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Automation of Large-Scale Gaseous Ozonation: A Case Study of Textile and PPE Decontamination

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Abstract: There is an ever-growing need in several industries to disinfect or sanitise products (i.e., to reduce or eliminate pathogenic microorganisms from their surfaces). Gaseous ozone has been widely applied for this purpose, particularly during the era of the COVID-19 pandemic. However, the large-scale deployment of this technology usually involves a manually-operated chamber, into which articles are loaded and subsequently unloaded after treatment—a batch process. Although the development of large-scale, automated and continuous ozonation equipment has hardly been reported in the literature, this has tremendous potential for industries seeking to decontaminate certain articles/products in a rapid and effective manner. In this paper, an overview of the design and implementation considerations for such an undertaking is evaluated. By presenting a case study for a developed automated system for clothing and personal protective equipment (PPE) disinfection, we provide key data regarding the automation procedure/design's considerations, risks, material compatibility, safety, sustainability and process economics. Our analysis shows that the transfer time for garments between successive chambers and the agility of the sliding doors are crucial to achieving the desired throughput. The automated system is capable of effectively treating (20 ppm ozone for 4 mins) 20,000 garments within an 8-hour shift, based on a transfer time of 2 mins and a sliding door speed of 0.4 m/s. The flexibility of the system allows for variation in the concentration or exposure time, depending on the contamination level and the consequent decontamination efficiency desired. This flexibility significantly limits the degradation of the material during treatment. A return on investment of 47% is estimated for this novel system.

Keywords: ozone decontamination; automation; throughput enhancement; textiles; PPE

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1. Introduction

The versatile applications of ozone (O_3) in various forms (aqueous, gaseous and mist/fog) have been largely recognised and relied upon in several industries. It has been applied for the removal of a variety of organic and inorganic pollutants (including pharmaceuticals and dyes) in drinking water and wastewater [1], for food preservation [2], to improve fish health in recirculating aquacultural systems [3], in animal husbandry [4], for bleaching in the pulp and paper and textile industries [5,6], to decontaminate reusable medical devices/instruments [7], to decontaminate personal protective equipment (PPE, e.g. face masks) [8], to disinfect several surfaces in different pathogen-laden environments [9] and, more recently, as a therapeutic agent for the SARS-CoV-2 virus (the virus responsible for the COVID-19 pandemic) [10]. The chemical and physical properties of ozone are well documented in many of the published literature [11,12] (Figure 1). However, its molecular instability (spontaneous decomposition to oxygen) makes it eco-friendly, particularly during gaseous application (where the probability of forming harmful disinfection by-products is low).

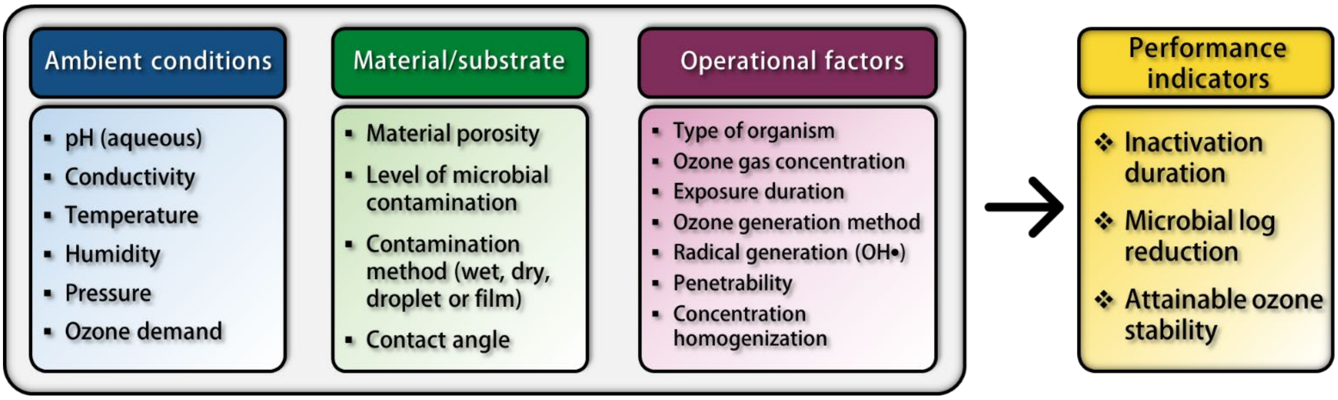

Figure 1. Factors affecting the efficacy of ozone decontamination processes; adapted from [11].

Different mechanisms, including cellular lysis during direct and indirect oxidation (via $OH^{\bullet}$ radicals) and subsequent intracellular damage, have been proposed for ozone's inactivation of various microbes (including bacteria, fungi and viruses) [13,14]. These tend to be affected by a variety of ambient, substrate and operational conditions, as shown in Figure 1. These antimicrobial properties of ozone are potent, irrespective of the form in which the ozone is applied. Nonetheless, depending on the specific application, the deployment of gaseous ozone may be more beneficial compared to aqueous ozone [15–17]. Besides the enhanced microbial benefits for selected organisms highlighted in [15], key operational factors, such as increased penetrability of gaseous ozone, higher attainable concentrations, efficient homogenisation of ozone concentration and removal of the additional complexity of drying the disinfected article if submerged in aqueous ozone, make gaseous ozonation more attractive. In the processing of used garments, for example (at industrial scale), where repeated laundry of unsoiled but contaminated clothing may lead to degradative effects from the consequent mechanical action, the application of gaseous ozone decontamination instead may enhance garment longevity. Besides garment longevity, gaseous ozonation for decontamination and deodorisation translates to significantly reduced water and detergent usage compared to the application of conventional high-temperature laundry procedures. For such large-scale applications, the speed and effectiveness of gaseous ozone treatment are crucial to ensuring the economic viability of the process.

The attainment of this large-scale efficiency is largely dependent on the ozone concentration '***c***' and exposure duration '***t***', the product of which is referred to as the ozone dosage or '***ct***' value. Most ozone decontaminating equipment at both the lab and industrial scales often rely on the manual loading of the items into an ozone chamber, commencing the ozone treatment process (involving the ozone's generation, stabilisation and decomposition phases [13,18]) and subsequently unloading the chamber upon completing the treatment cycle. However, during large-scale operations involving thousands of items, the loading and unloading process can be time-consuming and reduce the overall throughput of the ozone facility. As an example, Advanced Clothing Solutions (ACS—a sustainable clothing processing company in Scotland, UK) utilises an ozone chamber for the disinfection of clothing items, in order to enable their reuse. Between 2 and 3 workers spend 3 h loading and unloading up to 6000 items of clothing (2000 garments/cycle) into and from the chamber in a typical 8-hour shift, and this excludes the ozone treatment/exposure duration. A typical treatment cycle involves ozone exposures between 2 and 4 ppm for up to 1.5 h for effective decontamination. Since higher ozone concentrations for shorter durations are likely to yield a similar disinfection efficacy as lower concentrations for longer exposure durations (so far, the '***ct***' values are the same) [19], it became crucial to develop an automated system capable of reducing this 2.5-hour/cycle duration while increasing the throughput significantly.

Very few research papers in the literature have given attention to the subject of automating ozone processes, particularly at a large scale. Maurya et al. [20] developed an autonomous disinfection tunnel that helped tackle external surface disinfection in public spaces during the peak of the COVID-19 pandemic in India. Oliveira et al. [21] developed an instant decontamination device by means of an ozonated water spray chamber. The effectiveness of the chamber was verified using important pathogens on several PPEs. Recently, Mascarenhas et al. [22] extensively reviewed the technological advances in gaseous ozone and ozonised water spray devices, and realised up to 620 patent documents detailing these developments—a significant number of which have been filed in the Republic of Korea. Figure 2 highlights the geographical distribution of patent applications related to gaseous and aqueous ozone disinfection devices, as indicated in their study [22]. The interested reader may also refer to the following recent patents [23,24] on large-scale ozone disinfection of different articles. The designs in these patents tend to be adaptable to a batch mode of operation, unlike that presented herein, which is suitable for continuous operation. Furthermore, no analysis of the throughput has been presented to enable comparability. Despite these advancements, further developments of continuous ozone disinfection equipment are crucial to reducing the spread of pathogens in the environment while satisfying the constraints of high throughput and economic viability.

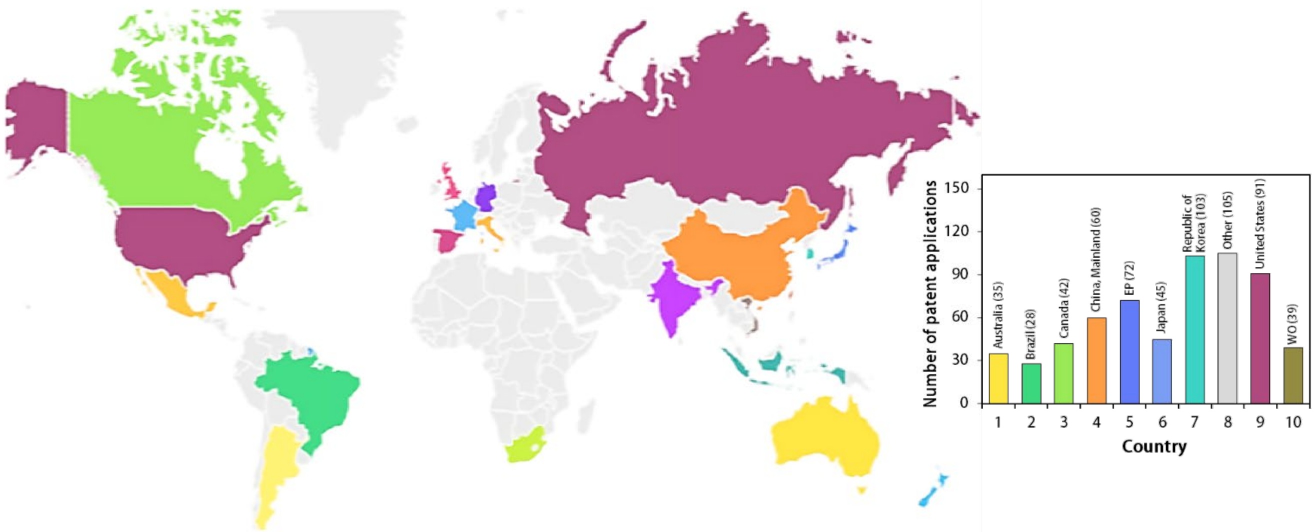

Figure 2. Global patent applications for gaseous or aqueous disinfection devices/chambers (European Patent Office—EP and World Intellectual Property Organisation—WO); adapted from [22].

In this paper, we present an in-depth assessment of the design and implementation considerations for automating large-scale gaseous ozonation processes. By analysing a case study for a developed automated system for clothing and personal protective equipment (PPE) disinfection, we provide key data regarding the throughput and economics of the process. It is expected that the presented study and the contained data will be relevant to researchers and industry professionals wishing to further develop and employ an automated procedure for large-scale decontamination of different articles using ozone technology. The described method is also adaptable to other sterilants, such as hydrogen peroxide and peracetic acid, which can be used in gaseous form or via non-wetting mists.

2. A Case Study of Textile and PPE Decontamination

In this section, a case study based on the efforts of ACS to transform their manually-operated ozone chamber to a fully automated one is presented. Factors such as material compatibility, efficient circulation and extraction, measurement and control, scalability, sustainability and process economics are discussed.

2.1. Ozone Generation, Control, Ultraviolet Radiation-C (Uvc) and Humidification

Ozone generators are a crucial component of ozone disinfecting systems. The generation of ozone may be carried out using ultraviolet radiation or dielectric barrier/corona discharge—the latter being more energy-efficient and better suited for large-scale applications. However, corona discharge may further produce considerable amounts of NOx, which could increase the maintenance cost [25]. Both generation methods typically involve the splitting of oxygen molecules, either in the air or in an oxygen-filled environment, into individual atoms. These atoms then react with other oxygen molecules to form ozone. The use of medical grade (high-purity) oxygen as the feed gas can produce an ozone yield up to four times higher, than when ordinary air is used [12]. However, the ozone yield also depends on the flowrate of the oxygen feed, and there is usually a critical point beyond which the increase the oxygen flow rate causes a reduction in the ozone yield [26]. Since ozone is an unstable gas that cannot be stored for long periods, it must be generated on demand. Thus, the use of controllers working in conjunction with the ozone generators is crucial for the maintenance of the desired ozone concentration. The time required to attain a desired ozone concentration is a function of the chamber volume, generation capacity and rate of ozone decomposition in the chamber. This decomposition rate is usually a function of the ozone-depleting matter in the environment. Equation (1) represents the mathematical relationship between these parameters affecting ozone generation rates.

$$t_{min} = 117.9 \times F \times \frac{C_{ppm} \times V_{m^3}}{R_{mg/hr}} \quad (1)$$

Where t_{min} represents the time required to run an ozone generator to give the target concentration (min); ***111.79:*** conversion factor from mg/m^3 to ppm and h to minutes; C_{ppm}**:** ozone concentration (ppm); V_{m^3}**:** chamber volume (m^3); $R_{mg/hr}$**:** ozone production rate from the generator (mg/hr); ***F:*** multiplication factor that depends on the set-up; for an airtight chamber, with 0 start-up time and non-reactive walls, $F = 1$ [27]. It is also worth pointing out that the gaseous ozone concentration may be reported in ppm or mg/m^3; the following equation (Equation (2)) can be used to convert gaseous ozone concentration from mg/m^3 to ppm; for aqueous ozone, ($C_{ppm} = C_{mg/m^3}$):

$$C_{ppm} = \frac{24.45 \times C_{mg/m^3}}{M_{O_3}} \quad (2)$$

where C_{ppm} is the ozone gas concentration in ppm; C_{mg/m^3}**:** ozone gas concentration (mg/m^3); M_{O_3}**:** the molecular weight of ozone; ***24.45****:* volume of a mole of ozone gas at 1 atm and 25 °C. Furthermore, it is often the case that manufacturers of ozone generators report the generation capacity based on a pure feed of oxygen. If air (~21% O_2) is utilised instead, it is expected that the ozone yield will be reduced by approximately four times. In the ACS automated system (Figure 1), eight 40 g/h ozone generators are utilised (although not fully shown in Figure 1); thus, for a chamber of ~99 m^3, and assuming F = 1, approximately 9 min of ozone generation time is required to attain a concentration of 20 ppm. This value of 20 ppm, coupled with a 4 min exposure duration, has been determined via the experiments detailed in [13,14]. The interested reader may also refer to the work of Souza et al. [9], in which the generation rates for a similar large-scale ozone generator are reported. It was important to ascertain that the effectiveness of the lab-scale treatment conditions could be replicated on an industrial scale. This was verified, and was in agreement with the findings of Zoutman et al. [28], who pursued a similar validation exercise.

To automate the disinfection process, it is important that the ozone chamber be maintained at the desired concentration continuously, so that contaminated articles are brought into a well-controlled ambience of ozone and microbial inactivation effectively occurs. As earlier mentioned, this desired concentration will usually depend on the experimentally-validated ozone levels required to achieve the desired microbial reduction efficiencies. Conversely, in manually-operated ozone systems, ozone must be generated from scratch, allowed to interact with the article and be fully decomposed back into oxygen before the chamber can be accessed for the unloading of the articles. The throughput of such a manual process depends on the size of the chamber and the number of processible articles (e.g., clothing/PPE items) in a single batch, whereas a smaller-sized automated chamber may provide a higher throughput. In the case of ACS, a manually-operated chamber described earlier could house up to 2000 garments at any given time—corresponding to an ozone disinfection capacity of ~6000 garments within an 8-hour shift. However, the developed automated system, as will be subsequently described, only accommodates 250 garments in any given batch, but possesses a disinfection capacity of 20,000 garments within the same timeframe (> 3.3 times the throughput of the manual system). Figure 3 represents a fully-annotated representation of a variation of the developed automated solution for ACS. It consists of three interconnected chambers (or, optionally, a chamber divided into three regions)—a waiting chamber (1), the main ozonation chamber (2) and the ozone decomposition chamber (3), in which the escaped ozone from Chamber 2 is converted to oxygen.

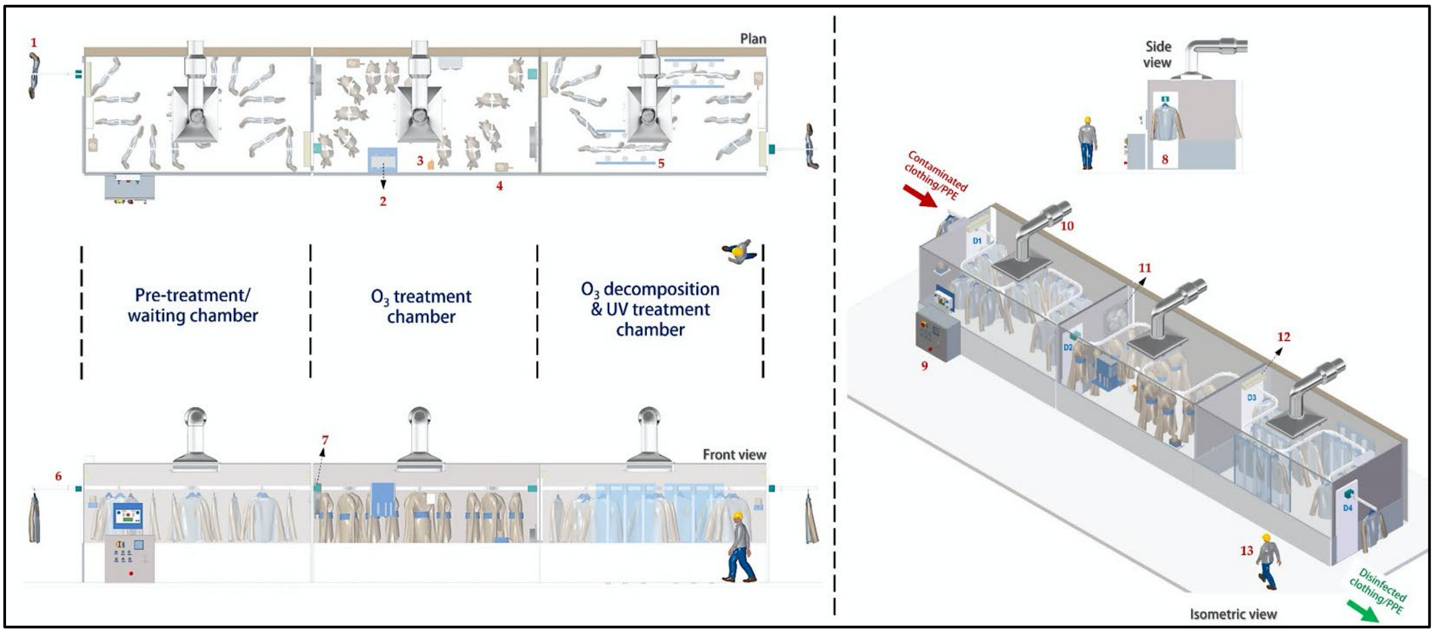

Figure 3. Automated ozone process for clothing and PPE disinfection showing the components of the system: (1) item of clothing or PPE; (2) ozone generator; (3) humidifier—dry fogger; (4) ozone sensor; (5) UVC tunnel; (6) conveyor; (7) transition system; (8) sliding door; (9) control panel; (10) extraction fan; (11) circulation fan; (12) air curtain (13) worker. Although not represented, UVC exposure may occur in the waiting chamber (1) before actual ozone treatment.

This configuration allows for the entry of a new batch of garments while the previous batch is still undergoing treatment. The pin and clip conveyor systems eliminate the need for manual handling (loading and unloading of the garments) during their movement into and out of the ozone facility. The conveyors are equipped with a transition system that facilitates the movement of garments between the doors, connecting the chambers. These transition systems are in the form of rotary clamp cylinders, which are both actuator-controlled and gravity-induced. Thus, the conveyors do not need to pass through the entry points, and allowing the sliding doors to shut hermetically. The use of air curtains mitigates the escape of ozone gas from Chamber 2 into Chambers 1 and 3 when doors D2 or D3 are opened. The arrangement of the ozone generators and the circulation system is such that there is a steep gradient between the ozone concentrations in the central region of Chamber 2 and the concentration towards doors D2 and D3. Thus, the escape of ozone gas into Chambers 1 and 3 is severely limited, allowing for rapid decomposition to oxygen before doors D1 and D4 are opened. As ozone inhalation causes severe irritation of the respiratory tract and lung damage via oxidation, it is important to prevent worker exposure; the Occupational Safety and Health Administration (OSHA) recommends a worker exposure limit of 0.1 ppm over an 8-hour shift. Hence, while ozone sensors in the main ozonation chamber (2) are capable of measuring up to 100 ppm of ozone with a detection limit of 0.1 ppm, the sensors closer to the exterior points of the unit have a lower detection limit (0.01 ppm), and are only capably of measuring up to 10 ppm. These sensors communicate with the control and trip-off alarm systems to notify the operator of any deviations.

The automated unit is equipped with a UVC tunnel and is shown to be situated in the ozone decomposition chamber (Figure 3). However, it is worth pointing out that the UVC treatment can occur pre- or post-ozone treatment. The direction of garment flow (Chamber 1 → Chamber 2 → Chamber 3) implies that there is an accompanying current of ozone gas which is carried with the garments from the middle chamber to the post-treatment chamber. Thus, the escaped ozone concentration in this post-treatment chamber will be higher than that in the pre-treatment chamber. Since UVC facilitates the conversion of ozone to oxygen [29], the action of the extraction fans in the post-treatment chamber will be facilitated by UVC radiation, leading to rapid ozone conversion in this chamber. This is the rationale for the UVC lamps being in the post-treatment chamber. Nevertheless, the advantage of UVC in the pre-treatment chamber is the following: should the cycle time be increased from 4 mins to, for example, 10 mins (the system allows for this flexibility), it means the *WAITING and UVC Exposure* period for the garments in the pre-treatment chamber will be longer than the 110 s shown in the process schedule (Figure 4). If the UVC treatment is situated in this pre-treatment section, the garments will receive better UVC bombardment. This contributes to the attainable disinfection efficiency and is the rationale for using UVC as a pre-treatment step. Since the efficacy of UVC treatment is dependent on the distance of the light source from the garments, they may be reoriented by the conveyor (Figure 1) so that either side of the garment receives adequate UVC bombardment at the desired intensity.

It is important to mention that the potential for fading and discolouration increase with UVC bombardment. According to a survey by Cooper and Claxton [30], this is a more challenging issue for jersey fabrics compared to woven garments and knitwear. UV exposure destroys colour through an oxidation process which causes the decomposition of dye molecules in the fibres [31]. UVA rays have considerable penetration power compared to UVB and UVC and are more likely to cause colour fading [32]. Moreover, the disinfection capabilities of UVA and UVB rays are significantly lower than that of UVC [33,34]. The use of UVC finds additional relevance through the fact that the described technology (Figure 3) is suitable to medical gowns and other textile-based personal protective equipment where decontamination is the primary requirement. Fading may also be caused by ozone exposure—a process known as ozone fading. Disperse and direct dyes are predominantly vulnerable to ozone fading, and according to Padhye and Nayak [35], red and blue dyes are the most affected colours. Additionally, the bleaching effects of ozone are particularly noticeable in acetate, cotton and nylon fabrics [35]. In light of these factors, adequate control and proper selection of the disinfection program (in terms of the administered UVC dosage (J/m^2) and ozone dosage (ppm.min)) are required to ensure acceptable treatment efficiency and to prolong the life of the garments or equipment.

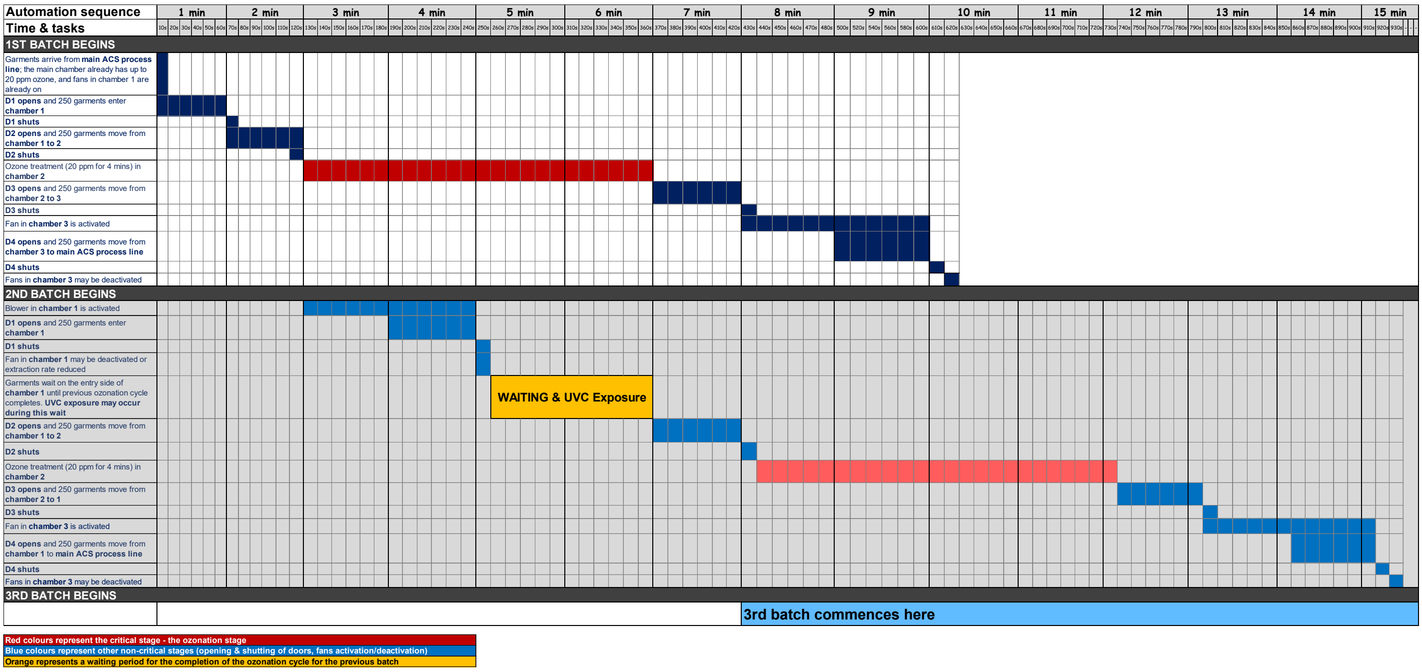

Figure 4. Process sequence of the automated ozonation system.

Considering the half-life of ozone in air, which may be as high as 43 mins [14], not all ozone generators necessarily have to be operated continuously over the entire working duration (an 8-hour shift for example) in order to maintain the ambient ozone concentration of 20 ppm. Thus, an optimal control system that conserves the energy requirement of the generators is crucial and has been implemented. Furthermore, the need to control the output of the ozone generators is not only a consequence of the auto-decomposition property of ozone, but also of the fact that when either of the doors in Chamber 2 (D2 or D3) is opened, the escape of ozone gas into Chambers 1 and 3 is somewhat inevitable, despite the action of the air curtains. This is mainly a result of the air currents generated by the moving garments during their transfers between the chambers.

The automated system is also equipped with a dry fogging humidification system, with accompanying temperature and humidity control functionality. Several studies have highlighted that an increase in the ambient humidity enhances the inactivation efficiency of ozone gas. This is because humidification induces spore swelling as well as the increased formation of OH• radicals [36]. These radicals have a higher oxidation potential (2.80 V) compared to ozone itself (2.07 V) [11,37]. The resultant effect is the rupture of the cells and the rapid diffusion of ozone and OH• radicals into the cells for further damage. Under dry conditions, the formation of OH• radicals is limited, and direct oxidation by ozone is the prevalent inactivation route [15]. This fogging unit utilises purified water and compressed air for the generation of non-wetting mists in Chamber 2. While an increase in the ambient temperature also enhances ozone's reactivity, it is often desirable to carry out ozone treatment under low temperatures [18], as this enhances ozone stability and reduces the need for continuous ozone generation. Thus, the main ozonation chamber (2) is maintained at a temperature range of 10 – 15 °C. Besides the disadvantage of poor ozone stability at high temperatures, there have also been reports of ozone sensor malfunctions at high temperatures during the summer (when operating ACS's manual ozonation chamber). This further substantiates the need for low-temperature operation.

2.2. Analysis of Throughput

With the process sequence (Gantt chart) shown in Figure 4, it is possible to determine the attainable throughput of the system within an 8-hour shift. Furthermore, in combination with the Gantt chart, the impact of certain critical steps on the throughput can be evaluated via discrete event simulation tools (e.g. Anylogic, Flexim or Tecnomatix Plant Simulation) (Figures 5 and 6). This is one of the key benefits of describing the process sequence using a Gantt chart rather than a flow chart, as shown in Figure 5a. The main constraints to achieving the shortest possible cycle time in the automated system include: the ozonation duration, the response time of the sliding doors, the possibility of emptying Chamber 2 while filling it up, the speed of the conveyors, the consequent transfer time for a batch of up to 250 garments between consecutive chambers and the rapid decomposition of the residual ozone in Chambers 1 and 3 in less than 4 mins (most of these crucial steps are highlighted in red in Figure 5a).

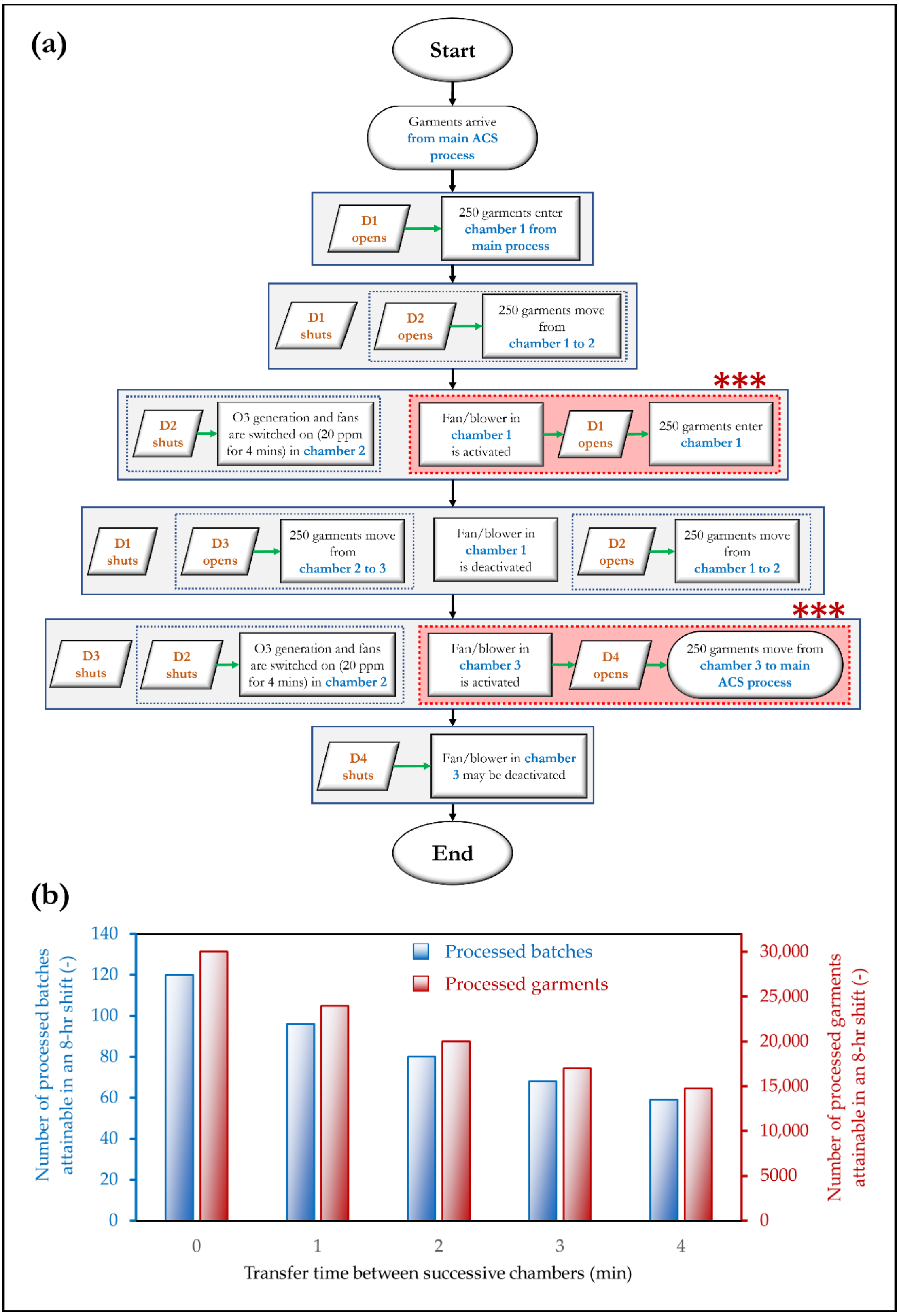

Figure 5. (a) Flowchart of the process sequence, with critical stages highlighted in red, and with an asterisk; (b) impact of garment transfer time on the throughput of the automated ozone decontamination system; '0' represents an instantaneous transfer of the garments; although this is not possible in practice, it is useful for troubleshooting discrete event simulations of the process.

While the impact of these parameters will be presented in detail as a separate study (a sequel to this publication), Figure 5b outlines the resultant impact of the garment transfer time on the number of processed batches and the corresponding total garments processed. It can be observed that the increase in the transfer time lowers the attainable throughput of the system. This analysis can be used to make decisions regarding the optimal conveyor speed and associated costs, as constrained by the throughput. The conveyors utilised in this automated ozone system are capable of achieving a transfer time of 2 min over the conveyor length utilised (corresponding to a throughput of 20,000 garments in an 8-hour shift). Garments are also adequately spaced to ensure good air flow and ozone penetration into all regions for effective decontamination. A key advantage of the automated system is the flexibility of choosing the desired '***ct***' value and how that would be implemented (i.e. high '***c***' and low '***t***', or low '***c***' and high '***t***'). Thus, process bottlenecks may be readily eliminated, particularly if the workstation after the ozone unit (in our case, the garment bagging machine) is unable to meet up with the high throughput of the automated disinfection system. The contact time can thus be increased (i.e. the throughput reduced to match that of the subsequent station) so far the minimum ozone dosage is met. Additionally, longer ozone exposure times (> 4 min) are typically required when the deodourisation of the garments is also a key requirement (used garments usually have odours, not only from body fluids but also from deodorants and sprays, which have to be eliminated before they are rented again).

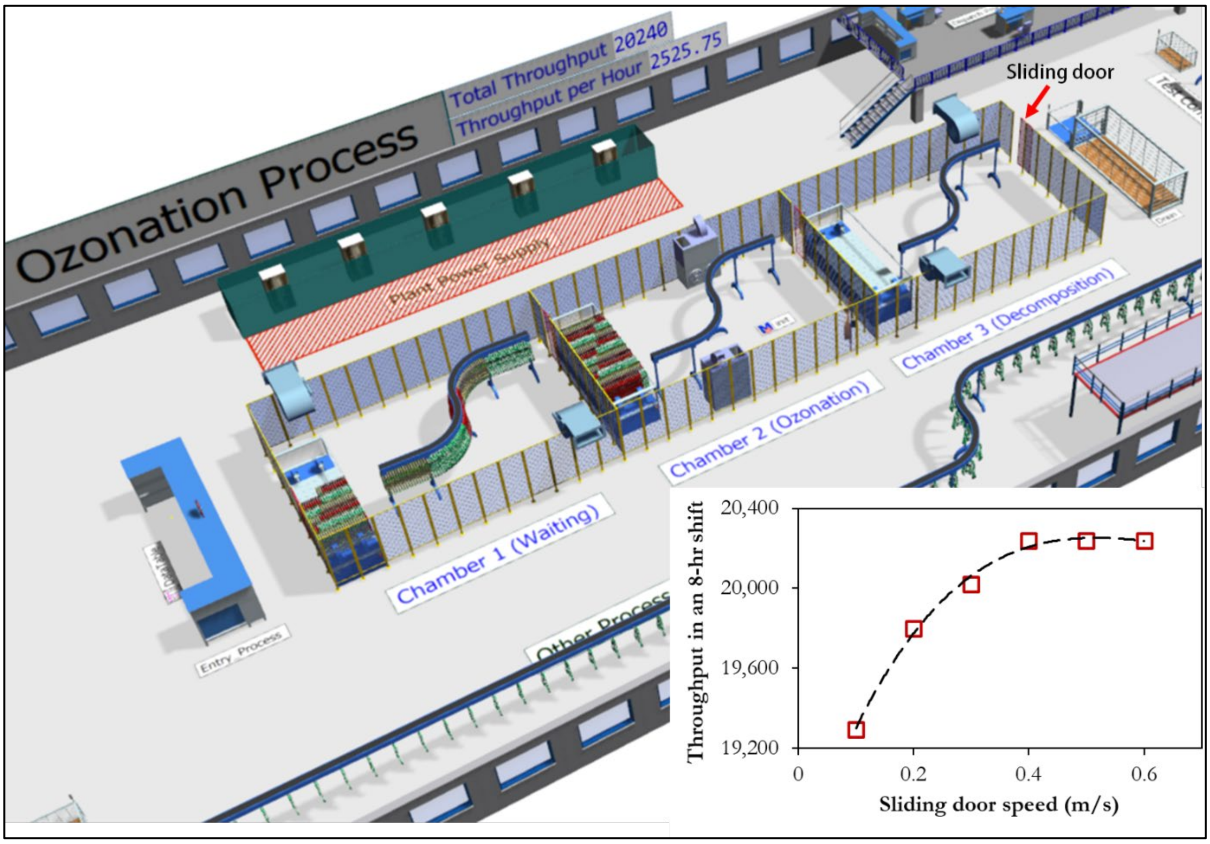

Figure 6. Discrete event simulation of the automated system, showing the impact of the sliding door's speed on the throughput.

Figure 6 illustrates the impact of the sliding door response on the attainable throughput in an 8-hour shift. Since this speed affects the transfer time of the garments between the respective chambers, the throughput can be observed to increase with the speed of the doors. Beyond a speed of 0.4 m/s, the simulation shows no additional benefit to the throughput. This crucial insight has been applied to select the approprate actuator system (with the required response times) for the automatic doors in the automated ozone unit (Figure 3).

2.3. Ozone Circulation and Decomposition

Crucial aspects of the automated system are the circulation (typically axial) and extraction (typically centrifugal) fans. As most ozone generators are already equipped with a fan for the dispersion of ozone, the use of additional circulation fans operating at a controlled rate facilitates the homogenisation of ozone concentration in the central region of Chamber 2. This is particularly important since the chamber has several obstructions (garments, conveyors, generators and other fittings) which are likely to interfere with the gas circulation. The application of computational fluid dynamics (CFD) can be utilised to identify zones of poor mixing, thus facilitating the optimal positioning of the axial fans and ozone generators. The following studies report on the application of CFD for this purpose using a variety of CFD models [9,38–40].

Of particular importance to this automated system was the selection of the ozone extraction (Figure 7a) and decomposition system, intended to ensure the full decomposition of escaped ozone in Chambers 1 and 3 before doors D2 and D4 are opened. It was estimated that the escaped ozone from Chamber 2 was unlikely to yield an average concentration > 2 ppm in Chambers 1 and 3. However, the extraction systems were designed, with the aid of a lab-based system (Figure 7b) and CFD (Figure 7c), to rapidly decompose up to 2.5 ppm of ozone in less than 4 min. For this purpose, a specialised catalyst (Carulite) was utilised; Carulite ($CuMnO_3$) is typically composed of Manganese dioxide (MnO_2) and copper oxide (CuO), and it possesses excellent reactive properties for ozone conversion to oxygen. The Carulite 200 catalyst (Oxidation Technologies LLC) is not considered hazardous waste and can be disposed of in landfills approved to accept chemical waste; so far, it is not contaminated with hazardous substances [41]. Activated carbon is an alternative catalyst that is also widely applied for ozone decomposition [42]. It is often required that the catalyst be replaced annually due to contamination that occurs over prolonged usage; this contamination limits its conversion efficiency. The review on ozone decomposition by Batakliev et al. provides an extensive discussion of alternative catalysts which may be utilised for this purpose [43].

Besides attaching a catalyst bed to the outlet section of the extraction fan (Figure 7a), an alternative configuration is to repeatedly pass the gas through the catalyst bed is illustrated in the work of Epelle et al. [14]; this is particularly important as the conversion efficiency may be dependent on the number of passes employed. However, this efficiency will also be affected by key parameters such as the pore size and permeability of the bed, packing length and diameter, flowrate through the bed, friction factor, gas density and viscosity and the pressure drop. These factors have been considered to ensure adequate sizing of the ventilation systems. The fans may be operated at a controlled rate via inverters to guarantee adequate ozone decomposition. It is worth mentioning that the extraction fan in Chamber 2 is mainly utilised for emergency ozone removal from the system; it is hardly employed, since the desired 20 ppm concentration is required to be maintained continuously during the unit's operation. It may be utilised to fully decompose ozone in Chamber 2 before the unit is powered down.

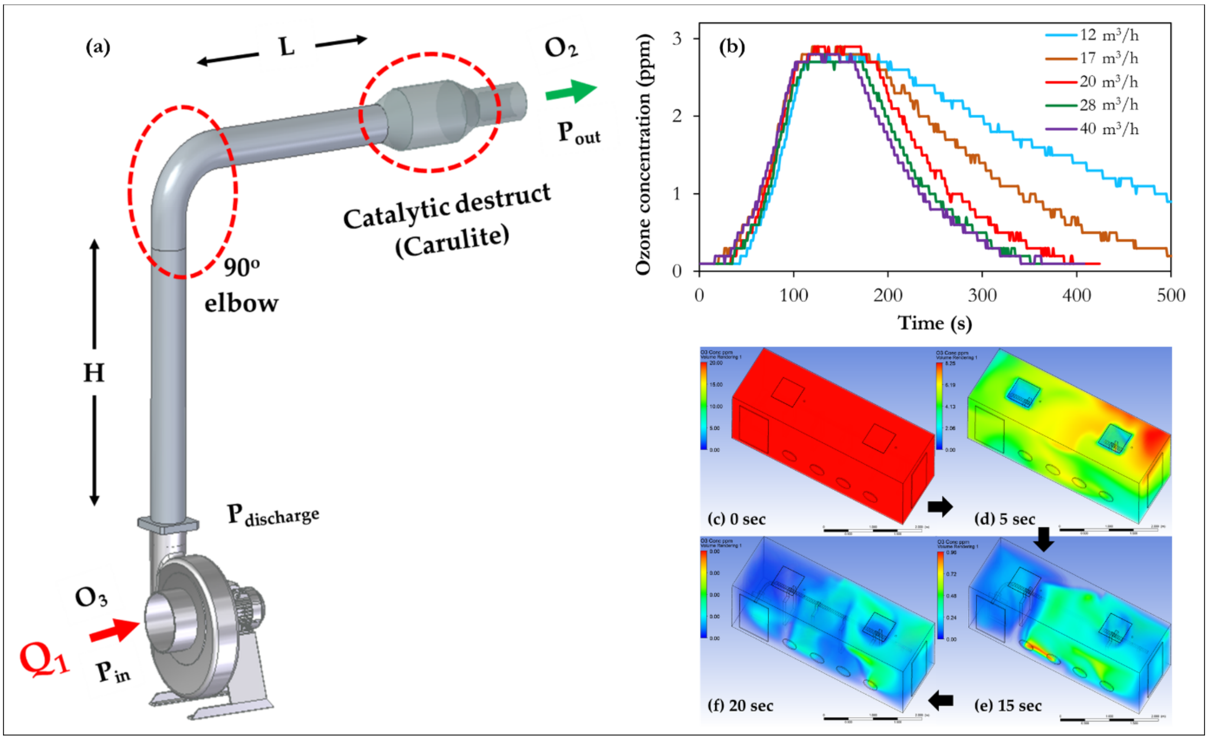

Figure 7. (a) Typical centrifugal fan system utilised for ozone gas removal; (b) analysis of ozone generation, stabilisation and decomposition using a lab-scale fan system [29]; application of CFD to analyse the removal rate of ozone gas in a chamber originally at 20 ppm.

2.4. Operational Risks

There are several risks attributable to different sections of the automated unit, as outlined in Table 1; mitigation strategies adopted to ensure the robustness of the proposed design are also included in this Table. Material compatibility is a key factor affecting the efficient operation of the system. The oxidative action of ozone is not selective to microorganisms alone; thus, inorganic and organic materials in the environment will also be affected. The use of inexpensive ozone-resistant polymers, cladding and metals in the unit was ensured. Wooden frames were also utilised as cheap and resistant materials for certain fittings in the system (e.g., the UVC lamp frames). A comprehensive ozone resistance chart can be found in [44,45].

Table 1. Risks to implementation.

Risk	Affected area of the automated system	Potential solution
Garment entanglement and drop/fall off	All areas (particularly transitions and bends)	Robust and stable hangers for conveyors; manual intervention assisted by real-time virtual monitoring and alarm systems
Jerky motion arising from start/stop motion or change in speed of the conveyor.	Conveyor bends and transitions	Robust configuration of variable speed drives
Failure of hydraulic- or actuator-induced transition.	Transitions	Gravity-based transition systems may be utilised
Materials degradation	All areas	Selection of only ozone-resistant materials
Poor performance of air curtains due to high density of ozone gas, leading to an excessive escape of ozone	Main ozonation chamber (Chamber 2)	Usage of laminar flow and high output curtains, with well-arranged baffles to minimize interference.

Difficulty attaining desired ozone concentration in a reasonable time	Chamber 2	Install additional high-output ozone generators; use O_2 gas as a precursor
Chamber pressurisation or explosion risks associated with the use of pure oxygen feed for ozone generation	Chamber 2	The use of ordinary air as a precursor is a safer alternative—although with lower ozone yields. Installation of pressure relief systems may also be pursued
Fading, discolouration and embrittlement of textile fibers due to very high ozone and UV doses	Chamber 2	Implement robust control after lab-based verification
Inefficient ozone gas decomposition/removal	Chambers 1-3	Optimise fan location and sizing
Bacteria buildup due to stagnant water in pipework for the humidification system	Humidifier	Implement a routine flush cycle in the system
Condensation due to the action of the humidifier and the consequent damaging effect on internal electrical components	Chamber 2	Employ only dry fogging systems, with adequate temperature control to ensure rapid evaporation

Additionally, the compatibility of the clothing's material (usually made of natural or synthetic materials) is also crucial to consider when applying ozone and UV treatment. Synthetic polymers, a key fibre component in most garments, tend to possess good ozone resistance. In the decontamination of facemasks, it was reported that gaseous ozone concentrations as high as 500 ppm had no degradative effects on the filtration efficiency of N95 filters [46]. Nonetheless, as reported by Epelle et al. [11], repeated ozonation over several cycles may induce some structural defects in fabric fibres composed of 35% cotton and 65% polyester (Figure 8e-f). Sørensen et al. [47] analysed the degradative effects of UV exposure on natural (wool) and synthetic (polyamide, PA and polyester, PET) fibres. Their experiments showed that PA mainly exhibited surface morphology changes, with little fragmentation, whereas PET and wool fibres showed changes in both surface morphology and fragmentation (Figure 8a). Maqsood et al. [48] reported on the oxidative effects of jute fibres after ozonation (Figure 8b-d). Their results showed that the tensile properties of the fibre gradually weaken as treatment time increases, with corresponding alterations to the surface functional groups and crystallinity. The lightness value also changed from a brownish shade to a lighter colour as a result of the treatment. It should be pointed out that the treatment doses employed in the automated system do not degrade the materials tested. Nonetheless, where a large group of items are to be decontaminated by ozone, and it is ascertained that certain items susceptible to degradation at high ozone concentrations (e.g., silk-, PA- or wool-based clothing) are present, a systematic grouping based on their oxidative tolerance is crucial. When this grouping is cumbersome, milder treatment conditions may be utilised to produce the same decontamination efficiency. Despite this degradation potential, it is also important to briefly highlight the beneficial effects of ozone as a feasible pre-treatment method for improving the dyeing efficiency (Figure 8-f) of polyester fabrics, as documented in the work of Gabarado et al. [49]. This is a further indication that adequate control is key to gaining the benefits of this technology.

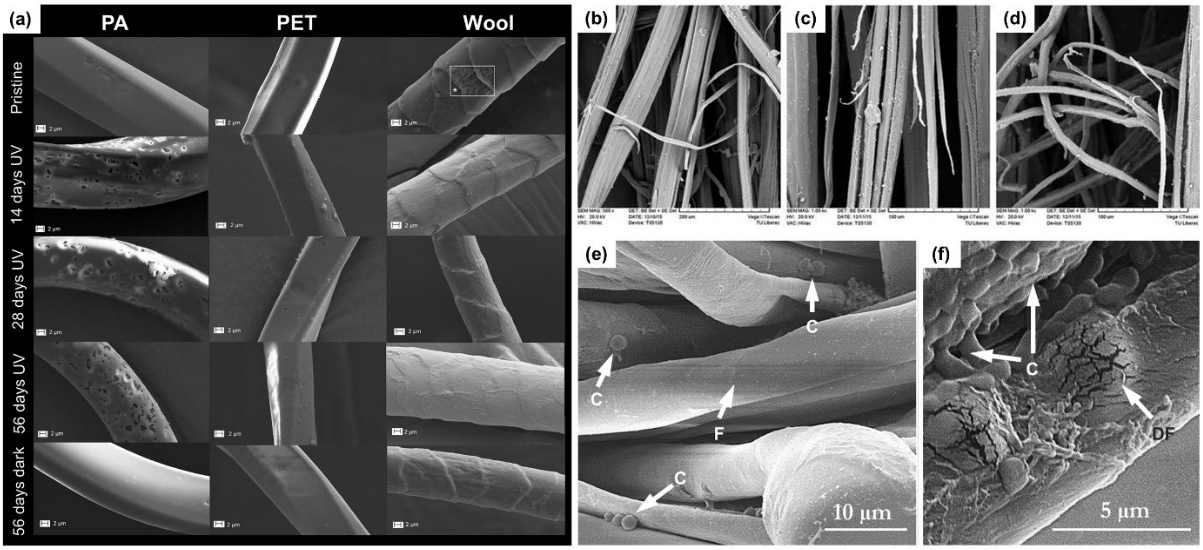

Figure 8. (a) SEM images illustrating the impact of UV exposure for 14, 28 and 56 days on polyamide (PA), polyester (PET) and wool fibres, relative to pristine and dark controls; the marked area on the pristine wool sample reflects SEM damage at 10kV and does not represent degradation [47]. (b) SEM images of untreated jute fibre (c), ozone-treated jute fibres for 4 h [48] and (d) ozone-treated jute fibres for 5 h [48]. (e) SEM images of cotton–polyester fibres (F) showing cells (C) of *C. albicans*, repeatedly exposed to 100 ppm.min (Figure 8e) and (f) 160 ppm.min of gaseous ozone. Cells of *E. coli* are shown; up 10 previous treatment cycles had been performed before this image was taken [11].

The use of oxygen as the feed gas creates an oxygen-rich environment inside the treatment room and along the circulation path of the fans. This is particularly undesirable as there are safety implications for the fans and other electrical equipment in the chamber (risk of explosion). If oxygen must be used (e.g., for increased ozone yield), it will need to be supplied via a duct from an oxygen tank/concentrator located outside the unit. An extract vent from the treatment chamber to remove oxygen-rich ozonated air at the same rate as the oxygen being supplied will be required to avoid pressurisation of the chamber. In our automated system, ordinary air is used because of these constraints; additionally, the ozone generators in our system can be located inside the chamber, thus reducing ducting-related costs. Other mechanical-related risks are summarised in Table 1.

2.5. System Location

The location of the automated system will depend on several factors, such as space availability for the desired throughput, access to a power supply and the ability to integrate the system with the existing workflow within the factory. Table 2 summarises some of the operational constraints considered by ACS before finalising the optimal location for the automated ozone disinfection system. While considering the available indoor space, it is important to mention that the sizing of the system was primarily determined by the business need for eliminating the bottleneck in the textile processing operations of the company (i.e., the manually-operated ozone system) while preparing for the projected capacity expansion. Thus, several throughput and sizing options were proposed and thoroughly analysed; an outdoor scenario was deemed the most beneficial.

This implied that a connecting bridge, equipped with a conveyor to link the automated unit to the interior areas of the factory, had to be constructed. This bridge, together with an external housing arrangement, shields the garments and the delicate components of the system from adverse weather conditions during normal operations; these housing components, coupled with the additional conveyor length required to transport the garments to the next indoor workstation (the bagging machine), significantly increased the cost (by ~%80) compared to an indoor scenario. Section 2.6 provides the costs of the system components based on the outdoor scenario.

Table 2. Location considerations for the automated ozone decontamination system.

Outdoor scenario	**Indoor scenario**
Pros	**Pros**
Easier to demonstrate the inherent safety of the system to regulatory bodies in the event of accidental ozone leakage	Although the system has been robustly designed to mitigate potential ozone leakage, this may not appeal as strongly to regulatory bodies regarding worker safety
Significant savings on valuable indoor floor space	Lower capital expenditure
The current outdoor position facilitates the system's integration with the existing workflow in the facility (with direct access to the bagging units via conveyors, after decontamination)	Can be easily integrated into the main electrical supply system and other indoor connecting workstations
Cons	**Cons**
Increased capital cost due to housing and extra components required to protect the equipment against bad weather	Would require a massive restructuring of the current indoor layout to accommodate the size. This requires thorough planning and would significantly delay the installation
Additional security and electrical installations (including fire alarm considerations)	A compromise on the attainable throughput of the system will be required due to constraints posed by the available floor space.
Requires approval from multiple entities (fire-safety contractors, buildings contractors and the council)	The loss of valuable storage space amounts to increased operational costs

2.6. Economics

Automating an ozone disinfection process is far more capital-intensive than installing a manually-operated one; Table 3 provides a summary of the capital expenditure (CAPEX) required for the system's installation, a total of GBP 270,000. In terms of operational expenditure (OPEX), instead of three workers (nine man-hours), who will typically be required to load and unload the old manually-operated chamber over a shift, the use of robust conveyor systems reduces the number to one worker (two man-hours). The worker is primarily tasked with routine inspection duties, which can also be carried out at a remote station through the camera systems and enhanced data visualisation capabilities of the system. Furthermore, the installed UVC lamps have an operating duration of 18,000 h, and would, thus, require replacement after every 2.5–3 years of operation. The annual replacement of the catalyst, coupled with routine servicing costs, is expected to contribute to the operational costs.

By assuming a single-shift operation per day, 245 active days of operation in a year (due to the seasonal demand for the unit) (Table 4) and an electricity cost of 30 p/kWh, the estimated annual energy cost is GBP 6935. An annual OPEX of ~GBP 20,000 (including all fixed and variable costs) is expected for the automated ozone disinfection system. By considering this seasonal nature of the facility's usage, the new system is capable of generating an additional annual revenue of ~GBP 73,000 (due to the throughput enhancement at full capacity) while providing an additional ~GBP 55,000 in annual cost savings—this yields a combined benefit of ~GBP 128,000. Thus, it is estimated that the payback period for this investment is 2.1 years, with a return on investment (ROI) of ~47%. This analysis excludes the additional revenue obtainable from the commercialisation of this technology, given its immense potential.

Table 3. Capital expenditure for the automated ozone system.

Components	Qty.	Cost (GBP)
Air curtains	4	GBP 3960.00
Ozone sensors	6	GBP 8280.80
Ozone generators	8	GBP 13,120.00
Humidifier (equipped with a temperature and humidity sensor)	1	GBP 1654.00
Extraction fans	3	GBP 4544.00
Circulation fans	2	GBP 1100.00
UVC Lamps (and tunnel and fittings)	16	GBP 6880.00
Ozone destruct catalyst	3kg	GBP 3000.00
Ducting and fan housing	-	GBP 10,000.00
Conveyor system (clip and pin)	-	GBP 89,425.00
Ozone chambers	3	GBP 35,820.00
Chamber fittings	-	GBP 45,255.00
Control unit (including Programmable Logic Controllers, PLCs)	1	GBP 19,580.00
Installation costs (labour and site supervision)	-	GBP 27,580.00
TOTAL	-	**GBP 270,198.80**

Quotations were obtained from various suppliers (Thermoscreens Air Systems, Biddle Air Systems Ltd, Ozone Solutions, Advanced Ozone Products Ltd. – AOZP, Sealpump Engineering Ltd, Dongguan Changyuan Spraying Technology Co., Ltd., Flextraction Ltd, Axair Fans UK, Ltd, YESSS Electrical, Central fans Colasit Ltd, Phillips, VTM (UK) Ltd., Oxidation Technologies LLC and Autopak Garment Solutions) in October 2022. The developed automated system (2500 garments per h) is capable of tripling the throughput of the manually operated system (750 garments per h).

2.7. Energy Requirements, CO_2 Emissions and Water Consumption

Table 4 shows the estimated energy consumption of the unit and the corresponding equivalent CO_2 emissions of the automated ozone facility. The estimated carbon emissions represent an intense working scenario of continuous operation for all components throughout an 8-hour shift. Some equipment (e.g., ozone generators) will be on standby mode at some points during the system's operation and would only be fully active as dictated by the control system. Thus, the actual equivalent CO_2 emission of the system is likely to be lower. Nonetheless, the total $CO_{2,eq}$ emissions from the automated system (4.5 tons) are only 1.6 times higher than those of the manually operated system, despite tripling its throughput. This is a resultant effect of its efficiency of operation.

The water consumption (primarily due to the humidification system) of the developed automated chamber is also an important sustainability metric. For a mains water supply of 1 bar and a 5-bar air pressure delivered to the humidification unit, the equivalent water consumption is 3.4 L/h (according to the manufacturer's specifications). This results in a total consumption of 28 L over an 8-hour shift. Again, as with the ozone generators, the humidity in the system is automatically controlled; thus, continuous operation over an 8-hour shift is unlikely, and the corresponding total consumption is expected to be less than 28 L. This is considerably low consumption, considering the volume and areal coverage of the chamber to be humidified.

Table 4. Electrical consumption of the system and corresponding CO_2 emissions.

Component	Quantity	Unit Electrical Load (W)	Total Electrical Load (W)	Energy Consumption in an 8-hour shift (Wh)
Conveyor motors	7	250	1750	14,000
Control system	1	250	250	2000
Ozone generators	8	220	1760	14,080
Extraction fans	3	2200	6600	52,800
Circulation fans	2	210	420	3360
Air curtains	3	269	806	6444
Humidifier	1	210	210	1680
TOTAL			11,796	94,364
Number of active days in a year (days)				245
2022 carbon conversion factor (kg $CO_{2,eq}$/day) [50]				0.19388
Equivalent CO_2 emissions (tons $CO_{2,eq}$/year)				4.5

3. Conclusions

With the increasing reliance on gaseous ozone for the decontamination of different surfaces and articles/products, new developments in the design and implementation of efficient ozone-contacting equipment are crucial. This study has provided key and recent advances in this regard using a real-world case study of an automated ozone disinfection unit designed for Advanced Clothing Solutions (a sustainable textile processing company in Scotland). The discussion presented herein addresses the design and implementation challenges from the perspectives of ozone generation and control, UVC treatment, humidification, throughput estimation, ozone circulation and decomposition, operational risks, optimal location (indoor versus outdoor scenarios), economic viability and sustainability metrics (CO_2 emissions and water consumption). This GBP 270,000 facility is capable of operating in a semi-continuous manner while tripling the throughput of the manually-operated ozone chamber previously used by the company; the new throughput is 20,000 garments in an 8-hour shift. This translates to an annual benefit (additional revenue and cost savings) of ~GBP 128,000, and yields to a payback period of ~2.1 years, with an ROI of ~47%. This represents an important and economically-viable development in the field of large-scale gaseous ozonation, which will be beneficial to other industries wishing to apply the outlined technology.

Pending Patent: The described technology for large-scale ozone decontamination has been captured in a patent application by ACS titled: **Automated Apparatus, System and Method for Disinfecting Products** (PCT Application Number: PCT/GB2022/052730; reference number: PE961467WO; earliest priority date: 27/10/2021). The patent contains other variations of the proposed design.

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