Proposal: Efficient re-use of FFP2-class masks

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1 Executive summary

Participating to the Hackathon "euvsvirus", our team proposes in the following report the results of its work for the problem of the section Health&Life – Protective equipment - Ways to clean and reuse mouth masks and other disposables.

The Hackathon staff has explained during its webinars it expects the submissions to be: (i) to be EU-wide implementable in c. 6 months (scalability criteria) and (ii) to be either prototyped during the weekend or based on scientific and practical evidence. Therefore, to address the problem chosen by our team, we adopted an approach based on interviews of staff working in healthcare facilities and the resources available in these facilities as well as a robust scientific literature review.

In the following report, we propose a disinfection solution for FFP2 or N95 masks using the re-adaptation of basin washers - present in all healthcare facilities.

We also propose using a physics-guided machine learning approach to predict how a given mask's protective power degrades over time while incorporating uncertainties. It would enable informed decision-making regarding the optimal wear time for each model of mask in a way that guarantees a good level of protection and a maximization of the product's lifetime.

The protocol for the re-adaptation of basin washers allows for rapid action, and is conceived to fit in with the disinfection and/or sterilization protocols already in place in medical facilities. Its implementation would allow (i) a greater availability of masks with a high level of protection, (ii) cost savings and a distressed dependence in the supply of quality masks and (iii) addressing crucial ecological issues at the level of production and waste management.

The model only requires a training dataset that can be provided by mask manufacturers in order to make reuse possible but wisely managed.

2 Overview of the team

For this unique experience and given the complexity of the challenges proposed by the Hackathon, we had to gather a multidisciplinary team with complementary skills and backgrounds.
Florent Moreau, is currently a student in the double cursus Centrale Paris-ESSEC Business School. He has a strong interest in applied physics and his dual skills allow him to adopt a pragmatic approach to complex problems.
Flore Vandier is currently a student-researcher at the ENS de Lyon in organic geochemistry and paleoenvironment reconstruction. She brings to the team a technical expertise in life sciences and has contributed a scientific approach to the problems we have faced.
Wilson Jallet is currently a student-researcher at Inria, and graduate of École polytechnique and ENS Paris-Saclay. His skills in modelling and machine learning enabled us to build the wear model presented in section 5.
Steven Deves-Girain is currently a student in the dual ESSEC Business School-Centrale Paris. He has a strong interest in modeling and his experience in entrepreneurship projects has been used to organize the team.
Maxime Jurrus is currently a student at the Toulouse Veterinary School. His skills in biology and his approach as a caregiver have guided our research of solutions.
Viktor Kupczyk is currently a student at ESSEC Business School and former treasurer of the ESSEC Junior Enterprise. His international profile and his experience in consulting and finance have allowed us to have a user-oriented and economic approach to the problems we faced.
Jean-Louis Lejay, a former engineer from the Ecole Centrale de Lyon and manager at Capgemini, brought us not only technical expertise but also his leadership and teamwork methods.

3 Formalisation of the problem

Healthcare facilities all over Europe are facing a major shortage in protective equipment and especially face masks. Safety measures and precautionary principles require a high rate of discard of possibly contaminated masks to efficiently protect workers and patients. However, this results in a huge demand for such equipment that European countries are unable to meet. In addition, interviews of healthcare workers in various French hospitals have stressed out the high numbers of faulty masks within available batches, making usable face masks an even more scarce resource.
The lack of protective equipment is exposing healthcare workers to extremely high risks

of infection. Indeed, SARS-CoV-2, the virus at the origin of the pandemic, is able to propagate through droplets and aerosols, and thus to infect human beings through direct contact with the mouth or the eyes, or to secondary contact with previously contaminated hands(citeauthorzhou2020pneumonia).
Facial protection is essential in preventing infection, especially for healthcare workers that operate in highly contaminated environments (Fisher et al.). Two strategies have been adopted by healthcare workers to deal with shortages of face masks: extended use (continuously wearing facemasks for a duration that is exceeding safety recommendations) or reuse (using several times the same mask).
Extended use presents a risk of accumulation of pathogens on the surface of the mask and hence increases the probability of self-inoculation (source). Besides, breathing through a mask with a high concentration of viruses on the filter is likely to generate virus-rich aerosols that can contaminate other healthcare workers or patients (Johnson et al.). In addition, continuous use is associated with high discomfort and potential adverse effects on the user's health, due to the high temperature within the mask, high carbone dioxide concentrations and high relative humidity that cause breathing difficulties (Roberge, Kim, and Benson, Radonovich et al.).
Reuse of face masks also presents high risks of infection due to the manipulation and storage of a contaminated surface (Fisher and Shaffer).
In addition, massive production and discard of single use masks are not compatible with a sustainable management of resources and waste management.

4 Disinfecting face masks with a fast and cheap ozone treatment

4.1 Requirements for a decontamination protocol and overview of already existing solutions

An efficient decontamination of face masks solution has to face three major challenges : 1. efficiently eliminate all pathogens, including viruses, bacteria and fungi. 2. avoid any degradation of the components of the mask and thus compromise its protective characteristics. 3. avoid any release of harmful chemical residuals that could later result in adverse health effects on the user or other persons in its environment Viscusi et al. Decontamination solutions have already been proposed in the previous decade. However, most of them fail to meet the above mentioned challenges 1.

4.2 The advantages of using ozone

A decontamination procedure using ozone would meet all mentioned challenges. Ozone is a gas with high diffusion efficiency that is highly toxic to all known pathogens (Mustafa). Airborne or waterborne treatment by ozone has been shown to efficiently eliminate viruses

Methods	Dry Heat	UVc	Hydrogen peroxyde	70 % Ethanol
Principle	Heating the masks until pathogens are eliminated	Irradiating the masks with germicidal UV	Exposing the masks to hydrogen peroxide	Treating the mask with a solution of 70 % ethanol
Elimination of pathogens	High level of certainty of SARS-CoV-2 elimination, but low level of certainty of elimination of known resistant pathogens	High level of certainty of elimination of known pathogens, but low level of certainty about the effect in the inner layers of the mask	High level of certainty of elimination of all known pathogens	High level of certainty of elimination of all known pathogens
Effect on the protective characteristics of the masks	Medium risks of degrading the components. (Known studies don't conduct tests on already used masks)	Low risks of degrading the components	Medium risk of degrading the components by condensation of water in the mask layers	Irreversible degradation of filtering ability
Harmful residuals associated with the treatment	None	None	None	None

Table 1: Overview of the main decontamination solutions proposed in the available literature: Viscusi et al.; Fischer et al.

(Akey and Walton; Wells et al.), bacteria (Kim and Yousef; Fontes et al.) and fungi (John et al.) on surfaces, in wastewater effluents, or in living tissues. Ozone is already used as a disinfection agent in laboratories (Akey and Walton), in the food industry (Kim and Yousef) or in wastewater treatment (Miller et al.). An extensive review of above cited literature and consultation with experts indicate that a treatment of 20 min with 25ppm of ozone should efficiently eliminate all known pathogens from face masks. Besides, since the nanoporous fabric of face masks layers are not suitable for bacteria growth, even in conditions favorable to their development, treated masks could be stored in hermetic boxes before reuse without any risk of recontamination (Wang; Reponen et al.) The treatment proposed would use low enough concentrations to avoid any risk of deteriorating the components of the mask. Previous tests of decontamination treatment using hydrogene peroxide, showed sufficient results for fit tests and filtration efficiency (Schwartz et al.). Since ozone has similar properties but doesn't form a liquid phase in standard conditions, it is expected to better conserve the physical properties of the masks treated than hydrogene peroxyde.

4.3 Implementation of the treatment in healthcare facilities : a protocol based on basin washers

In the context of the coronavirus crisis, it is necessary to find solutions that can be rapidly implemented and scalable at EU level, such as adapting Decathlon diving masks to become respirators. In addition, it is necessary to comply with health and safety measures in the manipulation of the equipment.
This is why we interviewed staff members from hospitals of all sizes (from small town hospitals to the largest of the APHP) as well as staff members of the French EHPADs (Etablissements d'Hébergement Pour les Personnes Agées Dépendantes, Hosting facilities for dependant and aged persons). These interviews allowed us to conclude that the universally available material in these healthcare facilities was the basins washer (1. We therefore wondered how to make this device adaptable to the ozone treatment described above.

First of all, it is worth highlighting that the basin washer fulfils a set of specifications that make it particularly tolerant to ozone treatment being :

- Hermetically sealed and does not leave any leaks of vapours (especially water vapours whose diameter is smaller than that of the ozone) produced in the chamber.
- Not sensitive to corrosion (because capable of withstanding hydrogen peroxide treatments).
- equipped with adaptable compartments to fit masks.
- Finally, programmed for drying cycles that are nothing more than fluid evacuation and dry heat heating cycles.

The basins washer are equipped with a clean water inlet and a waste water outlet. So we thought of :

- . Connecting an ozone generator (available in numbers on the net for a price of c. 400€ for systems used today in industry notably for disinfection and odour destruction) to the inlet initially planned for clean water. Let us recall here that an ozone generator only requires an electrical energy input, it also uses ambient air. Thus, electricity is the only consumable that is used!
- Connect an ozone catalityc converter (also available in numbers on the net for a price of c. 100€ for industrial quality systems that guarantee an output concentration of less than 0.01ppm far above the safety standards and below the olfactory limit).

Figure 1: Required devices to carry out the protocol: a basin washer, a device that is widely available in healthcare facilities (left), an ozone generator (top right) and a catalytic converter to eliminate ozone (bottom right)

- Carry out a 20 minutes cycle at a concentration of 25 ppm of ozone in the chamber according to the results of our study above. This concentration is easily reached thanks to the generators available for the industry and the tightness of the enclosure.

- Once the disinfection cycle has been completed, the laboratory protocols stipulate purges of 5 times the volume of the chamber in which the ozone has been diffused, which is easily achievable with the machine's waste water extraction system. Thus, given the capacity of the ozone destruction pots (c. 100L/min) this action can be carried out in c. 10min. We also propose to catalyse the destruction of ozone that would also be retained in the mask fibers to use a cycle initially designed for drying with a temperature of 70 °C (dry heat) demonstrated to have low effects on the integrity of the masks.

The cycle time values given here can be varied using experiments that allow measurements of ozone concentration inside the chamber and at the outlet of the destruction pot. We would like to emphasize here the highly conservative aspect of our approach. Indeed, we are aware of a certain aversion to the use of ozone and the values we have taken in this reasoning are the limit values. As example, the value at the outlet of the ozone destruction pot is the one where the concentration would be the highest. In practice, since ozone is extremely diffused in the air, the concentration would have to be calculated in volumes comparable to the rooms where the systems will be installed (i.e. several tens of m^3) but it is obvious that the concentrations would be negligible compared to 0.01 ppm.
The system being in place in healthcare facilities, here are the results of our study concerning the inclusion in the processes present in these structures. In these structures there is a circuit for the collection, treatment and redistribution of contaminated or soiled materials, as in the case of medical basins.
Based upon this model, it would be a matter of organizing a collection of the masks worn and judged re-usable by their wearers (i.e. no tears, obvious staining, etc.). We therefore recommend multiplying the number of collection points to limit the risk of infection due to the effect of concentration at one point.
In addition, the number of times the mask has been worn must be made visible so that the recommendations that may be made using the algorithm proposed in section 5 or recommendations based on an empirical model are not exceeded. For this purpose, the rings used to mark the electrical wires seem to us particularly adapted. They are in fact designed to be placed on strips and to be resistant to strong humidity and oxidation conditions (3).

Our interviews indicate two options at this stage:

- Either the health care staff accept a sharing of masks and a non-individual redistribution after disinfection;

- Either the personnel do not accept this option but accept a re-use after disinfection of masks already worn by themselves.

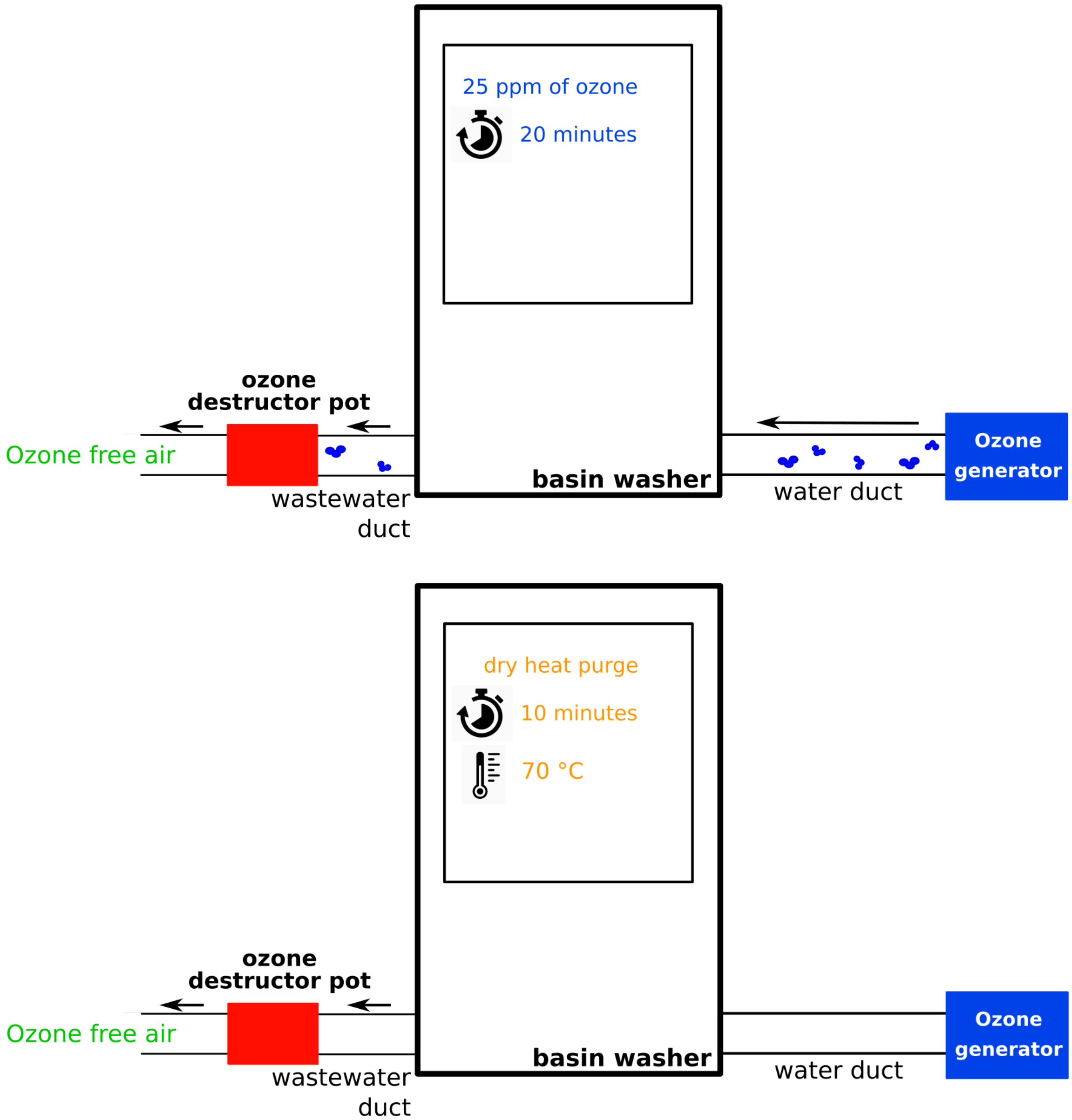


Figure 2: Description of the decontamination protocol using basin washers. Above, the decontamination treatment with ozone, and below, the following dry heat purge to destroy all remnants of ozone.

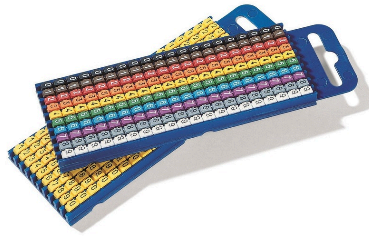


Figure 3: Rings used to identify electric wires

In the first case, we recommend a treatment of masks by services. The service may be indicated by the same ring system. In the second case, the ring system can be used to indicate: the service (first two), a person's identifier (next three), and the number of cycles.

We understand the level of risk taken by the choice of ozone and we would like to point out here the opportunity that basins washer represent. It is a high quality material which would allow dry heat treatments (it is already designed for that) or other treatments, notably thanks to its tightness.

However, face masks are designed as single-use devices and thus the guidelines for its use have not been conceived to optimise its lifetime. Since our procedure enables healthcare workers to reuse them, it is relevant to determine its optimal cycle of wear so as to maximize the protection and the comfort of the user, the filtration ability of the mask layers, and the seal of the mask to the face of the user. To this end, we adapted a model from (Bergman et al.) to simulate the evolution of the penetration of particles in function of the time of wear. We developed a machine learning algorithm that uses the characteristics of face masks to predict the optimal time a specific model should be worn.

5 Predicting mask wear and an optimal time for taking off a mask

We propose a complementary approach to assess optimal re-use of FFP2 or N95 masks while minimising risks. To our knowledge, masks are already being re-used despite official guidelines due to operational constraints and limited available equipment. We aim to find an optimal total mask wear time as well as optimal scheduling of when to take off a mask for dehumidification, cleaning, and rest.

In Bergman et al. [Ber+12], the performance of a mask is measured according to the penetration of nanoparticles of size from 10 nm to 600 nm that are not filtered and captured by the fabric. The mask is deemed to fail when penetration exceeds a given threshold such as 5%.

In practice, it is not possible to test a mask's performance in a live hospital setting during operations. Thus, it is necessary to build a **predictive model for how a mask would respond if it were to be tested for penetration**.

Modern machine learning approaches often have trouble with lack of data, or overconfidence in predictions: this is not suitable for safety-minded applications with not a lot of data which is the case here. We propose a **physics-guided machine learning** approach, with the following design principles: rely on a physical model and incorporate predictive uncertainty.

5.1 Predicting mask performance

In [Ber+12], a mathematical model for the penetration $P(d_p)$ of particles of size d_p is proposed: this model incorporates several and assesses the mask's penetration response under a given airflow – it is tested using experimental data gathered from measurements of particle concentrations on either side of mask inhalating at flows $30\,\mathrm{l\,min^{-1}}$ and $85\,\mathrm{l\,min^{-1}}$. However this model depends on difficult-to-measure parameters such as the fibre charge density which is seen to have a large impact on mask performance. Bergman et al. find a best fit for this parameter using some experimental data but with significant uncertainty.

Instead, we can follow the principled approach of **probabilistic machine learning** [Mur12]: critical uncertainties (e.g. on measurements) we have can be propagated to our penetration performance model. This is **very important for safety**: we see from fig. 6 in appendix A that even a small uncertainty in the charge density value creates large uncertainties for the penetration.

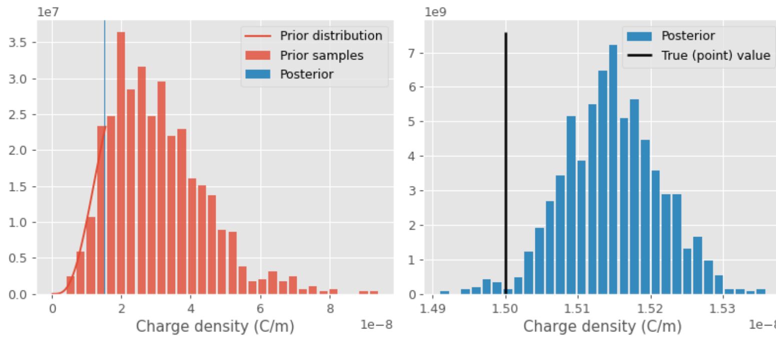
We illustrate this approach on synthetic data fig. 4. More details are given appendix A.

5.2 Mask degradation

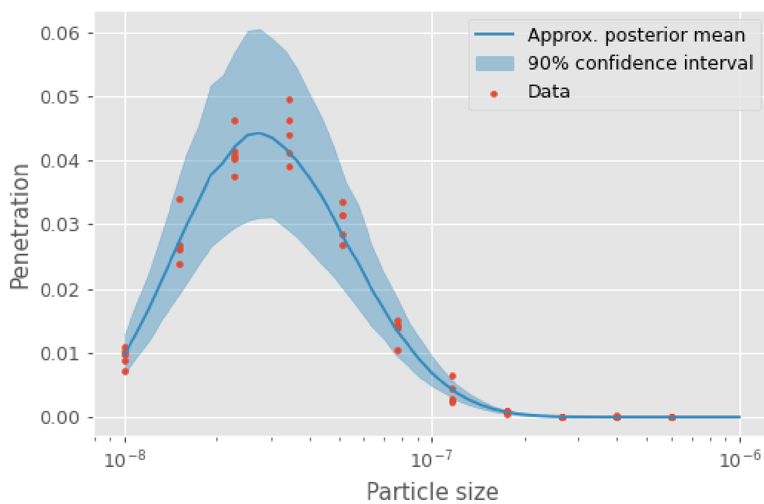
The model of Bergman et al. depends on the mask state. The initial state of a mask when taken out of its protective case corresponds to provided manufacturer information such as the number of layers, fabric type, fibre diameter.

Intuitively, continued use of a mask would degrade parameters conducive to protective power.

As a good first approximation, we can suppose the charge density is the primary factor to wear out. Yovcheva, Mekishev, and Marinov The accumulation of moisture in the woven fibers of the masks layers results in the condensation of droplets that degrade the charge of the electret Viraneva et al.



(a) Prior and posterior distribution after fitting for the charge q.



(b) Obtained prediction using the model, with confidence interval.

Figure 4: The synthetic data was generated using mask parameters for Respirator A in [Ber+12], a real charge density $q_{\text{true}} = 15\,\text{nC}\,\text{m}^{-1}$. We got five samples for 11 different values of the particle size d_p.

The results of [YMM04] suggest a sigmoidal evolution for the charge density, along the lines of $q(t) = (q_0 - \bar{q})\frac{1+\tanh\beta(T_0-t)}{1+\tanh\beta T_0} + \bar{q}$ where T_0 is the instant at which the charge decreases the fastest, $\bar{q}$ is the limit charge and β is a parameter that controls the decay speed. This kind of evolution is illustrated fig. 5. Roughly, it translates to the mask protection decreasing faster and faster until a critical point at which humidity accumulation will remove most of its protective power.

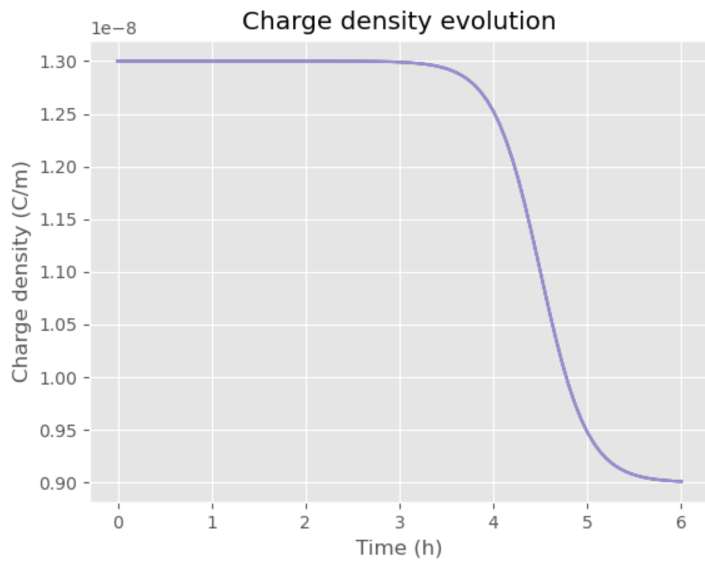


Figure 5: Evolution of the charge density using the sigmoid model. Parameters: $\beta = 2\,\mathrm{h}^{-1}$, $\bar{q} = 9\,\mathrm{nC\,m}^{-1}$.

5.3 Discussion on required data and further work

Further work on this model would involve performing more particle penetration tests on masks with physical parameters (fibre charge density and diameter, layer thickness...) either provided by the manufacturer or estimated, and gather a large dataset.

This should also include testing worn masks with the information of how much time they were worn, and an estimation of their physical state.

Having this data would enable us to couple the physical models with more complex machine learning, especially for estimating the mask state dynamics, such as **recurrent neural networks**.

6 Conclusions and next steps

Implementing the proposed solution in healthcare facilities would have a huge impact on public health. Indeed, it would enable healthcare workers to change masks as frequently as advised by safety guidelines without any risk of shortage, since used masks would be safely decontaminated and available for reuse. Above mentioned high risks of infection and adverse health effects associated with extended wear of face masks would then be avoided. It would also reduce the amount of waste that is produced in healthcare facilities and hence have an ecological impact.

To take our project to the next step, a week-long experiment for the validation of the efficiency of the ozone treatment on contaminated masks would have to be conducted in an accredited laboratory. We would then be able to build a prototype of our device by ordering all required equipment (basin washer, ozone generator, catalytic destructor pot) and by assembling components in a controlled environment. We could test its efficiency within a few days before starting trials in healthcare facilities.

In parallel, we would request factory data and products specifications from manufacturers to train our machine learning algorithm. We would also conduct physical data on filtration performance under varying humidity conditions in order to improve the fit between our model and experimental data.

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A Wear model details

The mathematical model for mask penetration is described in [Ber+12, p. 265], and involves fluid dynamic viscosity, temperature, and properties of the materials used for each layer such as fibre density, electrical charge, thickness, density and surface area. We can write the penetration of particles of size d_p as $P(d_p; s)$ where s denotes the mask's state.

Propagating uncertainty and posterior inference Given a prior distribution $q \sim p(q)$ for the charge, we can directly sample the values of the penetration $P(d_p; q^{(i)})$ by applying the model to random samples $q^{(i)}$. If we are given noisy observations of the penetration (for instance with Gaussian noise), we can condition on them and find a tighter *posterior* distribution of the charge q given the data: in probabilistic machine learning the exact posterior is often intractable and approximate inference algorithms are used [Hof+13]. This is how fig. 4a is obtained, where we start with a loose Gamma prior which covers a large range of $0\,\mathrm{nC\,m^{-1}}$ to $80\,\mathrm{nC\,m^{-1}}$ and fit a small set of data. The result is a much tighter distribution around the true value of $15\,\mathrm{nC\,m^{-1}}$. Once given the new distribution over parameters, we can once again use the sampling procedure for prediction and get fig. 4b.

Decision rule Given the predictive distribution for penetration $p\big(P(d_p; s)|\mathcal{D}\big)$ learned from data $\mathcal{D}$, we can decide that the mask fails whenever the penetration for some particle size d_p exceeds a threshold such as 6% (corresponding to regulatory guidelines) with probability greater than some other threshold e.g. 0.1 – in general having the distribution allows to choose arbitrarily in a risk-aware fashion.

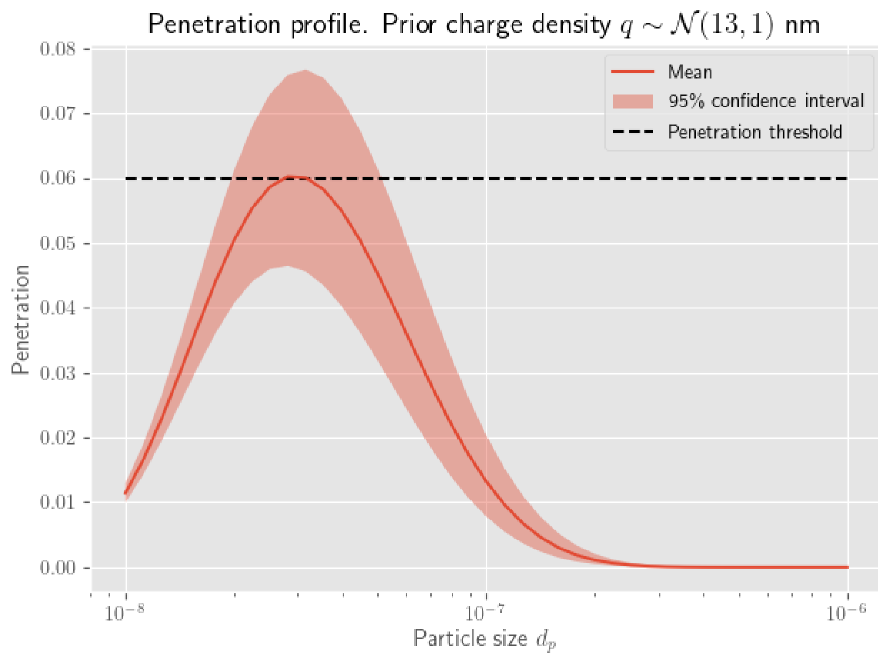

Figure 6: Theoretical penetration profile – with uncertainties – using the model of Bergman et al., and an uncertain charge density modelled as a tight Gaussian around 13 nm. Mask characteristics correspond to Respirator A in [Ber+12], with inhalation flow $85\,\mathrm{l\,min}^{-1}$. Here, the penetration threshold is well within the confidence interval for the penetration meaning it is likely a penetration test would fail.