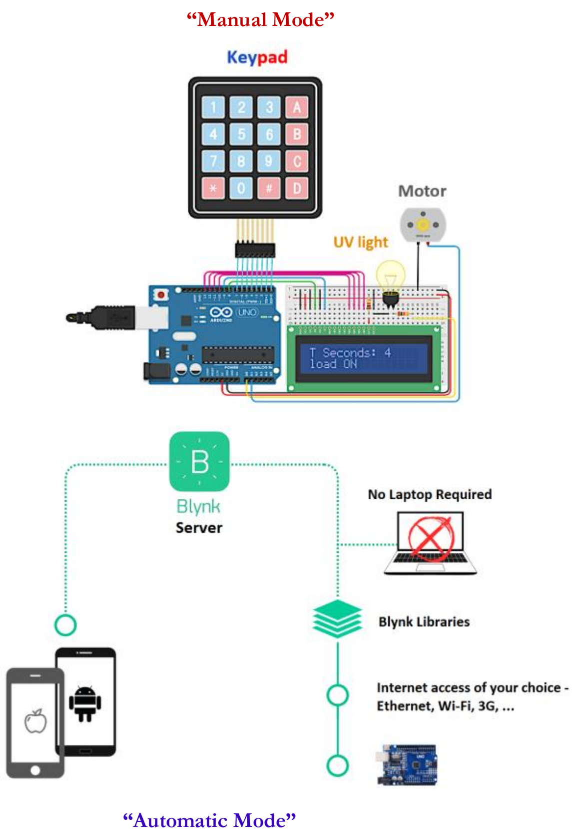
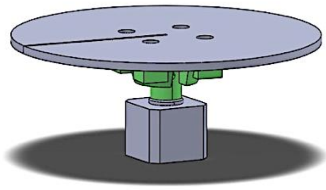
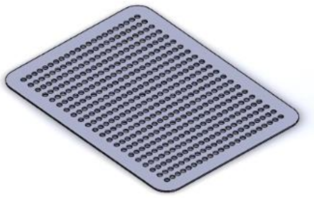
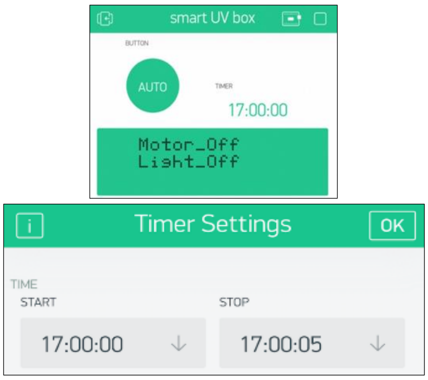
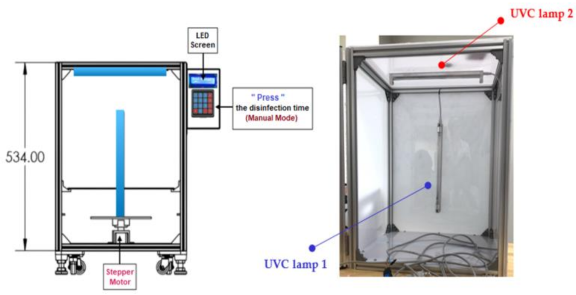
Concept	Details	Picture
Form	The size of UV sanitizer box is inspired from the size of a small storage cabinet with a single-hinged door that can be used in a small area or limited space. After observing various designs and sizes of the small cabinets/cupboards, which are popular and are sold out first from both online and onsite stores, the box dimension will be roughly 35.3 x 42.8 x 53.5 (in "cm" unit). With this desired size, the user can move and relocate the box easily, and the number of UVGI lamps needed to adequately light its room can be considered with lower units that are easier to control the intensity of emitted light output from the lamps comparing to a larger space. The design of the UV sanitizer box is made from polycarbonate and aluminum profiles as a main structure. Besides, the size of UV box can be redesigned to be slightly smaller or bigger from the suggested one.	
Fit	UV sanitizer box consists of four main parts, which are cabinet, UVGI lamp, rotary table, and sieve plate. The key point for this "Fit" concept is about the "90-degree corners design" where the corner or side of this box can be properly placed on the side of another object. The UVGI lamps, rotary table, and sieve plate are placed at the center point inside the main frame (housing) of a cabinet. A single-hinged door with handle will be located at the frontal area of UV box where two hinges on the vertical long edge of the door are mounted, and the location might be either left or right-handed. A hinged door can be fitted to swing inwards or outwards.	
Function	The key function of the UV sanitizer is to disinfect the bacteria, viruses, and other germs without leaving any residues. In order to disinfect these pathogens effectively, the wavelength of UV lamp, reflection of light, and the rotation angle of rotary table are taken into consideration. Arduino application is asked for controlling the rotary table's motor and disinfection time of UV light. The UV light and rotary table's motor are set to turn on at the same time for both manual and automatic mode. For *manual system*, the keypad with Arduino is used to specify the disinfection time. For *automatic mode*, Blynk application to control the disinfection time, which can be downloaded both IOS and Android. Three major components in a platform are Blynk application, Blynk server, and Blynk libraries [33-34]. At first, pressing button from manual mode to automatic mode (this needs a few seconds for execution.) is required, then the timer is set. For the speed of the stepper motor, the desired rotational speed value is assigned and transformed to be the code in Arduino software where the rotational speed is set to be 500 rpm, and step angle is 100 degrees.	

Table 5. The Key Components.

Concept	Details	Picture
Cabinet	Cabinet must be protected UV leakage or emitted out, which can be harmful to human body. The polycarbonate and aluminum profile are used for a UV protective and supporting structure of the cabinet.	
UVGI lamp	Four UVGI lamps will be install on 2-interior side of UV cabinet. “8W of UVGI lamp” is applied because it is the limited size of the UV cabinet.	
Rotary table	The rotary table is made of acrylic material, which is used to rotate the object in order to disinfection 360 degrees. The step motor of rotary table is controlled by Microcontroller (Arduino).	
Sieve plate	The sieve plate is used for placing the objects in disinfection process. The sieve plate is made of stainless steel, which is good for reflection of UV light.	
Easy-to-access Technology	UV sanitizer cabinet can quickly control by using mobile application. Once the functions are working as desired in the UV sanitizer cabinet, users can proceed to disinfect stuff(s) without onsite observation. Users can remotely proceed the function inside with little effort or difficulty - making use of communications technology between mobile application and UV sanitizer cabinet. The system can be started and stopped easily via “Timer” function.	
Convenient	All components are designed according to universal design concept; standard parts are selected – since they can be found easily in the markets (both online and onsite channels). Users can fix or replace the failed part(s) easily by themselves according to the user’s guide provided.	

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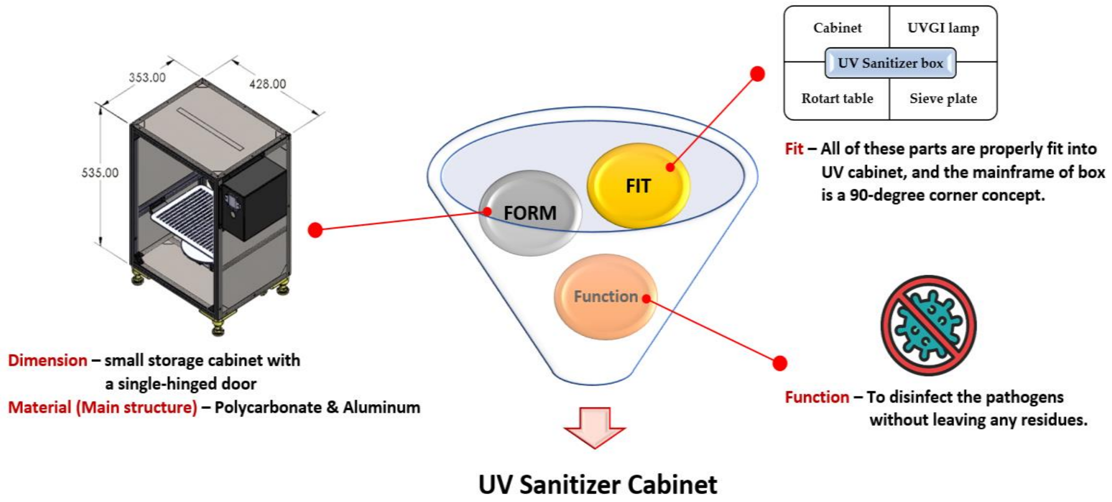

Fig. 3. 3Fs Approach (Form/Fit/Function).

5. Phase 2: System-Level Design

In order to identify the physical characteristics of the UV sanitizer box, all components are classified and operational stage conditions. This data can help the designer to minimize some mistakes that might occur during the design stage. Figure 4 illustrates the main frame and components of the developed prototype. For the UV cabinet, two main items are required: cabinet and controller box. For cabinet consists of door, aluminum profile, and polycarbonate sheet. These items build up the UV cabinet, which can make the cabinet have a strong structure and protect the UV light from emitting out to the human body. The sieve plate will attach to the UV cabinet by using sieve plate holder and to support object while putting on the sieve plate. Lastly, the UVC light and rotary system consist of UV light, rotary table. These two items are controlled by using Arduino system. At the bottom of the rotary table, the cabinet is attached with rotary mounting and step motor to control the speed and step while disinfecting. For supporting detailed design and maintenance viewpoint, classifying the UV sanitizer system into main components and sub-components are required (Fig. 5). The three main parts are power supply, controlling system, and controlling applications. Moreover, the description of each component is explained in Fig. 6 and Table 6. The 3D virtual model of the UV cabinet in three views is illustrated in Fig. 7.

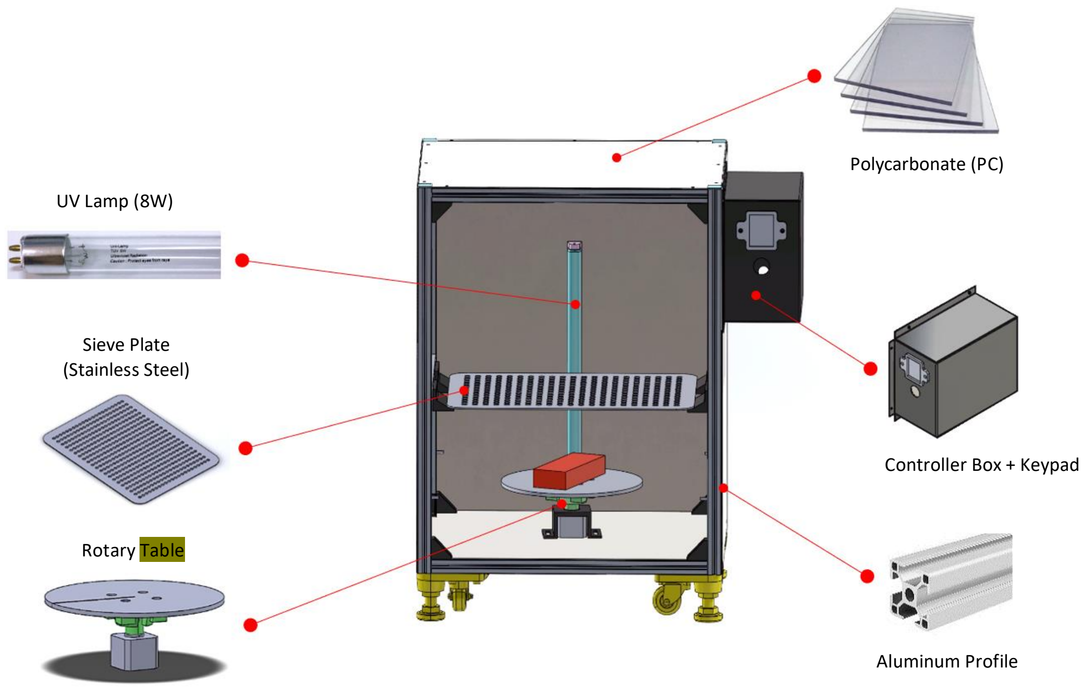

Fig. 4. The main components of UV cabinet.

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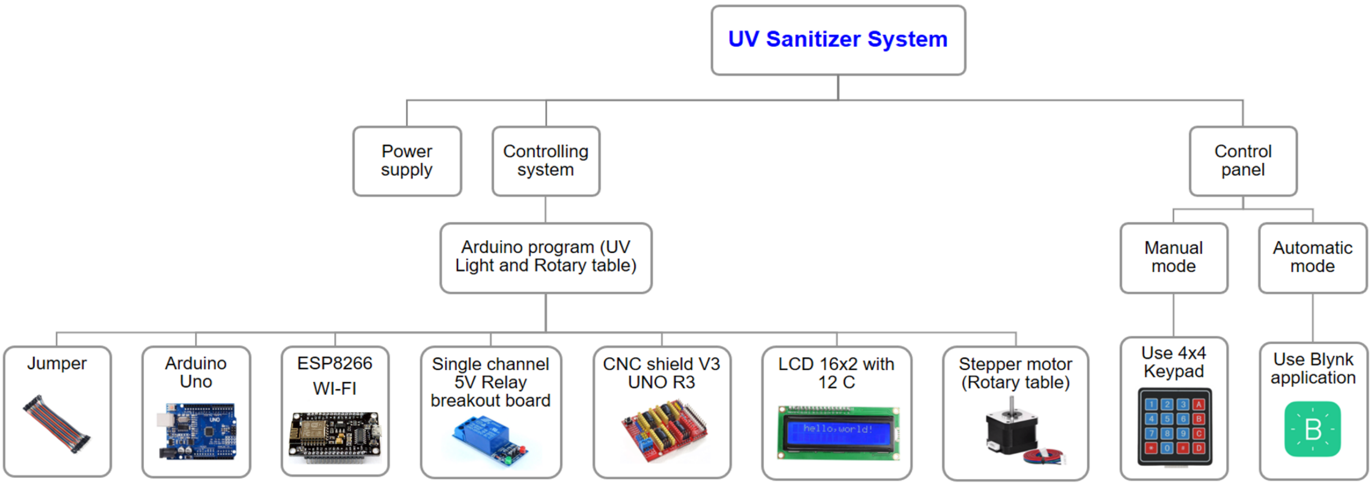
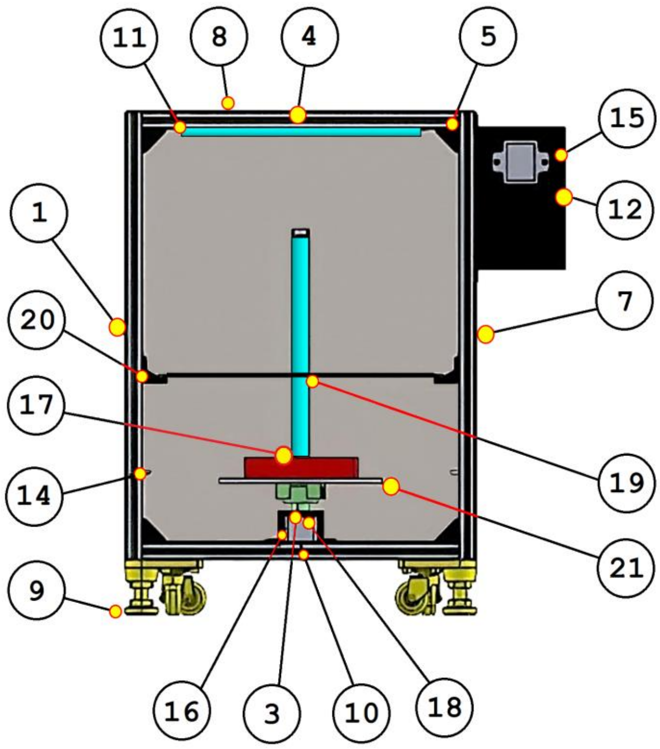


Fig. 5. System Level design of UV sanitizer system.



ITEM NO.	PART NUMBER	DESCRITION	QTY.
1	Frame 590	Aluminum	4
2	Frame 315	Aluminum	4
3	Support rotary	Plastic ABS	1
4	Frame 390	Aluminum	5
5	Bracket		28
6	Back	Polycarbonate	1
7	Side	Polycarbonate	1
8	Top	Polycarbonate	1
9	Feet	Rubber	4
10	Base	Polycarbonate	1
11	UV Light		2
12	Box Control	Stainless Steel	1
13	T nut		7
14	Secondary holder		4
15	LCD Display		1
16	Motor		1
17	Test Object		1
18	Mounting motor	Plastic ABS	1
19	Sieve Plate	Stainless Steel	1
20	Sieve Plate Holder		4
21	Rotary Table	Acrylic	1

Fig. 6. Components of UV sanitizer system with numbers.

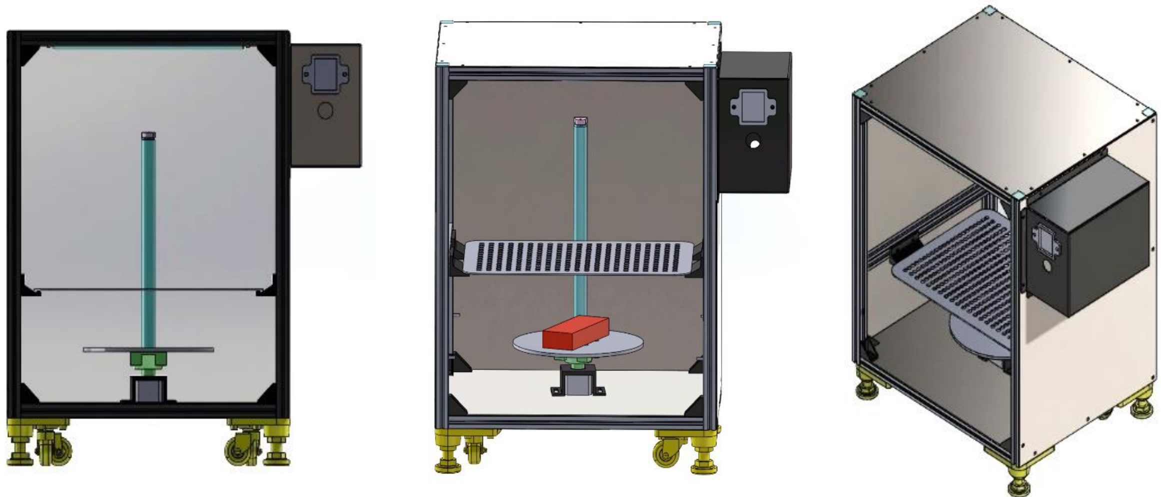


Fig. 7. 3D virtual model of UV cabinet.

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Table 6. Components of controlling system.

Component		Description
Male to Female Jumper		The jumper wire male to female is used in connecting female header pin of any board to other board having male connector.
Arduino Uno		Arduino Uno is a microcontroller board that contains several general pin functions, which is used to generate code to other microcontrollers.
ESP8266 Wi-Fi		ESP8266 modules is a low-cost Wi-Fi microchip, which can operate as a station. It is capable of either hosting an application or offloading all Wi-Fi networking function.
Single channel 5V Relay breakout board		A relay is an operated switch, which consists of a set of input terminals for a single or multiple control signals.
CNC shield V3 UNO R3		Arduino SB CNC Shield is the PCB you need to control the stepper motors. It supports up to 4 motors with A4988 or DRV8825 drivers. It has end stops and relays output and support the speed control by PWM.
LCD 16x2 with 12 C		An LCD is an electronic display module which uses liquid crystal to produce a visible image. The 16×2 LCD display is a very basic module commonly used in DIYs and circuits.
Stepper motor (Rotary table)		Stepper motor (DC motor) is moved in discrete step. With a computer controlled, we can get the precise and smooth rotational speed to rotate the rotary table.

6. Phase 3: Detailed Design

For this section, main components, sub-components, and factors related to the function and performance of the developed design of UV sanitizer cabinet are classified and specified into details of specific characteristics for supporting the design team to select the right or proper material to the right location of the product structure before fabricating the physical prototype.

6.1. Components of Cabinet

The specific characteristics of the key components of UV cabinet are considered in this subsection where the quadrilateral shape of the mainframe, (storage utilization), and the optimal number of UVC-light lamps are identified.

- *UV cabinet*

As the UV cabinet is designed to prevent the UV light from emitted out [35]. A controller box was attached to the cabinet to keep all the wire and other applications.

- *Sieve plate*

The sieve plate is designed to be able to put the daily gadget on it. The holes allow the UV light to pass through and disinfect at the bottom of the thing. The sieve plate holder is designed to hold the sieve plate at the appropriate level.

- *Rotary Table*

The rotary table is designed to be able to put the daily gadget on it and turn 360 degrees to disinfect the stuff thoroughly. *Rotary mounting*: The rotary mounting is designed to lock the stepper motor with the rotary table. *Stepper motor*: The stepper motor will turn the rotary table 360 degrees with 500 rounds per minute.

- *UVC light*

The UVC light will be installed inside the UV cabinet, at the top and the back of the UV cabinet where the UVC light can kill the pathogens up to 99.99%. To apply number of UVC light in the cabinet, the Rhinoceros program was applied to simulate (Fig. 8) for seeing the light incident on the objects and diffused light inside the UV sanitizer cabinet. The energy dosage of Ultraviolet radiation (UV dose) in μWs/cm² needed for killing factor and the predicted values for UVC sensitivity is studied before performing the design stage [36-38]. Moreover, from the research of using hand-held germicidal ultraviolet wand for surface disinfection [39], the UV-C was effective under a direct beam exposure, and a short target distance approximately 12.7 cm. Watts of UV emitted by fixtures per square meter of floor space are limited [40-41]. Simply saying that, considering and comparing the UV dose exposure needed are required for selecting the suitable type and pattern to inactivate the important viruses infecting human such as SARS Coronavirus, Ebola virus, Hepatitis B virus, Smallpox virus, Influenza Virus A-C, and Human rotavirus A, B (Table 7).

- *UV Test*

For the UV tests, they were conducted by applying the lamp that produced 21μW/cm² (for 1 lamp). The calculation can be performed by applying Eq. (1),

$$\text{UV dose} = \text{UV intensity x Time in seconds} \quad (1)$$

Time is about "time" needed to inactivate germs.

Table 7 are the incident energies of germicidal ultraviolet radiation at ~ 253.7 nanometers wavelength that is necessary to inhibit colony formation in microorganisms (90%) and for 2-log reduction (99%).

Table 7. Calculation of optimal UV dose for killing germs [40-41].

Energy Dosage of Ultraviolet radiation (UV dose) *μWs/cm²* needed for killing factor (Given range)	
Important Viruses infecting human	**90% (1 log reduction)**
SARS Coronavirus	700-1,100
Ebola virus	2,000
Hepatitis B virus	3,800-4,100
Influenza Virus A-C	1,800-4,300
Human rotavirus A, B	19,000-32,000

However, the number of UVC light is considered by amount of UV dose. The amount of UV dose can be calculated by using Eq. (2):

$$UV\ dose\ \mu Ws/cm^2 = UV\ intensity\ \mu W/cm^2 \times exposure\ time\ (seconds)$$

(Given: UV intensity for 1 UVC lamp = 21 μW/cm², and UV intensity for 2 UVC lamp = 42 μW/cm²)

Therefore, after applying Eq. (2) in this research, the result was expressed as,

$$\begin{aligned} UV\ dose\ \mu Ws/cm^2 &= UV\ intensity\ \mu W/cm^2 \times exposure\ time\ (seconds) \\ &= (42\ intensity \frac{\mu W}{cm^2}) \times (60\ seconds) \\ &= \mathbf{2,520}\ \boldsymbol{\mu Ws/cm^2} \end{aligned}$$

The design team decided to install 2-UVC lamp in our prototype of UV sanitizer cabinet (Figs. 8 and 9). After calculating UV dose, the results shows that the developed cabinet with 2 UVC lamps can disinfect the pathogens where the amount of UVC dose can disinfect the pathogens within shorten time (Fig. 10). The work process of this developed cabinet can be classified as two modes: manual mode, and automatic mode as shown in Fig. 11. The detailed design of the proposed system is presented in Table 8.

(a) One UVC light (b) Two UVC light

Fig. 8. The developed UVC cabinet – virtual simulation.

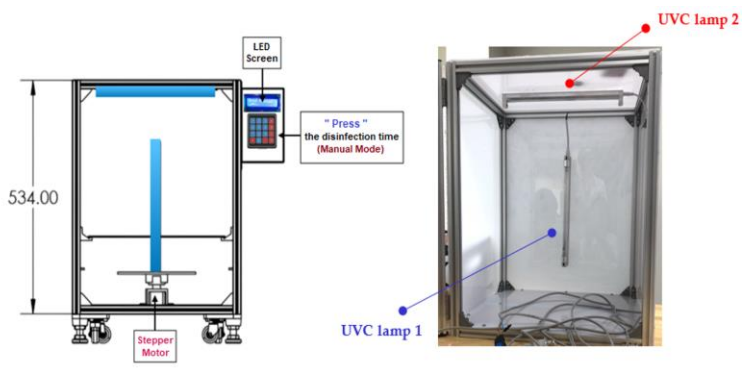


Fig. 9. Installing 2-UVC lamps in cabinet.

DOI:10.4186/ej.2023.27.4.1

Calculation of UV dose to find optimal number of UVC lamp

Number of UVC lamp	UV intensity (µW/cm²)	Exposure time (seconds)	UV dose (µWs/cm²)
1 	21	60	1,260
		180	3,780
		300	6,300
		900	18,900
		1800	37,800
Number of UVC lamp	**UV intensity (µW/cm²)**	**Exposure time (seconds)**	**UV dose (µWs/cm²)**
2 	42	60	2,520
		180	3,780
		300	6,300
		900	18,900
		1800	37,800

Fig. 10. Calculation of UV dose.

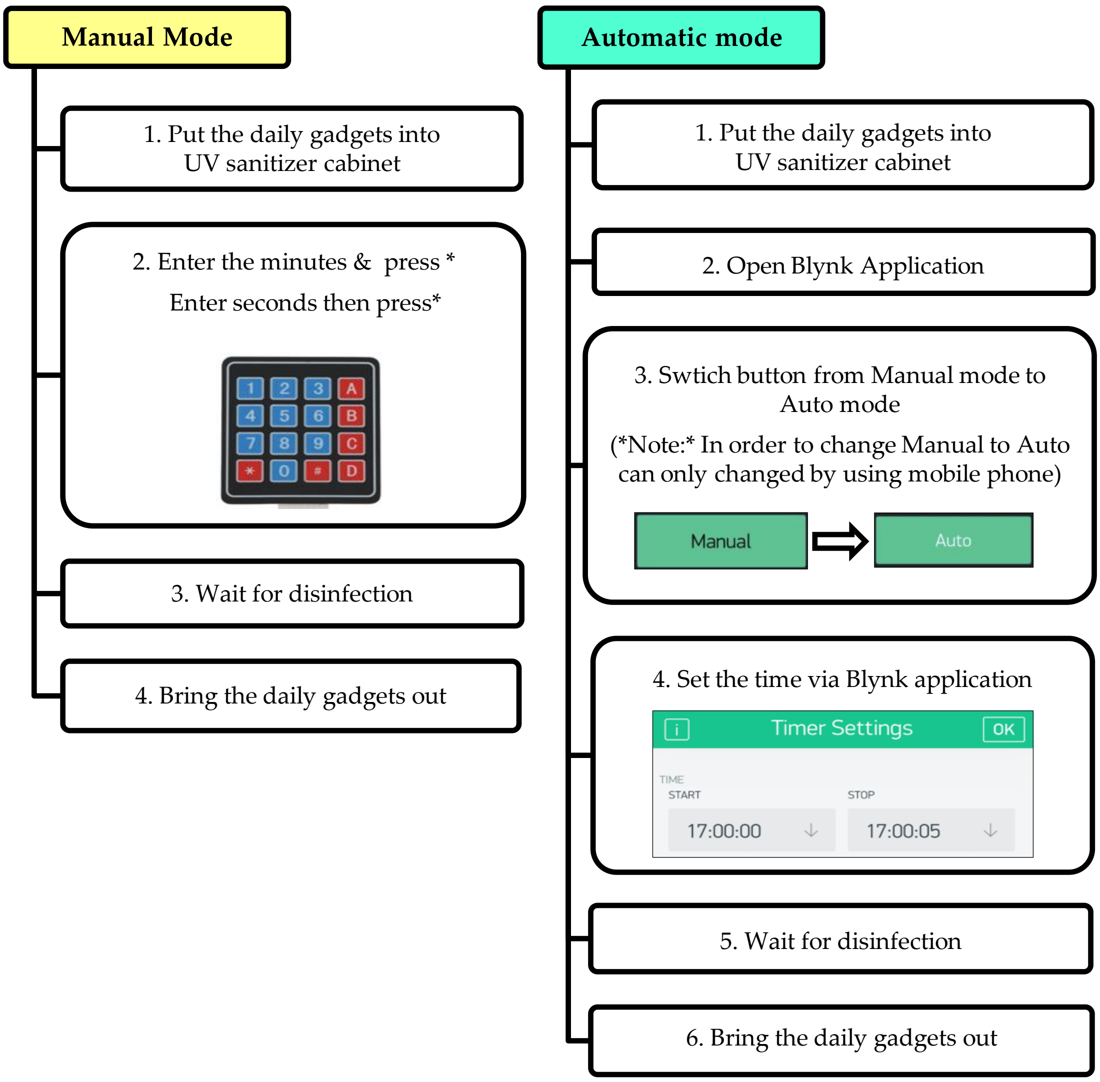
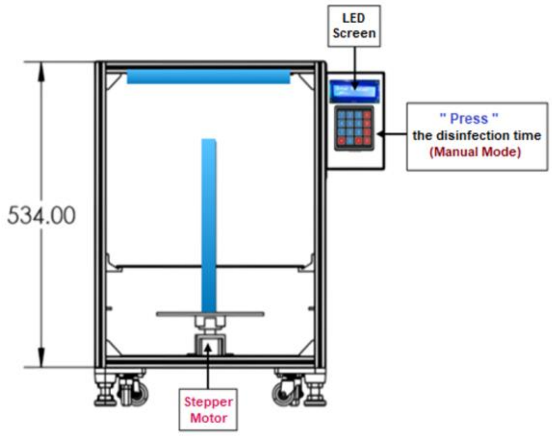
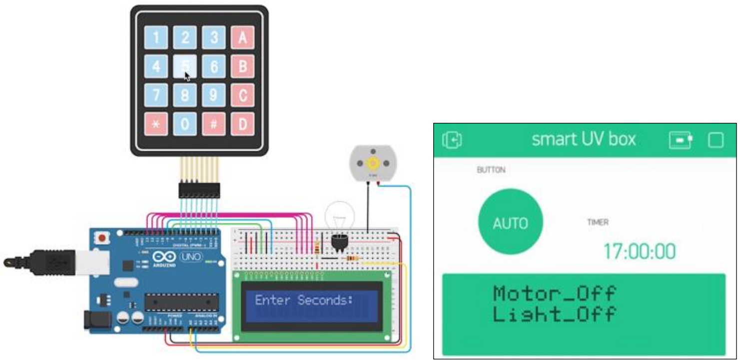
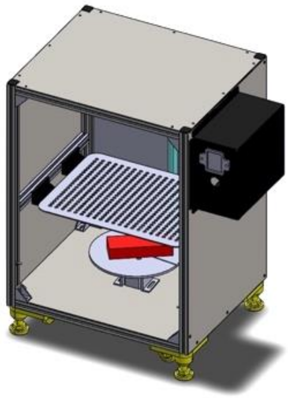


Fig. 11. Working process – two modes.

DOI:10.4186/ej.2023.27.4.1

Table 8. Detailed design of UV sanitizer cabinet.

Picture	Description
Manual system 	**Main requirements:** 1. **Appearance module:** The appearance of the UV sanitizer must be a simple design with edge shape. 2. **Material:** Polycarbonate is used as a cover body of the UV sanitizer cabinet. 3. **Accessing module:** Simple user interface that can take a few steps to operate the UV sanitizer cabinet.
Automatic system 	**Functional design:** The system of UV sanitizer consists of manual and automatic system that work with the Arduino program and Blynk application. The system is included as follow: • Code/ Arduino Uno • Esp8266 Wi-Fi • Single channel 5V Relay breakout board • CNC shield V3 UNO R3 • LCD 16x2 with 12 C • Stepper motor (Rotary table)
3D Virtual model 	**Drafted final design:** According to the requirement and functional design, the drafted UV sanitizer cabinet design was created.
Prototype 	**Final product:** Construct the prototype of UV sanitizer cabinet and test

DOI:10.4186/ej.2023.27.4.1

6.2. Material Consideration

From the mainframe diagram, different parts of UV cabinet will use different materials (Table 9). For the UV sanitizer cabinet will be set at the lowest price possible. However, the quality is also taken into our consideration. Two kinds of main material will be used to construct the UV cabinet are Polycarbonate (PC) and Aluminum profiles.

Table 9. Material used for each part.

Function Part:	Material Used
UV box	Polycarbonate (PC)
Structure	Aluminum Profile
Rotary table	Acrylic
Rotary Mounting	ABS plastic

- *Polycarbonate (PC)*

The main property of PC is shown in Table 10, *Polycarbonate (PC)* provides 100% protection from harmful UV rays. It also has light weight and is more efficient than other engineering thermoplastics. For making the wall of the cabinet, CNC-Router was applied for cutting polycarbonate into the desired size.

Table 10. Properties of Polycarbonate (PC) [35].

Physical Properties	Value
Tensile Strength:	66 MPa
Notched Impact Strength:	20-35 kJ/m^2
Thermal Coefficient of Expansion:	65-70 x 10^{-6}
Max. Continued Use Temperature:	80 ^{o}C (176 ^{o}F)
Glass Transition Temperature (T_g):	147 ^{o}C (297^{o}F)
Density:	1.2-1.22 g/cm^3

Fig. 12. Polycarbonate sheet.

- *Aluminum Profile*

Aluminum profile is an extrusion's process that is for creating objects of a fixed cross-sectional profile. A material is pushed through a die of the desired cross-section. The advantages of this material are its ability to create very complex cross-sections, and to form parts with an excellent surface finish. The properties of Aluminum are shown in Table 11.

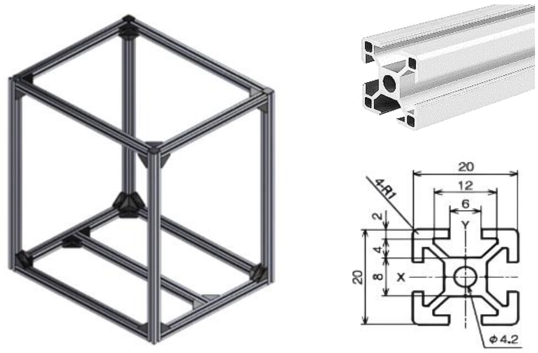


Fig. 13. Aluminum profile structure.

Table 11. Properties of Aluminum [42-43].

Mechanical Properties	Value
Tensile Strength:	150-680 MPa
Hardness	95 Hv50
Yield Stress	280 MPa
Strain Hardening exponent	0.095 n
Young's Modulus	68 GPa
Density:	2.8 g/cm^3

- *Acrylic*

Acrylic is a transparent plastic material with robustness, stiffness and very good for heat resistant which up to 130°C. As its special properties such as flexibility and easy-to-machine (i.e., for being molded into many shapes), the acrylic was cut as the rotary pad by using CNC machine. The properties of *Acrylic* are shown in Table 12.

Fig. 14. Rotary table made of Acrylic.

Table 12. Properties of Acrylic [44].

Mechanical Properties	Value
Tensile Strength:	65 MPa
Elastic modulus	3.17 GPa
Flexural Strength	90 Mpa
Specific Gravity	1.18
Young's Modulus	73 GPa
Density:	1.18 g/cm^3

- *ABS plastic*

This *Acrylonitrile Butadiene Styrene* (ABS) plastic has a low melting point, which enables its easy use in the injection molding or even 3D printing process. The acrylonitrile in ABS provides chemical and stability, while the butadiene adds toughness and strength. Styrene gives the finished polymer a glossy finish. ABS material was used for creating rotary mounting via rapid prototyping process (RP) with 3D printing machine. The properties of ABS plastic are shown in Table 13.

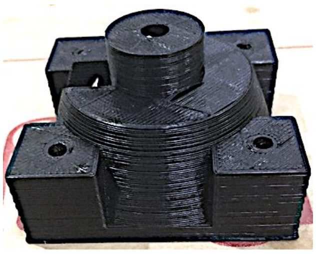


Fig. 15. Rotary Mounting made of ABS Plastic.

Since the location of this fabricated ABS part is placed under the acrylic rotary table, and it is not faced with UVC light directly. At risk of UV damage, this part might face with a few side effects comparing to automotive parts, which are high on list. The effects will primarily result in a change of the material's surface layer – a chalky appearance, the component surface becoming brittle, or a color change on the surface of the material. However, the developed UV sanitizer cabinet is not actually built for long-term usage as 10 – 15 years, the parts need to be maintained and replaced according to their conditions – preventive maintenance is planned and scheduled based on real-time data; it might be on the first day of every month or once in a three-month period.

Table 13. Properties of ABS Plastic [45].

Mechanical Properties	Value
Tensile Strength:	22 MPa
Tensile modulus	1360 MPa
Tensile elongation	6%
Specific Gravity	1.24
Thermal conductivity	0.1 W/mK
Density:	0.9-1.53 cm^3

6.3. Virtual Design Consideration

Since "Finite Element Analysis (FEA)" has been introduced in this study as one of the key methods for checking the load applied/distributed on the rotary table. Simply saying that FEA is applied as "Overload Protection Tool" for preventing the rotary table from being damaged by an excessive mass – preventing overloading the motor.; this implies the key point that, during disinfection process, system can offer excellent rigidity in the rotating direction, a 360-degree surface area of an object can be disinfected properly.

After the final virtual design of the UV sanitizer cabinet is finalized, "Finite Element Analysis" (virtual simulation) [46-47] is asked to test the rotary table support the weight of an object while disinfection. A standard value is used for both rotational speed of 500 rpm and step angle is 100 degrees. The simulated result is shown in Fig. 16.

Condition: A pair of shoes is applied as the case study for this case - applying mass of 1.5 kg according to the standard mass of shoes and applying torque of 42 N/cm according to the specification of stepper motor. Figure 16 below shows the simulation of the "Factor of safety distribution": the Min. FOS = 1.2×10^4 and the Max. stress = 3.561×10^7 N/m². We find the proper value of stress by $\frac{\sigma}{FOS}$ and got the proper value of stress = 2967.5 N/m².

Result: After calculating the proper force by using $= \frac{F}{A}$, the obtained force is equal to **93.23 N**, or simply saying that the maximum mass of an object that is placed on the rotatory table should be **9.5 kg.**

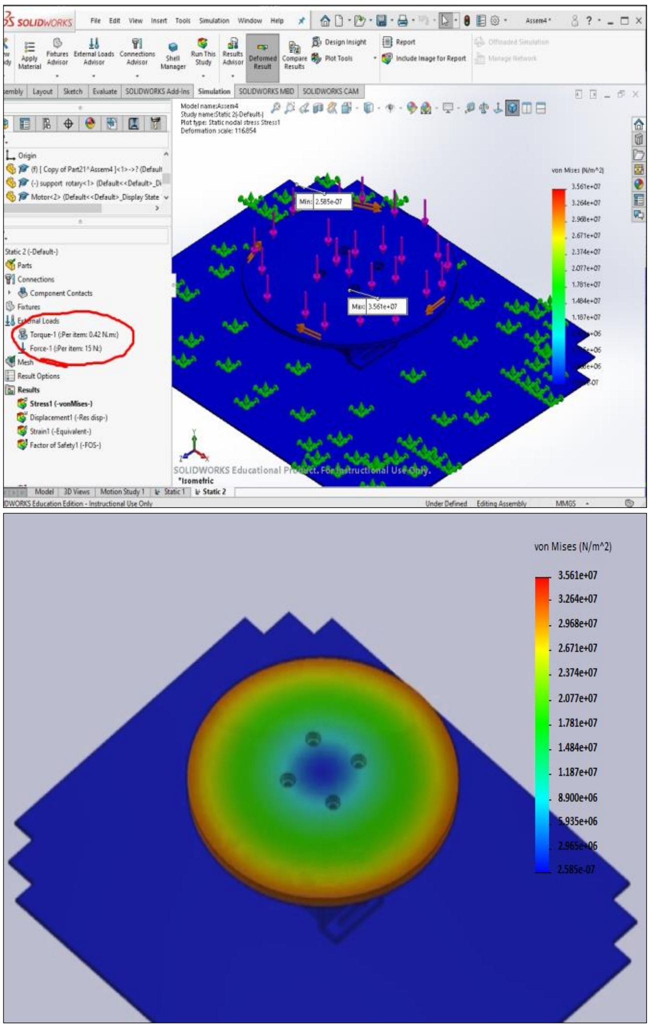


Fig. 16. Simulation of virtual design consideration.

6.4. Failure Analysis

Since the developed UV sanitizer cabinet (box) has been introduced as Do-It-Yourself (DIY) platform where the Arduino controlling system is applied as the key component for digitally managing the activities to disinfect the pathogens with a shorten time spent by concerning with the exposure of disinfection time and safety for human health. Designing a system with failure in mind can support the designers to estimate and plan for maintenance activities; preventive maintenance (PM) or corrective maintenance (CM).

After fabricating the prototype of UV sanitizer cabinet, for checking the status of the developed system whether it is in the operational stage and is ready for being used, "Failure Analysis" is raised as the main point. Failure can be defined as a lack of success or the inability to meet an expectation. The reasons for performing failure analysis; failure rate, are:

- When the failure rate is/are found, the reliability can be determined where the reliability is calculated as an exponentially decaying probability function which depends on the failure rate.
- System availability is affected by planned and unplanned downtimes – system stops to operate or produce the product, and equipment failure is an availability loss.
- Mean-time-to-repair (MTTR) can be applied as a measuring tool (i.e., maintenance metric) and key index for finding the average time required to troubleshoot and repair failed equipment. MTTR can reflect how quickly an organization can respond to unplanned breakdowns and repair them [48-52].

Another factor that impacts system availability is maintainability, which refers to how quickly technicians detect, locate, and restore asset functionality after downtime. When building a system, considering the availability during all aspects of a system design and construction can support the design team to plan what to do when a component fails and how to bring the failed item back to the normal stage. Moreover, the critical point is found when the problem is indicated as an unrecoverable (hard) failure, rather than a recoverable (soft) failure.

From the Fault Tree Diagram (FTA), the reliability and failure rate for each component of the machine can be determined by calculating from Mean time to repair (MTTR), Mean time to failure (MTTF), and Mean Time Between Failure (MTBF). The mathematical models and parameter considerations are mostly based on three major failure events and applying "AND" or "OR" gates on how the components interconnect to each other [48-52].

For the failure of the top event ("System failed to operate and move") in FTA diagram (Figure 17), OR gate is applied for representing the sensitive case; if any three major functions; disinfection system (mentioned in controlling system failure), rotational speed (mentioned in Stepper motor failure), and the brightness of UV (mentioned in UV light failure) is performed incorrectly, can cause the UV sanitizer cabinet failed. This UV sanitizer cabinet is expected to perform work with full capacity 100%. The key components and their normal stage are considered and defined as the conditions for supporting "FTA calculation" task (Table 15). Presented in Table 14 and 16 are the results obtained from the calculation parts of "failure analysis".

Case 1: Controlling system failed to function the moving and exposing the UV light

For controlling system failure, the disinfection system that command by auto mode and manual mode. It consists of a lot of electrical equipment, for example the Arduino and motor controller board. This equipment can be failed and give some effect to motor, UV light, LCD display and all electric system. All of this will make an imperfect disinfection.

Case 2: Stepper motor failed to move the platform

There is only one event, which is Stepper motor. Stepper motor should provide a constant rotational speed for the rotary platform; otherwise, the object spills may occur during disinfection.

Case 3: UV light failed

Two events; UV lamp 1 and UV lamp 2, are analyzed by OR gate. Both UV lamps are used to provide the UV radiation for disinfect the pathogens. If one of the UV lamps does not work properly, this will cause the UV sanitizer to not completely disinfect the pathogens.

Table 14. Normal Condition of Each Component of UV Sanitizer Cabinet.

Component	Details
Cabinet	The cabinet will be designed to be a cover, to protect us from the UVC light.
Controller box	The controller box will contain the Arduino system for automatic mode and control panel for manual mode.
Door	The door is designed to allow the user to open and close to put the daily gadget in and out.
Aluminum profile	The aluminum profile is designed to be a structure of the UV cabinet.
Polycarbonate sheet (PC)	The polycarbonate can prevent the UVC light from emitted out 100% and reflect the UVC light in the cabinet.
Door handle	The door handle is designed to allow the user to grab to close and open the door.
Door magnet lock	The door magnet lock will make the door close tightly – (manual mode).
Foam door seal strip	The foam door seal strips will the door close more tightly and prevent the leak points.
UV silicone	The UV silicone will cover all the leak point around the cabinet to prevent the UVC from emitted out.

Table 15. Failure Rate and Combined Reliability of 3-Major Failure Rate.

Summary of Reliability of 3 Events	
Event	**Reliability**
Controlling system failed to function moving and exposing the UV light	0.9592
Stepper motor failed to move the platform	0.9947
UV light failed	0.9901

Table 16. Reliability of UV sanitizer system.

Event	Reliability
UV Sanitizer System (operate and move)	99.47%

For one event (situation) of the UV sanitizer system, the process has been run for 15 minutes and 100 times to determine the failure rate of each component. However, after 15-minute mission, the system needs to be stopped (for 10 minutes) for checking the condition inside the UV cabinet (i.e., performing preventive maintenance task); especially temperature. For electronic capacitors, they are generally limited to temperatures below 85°C for reliable operation. Besides, their lifespan mainly depends on the environmental temperature in a range of -40 to 85 °C. When the temperature increases 10 °C, the lifespan is reduced by half. Thus, depending on the environmental condition, in hot temperature they can live from 2-3 years, whereas they can stay and work properly up to 10-15 years in cool environment. Along with the testing activities recorded and calculated by the observers, the failure rate formula (Table 17) is used to convert into reliability of each component and calculate the reliability of the system by bottom-up analysis. The UV sanitizer is very sensitive, because it is related to health, thus, "OR" gate is applied for identifying the reliability of system. Table 18 shows the calculation of reliability of each main component, and system (Top-event). All components can provide high reliability, which is more than 90% – they work properly without breaking down. For the jumper and UV light, they have 100% availability with "zero" MTTR. Since, when these components fail, they cannot be fixed, changing, replacing, or installing a new one for each instead of fixing – no MTTR consideration. Moreover, the time used to install these components is quite short, and it has less effect to the disinfection process; time is neglected. However, for some parts that required more than one-third of MTTF (good time/reliable operation), MTTR is counted.

The availability of power supply (89.69%) is the lowest value compared to the availability of another component. It has the longest value of MTTR; this makes power supply provide low availability. However, in theory, 89.69% is still high value for availability. In conclusion, the value of reliability and availability of UV sanitizer cabinet for 200-hour mission (the operating time) are high value (Table 18). The reliability of the UV sanitizer system is 99.47%; since this has been constructed as a new prototype that consists of new components and sub-components.

Moreover, availability is impacted by reliability and maintainability, which are influenced by the processes and tools of the maintenance team. Availability is used to measure and investigate the effectiveness of these processes and tools, and how they can be improved. Since MTTR is defined as Mean Time To Repair - the average downtime. Whereas, MTBF is defined as Mean Time Between Failures - the average uptime. Availability can be calculated directly from MTTR and MTBF as shown in Eq. (9).

Table 17. Steps and equations required for calculating "Failure Analysis" [48-52].

Steps for calculation	Equation	No.
Step 1: Calculate Mean time between failure (MTBF)	$MTBF = \frac{Total\ uptime}{no.of\ breakdown}$	(2)
Step 2: Calculate Mean time to repair (MTTR)	$MTTR = \frac{Total\ downtime}{no.of\ breakdown}$	(3)
Step 3: Calculate Mean time to failure (MTTF)	$MTTF = MTBF - MTTR$	(4)
Step 4: Calculate failure rate (λ)	$\lambda = \frac{1}{MTTF}$	(5)
Step 5: Calculate Probability of fail	$P_{of\ fail} = 1\text{-}R$	(6)
Step 6: Calculate Reliability (Probability of good): *t is total mission hour for performing task (hr)*	$R = e^{-\lambda t}$	(7)
Step 7: Apply "OR" gate calculation	*" OR gate"* $R_{system} = (1\text{-}P_{a\ failed})(1\text{-}P_{b\ failed})$	(8)
Step 8: Calculate for Availability	$Availability = \frac{MTBF}{MTBF + MTTF}$	(9)

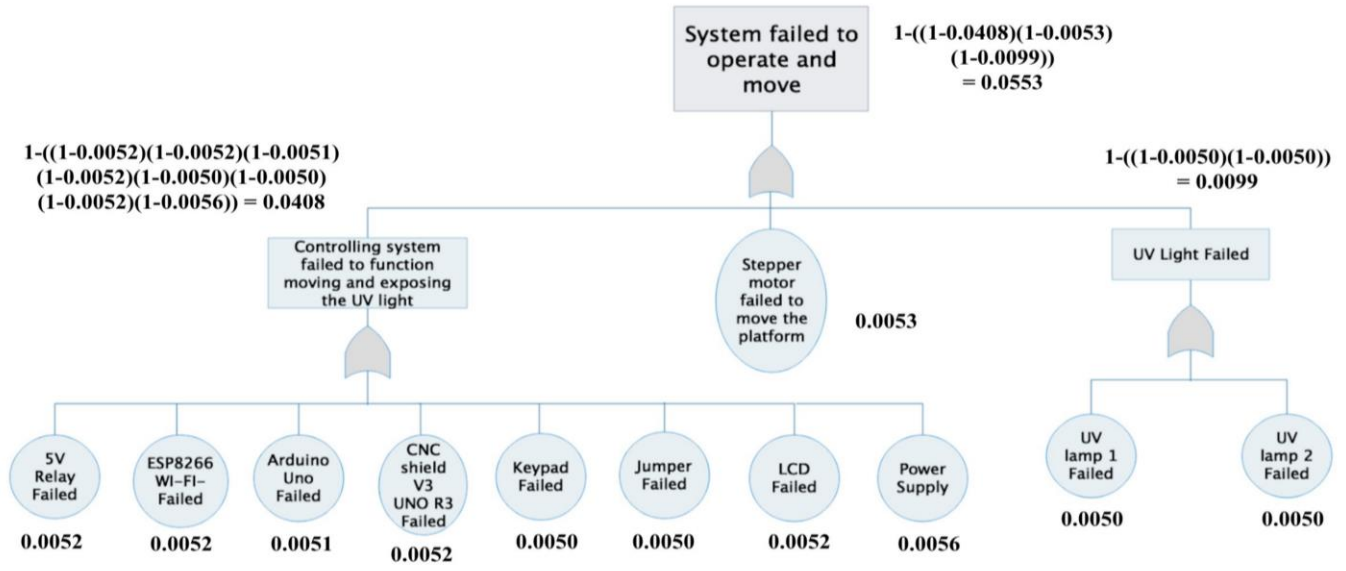


Fig. 17. Bottom-up analysis – FTA diagram.

Considering the life span of each component can be done by turning the UV sanitizer on for 720 hours (or ~1 month) as presented in Table 19, the reliability of each component obtained is still high. However, when the UV sanitizer has been run for 1 year, some of the component devices such as UV lamps need to change due to their life span that is around 1 year. Therefore, after 1 year, there is a reduction of UV radiation of more than 30%, although the usage time of UV lamp is still in the average range, it is recommended to replace it with a new one.

Table 18. Failure rate and Reliability.

Situation	Sub-component	MTTF (Hour)	MTTR* (Hour)	MTBF (Hour)	Failure rate (failure/100 tests)	Failure rate (failure/100 tests/minute)	Reliability	Availability (%)
Controlling system failed to function moving and exposing the UV light	5V Relay	192	8	200	0.52083	0.0003472	0.9948	96.15
	ESP8266 WI-FI	191	9	200	0.52356	0.000349	0.9948	95.69
	Arduino Uno	194.5	5.5	200	0.51413	0.0003428	0.9949	97.32
	CNC shield V3 UNO R3	194	6	200	0.51546	0.0003436	0.9949	97.09
	Keypad	196.5	3.5	200	0.50891	0.0003393	0.9949	98.28
	Jumper	200	0	200	0.5000	0.0003333	0.995	100
	LCD	192	8	200	0.52083	0.0003472	0.9948	96.15
	Power Supply	177	23	200	0.56497	0.0003766	0.9944	89.69
Stepper motor failed to move the platform	Stepper Motor	186	14	200	0.53763	0.0003584	0.9946	93.46
UV light failed	UV lamp 1	200	0	200	0.5000	0.0003333	0.9950	100
	UV lamp 2	200	0	200	0.5000	0.0003333	0.9950	100

**For MTTR, the average value of repairing time spent for fixing a failed part has been considered as the interval time starting from sending the failed part to the fail-and-repair station (i.e., the external service centers) until the failed part is completely fixed and returned to the laboratory. Some failed parts need to be replaced or changed instead of being fixed; thus, MTTP is considered to be "zero".*

Table 19. Calculation for the device run 720 hours mission.

Situation	Sub-component	720-hr-mission	Life span of each component (MTBF – Hour)	Reliability $R=e^{-t/MTBF}$
Controlling system failed to function moving and exposing the UV light	5V Relay	720	87,600	0.992
	ESP8266 WI-FI	720	105,120	0.993
	Arduino Uno	720	87,600	0.992
	CNC shield V3 UNO R3	720	43,800	0.984
	Keypad	720	87,600	0.992
	Jumper	720	87,600	0.992
	LCD	720	87,600	0.992
	Power Supply	720	17,520	0.96
Stepper motor failed to move the platform	Stepper Motor	720	42,048	0.983
UV light failed	UV lamp 1	720	8,000	0.914
	UV lamp 2	720	8,000	0.914

7. Phase: 4 Testing and Refinement

After identifying the reliability of the developed UV sanitizer cabinet, the real test is asked to perform to evaluate the performance of this system where the two main issues; *Bacterial culture test* and *UVC light meter test*, are taken into consideration. For *bacterial culture test*, it is applied for testing the performance and efficiency of UVC light disinfection from, the developed cabinet, and UVC light meter test is used to measure the UVC leakage emitted out from the UV sanitizer cabinet.

7.1. Bacterial Culture Test

The *bacterial culture test* has been conducted according to the method that about multiplying the microbial organism growing and reproduce in predetermined bacteria culture under controlled laboratory conditions. There are several types of bacterial culture methods that are selected based on the agent being cultured and the downstream use. In this case, streaking onto sheep blood agar plate is applied to do the bacterial culture according to the following steps. Bacterial culture streaking allows bacteria to reproduce on a culture medium in a controlled environment. The process involves spreading bacteria across an agar plate and allowing them to incubate at a certain temperature for a period of time [53-54]. Moreover, this bacterial streaking can determine and isolate the pure bacterial colonies from a mixed population. Microbiologists use bacterial and other microbial culture streaking methods to identify microorganisms and to diagnose infection [55-57].

<u>*Experimental equipment:*</u>

1. Sheep blood agar plate
   (Two agar plates are required per one test)
2. Latex gloves
3. Sterile cotton swab with wood shaft
4. Tape

<u>*Materials testing:*</u>

1. Five pens
2. Five spoons
3. Five paper plates

Step 1: The experimental equipment required are prepared and set as five units for each material testing (Fig. 18). For the material testing reference, spoons and paper plate are taken from the canteen, and the pens (everyday pens) are taken from some students who study in the same class.

Fig.18. Experimental equipment.

Step 2: Since the sheep blood agar plates are refrigerated (for preserving their original condition),

DOI:10.4186/ej.2023.27.4.1

before using, they need to be set their temperature condition by warming naturally to reach room temperature level (Fig. 19).

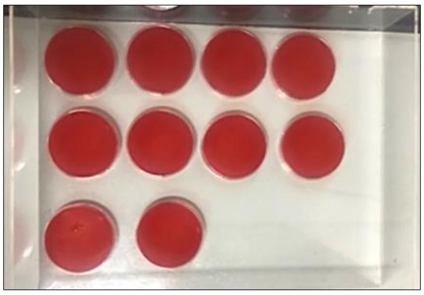


Fig. 19. Taking sheep blood agar plates (the lid is closed.) out from the refrigerator to settle down at room temperature.

Step 3: A sterile cotton swab with wood shaft is applied to rub the area of interest for getting the pathogens from a pen (Fig. 20)

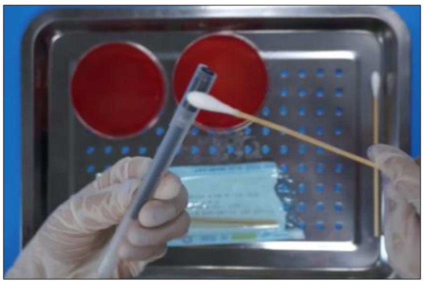


Fig. 20. Rubbing a pen to get the pathogens.

Step 4: The lid from a culture plate is removed, and then streaking the sterile cotton swab containing the bacteria at the top end of the agar plate moving in a zig-zag horizontal pattern until 1/3 of the plate is covered as shown in Fig. 21.

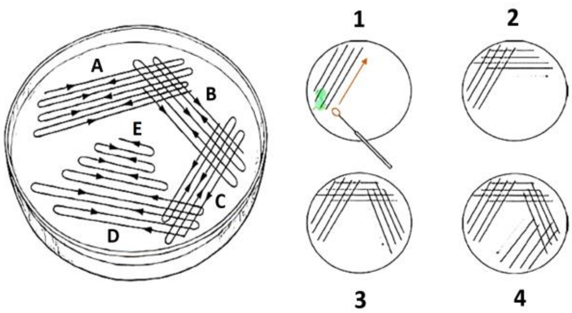


Fig. 21. Ways to perform zig-zag pattern on the plate.

Step 5: Change the sterile cotton swab with wood shaft to be a new one and rub a new area of pen. Do not allow the sterile cotton swab stick to touch the petri dish. Rotate the plate about 60 degrees and spread the bacteria from the end of the first streak into the second using the same motion in step 4.

(Changing the sterile cotton swab with wood shaft to be a new one is asked to perform every time when the new area of interest is swabbed.)

Step 6: Rotate the plate about 60 degrees and spread the bacteria from the end of the second streak into a new area in the same pattern. Do not dip the sterile cotton swab stick in the agar, let it glide gently over the surface with the same amount of force and speed.

(The streaking activity is kept repeating to the third and the fourth area in the same motion in step 4.)

Step 7: After swabbing the object's surface, streaks in a zig-zag pattern are done in a streak plate (i.e., sheep blood agar plate). Each agar plate needs to be uncovered and stayed in the room for a while after it was done with swabbing activity to inoculate the medium (Fig. 22).

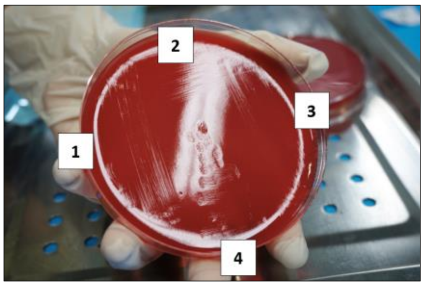


Fig. 22. After finishing four-streaking activity.

Step 8: Place the cover (lid) back on the plate immediately and secure with tape. Invert the plate and incubate overnight at 37 degrees Celsius (98.6 degrees Fahrenheit).

Step 9: Bring that referenced pen into UV sanitizer cabinet to get disinfection and prepare the second agar plate following the step 3 to 8 again to do the post - experiment of disinfected object from UV sanitizer cabinet.

Step 10: Repeat all steps for 5 times according to 1,3,5,15, and 30 minutes for disinfection period by applying UV sanitizer cabinet in step 9 with the same types but different object.

After preparing the agar plates, this step is called incubation phase which is the time when bacteria are growing. We place each agar plates inside a zip lock bag to prevent drying out and to control odors. Turn the plates upside down and put them in a warm place. The ideal temperature for incubation is 32°C or 90°F and bacterial growth should start visible in 1-2 hours. However, this step is under control of *Allied Health Sciences Laboratory* (Faculty of Allied Health Sciences, Thammasat University).

DOI:10.4186/ej.2023.27.4.1

Fig. 23. Experiment test after 3 minutes disinfection.

According to Fig. 23, shows the efficiency of 5 pens disinfection follow the disinfection time that before disinfection, there were >100% colony of pathogens, but after 3 minutes disinfection, the number of colonies decrease significantly to <5%. In Table 20 to 22 shows the efficiency of disinfection by using UVC lamp along with disinfection time 1,3,5,15, and 30 minutes respectively. We conduct the experiment by considering three small sizes of objects in range volume from 15 cm^3 to 35 cm^3.

Table 20. Disinfection time experiment of 5 pens.

Object	Disinfection time (Minutes)	No. of colony		Efficiency (%)
		Before	After	
Pen 1	1	>100	<10	>90
Pen 2	3	>100	<5	>95
Pen 3	5	>100	<2	>98
Pen 4	15	>100	0	100
Pen 5	30	>100	0	100

Table 21. Disinfection time experiment of 5 spoons.

Object	Disinfection time (Minutes)	No. of colony		Efficiency (%)
		Before	After	
Spoon 1	1	2	0	100
Spoon 2	3	3	0	100
Spoon 3	5	18	1	94.44
Spoon 4	15	16	0	100
Spoon 5	30	6	0	100

Table 22. Disinfection time experiment of 5 paper plates.

Object (Paper)	Disinfection time (Minutes)	No. of colony		Efficiency (%)
		Before	After	
Plate 1	1	1	0	100
Plate 2	3	3	0	100
Plate 3	6	6	0	100
Plate 4	15	2	0	100
Plate 5	30	2	0	100

7.2. UV Light Meter UVC-254SD

The application for the UVC light has been used to kill germs on surfaces, in the air and in the water, and UVC has been proven to kill up to 99.9% of germs. The technology used for checking the UV light is called "UV light meter". The UVC light meter is designed to measure ultraviolet light in the range from 220 to 275 nanometers [58]; normally, UVC has the range of 254 nm. (Table 23). The illumination range of the meter allows the users to conduct the most precise quantitative measurements of UV radiation. The UVC light meter is applied in many hospitals. The steps required to use UVC meter are very simple, and extra setting process or software is not necessary. When the meter finishes measuring data (execute datalogger), the users can take away the SD card easily and quickly from the meter. This SD card can be applied and plugged into the computer – uploading the measured data can be done shortly. The stored data (a set of time and value of UV found) can be transferred to Excel platform directly.

Table 23. Specification of UV light meter [58].

Specification	Value
Spectrum range	220-275 UVC
Illumination Range:	2 mW/cm^2 - 20 mW/cm^2
Accuracy	± (4 % FS + 2 dgt). FS : full scale
Memory Card	SD memory card 16GB
	Meter: 351 g.
Weight	UVC sensor: 103 g. Meter: 177*68*45 mm
	UVC probe: 38 mm DIA. * 25 mm

Fig. 24. UVC Light Meter (UVC-254SD) [58].

After checking the areas around UV sanitizer cabinet by UVC light meter, the results presented that there is no radiation emitted out through the box where 15-time testing activity was performed (Table 24).

Table 24. Result from UVC light meter testing.

No.	Date	Time	Value of UV found	Unit
1	20/10/2022	10:34:02	0	UVC mW/cm²
2		10:34:04	0	
3		10:34:05	0	
4		10:34:06	0	
5		10:34:07	0	
6		10:34:08	0	
7		10:34:09	0	
8		10:34:10	0	
9		10:34:11	0	
10		10:34:12	0	
11		10:34:13	0	
12		10:34:14	0	
13		10:34:15	0	
14		10:34:16	0	
15		10:34:17	0	

7.3. Experimental Results

The results consist of three main considerations: *efficiency of disinfection*, *efficiency of UV protective cabinet*, and *reliability of UV sanitizer system* (Mechanics and Electronics). According to the result of *Bacterial Culture Testing* shows the efficiency of disinfection that can disinfect the pathogens more than 95% within 3 minutes and 100% within 15 minutes.

Following with efficiency of UV protective cabinet, the polycarbonate sheet was decided to be applied as a UV protective cover or housing, which can protect UV 100%. The result 0 UVC mW/cm^2 demonstrates that, during disinfecting activity – the UVC lights are energized, there is no UVC radiation emitted out from the cabinet. Thus, this developed UV sanitizer cabinet is safe enough for the users to apply at home or workplace.

The UV sanitizer system (mechanics and electronics) is tested the reliability and failure rate by fixing the total mission time (200-hour mission). The UV sanitizer system is turned on continually and it is observed by the tester. After obtaining the value of failure rate of each equipment (at the end event of the diagram – Fig. 17), the reliability of each component can be calculated. The reliability of each component will be connected to the top event by "OR gate". The failure rate of each component is very satisfiable. The reliability of the top event (i.e., reliability of UV Sanitizer cabinet) is 99.47% - this is considered as high reliability – after fixing some failed items, the system can come back to its operational stage with as good as a new one or rebuild concept in maintenance viewpoint.

Therefore, this UV sanitizer system is reliable enough to be applied as supportive equipment to increase the quality of life with less human labor required. Besides, this can present the result of design stage of a building product in the way of "design for maintainability". This developed UV cabinet is constructed under the purposes of incorporating good maintainability considerations into building designs for achieving high building performance, easily supporting day-to-day performing tasks, making the building adaptable to future requirements, and maintaining a stable usage cost throughout the building's design life.

8. Conclusion and contribution

The proposed design allows users to disinfect gadgets in both manual and automatic modes without harmful UV leakage to the human body. This research of the UV sanitizer cabinet contributes to improving hygiene practices for better health and wellbeing. The key requirements obtained from customer viewpoints are the UV protective cover is required for blocking the UV ray emitted out to human body, and the functions can support the multipurpose disinfection of daily gadgets easily.

Design: UV sanitizer cabinet was constructed according to customer's requirement through material consideration and selection where PDD was applied to make the proposed model perfectly design. The compact size of the UV sanitizer can accommodate the customer to disinfect everyday stuff with an easy-to-access platform. The test result indicates that UV disinfection is very effective and has no leakage of UV radiation from polycarbonate cover material.

Accessibility: The UV sanitizer allows the users to easily understand the steps and set the time to the system within a few seconds in both manual and automatic mode. Since the objective of our project is related with health-product, we decide to give an alternative disinfection method through the compact size of UV-box which full of functions and easy accessibility to user. As the prototype has been created, we still have some factors that has to be concern such as, the smell of UV-C in the box, the additional design for 360 degrees covering all the disinfection area and also the mechanism of the Arduino system that we have to improve more.

Trend: This UV box can be an alternative method for effective disinfection the germs on daily gadget's surface such as utensils, hats, bags, keys, or even very useful for disinfect the hospital's equipment following to the shortage of hospital equipment in currently situation. This alternative method will give the satisfaction to the user because we improved on ideas about the compact size that reducing a lot of space for disinfection and developing our model to be more safety by implement the safety switch to cut off the light when the door opened to ensure the safety for users and develop the machine as one of the "Eco friendly products" that can make a huge difference on our environmental impact by reducing waste, energy, and chemicals.

Cost: Early phase of launching product to the market, the researchers have tried to do outsourcing for the production process with a small batch of products and send our sampling product to the local hospitals. The pricing strategy related with the demands in order to maximize the profit where "the reasonable price" is the key point needs to be set up at the initial stage before moving the production ramp-up stage. Currently, the cost of this developed in-house prototype was around 8,000 THB (~ 226 USD [59]). Since some components were purchased with small volume – 3-5 pieces per one component. The price-per-unit platform of this case is higher than purchasing as high volume, which uses price reductions to incentivize customers to purchase more than planned. Moreover, applying Economies of Scale (EOS) in the production planning can help reduce the production cost effectively. Therefore, unit cost is going to be less than 8,000 THB (~ 226 USD [59]) – it might be reduced by between 40–45% of this current amount, which can be a huge impact for setting up the price. We intend to set up the price to be more affordable for every household.

9. Discussion/Improvement

Cost improvement: This UV sanitizer cabinet was created using DIY parts, allowing for easy replacement and modifications. To further reduce production costs, multiple parts could be switched to cheaper components that perform the same function. For example, the Arduino could be replaced with a more basic custom circuit board since it has many unused functions.

Safety features: Germicidal lamps require proper care in terms of both physical handling and the light they emit. These lamps contain mercury, and if broken, can release mercury vapor. It is essential to contain the light produced by these lamps within the cabinet, as any escaped light can be harmful to human health. Additional safety features can improve the product and provide more information to the user for necessary maintenance. These features may include: a magnetic switch on the door that can instantly deactivate the germicidal lamp when the door is opened, a temperature sensor to ensure that the cabinet's temperature remains within set parameters, and a magnetic lock to keep the door securely closed. Time restrictions can be added to limit the maximum amount of time the cabinet can operate, while a cooldown period during runtime can help regulate temperature and prevent overheating during extended use. Current flow can be measured to determine whether the light is functioning as intended or has ceased to function. This information can be displayed to the customer in the form of an LED that can act as a "working" light.

Acknowledgement

The authors acknowledge resources and support from IE-Laboratory and workshop, School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, for the provided instruments, machining operation, and greatly assisted to finish this paper. Our team could not have undertaken this research without Asst. Prof. Dr. Kamphon Intharanut from Graduate Program in Biomedical Sciences, Faculty of Allied Health Sciences, Thammasat University, to support the *Bacterial Culture Test* for checking the performance of the developed design of UV sanitizer cabinet.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

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