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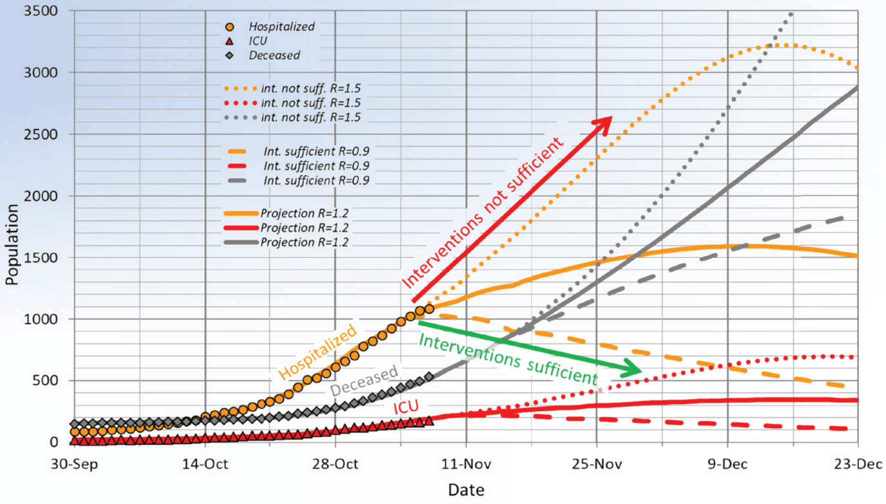

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Aim and Scope

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The journal follows new trends and progress proven practice in the mechanical engineering and also in the closely related sciences as are electrical, civil and process engineering, medicine, microbiology, ecology, agriculture, transport systems, aviation, and others, thus creating a unique forum for interdisciplinary or multidisciplinary dialogue.

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Cover:
The projected number of patients hospitalized in regular and intensive care units and deceased is depicted for the expected peak of the second epidemic wave in Slovenia at the end of the year 2020. Projections with various scenarios were developed primarily to visualize the uncertainties inherent in the epidemic data and model. The depicted scenarios include the best estimate projection, an optimistic scenario implementing sufficient non-pharmaceutical interventions and less optimistic scenario with insufficient implementation of interventions.

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Robust and Intuitive Model for COVID-19 Epidemic in Slovenia

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The main goal of epidemic modelling is to support the epidemic management through forecasts and analyses of past developments. With this in mind a robust and intuitive SEIR (Susceptible, Exposed, Infectious, Recovered) type model has been developed, applied and validated during the multiple waves of the COVID-19 epidemics in Slovenia since March 2020. The model parameters were based on the general characteristics of the COVID-19 disease reported globally for the entire planet and refined with the aggregate data available mostly on a daily basis in Slovenia, as for example the number of confirmed cases, hospitalized patients, hospitalized patients in intensive care units and deceased. The Slovenian aggregate data was also used to estimate the degree of immunisation due to past infections and vaccination, which reduces the number of susceptible persons for the disease.

Examples of the model application are presented to illustrate its robustness and intuitiveness in both the forecasts and analyses of past developments. The analyses of past developments provided specific estimates of modelling parameters for Slovenia and quantified the effects of pharmaceutical and non-pharmaceutical interventions and various events on the development of the epidemics as measured through the reproduction number R. This empirically obtained information was then applied in the forecasts. Accurate forecasts are a great support for decision makers and for hospitals to plan appropriate actions in advance. The inherent uncertainties in the model and data were quantified through intuitive sensitivity analyses represented as different scenarios. The observed accuracy of the forecasts was impressively good also in demanding conditions, when various complex processes influencing the spread of the disease were going on in parallel. This demonstrates the robustness and relevance of the proposed model.

Keywords: epidemic, COVID-19, modelling, SEIR, reproduction number, public health interventions

Highlights
- *Robust and intuitive susceptible, exposed, infectious, recovered (SEIR) type model has been developed.*
- *Model has been applied for analysis of COVID-19 epidemic in Slovenia.*
- *Some examples of model application are presented.*
- *Accuracy of forecasts is impressively good.*

0 INTRODUCTION

The COVID-19 epidemic might have caught many countries and governments by surprise since its beginnings in November 2019 in Hubei province, China. Till today a huge amount of data and information have appeared online [1] to [4] and in the literature [5] to [9]. In addition, several models aiming at forecasting the spread have been developed [10] to [14].

The main goal of epidemic modelling is to support the epidemic management in real time and with the available data being far from optimal. It is crucial to get a reliable insight in the trends as early as possible to enable timely and appropriate actions by decisionmakers and for the hospitals to prepare in time.

Traditional approach for the modelling of epidemics including the COVID-19 includes compartment models. In particular, the susceptible, exposed, infectious, recovered (SEIR) model appears to be widely used [15] to [17]. In this approach the observed population (e.g., in Slovenia) is divided into four compartments, the susceptible, the exposed, the infectious and the recovered. The transition between compartments is modelled with transition rates, which are proportional to the membership of the compartments. The SEIR model may be extended with additional compartments, like the hospitalized, the hospitalized in intensive care units (ICU) and the deceased. The time development of the membership in the compartments is usually governed by a set of ordinary differential equations, which need to be solved numerically.

Our interest was mainly in the aggregate results such as the number of infected, the number of hospitalized, the number of deceased, the reproduction number *R* characterizing the dynamics of the epidemic [18], and similar. Therefore, we decided to address the epidemic in Slovenia at the aggregate level and provide aggregate forecasts. Focus was on the time dependence of the aggregate results, but implicitly considering also local phenomena, including the age structure and the occasional localisation of infections. For this purpose, the SEIR type modelling approach is in principle well suited.

To perform well in realistic conditions, it is important that the model is robust and intuitive. In

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this way the uncertainties in data, like changes in the testing regimes, impact of limited testing capacity, changes in the hospitalization criteria, changes in data reporting, missing data etc. can be most appropriately considered through quantitative and qualitative approaches, as for example the modeler's expert judgment and holistic view.

With this in mind we developed an extended SEIR type model, formulated in integral form. In this framework the modelling becomes very intuitive and simple. The results, which are not distorted by numerical diffusion, become intuitively predictable and consequently strengthen the accuracy of the forecasts.

The developed robust and intuitive epidemic model is presented in the following Section 1, and then in Section 2 some examples of the model application are provided for illustration purpose.

1 MODELING

1.1 Epidemic Dynamics

The spread of a contagious disease in its early stages is an exponential process characterized by

$$N(t) = N_0 2^{t/t_2} = N_0 R^{t/\tau}. \qquad (1)$$

$N(t)$ is the number of exposed persons at time t, N_0 the number of exposed persons at $t=0$, t_2 the time in which the number of exposed doubles, R the reproduction number and τ the characteristic infection time. The reproduction number R is an average number of persons infected by a single person during his/her infectiousness period **[18]**.

Epidemics will only develop if $R>1$. When developing, the R will change with time. Gradual changes are usually consequence of immunisation, while steep changes may be related to the non-pharmaceutical interventions enforced in the observed population. If $R>1$ we have an exponential growth, if $R=1$ we have stagnation and if $R<1$ we have an exponential decay (Fig. 1).

The exponential growth of the number of exposed persons will be, usually with some delay, followed by exponential growth of other aggregate parameters, e.g., number of confirmed cases, the number of hospitalized patients, the number of hospitalized patients in ICU and the number of deceased.

Early stages of the exponential growth are not easily recognized by our intuition, which appears to be better adapted to linear or linearized phenomena. Fig. 2 shows an exponential growth with doubling time 7 days, where the aggregate parameters, e.g., the number of confirmed cases, will double every week. During the first month one could barely see anything happening, then the values start to rise and all of a sudden, the curve turns steeply upwards. This illustrates why it is so important to detect the exponential growth at the earliest possible stage.

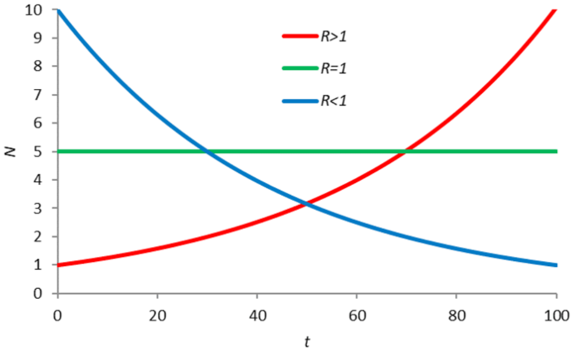

Fig. 1. *Dynamics of epidemic for various reproduction numbers R*

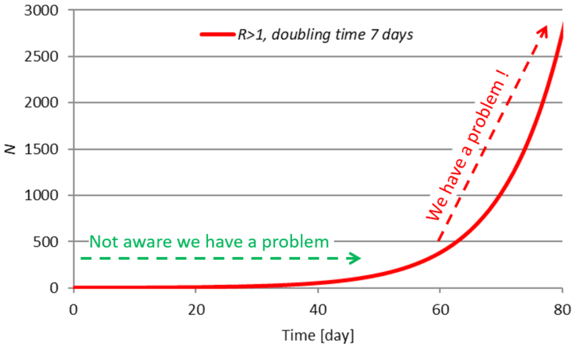

Fig. 2. *Exponential growth for reproduction number R > 1*

Fig. 3 shows the same curve as in Fig. 2 in logarithmic scale. We see that the red exponential growth curve is a rising straight line already from the beginning, and thus we know already from the very beginning where this curve will lead us if we take no action. In logarithmic scale an epidemic runs along more or less straight lines. If $R>1$ the epidemic will grow. This growth will not stop by itself as long as there are enough susceptible persons for the disease, and at that time the capacity of the hospitals may have been already exceeded by more than an order of magnitude. Therefore, the growth of an epidemic must be stopped in time with interventions, reducing the spread of the disease, to prevent the collapse of the health care system. And here the model forecasts can be of great help.

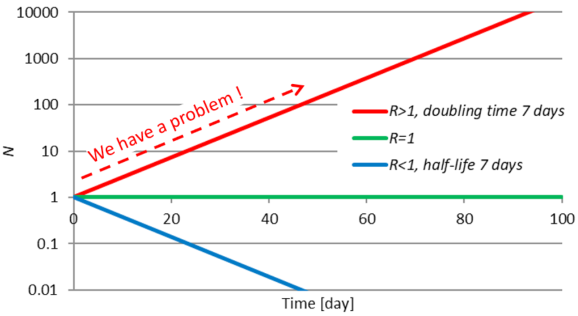

Fig. 3. *Dynamics of epidemic for various reproduction numbers R in logarithmic scale*

1.2 Model Setup

In this subsection the basics of the epidemic model are presented. It was strived to develop a knowledge-driven model as far as possible, with only the model parameters data-driven [19] and [20]. Therefore, the model was based on the exponential function, which is well suited for describing the spreading of an infectious disease. Eq. (1) can be written in difference form as

$$\Delta N(t) = N(t)\left(2^{\Delta t/t_2} - 1\right), \tag{2}$$

where $\Delta N(t)$ is the change of quantity $N(t)$ during the time interval Δt. Based on the form of Eq. (2) we derived the fundamental equation of our epidemiological model as

$$\Delta E(t) = I(t)\left(2^{\Delta t/t_2'} - 1\right), \tag{3}$$

where $\Delta E(t)$ is the change of the cumulative number of exposed persons $E(t)$ in time interval Δt, $I(t)$ the number of infectious persons and t_2' a modelling parameter. $I(t)$ is calculated by

$$E(t+\Delta t) = E(t) + \Delta E(t), \tag{4}$$

$$I(t) = E(t-\tau_{inc}) - E(t-\tau_{inc}-\tau_{inf}), \tag{5}$$

where τ_{inc} is the incubation time and τ_{inf} the infectious period, as depicted in Fig. 4.

Fig. 4. *Incubation time and infectious period after infection*

In Fig. 5 the course of the disease is presented. Let us assume that ΔE persons are exposed at time t. After a time τ_T a fraction α_T of them are tested positive ΔT. After a time τ_H a fraction α_H of them are hospitalized ΔH. After a time τ_{ICU} a fraction α_{ICU} of them are hospitalized in intensive care units ΔICU. And after a time τ_D a fraction α_D of them decease ΔD. At the current stage of the modelling, the average values of all time delays τ and fractions α were considered. They may nevertheless change with time due to for example the inherent variability of different strains of SARS-CoV-2 virus.

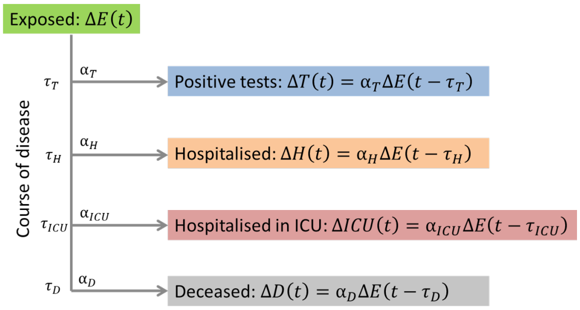

Fig. 5. *Course of disease*

From the number of exposed persons ΔE in a time interval Δt the time shifted number of cases ΔT, hospitalized persons ΔH, hospitalized persons in intensive care units ΔICU and deceased persons ΔD are calculated based on the equations presented in Fig. 5. The empirical estimation of parameters α and τ is described in section 1.6.

For more accurate modelling the equations in Fig. 5 may be written and solved separately for each age group i

$$\Delta T_i(t) = \alpha_T^i \Delta E(t-\tau_T), \tag{6}$$

$$\Delta H_i(t) = \alpha_H^i \Delta E(t-\tau_H), \tag{7}$$

$$\Delta ICU_i(t) = \alpha_{ICU}^i \Delta E(t-\tau_{ICU}), \tag{8}$$

$$\Delta D_i(t) = \alpha_D^i \Delta E(t-\tau_D). \tag{9}$$

The number of currently hospitalized persons H_{cur} is calculated from the number of cumulative hospitalized persons H as

$$H(t+\Delta t) = H(t) + \Delta H(t), \tag{10}$$

$$H_{cur}(t) = H(t) - H(t-\tau_{Hdur}), \tag{11}$$

where τ_{Hdur} is the average duration of hospitalization. Similarly, the number of currently hospitalized persons in intensive care units ICU_{cur} is calculated as

$$ICU(t+\Delta t) = ICU(t) + \Delta ICU(t), \tag{12}$$

$$ICU_{cur}(t) = ICU(t) - ICU(t-\tau_{Idur}), \tag{13}$$

where τ_{Idur} is the average duration of hospitalization in ICU.

1.3 Reproduction Number

Eq. (3) can be expressed as a function of the time dependent reproduction number $R(t)$ as

$$\Delta E(t) = I(t) R(t) \frac{\Delta t}{\tau_{inf}}, \quad R(t) = \frac{\Delta E(t)}{I(t)} \frac{\tau_{inf}}{\Delta t}, \qquad (14)$$

assuming that the infection rate during the infectious period τ_{inf} is constant. The incubation time and the infectious period in this simplified approach were adjusted to result in the correct serial interval, i.e. the time between successive cases in a chain of transmission [21]. Considering Eq. (5) the reproduction number can be calculated from

$$R(t) = \frac{\Delta E(t)}{E(t-\tau_{inc}) - E(t-\tau_{inc}-\tau_{inf})} \frac{\tau_{inf}}{\Delta t}. \qquad (15)$$

As the number of confirmed cases ΔT, hospitalized persons ΔH, hospitalized persons in intensive care units ΔICU and deceased persons ΔD is a linear function of the number of exposed persons ΔE (see equations in Fig. 5), the reproduction number can be calculated from these quantities by substituting them in Eq. (15). Thus, based on the number of daily ΔT and cumulative T cases one obtains the following expression

$$R(t-\tau_T) = \frac{\Delta T(t)}{T(t-\tau_{inc}) - T(t-\tau_{inc}-\tau_{inf})} \frac{\tau_{inf}}{\Delta t}, \qquad (16)$$

where the reproduction number is being estimated for the time τ_T in the past. The current estimate of R from the number of confirmed cases is therefore valid for the time in the past, characterized by an (average) time needed from infection to a confirmation by test. Similarly, the reproduction numbers can be estimated for the past also from the data of hospitalizations, hospitalizations in ICU and deceased, with a time delay from infection till the data, replacing in Eq. (16) T with H, ICU or D, and τ_T with τ_H, τ_{ICU} or τ_D.

Due to the predominantly weekly rhythm of the society, the data shows strong daily variations with a weekly period. Weekly averages of the aggregate parameters in the equations could therefore make the results more stable and reliable.

1.4 Immunity

Immunity may be obtained by infection or vaccination. The number of exposed people is reduced by the fraction of people which obtained immunity due to past infections according to

$$\Delta E_{inf}(t) = \left(1 - \frac{e_E E(t)}{N_{pop}}\right) \Delta E(t), \qquad (17)$$

where e_E is the efficiency of immunization due to past infections and N_{pop} is the number of all people in the considered population (e.g., 2.1 million for Slovenia). Similarly, the number of exposed people is reduced by the fraction of people which obtained immunity due to vaccination as

$$\Delta E_{vac}(t) = \left(1 - \frac{e_V V(t)}{N_{pop}}\right) \Delta E(t), \qquad (18)$$

where e_V is the efficiency of immunization due to vaccination and V is the number of vaccinated people. The efficiency of immunisation due to past infections and vaccination is obtained from global data available in the literature. The population with past infection and the vaccinated population partly overlap. This is considered with the following general equation

$$\Delta E_{im}(t) = \left(1 - \frac{\mathrm{IM}(t)}{N_{pop}}\right) \Delta E(t), \qquad (19)$$

where IM is the equivalent number of totally immunized people, which may be calculated from E and V considering their efficiencies of immunisation and overlapping.

Vaccination does not reduce only the number of susceptible people but may also change the age structure of the exposed. The vaccination was namely prioritizing the more vulnerable elders. The fractions of exposed, which need hospitalization, intensive care or die, depend strongly on the age structure of the infected, which changes due to vaccination. The influence of vaccination therefore depends on the fraction of vaccinated v_i in each age group i and the relative contribution of this age group, which may be described with weights w_i. Thus, the time dependent fraction of exposed people who need hospitalization considering the vaccination dynamics may be calculated as

$$\alpha_{Hvac}(t) = \alpha_H \sum_{i=1}^{n} w_H^i \left(1 - v_i(t)\right), \qquad (20)$$

where w_H^i are the weights for hospitalisation, which may be obtained from Eq. (7) as

$$w_H^i = \alpha_H^i / \alpha_H. \qquad (21)$$

Similarly, the influence of vaccination on the corresponding fractions for hospitalizations in ICU and deaths can be calculated by replacing in Eq. (20) and Eq. (21) α_H with α_{ICU} or α_D, α_H^i with α_{ICU}^i or α_D^i, and w_H^i with w_{ICU}^i or w_D^i.

1.5 Virus Variants

The spreading of various virus variants is considered by modelling each variant separately and then summing the results. The variants share the same susceptible population or part of it, depending on the cross-immunity of the variants. The characteristics of the variants are obtained from global data available in the literature. For practical reasons, in the model the characteristics of the variants are expressed by the characteristics of the chosen basic variant multiplied by a constant proportionality factor to enable a straightforward fitting of the model parameters to data. Consequently, only the characteristics of the basic variant are independent variables and so the same fitting procedure can be applied as when treating only a single variant. Typically, only two variants are of interest at the same time. Thus, the equations are presented for the parallel treatment of two variants, but the approach could be easily extended for the general parallel treatment of more variants.

If variant $v1$ is chosen as the basic variant, then the characteristics of the other variant $v2$ are expressed by the characteristics of variant $v1$ as follows. Different contagiousness of both variants is considered by linking the reproduction numbers R_{v2} and R_{v1} of both variants as

$$R_{v2} = r_{v2} R_{v1}, \tag{22}$$

where r_{v2} is a constant proportionality factor and R_{v1} is the independent variable. Different severities of the disease for both variants are considered by linking the fractions of the exposed for hospitalization α_H, hospitalisation in ICU α_{ICU} and death α_D for both variants as

$$\alpha_H^{v2} = A_H^{v2} \alpha_H^{v1}, \tag{23}$$

$$\alpha_{ICU}^{v2} = A_{ICU}^{v2} \alpha_{ICU}^{v1}, \tag{24}$$

$$\alpha_D^{v2} = A_D^{v2} \alpha_D^{v1}, \tag{25}$$

where A_H^{v2}, A_{ICU}^{v2} and A_D^{v2} are the corresponding constant proportionality factors and α_H^{v1}, α_{ICU}^{v1} and α_D^{v1} are the independent variables. Similarly, also different time delays from infection to hospitalisation, hospitalisation in ICU and death may be considered for both variants.

The aggregate results are then obtained by summing the results over all considered variants vi, presented here for the exposed, as

$$\Delta E(t) = \sum_{vi} \Delta E_{vi}(t). \tag{26}$$

Similarly, the aggregate results for the other considered quantities are obtained by replacing in Eq. (26) ΔE with ΔT, ΔH, ΔICU or ΔD.

The time development of fraction f_{vi} of variant vi is obtained from

$$f_{vi}(t) = \Delta E_{vi}(t) / \Delta E(t). \tag{27}$$

1.6 Model Parameters

If the data is presented in logarithmic scale, we realise that the data curves for the daily positive tests, hospitalized, hospitalized in ICU and the deceased are in the simplified case just shifted curves of the infected (Fig. 6). The slope of all these curves is the same and depends on the reproduction number R. From the slope of these curves we can estimate the reproduction number, as presented in Section 1.3.

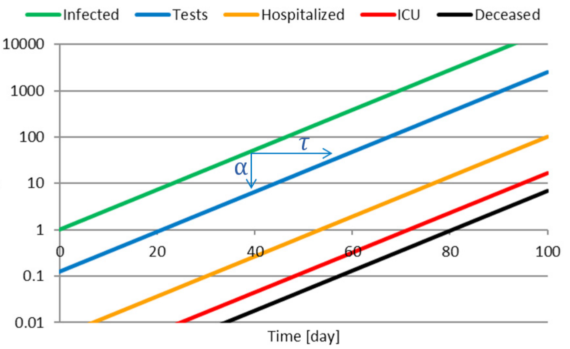

Fig. 6. *Presentation of data in logarithmic scale; example with straight lines*

The curves are shifted vertically and horizontally. They are shifted vertically due to the fractions α in the equations presented in Fig. 5, i.e. the fraction of the infected α_T that are tested positive, the fraction of the infected α_H that are hospitalized, the fraction of the infected α_{ICU} that are hospitalized in ICU, and the fraction of the infected α_D that die. Further, they are shifted horizontally due to the time delays τ, i.e. the time τ_T from infection to a positive test, the time τ_H from infection to hospitalization, the time τ_{ICU} from infection to hospitalization in ICU and the time τ_D from infection to death.

It may be observed in Fig. 6 that the fractions α and time delays τ cannot be determined uniquely, because e.g. from the green curve of infected we can come to the blue curve of positive tests with different combinations of vertical and horizontal shifts. These shifts could be determined uniquely only if there would be a change in the slope of the curves defining a reference point.

Fig. 7 presents an example, where the curves are kinked due to the sudden introduction of non-pharmaceutical interventions, which reduce the reproduction number R to 1 and change the slope of the curves from an exponential growth to horizontal stagnation. In this case both, the fractions α and time delays τ can be determined uniquely, as there is a reference point, i.e. the kink in the curves, which occurs when the non-pharmaceutical interventions are implemented. The fractions α can be determined from the vertical shifts of the kinks in the curves and the time delays τ can be determined from the horizontal shifts.

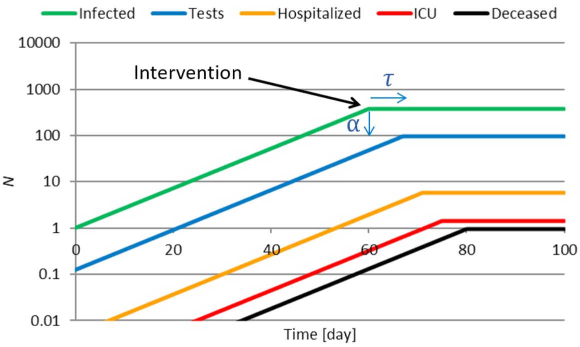

Fig. 7. *Presentation of data in logarithmic scale; example with kinked lines due to non-pharmaceutical intervention*

The easiest way to estimate the fractions α is when the epidemic stagnates, as we are not limited only to the kinks in the curves, but we can determine it in the entire stagnation area (Fig. 7). The time delays τ are most easily estimated when very stringent non-pharmaceutical interventions are implemented maximizing the change in the slope of the curves.

With this approach the fractions α can be established also for age groups, as addressed in Section 1.2. This information is also needed to consider the influence of age group specific vaccination, as presented in Section 1.4.

Once we estimate the fractions α for age groups one can use Eq. (6) to Eq. (9) for short-term estimations of hospitalizations, hospitalizations in ICU and deaths based on the known number of confirmed cases in age groups in the last period as

$$\Delta H(t)=\sum_{i=1}^{n}\frac{\alpha_H^i}{\alpha_T^i}\Delta T\left(t-\left(\tau_H-\tau_T\right)\right), \qquad (28)$$

$$\Delta ICU(t)=\sum_{i=1}^{n}\frac{\alpha_{ICU}^i}{\alpha_T^i}\Delta T\left(t-\left(\tau_{ICU}-\tau_T\right)\right), \qquad (29)$$

$$\Delta D(t)=\sum_{i=1}^{n}\frac{\alpha_D^i}{\alpha_T^i}\Delta T\left(t-\left(\tau_D-\tau_T\right)\right). \qquad (30)$$

The model parameters were estimated based on the following daily and cumulative available aggregate data for Slovenia **[4]**, **[22]** to **[26]**:

- Number of positive tests, share of positive tests, number of PCR and rapid antigen tests, age structure of persons with confirmed infection.
- Daily admissions and discharges from hospitals and ICU, current and cumulative number of hospitalized patients and hospitalized patients in ICU, age structure of hospitalized patients and hospitalized patients in ICU.
- Number of deceased, age structure of deceased.
- Share of SARS-CoV-2 virus variants.
- Concentration of SARS-CoV-2 virus in sewage.

The ratio of confirmed cases and all cases α_T was estimated based on seroprevalence data of SARS-CoV-2 virus for Slovenia **[27]** and expert judgement. The fractions α and time delays τ were estimated regularly at changes of the trend of the epidemic, considering also the age structure. The duration of hospitalizations and hospitalizations in ICU were estimated based on the known data of daily admissions and the current number of hospitalized patients and hospitalized patients in ICU. The reproduction number was estimated based on the daily number of positive tests, admissions in hospitals and ICU, and deceased. When estimating the model parameters, we tried to consider all available data in a holistic way, considering also soft data, like the social climate affecting the consistent implementation of non-pharmaceutical interventions.

2 RESULTS

The developed model was applied for the analysis of the COVID-19 epidemic situation in Slovenia and to forecast the epidemic development **[28]**. In this section some examples of the model application are provided for illustration purpose.

The forecasts were performed in the following way. If no major change in people's behaviour in near future influencing the disease transmission was expected, it was assumed that the model parameters will not change. In this case the disease transmission is influenced only by changes in the immunity of the population due to vaccination and past infections, as described in Section 1.4.

Planned implementation or release of non-pharmaceutical interventions and important changes in people's behaviour, such as the beginning or end of holidays, are taken into account by changing the reproduction number R based on past experience in Slovenia or other countries, or expert judgement. Similarly, also the influence of weather, where e.g. in colder conditions people stay indoors enhancing disease transmission, was considered. We tried to consider as far as possible also soft data, i.e. information that is not given in form of numbers, like the social climate affecting the consistent implementation of non-pharmaceutical interventions, or that the virus entered a retirement home generating an outbreak within a specific age structure.

The initial part of the forecast is checked with the short-term prediction based on the known number of confirmed cases in age groups in the last period, as described in Section 1.6.

2.1 Scenarios

Fig. 8 shows a typical example of an epidemic forecast with different scenarios, when approaching the peak of the second wave in Slovenia end of year 2020. On October 26, 2020 stringent non-pharmaceutical interventions were implemented [4]. Before that some non-pharmaceutical interventions were already implemented and the reproduction number was estimated to be $R = 1.5$.

In the forecast three scenarios are presented for the number of hospitalized patients, hospitalized patients in ICU and deceased. The dotted curves present the scenario without additional non-pharmaceutical interventions. In this case the epidemic continues to growth with the reproduction number R, that gradually decreases due to the build up of immunity in the population caused by past infections. When the reproduction number is reduced to $R = 1$ the peak is reached and after that the curves start to decrease, except for the deceased, where the cumulative number is shown.

The dashed line shows the scenario with successful non-pharmaceutical interventions, reducing the reproduction number to $R = 0.9$. Because $R < 1$, the epidemic starts to decrease and consequently with the time delays τ also the number of hospitalized patients and hospitalized patients in ICU decreases.

The full line presents the forecast, where it is estimated that the non-pharmaceutical interventions

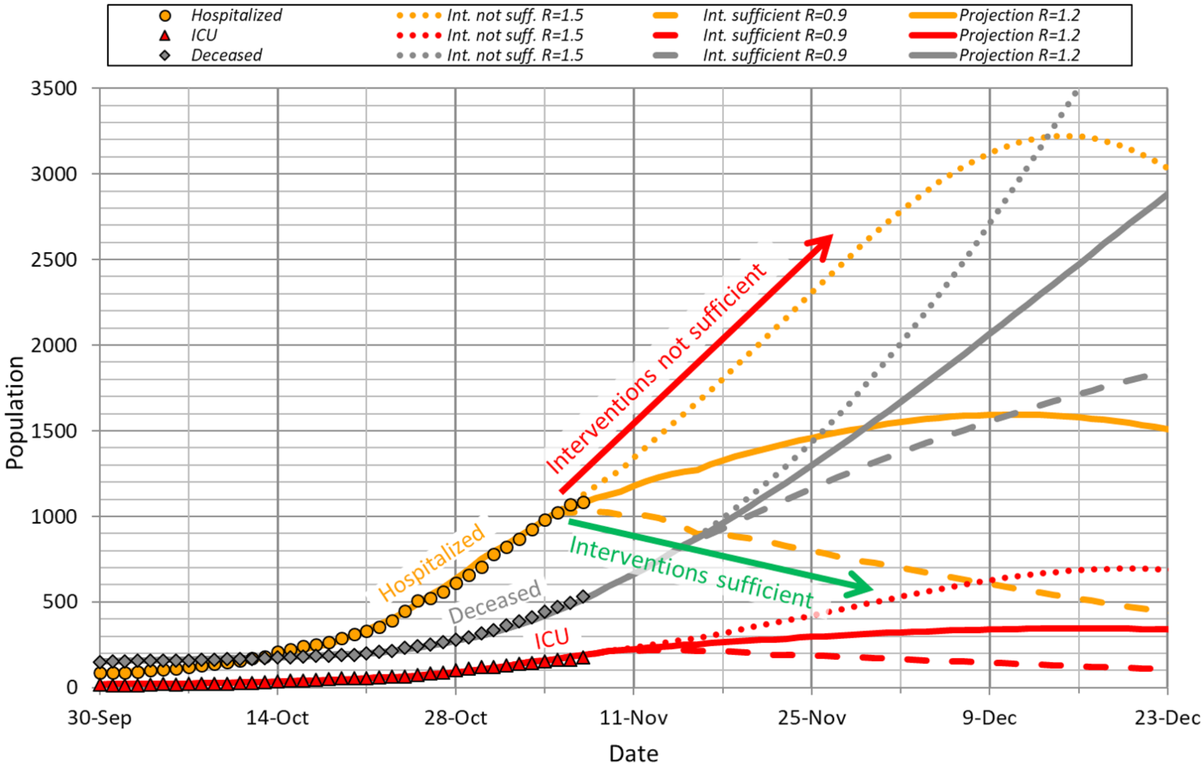

Fig. 8. *Forecast with different scenarios for the second wave in Slovenia end of year 2020; the following scenarios are presented: without any additional non-pharmaceutical interventions (dotted line), with successful non-pharmaceutical interventions (dashed line) and forecast (full line); the curves show the number of hospitalized patients (orange curves), hospitalized in ICU (red curves) and deceased (gray curves)*

reduce the reproduction number to $R = 1.2$. In this case the epidemic still rises, but the peak is significantly lower than without any additional non-pharmaceutical interventions.

The purpose of presenting such scenarios is to get an impression about the uncertainties of the forecasts, the characteristic times, the possible maximal values of the presented results, the possible course of events etc. The calculated curves serve primarily for the qualitative and quantitative orientation of the possible development of the epidemic.

2.2 Analysis

As an example of an epidemic analysis the second wave in Slovenia end of year 2020 and beginning of year 2021 is analyzed in Fig. 9. The orange dots and curves show the number of hospitalized patients and the blue curve shows the estimated reproduction number *R*.

Already at the end of August 2020 the reproduction number *R* was bigger than one due to the end of holidays. It then increased sharply due to the start of the school year and then declined due awareness rising and some non-pharmaceutical interventions, but remained above 1, meaning that the epidemic grew during all that time. As a result, the number of confirmed cases became so large, that the capacity for epidemiological contact tracing was gradually exceeded, which significantly increased *R*. In addition, during this period the share of the more contagious variant B.1.258 significantly increased, further contributing to the rise of *R*. As a consequence, the epidemic started to grow extremely fast with a doubling time of only about one week. With a series of increasingly stringent non-pharmaceutical interventions Slovenia finally managed to stop the growth, but the numbers remained high. The epidemic then began to slowly decline due increased immunity of the population caused by past infections. During the Christmas and New Year holidays, the epidemic started again to rise due to more contacts among people. After that it started to decline faster and faster due to mass testing with rapid antigen tests, past infections and vaccination. First the vulnerable population was vaccinated, which significantly reduced the number of hospitalizations. The decline of the epidemic was then slowed down by some relaxation of non-pharmaceutical interventions. Then the more contagious alpha variant occurred and the epidemic started again to rise. The rise was so fast that in April 2021 a short lockdown had to be implemented,

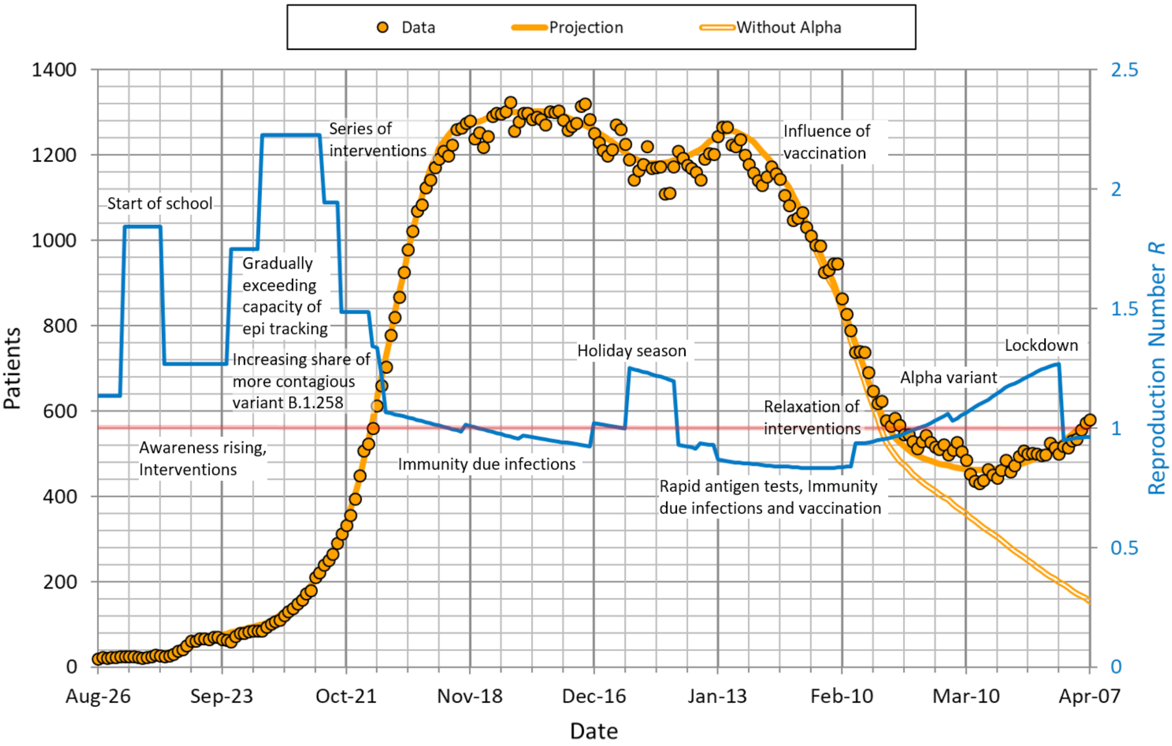

Fig. 9. *Analysis of second wave in Slovenia end of year 2020 and beginning of year 2021; the orange dots and curves show the number of hospitalized patients; the blue curve shows the estimated reproduction number R*

which successfully contained the epidemic. Without the alpha variant the epidemic would just continue to decline and no non-pharmaceutical interventions would be needed.

On the basis of such analyses it is possible to find out how pharmaceutical (e.g, vaccination) and non-pharmaceutical interventions (e.g. masks, lockdowns) and various events (e.g. holidays) affect the reproduction number *R*. Such empirically obtained information was successfully applied in forecasts, as presented in the next Section.

2.3 Accuracy of Forecasts

To get an impression how accurate the forecasts are, some examples are provided for the third wave in Slovenia in the year 2021.

Fig. 10 presents the share of the alpha variant in Slovenia, which displaced the B.1.258.17 variant. Based on the data from Denmark [1], the model parameters of the alpha variant were determined. It was assumed that the ratio of the contagiousness of the alpha variant and the at that time dominant variant in Slovenia is the same as it was in Denmark and that consequently the dynamics of the alpha variant share will be the same in Slovenia as it was in Denmark. Based on that the green curve of the alpha variant share was calculated. When the data for Slovenia became available [24] and [25], the calculated curve was fitted to that data by accordingly time shifting it horizontally. Based on our calculations we forecasted already end of January 2021 that the third wave in Slovenia will probably start mid March, which turned out to be true. It may be seen that the agreement of the green curve with the data is nearly perfect, which means that the alpha variant share increased in Slovenia like it did in Denmark. This is also the reason why our forecast was so accurate.

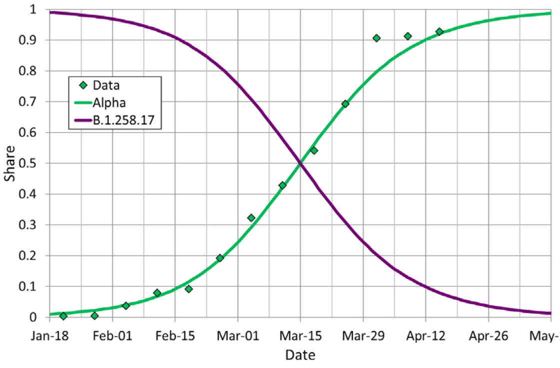

Fig. 10. *Share of alpha variant in the year 2021*

Figs. 11 and 12 show a demanding forecast for the third wave in Slovenia for hospitalizations and hospitalizations in ICU, considering the implemented non-pharmaceutical interventions, the spreading of the alpha variant, and the immunity due to past infections and vaccination. The forecast was prepared on March 31, 2021 before the 11 days lockdown, which was implemented on April 1, 2021 [4]. Based on past experience, where a similar set of non-pharmaceutical interventions was released as was now implemented in the lockdown, we estimated that during the lockdown the reproduction number *R* will be reduced by 25 % and then after the lockdown increased by 10 % according to the Slovenian COVID-19 traffic light non-pharmaceutical intervention system.

The epidemic modelling in this period was very demanding as various processes were going on in parallel: non-pharmaceutical interventions were implemented, the share of the alpha variant was rising, the people were extensively vaccinated and the rate of infections was high, both importantly increasing the immunity of the population. Due to all these complex parallel processes it was anticipated that the uncertainties of the forecasts will be large. To capture them, in the presented scenarios the reproduction number *R* was varied by approximately ±10 % in regard to the projection, which had a large effect on the results, as may be seen on the figures.

In Figs. 11 and 12 with green dots the actual data after the forecast was prepared is plotted. We see that till the time, when it is anticipated that the non-pharmaceutical interventions have an influence, i.e. the point when the curves for various scenarios start to separate, the forecasts are in nearly perfect agreement with the data. Also later, the agreement is impressively good, especially for the hospitalizations in ICU. Thus, it seems that with an appropriate modelling approach it is possible to make quite accurate medium-term forecasts also for a few months. It may be observed that without the alpha variant (and later new variants) the epidemic would end already in May 2021.

During our epidemic modelling we realized that at an extensive epidemic epistemic uncertainties dominate, like the influence of interventions and events significantly affecting people's behaviour, e.g. start of holidays or school. The impact of aleatory uncertainties, such as random infections, is much smaller than one would expect based on the observed large daily variations of data. Namely, these daily variations are often only a consequence of the weekly rhythm of the society, and if we average the data over one week the average values become very smooth and much more predictable.

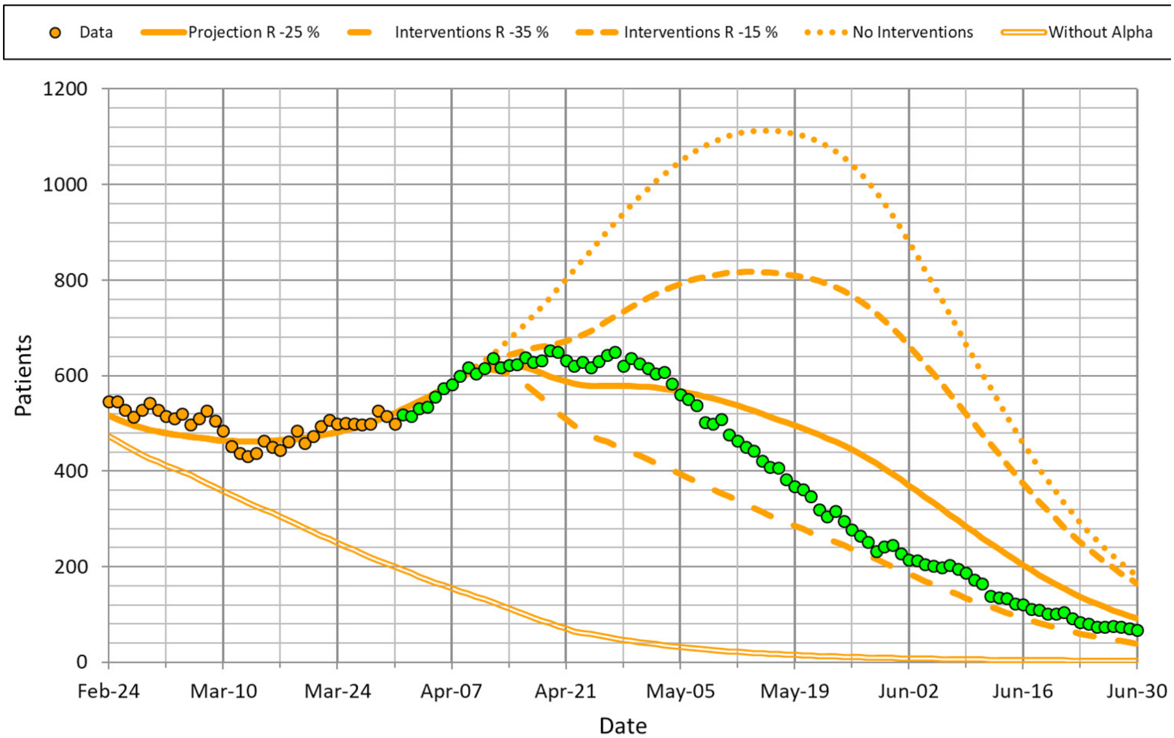

Fig. 11. *Forecast for third wave in Slovenia in the year 2021 for hospitalizations, considering the implemented non-pharmaceutical interventions, spreading of alpha variant, and immunity due to past infections and vaccination; the green dots show data after the forecast was prepared, which are in good agreement with the projection*

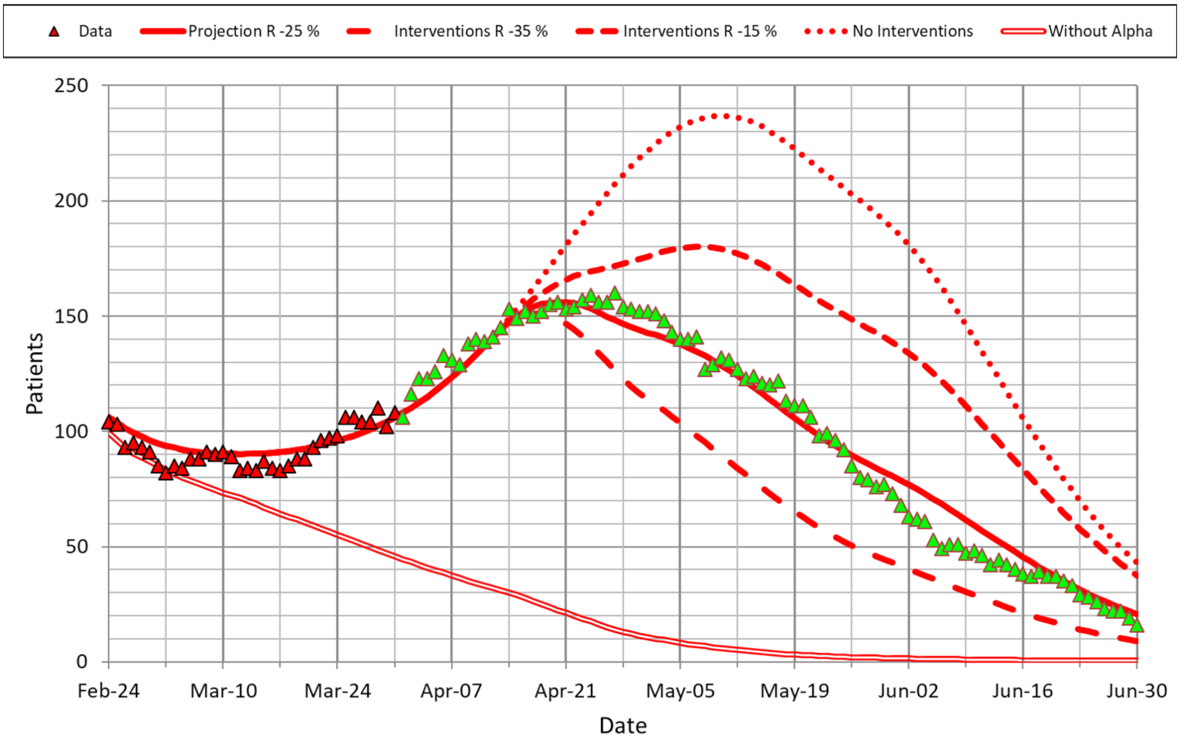

Fig. 12. *Forecast for third wave in Slovenia in the year 2021 for hospitalizations in ICU, considering the implemented non-pharmaceutical interventions, spreading of alpha variant, and immunity due to past infections and vaccination; the green dots show data after the forecast was prepared, which are in good agreement with the projection*

3 CONCLUSIONS

An epidemic is a complex nonlinear time dependent phenomenon. While it appears to be governed by a number of random processes and events, it is also reasonably predictable on the aggregate (e.g., country) level using purely deterministic models.

The main goal of epidemic modelling is to support the epidemic management through forecasts and analyses of past developments. Modelling during a developing epidemic must rely on the data available in real time, which may not be always optimal and might also change with time significantly. A robust and intuitive SEIR type epidemic model was developed, applied and tested in the realistic conditions of the COVID-19 epidemic developments in Slovenia since March 2020.

The model, formulated in the integral form for better robustness and intuitiveness, is described. Examples of applications include the analysis of the past epidemic situation in Slovenia and a forecast of the epidemic development.

Analyses of past epidemic developments help to explain the effect of non-pharmaceutical interventions and various events on the development of the epidemics characterized through the reproduction number R. This empirically obtained information was then used in the simulation of different scenarios, providing valuable qualitative and quantitative insight of the possible future development of the epidemic.

The accuracy of the forecasts of the number of hospitalized patients and hospitalized patients in ICU was impressively good also in demanding conditions, when various complex processes influencing the spread of the disease were going on in parallel. This demonstrates the robustness and relevance of the proposed model.

Accurate forecasts offered valuable support for decision makers and for hospitals to plan appropriate actions in advance.

4 ACKNOWLEDGEMENTS

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Bacterial Filtration Efficiency of Different Masks

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Face coverings, such as surgical masks and respirators, have an important role in preventing bacterial and viral transmission, especially during a global pandemic like COVID-19. Therefore, to secure their availability, new manufacturers and the use of novel materials must be encouraged. However, masks and their materials must first be properly tested for safety and efficiency, as required by the relevant standard, valid in a specific region. All standards prescribe determination of the bacterial filtration efficiency (BFE) of masks. In this study, we report the establishment of a test method for the BFE of face masks in accordance with European standard EN 14683:2019, by which we tested 52 samples, each composed of 3 to 5 subsamples, of surgical and cloth masks, respirators, filters, and mask materials. Forty-seven out of the 52 samples reached a BFE above 75 %. Of these, 16 samples had a BFE of 75 % to 95 %, 3 had a BFE of 95 % to 98 %, while 28 reached a filtration efficiency above 98 %. Our findings show that all tested samples provided some level of protection, most of which met the requirements for the national or European market.

Keywords: bacterial filtration efficiency, face coverings, masks, respirators, Andersen Cascade Impactor, EN 14683:2019

Highlights

- *A method for the determination of BFE testing was established according to the European standard EN 14683:2019, using bacteria Staphylococcus aureus subsp. aureus (ATCC® 6538™).*
- *The method was shown to be robust and provided high quality and well reproducible results.*
- *A total of 52 experiments were conducted and 245 mask subsamples were tested, including 153 surgical and cloth masks, 20 respirators, 25 filters, and 47 mask materials.*
- *Tested masks and materials were evaluated based on their BFE values and grouped according to the national and European standard.*
- *The majority of the tested samples, i.e., 90.38 %, reached the BFE ≥ 75 %, while 5.77 % and 53.85 % had even higher filtration efficiencies of 95 % to 98 % and ≥ 98 %, respectively.*

0 INTRODUCTION

In December 2019, several cases of pneumonia-like disease of an unknown cause were reported in Wuhan, China. This disease was later named COVID-19 and its novel viral agent, severe acute respiratory syndrome coronavirus (SARS-CoV-2), was identified [1]. The virus is transmitted mainly by respiratory secretions that include both larger and smaller droplets (the latter are also known as aerosols). These are expelled during coughing, sneezing, talking, and singing, and may continue to linger in the air for longer periods of time depending on their size. Such mode of transmission is highly efficient, and resulted in a surge of number of cases, soon leading to a worldwide pandemic [2].

To reduce the number of active cases of COVID-19 and prevent further transmission of SARS-CoV-2, certain government-issued measures and restrictions were set in place. These differed slightly from country to country, but most included social distancing, vaccination, regular testing, proper hand hygiene, and the use of masks as personal protective equipment (PPE) [3] and [4]. As a result, the use of face masks become mandatory not only in the public health sector, but also in people's everyday life. Due to the sudden increase in demand and the disruption of global supply chains, countless countries faced a shortage of aforementioned items [3] to [5]. To combat these problems and secure the general availability of PPE, certain strategies have been proposed. These included decontamination of respirators, reuse of disposable masks and their extended use, and the use of expired masks. The appearance of new manufacturers of face masks on the market was also noted, as was the number of novel materials being tested for their safety and filtration efficiency. In addition, the introduction of disposable mask replacements, such as machine-washable cloth masks, was encouraged, resulting in a high occurrence and availability of handmade cloth masks [3] and [4].

Many types of face masks with a broad range of filtration efficiencies are currently available and include surgical masks, cloth masks, and respirators, with surgical masks being the most widespread [6]. A standard surgical mask consists of three layers (Fig. 1). The outermost layer is waterproof and repels external fluids, such as salivary droplets produced by breathing, speaking, coughing, and sneezing. The middle layer is a filter, composed of tightly interwoven thin synthetic fibres. This prevents particles, including

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microorganisms, above a certain size from penetrating the mask from either side. Lastly, the innermost layer absorbs salivary droplets from the user, and moisture from the exhaled air, aiding in the comfort and wearability of the mask. Such masks are typically made of polypropylene, although polystyrene, polycarbonate, polyethylene, and polyester can also be used **[6]**. Similarly, respirators consist of four layers of materials. The outermost and innermost are made from hydrophobic non-woven polypropylene. This prevents external moisture and liquid particles, exhaled during the user's breathing, from being absorbed and penetrating the mask, respectively. The second outer layer is a melt-blown non-woven polypropylene layer, which captures oil and non-oil-based particles. The third layer is made from modacrylic. It provides rigidity and thickness to the mask, giving it more structure and aiding in comfort **[7]**.

The number of layers and the properties of the materials used contribute to the high efficiency and safety of surgical masks and respirators **[8]**. Therefore, masks made of other materials (e.g., cloth masks) are of different quality and efficiency. The most common fabrics used in the production of cloth masks are cotton and different cotton blends, silk, linen, and certain synthetic fabrics **[8]**. Multi-layer cloth masks made of a combination of fabrics, such as cotton and chiffon or cotton and silk, are most efficient, but still do not provide the same protection as surgical masks or respirators **[9]** to **[11]**.

When it comes to producing new types of masks, the most common strategy is to use new materials and materials with specialized functions (i.e., functionalized materials and masks). The latter enhances the protective properties and longevity of masks by incorporating graphenes, alkyl silanes, and metal nanoparticles into otherwise standard materials used for production of face coverings **[6]**, **[12]** and **[13]**.

With the increase of newly available face masks and materials, the number of inadequate products also increased. In Europe, medical face masks must comply with the standard EN 14683 **[14]**, which prescribes testing requirements and relevant methods. Masks must be tested for their general construction and design, cleanliness of materials used, splash resistance, breathability, microbial cleanliness, biocompatibility, and bacterial filtration efficiency (BFE). The latter is determined based on filtration efficiency of bacterial droplets and aerosols, carried by ambient air, mimicking air exhaled into the environment. Therefore, this parameter defines the tested masks' ability to prevent further spread of bacteria. As of October 25, 2021, the European co-operation for Accreditation (EA) **[15]** reports 52 accredited laboratories for face mask testing, of which only 40 are accredited for the scope EN 14683. Due to the limited number of available accredited testing laboratories, many newly available face masks or materials have not been properly tested, rendering them unsuitable as part of effective PPE **[15]**.

In this study, we report the process of establishing and validating a protocol for determining BFE of face masks, compliant with the European standard EN 14683:2019. Using the six-stage Andersen Cascade Impactor (ACI), we determined BFE of 52 different face coverings and materials. This resulted in a total of 245 items tested (3 to 5 subsamples of each face covering or material were tested). We evaluated the reproducibility of the used method, and its suitability for testing different masks and materials.

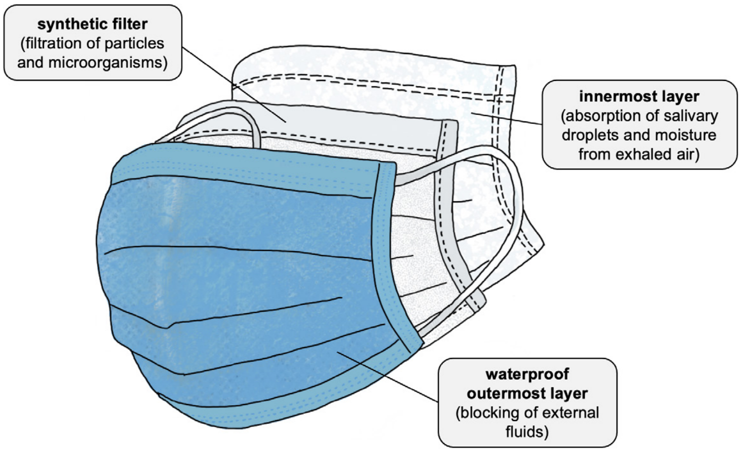

Fig. 1. *Layers of a standard surgical mask*

1 TEST METHOD

The test method for determining the BFE of masks and materials was performed as required by the European standard for face mask testing EN 14683:2019. This included the construction of a test apparatus and its validation. The standard defines testing methods and requirements for medical face masks only, although filters, respirators, and mask materials were tested using the same procedure.

The test apparatus consists of multiple parts with different functions (Fig. 2). The nebulizer is used to produce droplets and aerosols with an average diameter of 3.0 µm ± 0.3 µm (Fig. 2b) from a bacterial suspension (Fig. 2c). These are then mixed with ambient air and travel through a cylindrical glass chamber (Fig. 2d), which ends with a smaller and narrower cylindrical glass outlet connected to a two-piece metal clamp (Fig. 2e), between which mask samples are attached during testing of BFE (masks were not used for the positive controls, as discussed below). Droplets and aerosols are then collected using the ACI (Fig. 2f), which contains six agar plates (i.e., one per stage). Each stage has 400 holes that differ in diameter, which decreases from top to bottom stage. These dictate the size of particles (i.e., aerosolized bacterial suspension) that can pass through a certain stage and settle on the plate **[16]**. The bottom part of the ACI is attached to a vacuum pump that controls the airflow in the system (Fig. 2h). In between is a HEPA filter (Fig. 2g), which prevents aerosolized bacterial particles from leaving the test system. The entire setup is located in a Class 2 biological safety cabinet to minimize the risk for infection with bacteria *S. aureus*.

2 EXPERIMENTAL PROCEDURE

We tested several types of face masks and materials from different manufacturers. We grouped these samples into four types, which included face masks, respirators, filters, and mask materials (henceforth referred to as mask samples). Note that the group of face masks included not only surgical masks but cloth masks as well, while the group of filters included filters for hospital ventilators (aiding patients in breathing) and standalone filters, usually attached to respirators.

The experimental setup was the same for all experiments and followed the principles described in EN 14683:2019, with minor optimizations **[14]**. Suspension of the bacterium *Staphylococcus aureus subsp. aureus* (ATCC® 6538™) was used in all BFE tests. It was prepared by inoculating 30 ml of tryptic soy agar (TSB) prepared from 30 g/l TSB (BD), with the frozen Microbank bead containing the bacteria. This was incubated for 24±2 h at 37±2 °C with shaking at 240 rpm. The appropriate dilution of the bacteria was then prepared in peptone water [10 g/l peptone (BD) and 5 g/l NaCl (Merck)]. So prepared bacterial suspension was aerosolized in the nebulizer and the concentration was maintained at 1.28×10^3 to 3.07×10^3 colony forming units (CFU)/test. The generated droplets and aerosols were then mixed with high-pressure ambient air at a flow rate of 28.3 l/min, mimicking the respiratory flow rate. After the

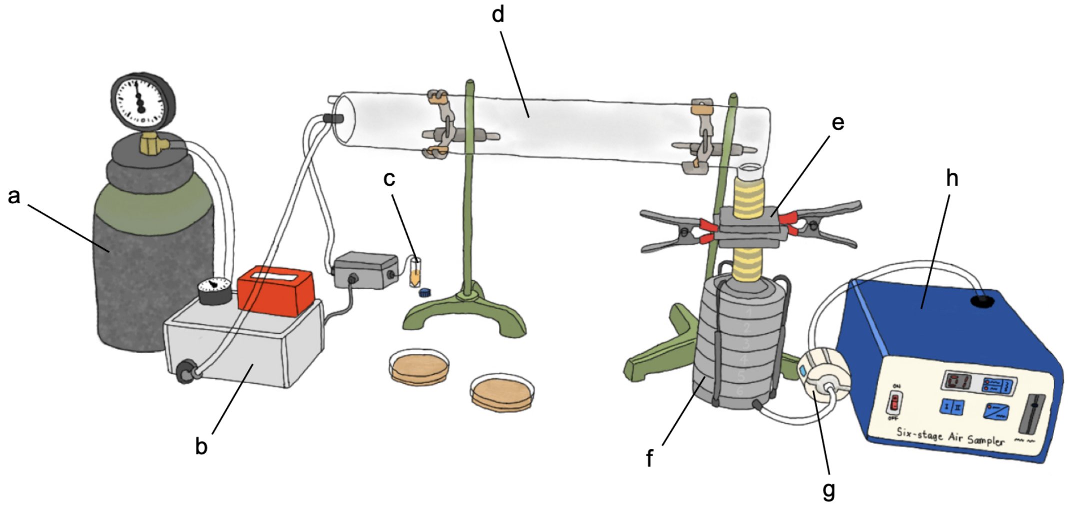

Fig. 2. *Scheme of the test apparatus; a) high-pressure air source, b) nebulizer, c) suspension of S. aureus, d) cylindrical glass chamber, e) two-piece metal clamp, f) Andersen Cascade Impactor (ACI), g) HEPA filter, and h) vacuum pump*

1-minute aerosolization, airflow through the system was maintained for an additional minute, so that the total test time was 2 minutes. The air carried the generated droplets and aerosols through a cylindrical glass chamber and on through a metal clamp, with or without (in the case of positive controls) a mask sample. The mask sample was firmly attached with the innermost layer facing upward and the area of (10 × 10) cm^2 was exposed to droplets and aerosols. In the case of filters and respirators, modified clamps were used to enable their proper fitting on the test apparatus (the area tested was smaller than for the surgical or cloth masks). Particles, which were not intercepted by the attached face mask, passed on to enter the ACI and were collected on agar plates.

The ACI is designed to mimic the flow of inhaled particles through the human respiratory system. During nasal breathing, larger particles (5 µm and larger) get caught in the nasal cavity and esophagus, while smaller droplets and aerosols enter the lower respiratory system. In the first stage of the ACI, particles larger than 7 µm in diameter are captured and represent droplets that remain in the nasal area. Particles with a diameter of 4.7 µm to 7 µm are collected in the second stage and can enter the lower levels of respiratory system, the pharynx. Droplets with a diameter of 3.3 µm to 4.7 µm, collected in the third stage, remain in the trachea and primary bronchi. Particles (2.1 µm to 3.3 µm) that can reach the secondary bronchi are collected in the fourth stage, whereas those with a size of 1.1 µm to 2.1 µm reach the terminal bronchioles and are collected in the fifth stage. The smallest aerosols (up to 0.65 µm to 1 µm) can penetrate the lowest parts of the respiratory system, the alveoli, and reach the sixth and final stage of the ACI [16] and [17]. Particles that reach the lower respiratory organs (i.e., those with a size of 5 µm or less) pose the highest risk of infection, as they can carry harmful bacteria and viruses into the lungs [17].

As the ACI used consisted of six stages, six plates were used for each positive control, mask sample, or negative control (henceforth referred to as subsamples). The plates were prepared from 40 g/l tryptic soy agar (Fluka). After collection of the aerosolized particles, the plates were left to dry and were then incubated overnight at 37 °C. The following morning, bacterial colonies were counted (Fig. 3) and CFU of each subsample was determined. Colonies on plates 1 and 2 are scattered, and therefore counted normally, while colonies on plates 3 through 6 form a pattern similar to the layout of holes on each corresponding plate, increasing the likelihood that multiple colonies are growing in the same location. Therefore, when counting these colonies, the positive hole correction must be taken into account [16]. The number of CFU on each plate is used to calculate the BFE of each mask, as described below.

The experimental design is as follows: the experiment started with a positive control (PC), in which no mask was used to intercept the generated droplets and aerosols. Then, testing of mask subsamples was performed, where three to five mask subsamples were tested, followed by another PC. Lastly, a negative control (NC) was carried out, where air without addition of the bacterial suspension was passed through the system for 2 minutes. At the end of each experiment, the system was first cleaned by the aerosolization of 70 % ethanol (Merck) for 30 minutes, and then MilliQ water for 10 minutes. Efficiency of cleaning was monitored regularly by placing agar plates into the ACI during the 10-minute aerosolization of water. To minimize the possibilities

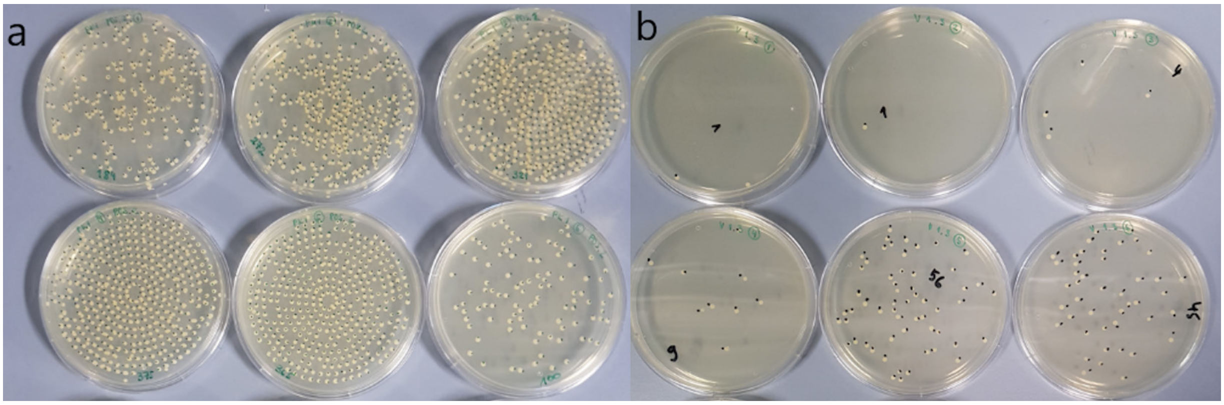

Fig. 3. *Agar plates with colonies of S. aureus used to calculate bacterial filtration efficiency (BFE) of a face mask; a) positive control run plates (one of two runs), where no mask was used during testing, and b) mask subsample run plates; the BFE of the tested mask was 83 %*

for contamination of the system, heat-resistant parts of the apparatus were autoclaved strictly after each experiment.

The average positive hole value of PCs was used to calculate the mean particle size (*MPS*), using Eq. (1). The values of P_1 through P_6 are 7.00 µm, 4.70 µm, 3.30 µm, 2.10 µm, 1.10 µm, and 0.65 µm, while C_1 through C_6 represent the number of colonies on plates 1 through 6 with the positive hole correction taken into account.

$$MPS = \frac{(P_1 \times C_1) + \ldots + (P_6 \times C_6)}{C_1 + \ldots + C_6}. \qquad (1)$$

Using the average bacterial concentrations of both PCs (C_{PC}), and the bacterial concentration in a mask subsample (C_{SB}), the BFE for mask subsample ($BFE\,(SB)$) was calculated according to the Eq. (2).

$$BFE(SB)(\%) = \frac{(C_{PC} - C_{SB})}{C_{PC}} \times 100. \qquad (2)$$

The final (i.e., average) *BFE* was then calculated with the Eq. (3) as the average value of all mask subsamples of the same experiment:

$$BFE(\%) = average\left[BFE(SBs)\right]. \qquad (3)$$

The validity of the results was monitored with two parameters, i.e., MPS and the concentration of bacteria in the airflow, which must be within their determined range in each experiment. MPS values must be maintained at 3.0±0.3 µm, while the concentration of bacteria between 1.7×10^3 and 3.0×10^3 CFU/test **[14]**.

3 RESULTS AND DISCUSSION

Overall, we conducted 52 BFE tests (Fig. 4). This included a total of 245 mask subsamples or 153 surgical and cloth masks, 20 respirators, 25 filters, and 47 mask materials. In addition, each experiment included two positive and one negative control. In parallel, cleaning of the system was monitored to prove the sterility of equipment and thus the adequacy of the whole testing procedure.

The most frequently tested sample type were cloth and surgical masks, as they were tested in 32 out of 52 experiments. Their average BFE was 94.23 %, with the minimum and maximum of 72.64 % and 100 %, respectively. The lower filtration efficiencies are from the cloth masks, which generally have lower filtration efficiencies than surgical masks **[10]** and **[11]**. Filters had the lowest average BFE of 74.27 % (with a range of 64.44 % to 83.51 %), which may be due to the fact that they are not meant to be used as PPE (filters for ventilators) or are less effective in bacterial filtration when used on their own (i.e., not as a part of a respirator). It is also important to mention that EN 14683:2019 does not define the testing methods and requirements for filters, which could affect their determined BFE values **[14]**. The average BFE of mask materials was 93.84 %, while the average BFE value of respirators was 96.18 %, which is similar to that of surgical and cloth masks. While respirators generally offer more protection than surgical masks, this is due to their better fit (when fitting is possible) and not necessarily to their higher filtration efficiency **[18]**, as discussed below. However, as with filters, the testing methods and requirements for respirators are defined by a different standard, EN 149:2001 **[19]**.

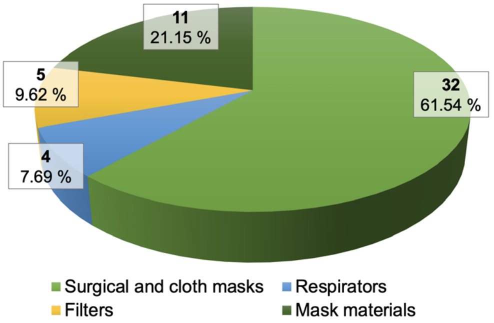

Fig. 4. *Number and percentage of mask samples tested*

At the beginning of the epidemic, as a response to the shortage in mask availability in Slovenia and EU, Slovenian Institute of Standardization prepared the Slovenian Specification for personal half masks SIST-TS 1200:2020 **[20]**, which prescribes a minimal BFE of 75 %. The European standard EN 14683:2019 sets the criteria even higher, i.e., for Type I masks at a BFE of 95 % and for Type II masks at a BFE of 98 % **[14]**. Forty-seven of the 52 (90.38 %) tested mask samples had a BFE of at least 75 %, meeting the criteria of SIST-TS 1200:2020. These included 30 surgical and cloth masks, 4 respirators, 3 filters, and 10 mask materials. Of these, 16 mask samples had a BFE in the range of 75 % to 95 %, 3 had a BFE of 95 % to 98 %, and 28 had a BFE above 98 % (Table 1) (Fig. 5). These findings show that the majority of tested mask samples are suitable for general use and sale at the national (i.e., Slovenian) level, while more than half meet the demands of the European market, either as Type I or Type II.

The BFE of mask samples is dependent on the conditions in the test system during the experiment, and the characteristics of the mask samples themselves. The former are defined by MPS (i.e., the range and average size of droplets and aerosols in the airflow), and the concentration of bacteria in the particle-carrying droplets and aerosols, both of which are determined in PCs when masks are not used. These parameters must be maintained during all experiments **[14]**. As shown in Tables 2 and 3, the MPS for 52 experiments was maintained at 2.802 ± 0.004 µm, while the average bacterial concentration was $2.96 \times 10^3 \pm 1.86 \times 10^1$ CFU/test (i.e., the average error rate was 0.63 %). Both values are within their required ranges and have a small margin of error. While the MPS and concentration values are not expected to depend on the mask samples, both values are consistent regardless of the mask samples used, making the results highly reproducible. As such, the test system and method are stable and provide consistent results. They can be reliably used to test different kinds of cloth and surgical masks, respirators, filters, and mask materials.

As the test conditions were consistent, the differences in BFE between the four groups of samples and between multiple experiments within each group can be attributed to the differences in materials. As previously stated, surgical and cloth masks were grouped together, resulting in the broadest range of BFE (the minimum BFE value in this group was 72.64 % and belonged to a machine-washable cloth mask). The filtration efficiency of masks depends on the characteristics of the materials, such as chemical structure, number of layers, pore size, fibre organization, thickness, and diameter, packing density, charge, and hydrophilicity. Masks, woven from fibres with a small diameter (and therefore a large surface area), which form small pores, display the highest efficiency in particle trapping. Electrostatic properties are also critical – charged materials enable attraction between fibres and air droplets or aerosols, that may carry bacteria, preventing the latter from penetrating the mask. Therefore, polypropylene, polyethylene, polyacrylonitrile, and other polymeric materials are the best choice for production of face masks. Highly

Table 1. *Number and percentage of mask samples meeting different bacterial filtration efficiency (BFE) requirements and classification of the masks into Type I and II (EN 14683:2019)*

	BFE < 75 %		BFE 75 % to 95 %		BFE 95 % to 98 % (Type I)		BFE ≥ 98 % (Type II)	
Sample type	Number of masks	% of masks	Number of masks	% of masks	Number of masks	% of masks	Number of masks	% of masks
Surgical and cloth masks	2	6.25	9	28.13	2	6.25	19	59.38
Respirators	0	-	1	25.00	0	-	3	75.00
Filters	2	40.00	3	60.00	0	-	0	-
Mask materials	1	9.09	3	27.27	1	9.09	6	54.55
Total	5	9.62	16	30.77	3	5.77	28	53.85

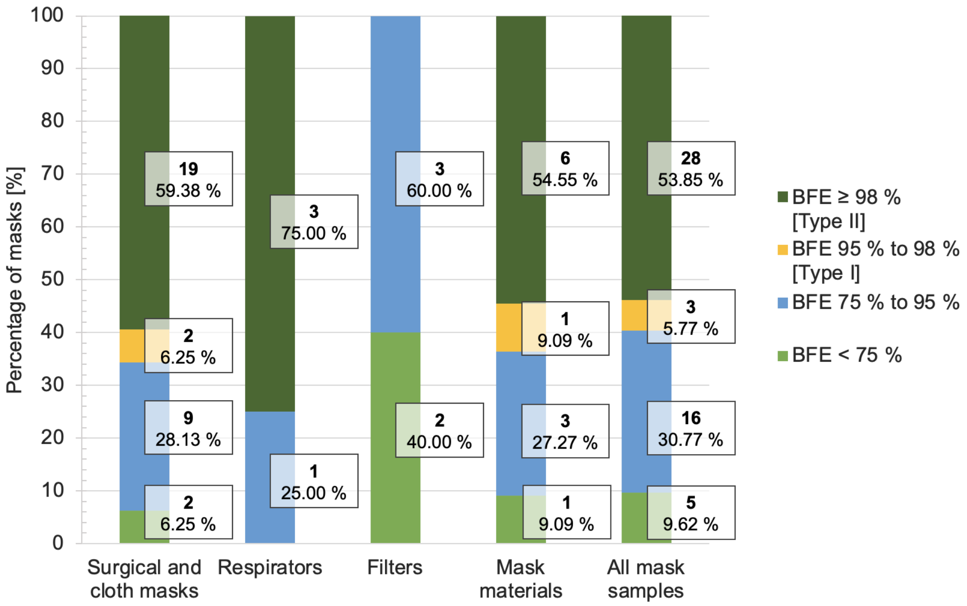

Fig. 5. *Number of samples meeting different bacterial filtration efficiency (BFE) requirements*

Table 2. *Average mean particle size (MPS) values*

Sample type	Number of experiments	Average MPS [μm]			
		Minimum	Maximum	Average	Standard error
Surgical and cloth masks	32	2.35	3.14	2.76	0.01
Respirators	4	2.54	3.05	2.74	0.05
Filters	5	2.42	2.95	2.77	0.03
Mask materials	11	2.35	3.39	2.83	0.02
Total	52	2.35	3.39	2.802	0.004

Table 3. *Average bacterial concentrations*

Sample type	Average concentration [CFU/test]				Error rate* [%]
	Minimum	Maximum	Average	Standard error	
Surgical and cloth masks	1.51×10^3	5.16×10^3	2.78×10^3	77.57	1.29
Respirators	1.51×10^3	4.45×10^3	2.94×10^3	37.79	11.69
Filters	2.14×10^3	6.62×10^3	3.70×10^3	432.22	4.43
Mask materials	2.04×10^3	4.68×10^3	3.18×10^3	140.75	2.79
Total	1.51×10^3	6.62×10^3	2.96×10^3	18.69	0.63

*The error rate was calculated as standard error divided by average concentration.

hydrophilic materials are also efficient in trapping and filtration of liquid particles [8]. This is also related to the number of layers of a mask, as each layer acts as an obstruction for droplets and aerosols, carried by the airflow. This further explains the three and four-ply structure of standard surgical masks and respirators, respectively [6] and [7]. Although it does not affect the BFE of face masks, proper fit further improves their protective properties [21]. Fit is especially relevant when comparing the filtration efficiency of surgical masks and respirators. As shown above, these often have a similar BFE, however due to their design and fit (if properly fitted on each individual), respirators seem to offer better protection [18]. This, however, is not evident in the proposed results, as we only tested the filtration efficiency or the material, irrespective of shape and fit.

4 CONCLUSIONS

Our study offers valuable results and information regarding the establishment of a test method for the BFE of masks, as required by EN 14683, especially considering lack of recent studies on this topic. Since the process parameters, i.e., MPS and bacterial concentration, were similar in all experiments, regardless of the mask sample tested, this indicates that used method is stable and reproducible, and thus can be used for determining BFE of different types of face masks. This is especially valuable in situations with limited availability of PPE, as is the case with the COVID-19 pandemic.

Based on the determined BFE values of the tested samples, a number of face masks provided adequate protection against aerosolized bacteria, with 90.38 % having BFE of more than 75 %. Therefore, they are suitable as PPE, and prevent or lower the possibility of spread of pathogenic bacteria and other microorganisms through exhaled air. However, other properties of the face masks need to be tested in addition to the BFE, highlighting the need for more EA-accredited testing laboratories.

By proper and widespread testing of masks, additional masks could be available on the market, making such protective equipment more accessible, especially in times of need. This would aid in prevention of further dissemination of pathogens, as face coverings protect not only the user, but others as well.

Although this study focused on the BFE of different mask samples, they also play an important role in the defense against viral pathogens. However, to properly determine their protection against viruses such as SARS-CoV-2, they must be tested for viral filtration efficiency (VFE). We have also established a protocol for VFE and tested a number of masks using it. The results, which will be published in an upcoming paper, will give insight into the protective abilities of face masks against virus spread.

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Analysis of Educational Building's Ventilation Suitability to Prevent the Spread of Coronavirus (SARS-CoV-2)

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In a larger educational building in Slovenia, we examined the efficiency of ventilation systems by analysing the operation of the heating, ventilation, and air conditioning (HVAC) system in several classrooms. Using the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) COVID-19 ventilation calculator, the probability of infection due to the spread of coronavirus through aerosol particles and the reproduction number were calculated based on the classroom occupancy, ventilation rates, and other parameters (i.e., classroom characteristics, preventive measures). Firstly, different levels of ventilation capacity (50 % and 80 %) were applied. Considering the distance between occupants 1.5 m and wearing the masks of all participants, the probability of infection during lectures was always lower than 1 %. Secondly, the maximum number of students that can attend lectures is about 30 %, as calculated according to the legal requirements, recommendations, and given conditions.

Keywords: classroom ventilation, REHVA calculator, probability of infection, reproduction number, HVAC system

Highlights

- *A mixed-mode ventilation in the examined large classrooms is not appropriate for effective control and prevention of transmission risks in the educational environment.*
- *Considering the ventilation efficiency increase from 50 % to 80 %, in a larger size classroom, the probability of infection is reduced from 0.40 % to 0.27 %.*
- *Considering the ventilation efficiency increase from 50 % to 80 %, in a larger size classroom, the reproduction number decreases from 0.11 to an acceptable level of 0.07.*
- *During the restrictions against the spread of coronavirus, maximum occupancy of the classrooms is not recommended.*

0 INTRODUCTION

It is well known how important the design of heating, ventilation, air conditioning (HVAC) systems is to achieve adequate air quality, while not deteriorating thermal comfort **[1]**. Since the Coronavirus disease COVID-19 outbreak, preventive measures have been taken to mitigate transmission risks (i.e., airborne, contacts) in buildings. Ventilation solutions present the main engineering controls described in the traditional infection control hierarchy **[2]** to reduce environmental risks of airborne transmission **[3]** to **[5]**.

Expelled respiratory droplets that are airborne range from less than 1 μm to more than 100 μm in diameter. Airborne transmission depends on the droplet size and includes i) short-range region for close contact (i.e., large droplets up to 2 mm that fall within 1.5 m) and ii) long-range region (i.e., small droplets less than 50 μm fall beyond 1.5 m distance) **[6]** and **[7]**. In indoor air, coronavirus SARS-CoV-2 can remain active for up to 3 hours and up to 2 to 3 days on room surfaces in common indoor conditions **[8]**. Therefore, the main role of efficient ventilation is to ensure a sufficient amount of fresh air per occupant while simultaneously removing the harmful airborne microbes. A study by Nishiura et al. **[9]** highlighted that the odds that a primary case transmitted COVID-19 in a closed environment was 18.7 times greater compared to an open-air environment.

Poorly designed and/or not properly maintained HVAC systems enable the airborne droplets to be easily transported around the spaces in buildings, and therefore, such a method of transmission is becoming increasingly important **[10]** and **[11]**.

Quite a few studies have been done analysing HVAC systems and the impact of natural ventilation (opening of windows) **[4]**, **[12]** and **[13]**. It was found that with appropriate measures regarding ventilation, the probability of infection is relatively low (less than 1 %) **[14]**.

Similarly, our study aimed to verify the ventilation efficiency in the selected educational building in Slovenia and to calculate the transmission risks for COVID-19. The main question was whether the existing ventilation system meets the requirements of standards to prevent the spread of SARS-CoV-2

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during normal occupancy of classrooms and how the probability of infection could be quantified.

1 METHODS

To be able to assess the current state of the probability of infection in the selected building and to be able to propose appropriate measures, the REHVA COVID-19 ventilation calculator was used **[15]**. The calculation is based on the Wells-Riley model **[16]**, which determines the probability of infection for the selected space and human activity. The probability of infection (p) is defined by Eq (1):

$$p = 1 - e^{-n}, \qquad (1)$$

where n is the number of quanta inhaled.

Quantum represents the number of airborne droplet nuclei that cause infection in 63 % of susceptible individuals. This depends on the origin of the viruses, which is defined with quanta emission rate, E, [quanta/h]. The quanta inhaled (n, quanta) depends on the time-average quanta concentration, C_{avg}, [quanta/m^3], the volumetric breathing rate of an occupant, Q_b, [m^3/h] and the duration of the occupancy, t, [h] as shown in Eq. (2):

$$n = C_{avg} Q_b t. \qquad (2)$$

C_{avg} is defined in Eq. (3), where V represents the volume of the room [m^3], λ is a first-order loss rate coefficient for quanta/h due to the summed effects of ventilation, deposition onto surfaces and virus decay. Values for λ are taken from studies **[17]** to **[19]**. Estimated values for E and Q_b are based on the studies of the Skagit Valley Chorale event **[5]** and quanta generation rates for SARS-CoV-2 **[6]** and are given in Table 1.

$$C_{avg} = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda t}\left(1 - e^{-\lambda t}\right)\right]. \qquad (3)$$

Table 1. *66th percentile SARS-CoV-2 quanta emission rates for different activities* **[20]**

Human activity	Quanta emission rate, E, [quanta/h/occupant]
Resting, oral breathing	0.72
Heavy activity, oral breathing	4.9
Light activity, speaking	9.7
Light activity, singing (or loudly speaking)	62

In addition to the calculation of the probability of infection, it was also necessary to define its acceptable value. For this, several studies propose to define the event reproduction number R. It is defined as the number of new disease cases divided by the number of infectors and its value should be below 0.1 **[15]**.

Table 2. *Volumetric breathing rates* **[21]** *and* **[22]**

Human activity	Breathing rate, Q_b, [m^3/h]
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.10
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.30

Mentioned should also be the assumptions made in this model. It is assumed that quanta are emitted at a constant rate throughout the event; the infected occupant is present in the room throughout all occupancy time; an infectious respiratory aerosol is evenly distributed throughout the well-mixed room air; infectious quanta are removed by ventilation, filtration, deposition, and airborne virus decay.

2 EXPERIMENTAL AND CALCULATIONS

2.1 Experimental

An inspection of ventilation systems with a description of mechanical installations of the selected educational building was made as part of the energy audit in 2012. Mechanical installation systems have not changed much since then, as only service and maintenance works have been carried out in the meantime. We also reviewed some parameters (type of recuperation, surface area, height and volume of the classrooms, air flow rate of air-conditioning (AC) unit, type of air inlet, the maximum number of occupants, number of seats, etc.) and measured them based on the obtained data. The results are given in Table 3. Validation of their Supervisory control and data acquisition (SCADA) system was performed using the reference measuring equipment Testo 400 (Universal IAQ instrument), according to the standard EN ISO 12599 requirements **[23]**. The cross-checking of temperature, CO_2 and air inlet velocity showed that their system deviates by less than 6 % from the reference. It should be noted that the CO_2 sensors from their SCADA system detect a higher value than the reference one, which in turn means that the ventilation turns on at lower CO_2 concentrations and consequently the ventilation is better. At the time of our measurement, the SCADA was set to increase the power of the ventilation system at elevated CO_2 concentrations (>1000 ppm) in the air of classrooms.

Table 3. *Characteristics of AC units, classrooms and analysed ventilation scenarios*

Classroom	Air-conditioning unit	The airflow rate [m³/h]	Surface area of classroom [m²]	Classroom height [m]	Max number of occupants (with 1.5 m distance)
LCR 1_G	NP1: IMP KNMD 9/6 D25	4500	197	2.9	28
LCR 2_G	NP2: IMP KNMD 9/6 D25	4500	198	2.9	25
LCR 3_G	NP3: IMP KNMD 12/6 D25	5800	245	4.5	32
LCR 4_G	NP4: IMP KNMD 12/6 D25	5800	267	3.95	39
LCR 5_G	NP5: IMP KNMD 12/6 D25	9400	307	4.5	35
LCR 6_G	NP6: IMP KNMD 12/6 D25	9400	624	4.5	42
SCR 1_B – SCR 6_B	N1: IMP KNMD 9/9 D25	7505	509	2.9	73

The inspection followed the Methodology for Regular Inspections of Air-conditioning Systems [24].

6 AC units supplied air for 6 large classrooms (LCR) on the ground floor (LCR 1_G – LCR 6_G) and 1 AC unit for small classrooms (SCR) in the basement (SCR 1_B – SCR 6_B).

2.2 Calculations: the Probability of Infection and Reproduction Number

The following assumptions had to be made when calculating the probability of infection and the reproduction number using the REHVA COVID-19 ventilation calculator [15]:

- Proper wearing of the masks of all occupants was envisaged; the value for mask efficiency for susceptible occupant is 0.3, and the value for mask efficiency for the infectious occupant is 0.5.
- The virus decay was the default from the study by van Doremalen et al. [8], and its value is 0.63 h^{-1}.
- Deposition to surfaces was defaulted from the studies by Buonnano et al. [20] and Miller et al. [25], where the value could vary between 0.24 and 1.5 h^{-1}, depending on the aerosol particle size range. For the study, the value taken was 0.24 h^{-1}.
- Additional control measures (such as a removal rate of UV disinfection) were 0 h^{-1}.
- Quanta emission rate was 5 quanta/h.
- Breathing rate was 0.54 m³/h.
- Classroom occupancy was 12 h/day.
- The distance between the occupants is at least 1.5 m.
- There is only one infected occupant in the classroom.

3 RESULTS AND DISCUSSION

As presented in the previous chapter, we analysed the ventilation systems in the educational building and came to the following conclusions:

- All larger ventilation devices have rotary heat exchangers, which means that there is a possibility of the virus being transferred back into the classroom in the event of a leak.
- There is mixed-mode ventilation in large classrooms, which is not suitable for keeping the sufficient quality of air in the classroom. Small classrooms have a displacement mode of ventilation, which is more suitable from the air exchange point of view.
- The windows were opened after each lecture so that a large number of windows were completely opened for several minutes. Windows were also opened if the CO_2 sensor showed values above 1000 ppm.
- Ventilation ducts are not being cleaned.
- Large classrooms have ventilation efficiency controlled by CO_2 sensors, while small classrooms do not.

The results obtained from the computations are shown in Figs. 1 to 4 and Table 4. For LCR 1_G – LCR 6_G, the ventilation capacity was set at 50 % and 80 % (Figs. 1 and 2), and for SCR 1_B – SCR 6_B was assumed the ventilation with the same share of airflow (Figs. 3 and 4). Note: in some figures, the lines overlap.

As seen from Fig. 1, the probability of infection after 12 h is the highest in LCR 2_G, when it reaches 0.4 % with 50 % ventilation capacity. If ventilation capacity is increased to 80 %, the probability of infection is reduced to 0.27 %. This means a 28 % lower probability of infection. The lowest probability of infection is in LCR 6_G and LCR 5_G.

The same is true when comparing the reproduction number (Fig. 2). At 50 % ventilation capacity, the maximum value is 0.11 in LCR 2_G, and at 80 %, it is reduced to 0.07. The recommended value of the reproduction number is 0.5, and to control the epidemic, it should be kept below 1 [1].

It was envisaged that the fresh air is distributed equally among SCR 1_B – SCR 6_B. We can see that the probability of infection is still below 1.5 % (Fig. 3). The reproduction number is the highest in SCR 5_B (0.21 – Fig. 4), which is also the most problematic classroom because it has no windows. In Figs. 1 to 4, the values only consider the transmission of the virus by air in aerosols, i.e., assuming a distance of 1.5 m between occupants. Transmission with contact or droplets is not taken into account.

The evaluation of the adequacy of the value of ventilation was carried out with the legally required **[24]** and recommended values **[26]**, where large classrooms (LCR 1_G – LCR 6_G) require 30 m^3/h air per occupant. 4 loads of classrooms were inspected (scenarios S1 – S4) according to the number of occupants present, which were determined for each classroom separately:

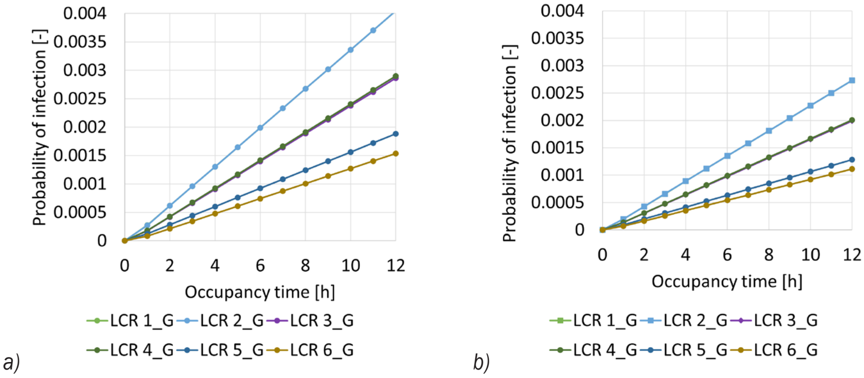


Fig. 1. *Probability of infection for the ground floor and the ventilation of a maximum value of; a) 50 %, and b) 80 %*

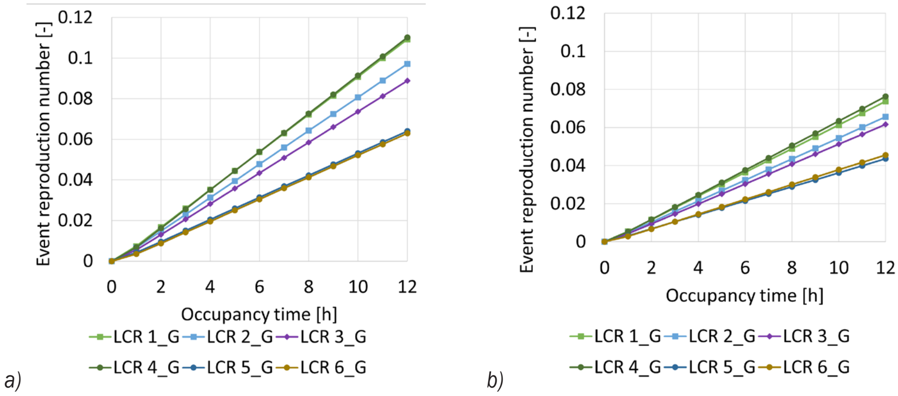


Fig. 2. *Event reproduction number for the ground floor and the ventilation of a maximum value of; a) 50 %, and b) 80 %*

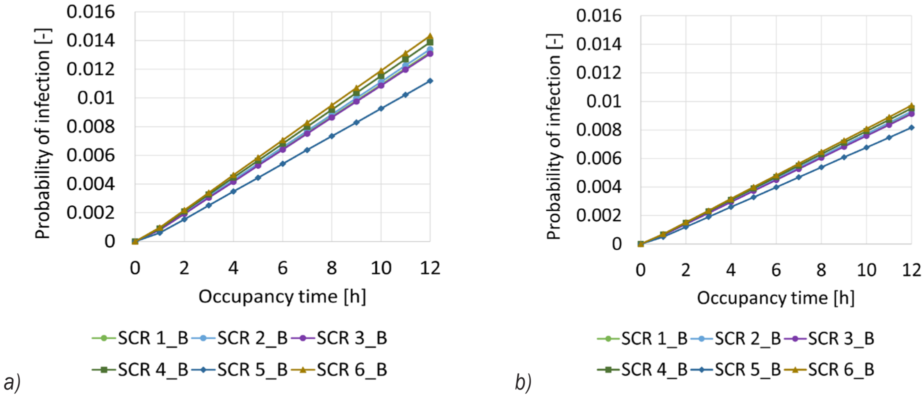
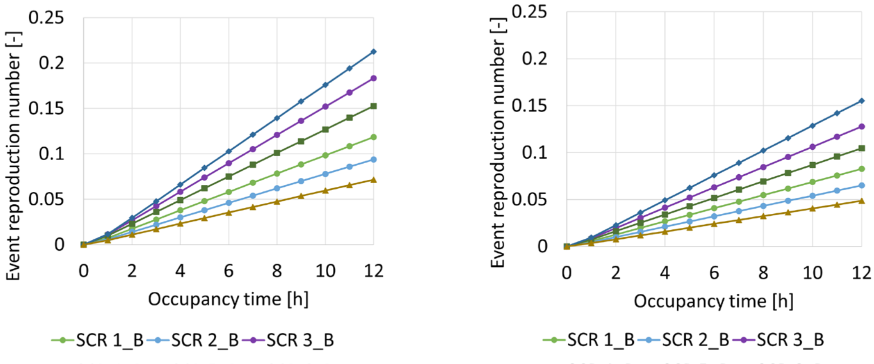


Fig. 3. *Probability of infection for the basement and the ventilation of a maximum value of; a) 50 %, and b) 80 %*



a) b)

Fig. 4. *Event reproduction number for the basement and the ventilation of a maximum value of; a) 50 %, and b) 80 %*

Table 4. *Set of scenarios on occupational load, airflow and AC capability*

Classroom	Number of seats [-]	AC capability at 100 % [m³/h]	S1: Covid - needed airflow [m³/h]	S2: 50 % occupancy - needed airflow [m³/h]	S3: max occupancy – needed airflow [m³/h]	S4: max number of occupants at 100 % capability [-]
LCR 1_G	210	4500	840	3150	6300	150
LCR 2_G	196	4500	750	2940	5880	150
LCR 3_G	270	5800	960	4050	8100	193
LCR 4_G	330	5800	1170	4950	9900	193
LCR 5_G	304	9400	1050	4560	9120	313
LCR 6_G	200	9400	1260	6000	6000	313
SCR 1_B	63	1250	300	945	1890	41
SCR 2_B	56	1250	240	840	1680	41
SCR 3_B	56	1250	450	840	1680	41
SCR 4_B	42	1250	360	630	1260	41
SCR 5_B	70	1250	600	1050	2100	41
SCR 6_B	12	4500	180	180	360	41

S1: Subject to minimal required airflow and COVID-19 recommendations, safety distance between persons 1.5 m.
S2: Half occupancy of classrooms.
S3: Maximum load after the epidemic (full occupancy of classrooms with occupants).
S4: Sufficient air volume (30 m³/h/person), 1.5 m distance between persons not taken into account.

S1: Subject to all regulations and COVID-19 recommendations, safety distance between occupants 1.5 m.

S2: Half occupancy of classrooms.

S3: Maximum load after the epidemic (full occupancy of classrooms with occupants).

S4: Sufficient air volume (30 m³/h/occupant), 1.5 m distance between occupants not considered.

Table 4 lists the number of seats in each classroom, the maximum airflow that AC units can supply (100 % capability), required airflow rate according to S1 and S2. The amounts of air determined by the REHVA calculator for one-third load of classrooms with users (S1) represent a minimal risk of infection and at the same time meet the requirements of the regulations and recommendations of the standard. The quantities for the anticipated half-load in scenario S2 are sufficient and meet the requirements of the rules and recommendations of the standard, except for LCR 4_G and SCR 5_B. It should be noted that the quantities in S2 are valid only for the time after COVID-19 as minimum distance of 1.5 m is not achieved.

The quantities set for the estimated maximum load in scenario S3 do not meet the requirements. The S4 scenario includes the maximum number of students in each classroom to meet the requirements. This scenario is taken into account only in the period after the end of the COVID-19 pandemic, as it does not take into account the distance of 1.5 m between space users.

5 CONCLUSIONS

Using the REHVA calculator, the probability of infection due to the spread of coronavirus through aerosol particles and the reproduction number for each classroom at the selected educational building were calculated. Considering the distance between occupants 1.5 m and wearing the masks of all participants, the probability of infection was always lower than 1 %. The acceptable reproduction number is less than 0.1 which was achieved in most of the cases. The most critical are cases with 50 % capability and when the occupancy time approaches 12 h. In reality, such a case is highly unlikely therefore spread of the virus should not be an issue.

In the calculations for the maximum allowed number of people in each classroom assuming all corona measures, i.e. 1.5 m distance and wearing the mask of all participants, about a third of the number of seats could be occupied.

The AC system was analysed also according to the required amount of fresh air to define how many people can be in individual classrooms with four specific scenarios (S1 to S4). It should be noted that scenarios S2, S3 and S4 are not appropriate during the COVID-19 situation and do not take into account the distance of 1.5 m, but the prescribed value of the fresh air is guaranteed according to the rules (ventilation rate of 30 m^3/h/occupant). Due to the construction of the ventilation system at the educational building before 2002, when the Rules on ventilation and air conditioning of buildings **[27]** were amended, we concluded that the occupancy of large classrooms could be 70 % if the ventilation system is operating at full power. In the case of full-day occupancy of large classrooms the ventilation system operating with at least 80 % power is recommended. In the case of 80 % ventilation capacity, a sufficient amount of fresh air is provided for the half occupancy of classrooms.

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Comparison Study of Four Commercial SARS-CoV-2-Rapid Antigen Tests: Characterisation of the Individual Components

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During the corona virus (COVID-19) pandemic, there was a sharp increase in the need for diagnostic tests that could detect the presence of SARS-CoV-2 virus or its antibodies quickly and reliably. An important type in the group of diagnostic tests are rapid antigen lateral flow immuno-assay (LFIA) tests, which operate on the immuno-chromatographic principle with the lateral flow of analyte. Clinical practice in the last year has shown that such diagnostic tests can be effective in preventing the spread of the SARS-CoV-2 virus.

The development, and, thus, the production of the rapid antigen LFIA tests, is influenced by a number of factors that determine their sensitivity and accuracy indirectly. These factors are directly dependent on the type of antibody produced, which is formed as an immune response when infected with the virus. The production of the rapid antigen LFIA tests is associated with the appropriate selection of basic components that determine the type and quality of these tests. The basic components include: substrates and membranes, antigens, antibody labels and compatible buffers. The correct choice of membranes and their materials is crucial to compiling an effective rapid antigen LFIA test.

This study therefore presents a comparative analysis of four commercially available SARS-CoV-2-rapid LFIA tests using state-of-the-art characterisation techniques scanning electron microscopy (SEM), inductively coupled plasma-optical emission spectrometry (ICP-OES), environmental scanning electron microscope / energy-dispersive X-ray spectroscopy (ESEM/EDX), Fourier-transform infrared spectroscopy / attenuated total reflection (FTIR/ATR) for the individual components. The obtained results were the starting point for the development and assembling of our own rapid antigen LFIA test based on gold nanoparticles as antibody labels.

Keywords: rapid antigen test, components, characterisation, analysis

Highlights

- *The characteristic of commercially available SARS-CoV-2-rapid LFIA tests were studied.*
- *The structures and morphology of the pads (sample, conjugate, additional pad, absorbtion) were described.*
- *The Au content in the conjugate pad varies between 0.05 µg to 0.12 µg.*
- *The presence of the impurities: Ca, Al, Si, K, Fe and Ni was detected by ESEM/EDS analysis on fibre surfaces in the conjugated pads.*
- *The total time until the control line becomes visible varies between 42.5 s to 86.77 s.*

0 INTRODUCTION

Given the severity, speed and complexity of the transmission of SARS-CoV-2 virus, it is particularly important for early diagnosis and understanding of the epidemiological characteristics of the disease, to ensure the safety of the population while reducing disease transmission. The field that offers innovative solutions to many clinical problems related to the diagnosis, treatment and prevention of COVID-19 is the field of Nanotechnology and the use of nanomaterials for virus detection. Among nanomaterials, gold nanoparticles (AuNPs) are the most promising, as they have unique optical properties associated with localised surface plasmon resonance, and, at the same time, they are highly biocompatible [1] and [2]. AuNPs can also be used use in medicine and biomedicine, especially in diagnosing viruses, bacteria, as well as in the treatment of cancer. In order to prevent the spread of COVID-19, a fast and reliable diagnosis is a must [3] to [6].

Lateral flow immuno-assay (LFIA) is a quick and easy method to detect various analytes (viruses, antibodies, bacteria, hormones, etc.) in various samples, such as blood, urine, saliva, serum, plasma. The result of the test is shown in only a few minutes, and the result itself is the signal (colour) of the test area test line, which is most often marked as ‘’T’’. The indicating pigment is formed from protein conjugates with AuNPs, that can bind selectively to specific proteins or molecules [7]. These are later immobilised on a thin line when they are captured by surface bound antigen molecules on the test line. AuNPs, namely, give quantitative and/or semi-quantitative responses, and, with that, a direct signal soon after the reaction with the proteins.

Rapid antigen LFIA tests present an important aspect in preventing the spread of the diseases such as SARS-CoV-2 coronavirus (COVID-19) [8]. The principle of operation of a typical LFIA test is simple: A liquid sample (or an extract thereof) containing the analyte is applied to a sample pad that acts like a sponge, as it retains the excess liquid sample. After

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wetting the sample pad, the sample begins to move laterally due to capillary action - first to a conjugate pad containing the applied dry AuNPs or a similar marker (e.g., latex, silica, carbon) **[9]** conjugated to a specific protein such as the SARS-CoV-2 Spike S1 antigen, and AuNPs conjugated to monoclonal recombinant IgG antigens (e.g., rabbit, mouse, chicken) **[10]** and **[11]**. At this point, a chemical reaction (binding) occurs between the desired analyte and AuNPs conjugated to the SARS-CoV-2 Spike S1 antigen to form a complex. The antibody-conjugate/analyte complex is captured on the test line, which contains either an identical protein or similar antigens. The remaining AuNPs conjugated with the IgG antigen travel to the control line, which is most often marked: ‘’C”, and are immobilised, forming a line. After passing the sample across the membrane and test lines, the excess fluid or buffer is adsorbed into the absorbent pad.

If the target analyte is present, the test line will be coloured. The control line must be coloured even if the target analyte is not present, since this signifies the correct operation of the test.

Acute coronavirus 2 respiratory syndrome (SARS-CoV-2) leads to the infectious disease COVID-19, first reported in Wuhan, China in December 2019. Since then, the disease has spread worldwide. SARS-CoV-2 is a highly contagious virus and spreads to humans through the respiratory tract, especially through droplets, aerosols, and contact with contaminated surfaces **[12]**. The number of virus replicates was estimated to be about 2.68, with a doubling time of 6.4 days. Its incubation period from infection to the first symptoms in a person is, on average, 5 to 14 days **[13]** and **[14]**.

SARS-CoV-2 is a single-stranded, positive-directional RNA virus. The virus belongs to the genus beta-coronaviruses, and has a diameter of 50 nm to 200 nm. SARS-CoV-2 is characterised by spike glycoproteins that protrude from its surface and give it its characteristic appearance. The SARS-CoV-2 genome encodes four major structural and functional proteins: Thorns (S), membrane (M), envelope (E), and nucleocapsid (N) proteins. Protein S consists of two functional subunits, S1 and S2; S1 is responsible for recognising and binding the host cell receptor, i. angiotensin 2 conversion enzyme (ACE2) **[15]**, while S2 mediates membrane fusion. Protein M is the most common structural protein that determines the shape of the virus. Protein N is the most secreted viral protein among infections, and can be detected in serum and urine samples during the first two weeks of infection. The smallest major structural protein is E, which is involved in the virus assembly and pathogenesis **[16]** and **[17]**. Lateral traction analysis allows qualitative virus detection. Such tests have many advantages for rapid diagnostic testing of COVID-19, as they are simple, affordable, require minimal sample volumes (10 µL to 20 µL), do not require additional analytical equipment and give results in minutes **[18]**.

A key requirement for LFIA rapid antigen tests set by the World Health Organization is that they have at least 90 % diagnostic sensitivity. In the case of diagnostic performance compared with the device used as a reference, the diagnostic sensitivity must be at least equivalent to the reference devices as defined in Directive 98/79/EC. The diagnostic specificity must be at least 98 %. Assessments of diagnostic specificity and diagnostic sensitivity must have at least 95 % confidence intervals **[19]**. In this study, we compared four commercially available rapid antigen LFIA tests using state-of-the-art characterisation techniques for individual components, with the aim of identification their chemical composition and other properties that are crucial for the operation of these tests.

1 EXPERIMENTAL

Four (4) LFIA rapid antigen tests from different manufacturers were evaluated according to their individual components, their chemical composition, morphology and structure. The following rapid tests were examined, as presented in Table 1. Particular attention was focused to the investigation of a conjugate pad containing dry antigens conjugated with AuNPs.

To achieve a concise overview of their manufacture we used the following analytical methods:

Table 1. *List of the Sars-Cov-2 LFIA antigen rapid tests*

Short name	Full name	Manufacturer
Acro	ACRO Rapid Test	ACRO BIOTECH, Inc.
Citest	Citest	CITEST DIAGNOSTICS INC.
Singclean	Singclean IVD COVID-19 Test Kit (Colloidal Gold Method)	Hangzhou Singclean Medical Products Co., Ltd.
UNscience	UNscience SARS-CoV-2 Antigen Rapid Test	Wuhan UNscience Biotechnology Co., Ltd.

1.1 Scanning Electron Microscopy (SEM)

SEM (SEM, FEI Sirion 400 NC, FEI Technologies Inc., Hillsboro, Oregon, USA) was used for observation of all the different membranes` structures (sample pad, conjugate pad, additional pad, chromatographic membrane, absorbtion pad) from the chosen rapid antigen LFIA tests. The samples were glued onto graphite holders. To minimise static charging with the electron beam during SEM observations and to ensure sample conductivity, the samples were subsequently sputtered on a JFC-1100E ion sputter machine (Jeol, Akishima, Japan) with Au for 40 s at a distance of 3 cm from the Au source.

1.2 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)

The ICP-OES (Agilent 720/725 ICP-OES, Agilent Technologies, Santa Clara, USA) analysis was used for the measurement of the Au content on the conjugate pads. The following procedure was performed in order to measure the Au concentration: The conjugate pads were removed from the test strips and immersed in 0.5 mL of Phosphate buffered saline (pH = 7.4, Sigma-Aldrich Chemie GmbH Steinheim, Germany) and sonicated for 15 min, in order to ensure adequate Au release. Prior to analysis, the sample was acidified with aqua regia, and the analysis was performed at the following operating parameters: RF power: 1.5 kW, nebuliser: Meinhard, plasma flow: 15 L/min, nebuliser flow gas: 0.85 L/min, make up gas flow: 0.28 L/min, reaction gas flow: 4.0 mL/min. Calibration of the instrument was performed with matrix standard calibration solutions. The relative measurement uncertainty was estimated to be ± 3 %.

1.3 Environmental Scanning Electron Microscope (ESEM) with Energy Dispersion Spectrometer (EDS)

An ESEM (Thermo Fischer Scientific, environmental Prisma-E) was used in an attempt to evaluate the structure and composition of the conjugate pads. The purpose of this observation was to obtain information on the volume distribution and potential type of surface binding of AuNPs. Samples were non-coated, and analysed at 40 Pa to avoid degassing and vacuum drying of the sample. An EDX semi-qualitative analysis using a detector (EDS Oxford INCA 350) was performed to obtain information about the chemical composition and distribution of the individual elements (as element mapping). EDS mapping was performed in an attempt to differentiate Au from the background.

1.4 LFIA Test Duration

The speed of the chosen rapid antigen LFIA tests` duration was measured by using the tests as intended, and as described in the accompanying instructions with just their supplied buffer solution. The start time was taken when the first drop was placed into the sample well, and the end time just as the control line began to become visible. This was done on 6 consecutive tests for each different test to get an average value.

1.5 Fourier-Transform Infrared Spectroscopy (FTIR) with Attenuated Total Reflection (ATR)

The chemical composition of the membranes for all chosen rapid antigen LFIA tests was determined with FTIR (Spectrum 3, Perkin Elmer, Waltham, USA) and ATR (GladiATR, Pike Technologies, Fitchburg, USA) spectroscopy. The samples were placed face up on the ATR crystal, so as to avoid the adhesive backing that is used in rapid antigen LFIA tests. The samples were scanned in the range of 650cm^{-1} to 4000 cm^{-1}, with 4 samples` scans.

2 RESULTS

2.1 Scanning Electron Microscopy (SEM)

SEM micrographs of all membranes` structures from the sample pad, conjugate pad, additional pad and chromatographic membrane were taken at comparative and identical magnifications. In this way, an insight was obtained into the structure and morphology of each component.

SEM analysis revealed that the sample pads were composed of interwoven glass fibres, together with a binder (Figs. 1a to 4a). The diameter of the glass fibres bottles was a few µm.

SEM analysis of the conjugate pads showed that they were also composed of fibres, which had a bigger diameter of some 10 µm. The use of inert materials in the conjugate pad is crucial, as they must ensure low non-specific binding to the analytes, allow a constant and even flow of the sample, as well as a consistent volume of reagent / buffer [20] and [21]. The conjugate pads in the Acro and Citest rapid antigen tests were composed of organic polymer fibres (Figs. 1b and 2b), compared to the Singclean and UNscience rapid tests (Figs. 3b and 4b) which had a fibreglass-based pad.

The Acro and Citest tests had an additional pad (Figs. 1c and 2c), with similar structural and morphological properties as the conjugate pad. Examination showed that it was composed of tightly woven polymer fibres. Its intended function was most likely as a filter pad, meant to protect the fine-pores of the chromatographic membrane.

The surface of the chromatographic membranes of the Acro and Citest tests (Figs. 1d and 2d) were visibly more uniform in morphology when compared to the Singclean and UNscience tests (Figs. 3c and 4c). It is a representation of a homogeneous network structure. Due to such a surface topology, these rapid antigen tests have a larger surface area in the chromatographic membranes. In contrast, at larger magnifications, the finer pore sizes of the Acro and Citest tests (Figs. 1e and 2e) clearly indicate that they have a significantly higher available surface area. The surface area in the

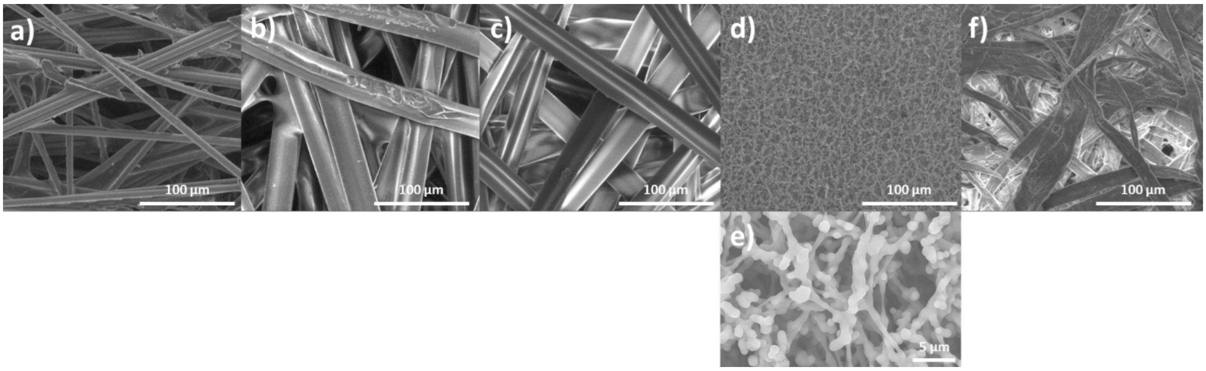

Fig. 1. *SEM micrographs of the Acro rapid antigen test membranes: a) sample pad, b) conjugate pad, c) additional pad, d) chromatographic membrane, e) detail from the chromatographic membrane, f) absorption pad*

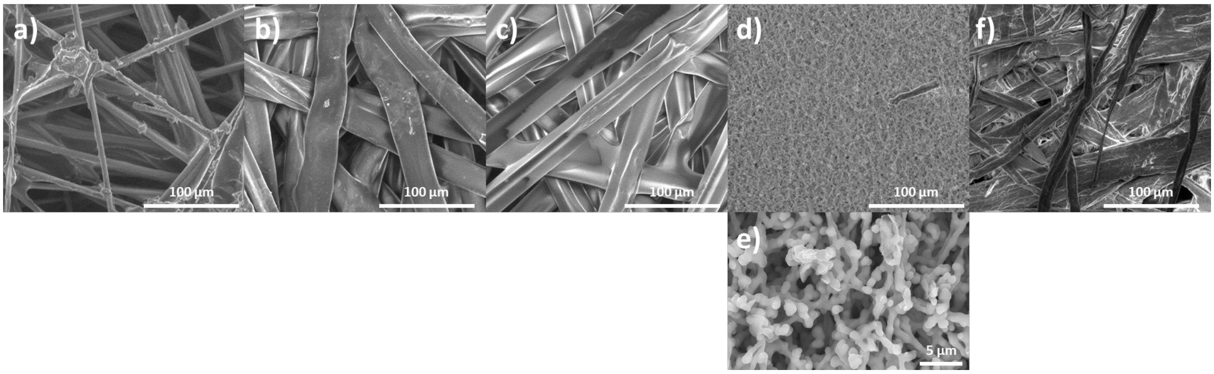

Fig. 2. *SEM micrographs of the Citest rapid antigen test membranes: a) sample pad, b) conjugate pad, c) additional pad, d) chromatographic membrane, e) detail from the chromatographic membrane, f) absorption pad*

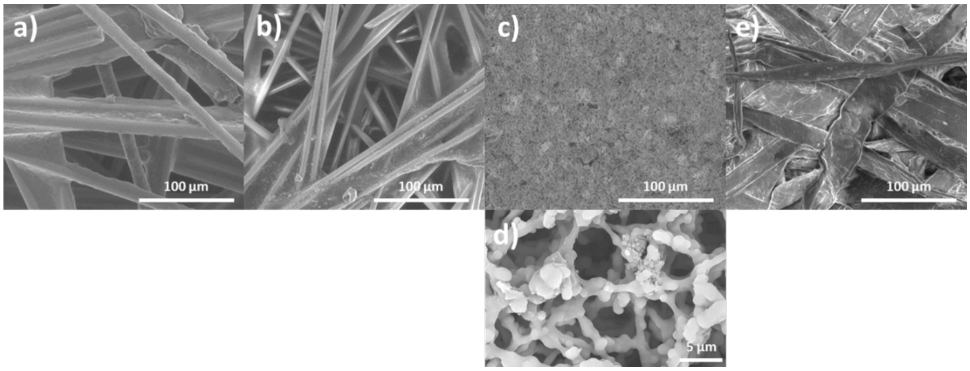

Fig. 3. *SEM micrographs of the Singclean rapid antigen test membranes: a) sample pad, b) conjugate pad, c) chromatographic membrane, d) detail from the chromatographic membrane, e) absorption pad*

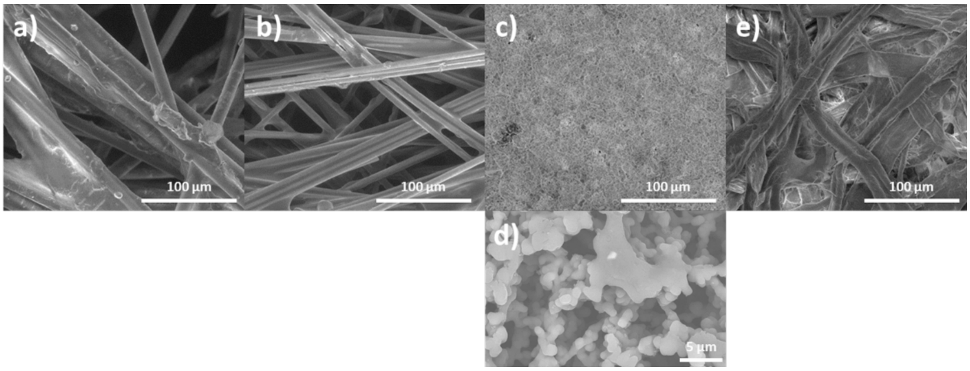

Fig. 4. *SEM micrographs of the Singclean rapid antigen test membranes: a) sample pad, b) conjugate pad, c) chromatographic membrane, d) detail from the chromatographic membrane, e) absorption pad*

chromatographic pad was of concern, since it dictates the degree to which it is possible to bind the binding biomolecules to the membrane. This is the place where the binding between the nitrocellulose esters and protein dipoles takes place **[21]** and **[22]** with an average diameter of approximately 18 nm. We used the conjugation between AuNPs and MAbs against SSd to prepare immunochromatographic strips (ICSs.

The SEM micrographs show that the structure of the absorption pads was almost similar, and no porosity was observed (Figs. 1f and 4f). The fibres were non-uniform in width and compressed in several planes.

2.2 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)

Table 2 shows the average Au content in each rapid antigen test, obtained indirectly by the ICP-OES method. The results suggest that the Au content in the rapid antigen test varies between 0.05 µg to 0.12 µg on a single conjugate pad. The lower concentration of Au in the Acro and Citest tests also suggests higher colour intensity and plasmonic resonance in the AuNPs that were used **[23]** and **[24]**.

Table 2. *Au content on single conjugate pads*

Test	m (Au) on single conjugate pad [*µ*g]
Acro	0.055
Citest	0.05
Singclean	0.125
UNscience	0.105

2.3 Environmental Scanning Electron Microscope (ESEM) with energy dispersion spectrometer (EDS) mapping

ESEM by using EDS quantitative analysis was performed to determine the distribution of individual elements to gain insight into the elemental mapping on the fibre surface of the conjugate pad.

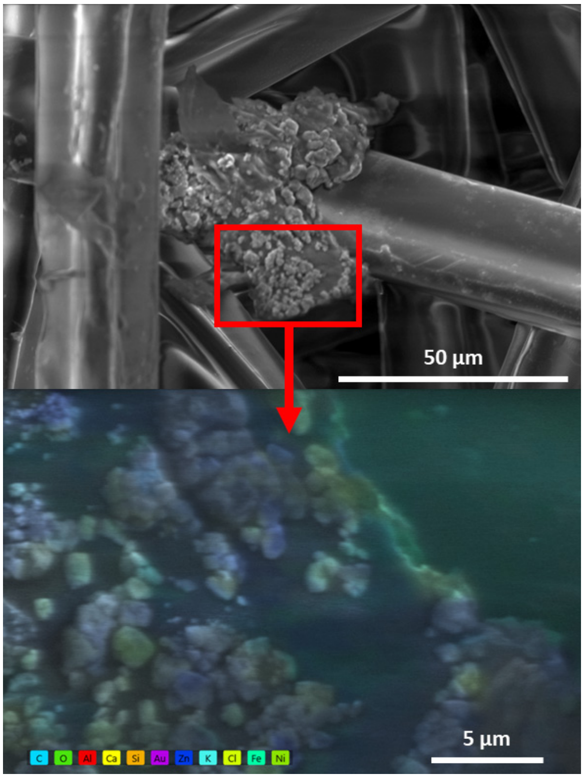

Fig. 5. *ESEM/EDS elemental mapping on the fibre from the conjugate pad (Acro rapid antigen test)*

Fig. 5 shows the EDS elemental mapping of the area on the fibre surface (as presented with the red frame) of the Acro rapid antigen test conjugate pad.

The analysis confirmed the presence of ZnCl on the fibre surface, as well as carbon and oxygen, which are present throughout the analysed area and originated from the polymer base. No Au was detected in this rapid antigen test, as well as no impurities such as e.g. Ca, Al, Si, K, Fe and Ni.

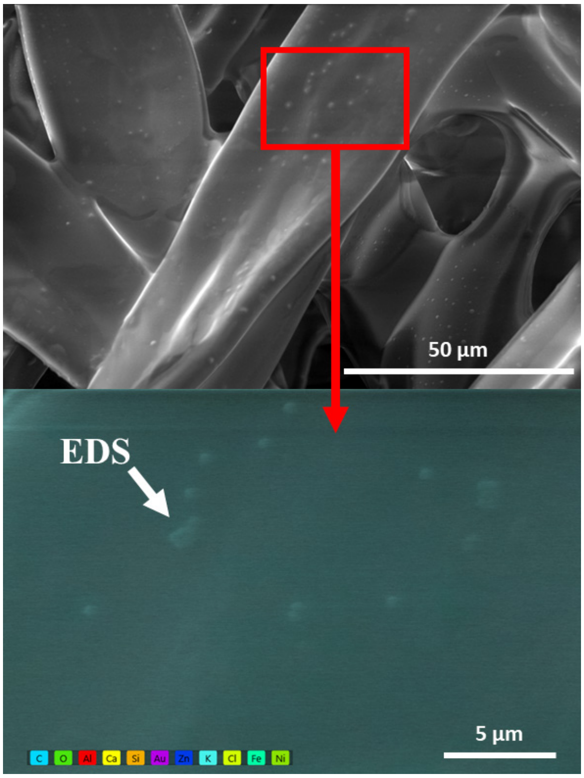

Fig. 6. *ESEM/EDS elemental mapping on the fibre from the conjugate pad (Citest rapid antigen test)*

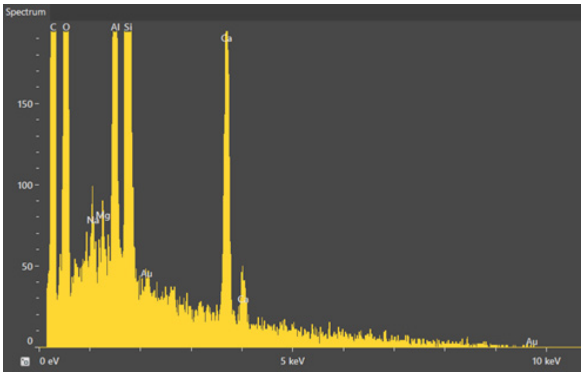

Fig. 7. *EDS spectrum of the surface spots - link Fig. 6*

Fig. 6 shows the EDS elemental mapping of the area on the fibre surface of the conjugate pad of the Citest rapid antigen test. Carbon and oxygen are present across the entire analysed area. Au and impurities such as Ca, Al, Si, K, Fe and Ni were

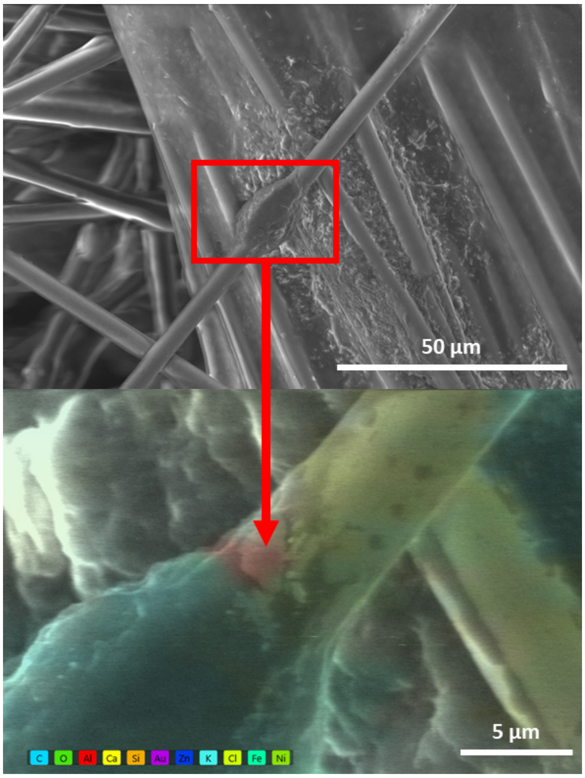

Fig. 8. *ESEM/EDS elemental mapping on the fibre from the conjugate pad (Singclean rapid antigen test)*

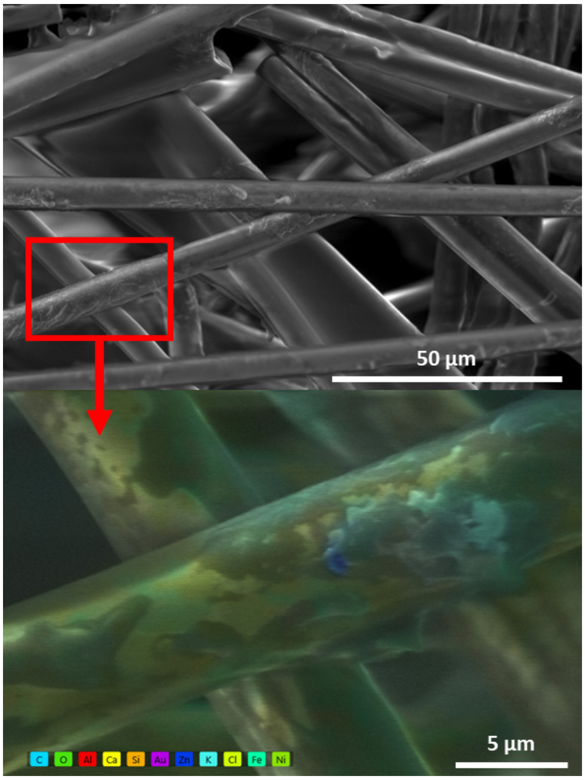

Fig. 9. *ESEM EDS map of the UNscience test conjugate pad*

detected in trace amounts. The additional EDS point analysis shows that the spots on the fibre surface are rich in Al (see the spectrum in Fig. 7).

Fig. 8 shows the EDS elemental distribution of the region on the fibre surface of the Singclean rapid antigen test conjugate pad. The fibres appear to be rich in Si, Ca and Al. Au and impurities such as Ca, Al, Si, K, Fe and Ni were detected in traces at the sites of analysis. The fibres are mostly organic, consisting of O and C.

Fig. 9 shows the EDS elemental distribution of the area on the fibre surface of the UNscience rapid antigen test conjugate pad. The fibres appear to be rich in Si, Ca, K and Al. Au and additional impurities Fe and Ni were detected in traces at the analysis sites. Also, here, the analysis shows that the fibres are mostly organic, consisting of O and C.

Based on the revealed morphology of AuNPs, it can be concluded that the AuNPs were synthesised with the same technology.

2.4 LFIA Test Duration

The total test time of all SARS-CoV-2 antigen rapid tests was read from the instructions, and was, in almost all cases, recommended at about 20 min. This time is defined as required in order to ensure that all the reagents have time to be rehydrated, released, and can react with the target proteins.

Experiments with all the SARS-CoV-2 antigen rapid tests have shown that the total time until the control line becomes visible, was considerably shorter compared to the instructions (see Table 3). On this basis, the fact was established that the affinity between the conjugated AuNP and glass fibres was significantly lower. This means that it took significantly less time to colour the control line and its full visibility. The next important finding is that the time when the control line is completely coloured is of the essence. Namely, a faster time usually does not mean that a quick antigen test is better. Previous studies [21], [22], [25] and [26] have found the exact opposite, finding that the longer the analyte flow time, the longer the test time, the better the sensitivity of the rapid antigen test.

2.5 Fourier-Transform Infrared Spectroscopy (FTIR) with Attenuated Total Reflection (ATR)

FTIR/ATR spectra of the individual pads were performed in order to identify their composition. Since conjugate pads are coated with AuNPs` conjugates, before analysis they were washed with demineralised water and sonicated individually for 1 min in demineralised water.

The spectra of the individual sample pads for all rapid antigen tests as shown in Fig. 10, indicate that they are composed of silicon boron glass fibres. The EDX spectrums (from Part 2.3) suggest a similar composition. FTIR also revealed the presence of a polyester based binder [27].

The spectra in Fig. 11 showed that both the Acro and Citest rapid antigen tests use a similar material for a polyester fibre-based conjugate pad [27]. In comparison, the spectra of the Singclean and UNscience conjugate pads, shown in Fig. 12, revealed that they are composed mainly of glass fibres. The spectra suggest that small residues of the binder remained. Most of the binder was likely removed during the washing steps. Both the Acro and Citest tests had an additional pad, placed after the conjugate pad. The chemical composition as identified by FTIR is shown in Fig. 13, and it was identical to the polyester based conjugate pads. The SEM micrographs, however, revealed a significantly finer pore size, suggesting these pads are used for filtration.

The chemical composition of the chromatographic membrane was similar in all the sampled tests. The spectra displayed in Fig. 14, reveal the content of a nitrated cellulose [28]. Analysis of the absorption pads revealed that they are composed of cellulose, as shown in Fig. 15.

3 DISCUSSION

Detailed analysis of the SEM micrographs showed that the available rapid antigen LFIA tests are

Table 3. *Time needed for the control line to become visible*

Test	*t* [s]							t [s]						
	t_1	t_2	t_3	t_4	t_5	t_6	Average	t_1	t_2	t_3	t_4	t_5	t_6	Average
Acro	52	55	52	60	57	54	55.00	56	59	54	60	59	56	57.33
Citest	55	60	60	62	63	55	59.17	74	80	91	83	78	78	80.67
Singclean	35	37	35	39	43	38	37.83	44	42	42	44	56	43	45.17
UNscience	41	42	38	40	28	32	36.83	44	45	46	49	33	38	42.50

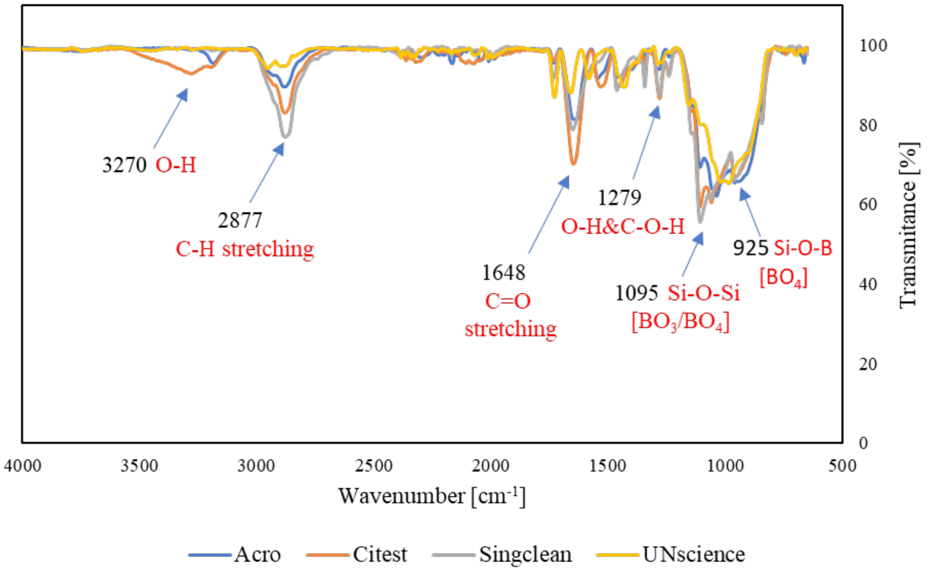

Fig. 10. *ATR-FTIR spectra of sample pads for all rapid antigen tests indicate the presence of glass fibres with a polyester-based binder*

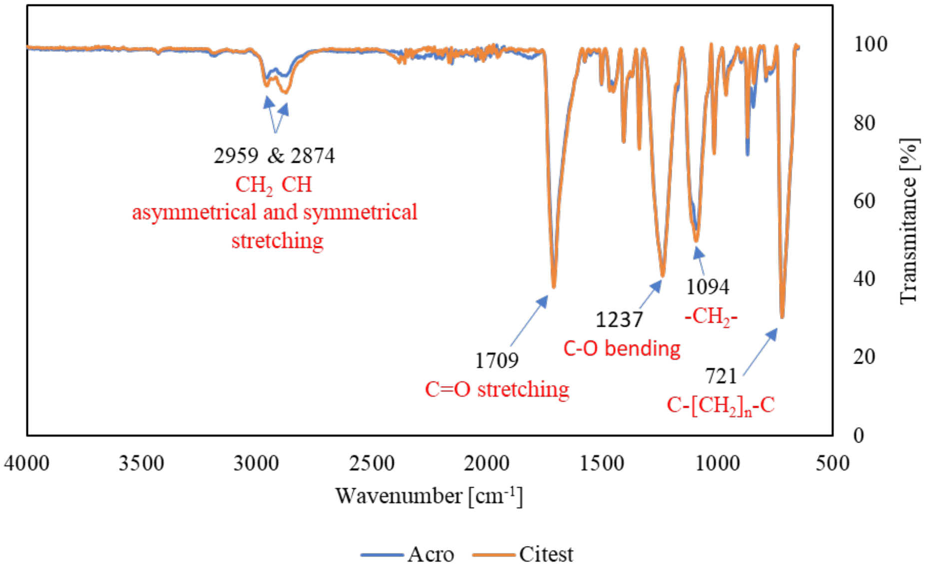

Fig. 11. *ATR-FTIR spectra of the conjugate pads from the Acro and Citest rapid antigen tests show the presence of polyester fibres*

generally similar in construction, not in the materials used, and with some special technical details such as the use of additional filter membranes. Comparative SEM/ESEM/EDX and FTIR/ATR analyses revealed that the use of fibrous materials was limited to polymers, cellulose, glass fibres and nitrocellulose. Investigations have shown, that nitrocellulose is an exclusive material that is used typically in chromatographic membranes.

The ESEM/EDS elemental mappings showed significant contaminations with impurities such as Ca, Al, Si, K, Fe and Ni in the conjugate pad. Whether this was a result of impurities in the reagents or residue from machinery cannot be determined at this point. The results of the impurity research show that LFIA rapid antigen tests are insensitive to impurities, although their concentration on the conjugate pad is not negligible. The presence of Si and Al, as detected by EDX analysis, and the presence of B-Si glass detected by FTIR, indicate that the glass fibres are based on the borosilicate glass of alumina.

A study of the individual components of four commercially available rapid antigen LFIA tests showed that the materials used for the key components

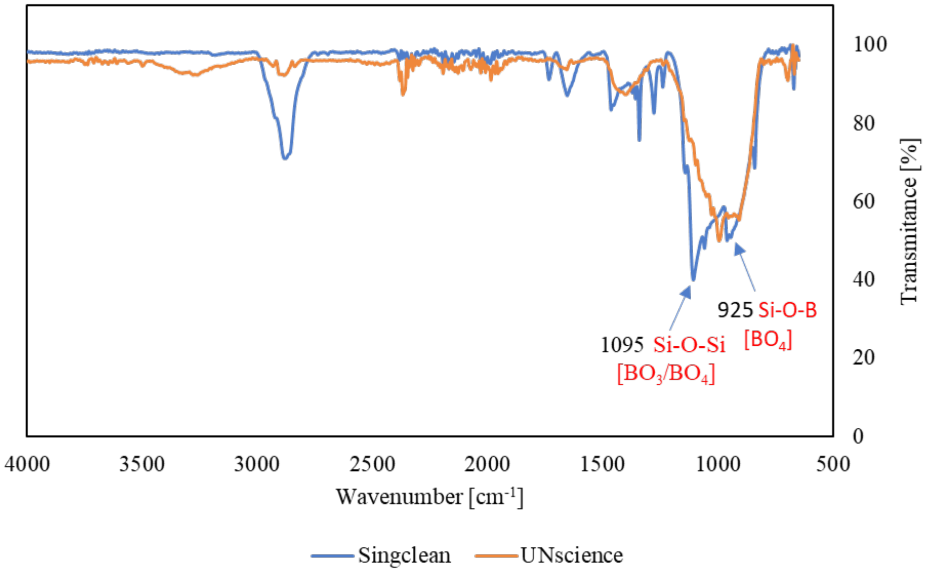

Fig. 12. *ATR-FTIR spectra of the conjugate pads from the Singclean and UNscience rapid antigen tests show the presence of glass fibres with a binder residue*

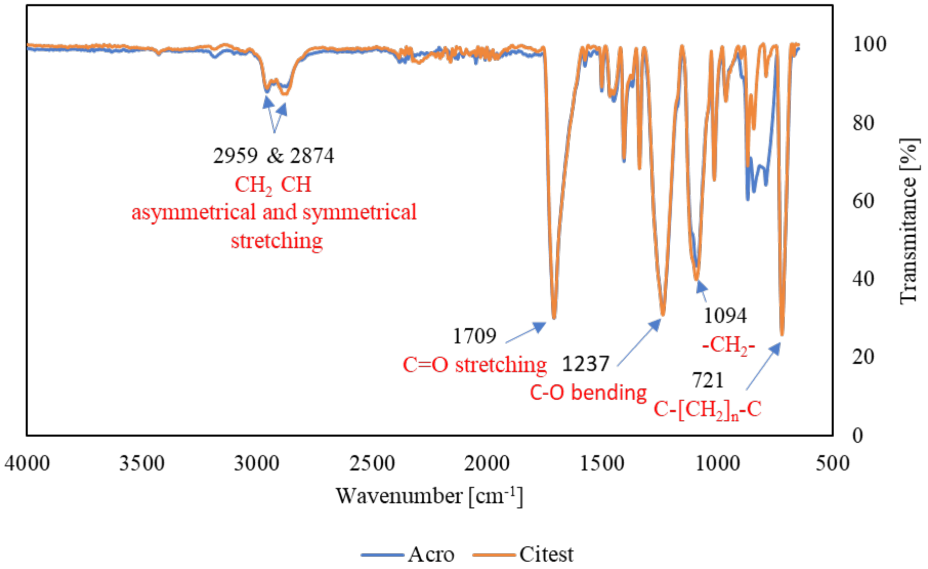

Fig. 13. *ATR-FTIR spectra of additional pads on the Acro and Citest rapid antigen tests*

are different. On the contrary, a review of the literature **[25]**, **[29]** and **[30]** showed that the materials currently used for development of rapid antigen LFIA tests are completely different.

The results of the SEM investigations showed that the selection of sample and conjugate pad material did not affect the performance of the rapid antigen LFIA test used significantly. The structure of the chromatographic membrane has the greatest influence on the sensitivity of the test, where the key factor is the size of the pores, which direct the performance, sensitivity and speed of the rapid antigen LFIA tests **[31]**.

The structure of the chromatographic membranes is homogeneous, with porous spaces about 5 µm in size, as can be seen from the SEM micrographs. From the results of an additional experiment that revealed the time required to obtain the coloured control line, it can be estimated that faster LFIA antigen tests have chromatographic membranes **[21]** with larger pores that are estimated to be > 5 µm.

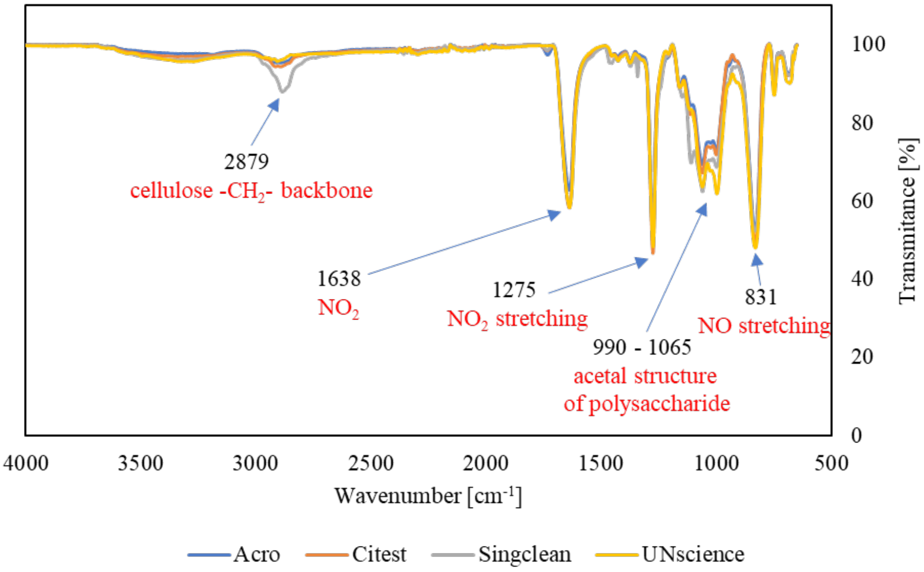

Fig. 14. *ATR-FTIR spectra of the nitrocellulose-based chromatographic pads for all the rapid antigen tests*

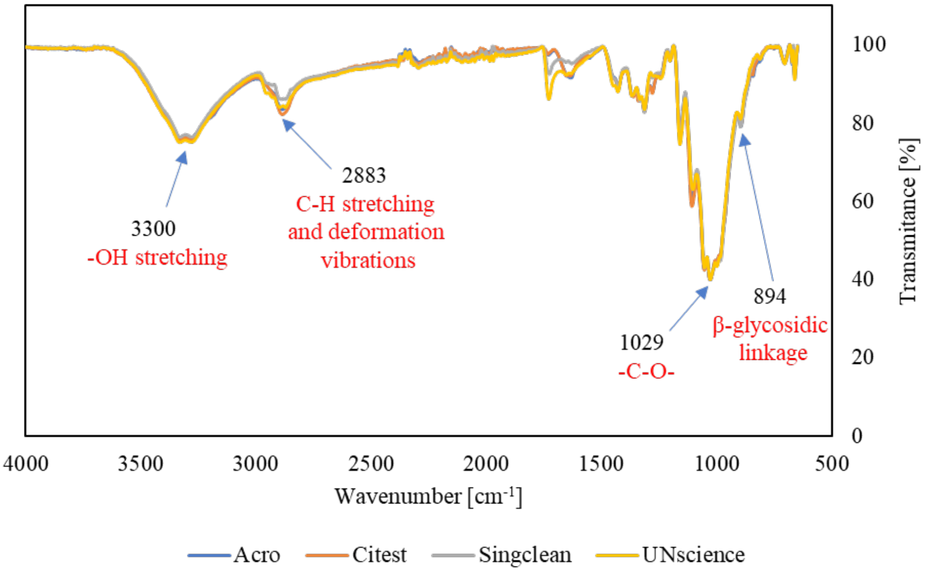

Fig. 15. *ATR-FTIR spectra of the cellulose-based absorption pads for all the rapid antigen tests*

Table 4. *Presentation of the materials identified in each component of the rapid antigen test*

Test	Sample pad	Conjugate pad	Filter pad	Chromatographic pad	Absorbtion pad
Acro	Glass fibre	Polyester	Polyester	Nitrocellulose	Cellulose
Citest	Glass fibre	Polyester	Polyester	Nitrocellulose	Cellulose
Singclean	Glass fibre	Glass fibre	//	Nitrocellulose	Cellulose
UNscience	Glass fibre	Glass fibre	//	Nitrocellulose	Cellulose

The performed analyses enabled the acquisition of the characteristics and properties of individual components of the rapid antigen LFIA tests, as well as their comparison. Based on this, the final Table 4 was prepared, which gives a quick insight into the analysed commercially available rapid antigen LFIA tests: Acro, Citest, Singclean and UNscience.

This study served as a basis for starting the development of an own rapid antigen LFIA test based on AuNPs for the detection of antibodies for the SARS-CoV-2 virus [32].

4 CONCLUSIONS

From this study the following conclusions can be drawn:

- Rapid antigen LFIA tests are complex in composition, as individual components have different chemical compositions and morphological characteristics, which ultimately results in different properties.
- For the pads in rapid antigen LFIA tests different materials are used, from glass fibre, polyster and cellulose.
- The choice of chromatographic membranes with larger pores does not affect the sensitivity of rapid antigen LFIA tests significantly.
- In order to know as accurately as possible the operation of rapid antigen LFIA tests, it is necessary to combine different characterisation techniques and experiments that can set up models, and, thus, a prediction for the most reliable operation in the clinical environment.

5 ACKNOWLEDGEMENTS

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Surveying Healthcare Workers to Improve the Design, Wearer Experience and Sustainability of PPE Isolation Gowns

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This protective clothing design project responds to the urgent need for research into the redesign of personal protective equipment (PPE) isolation gowns, to be more fit for purpose and reusable to enhance the experiences of healthcare workers treating patients with COVID-19 and variants. Funded by the Arts and Humanities Research Council (AHRC) the research addresses the engineering question: "What new materials, design and manufacturing approaches should we start to consider in preparation for pandemics e.g. reusable PPE to replace single use?" The article focuses on the online questionnaire/ survey, its main findings and the 'participatory clothing design' methodology which prioritises the lived experiences and expressed needs of healthcare workers wearing disposable and reusable PPE in acute care scenarios. Research methods include literature and gown reviews, selected interviews and survey directed at nurses, to acquire first-hand qualitative data about the impact of current gown design and procurement policies on wearers. Selected results and commentary from the ongoing survey are presented and thematically analysed to inform the development of reusable gowns. Semi-structured interviews with clinical leads and caregivers, as well as responses from users, will be important to integrate expertise in fashion, textile and uniform design, clinical practice, and manufacturing. Further design will be based on a complex design brief that balances the needs of wearers and critical care providers while considering regulations, protection, comfort, sustainability, and cost. This research focuses on enhancing an overlooked area of critical care clothing and the people who wear it while reducing its detrimental impact on the planet.

Keywords: healthcare workers, survey, isolation gown, reusable PPE, wearer experience, qualitative research

Highlights

- *Gown review involving the contextual and sensory analysis of disposable and reusable gowns, including items supplied by the NHS and industry partners.*
- *Qualitative analysis of interviews and survey responses to identify key gown design issues.*
- *The literature review, interviews, market research and survey feedback, represent a creative, collaborative, and complementary way to define the foundation for further redesigning PPE.*
- *The goal we pursued was to identify critical key elements that could improve the user experience with PPE.*
- *Reusable gowns are more sustainable solution than disposable gowns.*
- *The critical situation shows the one-size gowns that hindered the work of all users who were at least 160 cm tall, which was 35 % of our respondents*

0 INTRODUCTION

The research was undertaken for the project: 'Redesigning PPE: enhancing the comfort and safety of healthcare workers wearing isolation gowns to treat patients with COVID-19' [1]. The project was devised to tackle the engineering-based question: "What new materials, design and manufacturing approaches should we start to consider in preparation for pandemics e.g. reusable PPE to replace single use?" [2].

Following a review of recent literature, reinforced by findings from our online survey, we identified particular dissatisfaction with the performance of disposable oversized gowns. This was acknowledged early in the pandemic by the Royal College of Nursing [3] who recognised that a generic "one-size-fits-all" (one-size) approach to personal protective equipment (PPE) was "problematic" and "restrictive" when worn for 12-hour shifts [4].

Our research goal was to find the best possible solution to a crisis in which the PPE industry was adopting a non-circular, single-use approach to meet demand, resulting in human and environmental problems. Through contact with leads in Clinical Procurement and Therapies from Northampton, and Nottingham University NHS Hospital Trusts in the East Midlands, UK, we obtained initial information about their nursing teams' experiences of wearing disposable gowns. Based on this collaboration and a review of products on the market, we prepared a survey for different health professionals to complete anonymously. Their responses revealed the most common problems with wearing generic gowns. Based on the analysis of the interviews, we applied 'material methods' [5] to design models by researching details, developing sketches, patterns and specifications

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resulting in prototypes incorporating variations of sizing, cuffs, necklines, and fastenings.

The goal of the article is to highlight the relationship between problems observed in practice, the importance of research, and the involvement of users with practical experience, whose information is crucial for developing clothing that supports people's working needs.

1 METHODS

This practice-oriented study responds to the identified need for research into PPE isolation gowns. The first step was the literature review. We analyzed journal articles, press and reports. The product review of disposable and reusable isolation gowns included measurements, specifications, design details, construction techniques and fabrication.

After researching papers to gain insights into the problem, we then interviewed Clinical Procurement and Therapist managers in NHS Trusts. We had five discussions with project partners in the (Northampton General Hospital (1), Queens Medical Centre (1) and Nottingham University Hospital Trust (1), Diaverum (2)) and five online interviews with medical staff from different healthcare organisations.

Based on this information, we prepared a related survey that we sent to healthcare professionals in the East Midlands, UK. The individual responses to survey questions, predominantly from nursing staff working in acute care provided qualitative data which was 'thematically analysed' [6]. Creative methods of experimental research included textile sourcing, gown design and garment detail developments. The findings informed the subsequent phases of design development. This 'constructive design' approach prioritises knowledge of the 'action of the body' of the healthcare wearer (HCW) alongside theoretical and practical methods [7].

The co-design methodology draws on the principles of 'participatory clothing design' by involving and acting on the lived experience of the wearer [8] though the application of an 'intentional, circular' approach that considers PPE product lifetime [9].

2 EXPERIMENTATION

The research group members met weekly on the MS Teams platform to exchange research ideas, references and emerging findings. This hybrid way of working, online and in real time resulted in an experimental 'visual methodology' [10] comprising text, gown dimensions, contextual images and photographs. Visual research information was developed and disseminated using Conceptboard [11].

The literature review, interviews, market research and survey feedback, represent a creative, collaborative, and complementary foundation for redesigning PPE. The goal we pursued was to identify critical elements that could improve the user experience of PPE gowns.

The methods are presented in the following subsections.

2.1 Literature and Gown Review and Interviews with Clinical/ Procurement Leads

The first phase of the research was carried out between February and April 2021 (10 weeks) to fulfil Aim 1: Understand the issues experienced by health workers wearing PPE gowns. Gowns are primary garments classified as uniforms intended for employees of various professions in the public sector, as corporate clothing, for tourist or sports purposes. In all examples, in addition to clothing for protection at work, uniforms are also clothing that provides information about what we can expect from the person we meet in certain clothing [12].

Common to all uniforms are the special properties of fabrics that can provide durability in different workplaces and working conditions. All uniforms are also an important tool of communication in society, but in the case of uniforms for healthcare workers, a focus on practical solutions has resulted in an overllooked area of design with potential for improvement.

The design of uniforms must be, above all, functional and supportive to facilitate the roles of healthcare workers. Our literature review identified various examples where isolation gowns failed to adequately support staff in their work in relation to design [13], inappropriate size or length [4], or unsuitable, heat-inducing fabrication [14]. Direct user feedback is therefore very important for designers and manufacturing companies to be able to constantly improve the design of critical clothing items [15].

The methodology merges principles of interpretative phenomenological analysis and co-design to acquire empirical evidence to act upon, comprising qualitative data of the 'everyday phenomenon' of wearing of an isolation gown and quantitative data in the form of gown measurements, specifications, and textile composition [8]. Analysis of both sets of data provided a platform for adopting an intentional design approach with the aim of developing a circular gown system which can sustain the end user more effectively through an extended product lifetime [9].

Medical gowns play an important role in protecting the health care from the transmission of microorganisms and body fluids. [16]. The decision of whether a hospital uses a reusable or disposable gown is a selection process based on factors such as sustainability, barrier effectiveness, cost, and comfort [16]. The results of a US-based study into environmental implications of disposable vs reusable showed that compared to the disposable gown system, the healthcare facility had "a 28 % reduction in energy consumption, a 30 % reduction in greenhouse gas emissions, a 41 % reduction in blue water consumption, and a 93 % reduction in solid waste generation."[16]. The researchers conclude that choosing reusable gowns over disposable gowns can have significant environmental benefits. The US-based Centers for Disease Control and Prevention (CDC) also recommend that in situations such as the current COVID-19 pandemic, washable isolation gowns should be used [17].

The gown review involved the contextual and sensory analysis of 30 disposable and reusable gowns, including 12 physical items which were ordered online, and two garments supplied by the NHS and the industry partner. An overview of the rationale and process of analysis is provided in a short video [18].

All (12) gown models were also measured and compared. We particularly focused on the gown length (front and back); neck, shoulder, sleeve, and cuff (width and length); chest, waist, hip circumferences. Table 1 illustrates the variations in sizes between five disposable and two reusable gowns.

All the models were reviewed by three members of the research team who are respectively a UK dress size 10, 12 and 14. When trying the gowns on, the researchers adopted various body positions, mimicking those involved in treating patients e.g. bending (as if over a bed), reaching forward (Fig. 1) walking quickly etc. Best fitting disposable and reusable gowns can be basis for paper patterns. An average of these measurements informed the design and dimensions for the first prototype.

Fig. 1. *Reviewing the same disposable model on two different sized people (UK 10 and 14) in various postures*

Up to 10 semi-structured interviews are planned to be undertaken with clinical leads and nursing staff throughout the project. In April 2021 we interviewed the Clinic Manager at Diaverum, UK, Nottingham (online) where he revealed that the organization procured disposable gowns in one-size for all staff, which were incinerated after single use. The gowns are used to protect staff when treating patients

Table 1. *Measurements of different gowns [cm]*

Model Nr.	Length front / Length back	Neck width / Shoulder / Sleeves / Cuff	Chest, Waist & Hip circumference / Size
1. Arma (Disposable)	106 / 112	26 / 20 / 55 / 4.5	69 L (one-size)
2. Bestsanitizer (Disposable)	113 / 110	19.5 / 24 / 54 / 5	71 (one-size)
3. SubMed (Disposable)	119 / 112.5	22.5 / 19 / 59 / 7	71 (one-size)
4. Lux (Disposable)	129 / 116	N/A / 81 / Thomb hole	90 (Unisex)
5. Matrix (Reusable)	128 / 125.5	24.5 / 22.5 / 55.5 / 10	133 (L)
6. Sciquip (Disposable)	118.5 / 111.5	22.5 / 80.5 / Thomb hole	108 (One-size)
7. Swallowdental (Reusable)	115 / 121	18 / 24 / 57 / 10 /	139 (One-size)

with different kidney related diseases, hepatitis B, Cytomegalovirus (CRV) and coronavirus. He pointed out that while most nurses found the gowns comfortable, they were too large and long for shorter and petite builds. This included male members of the nursing team, reinforcing the fact that this was a non-gendered general issue, despite impacting more of the 75 % of female nurses in the NHS [4]. The disposable gown donated to the team by Diaverum, included a ribbed neckline, which was very comfortable to wear, while providing a good fit and better protection for the skin.

In addition to the sizing issue, a common problem raised by his staff was the heating effect of the composite polyester fabric. This issue is often exacerbated by waterproof PU (plastic) coatings on both disposable and reusable gowns causing the wearer to experience 'heat stress' [14]. Similar issues were identified in other interviews with a head of theatres, an Intensive Care Unit (ICU) nurse, a trainee doctor and an anaesthetist from different NHS trusts.

2.2 Survey

The survey was designed in response to the initial findings of the literature, gown reviews and interviews [18]. We developed 25 questions to address key criteria for redesigning PPE isolation gowns, with emphasis on enhancing the comfort and safety of healthcare workers treating patients with COVID-19. Initially, the survey was sent to our two main NHS partners in Nottingham in July 2021. Due to the low response rate impacted by the ongoing pandemic, the survey remains open and has been extended to nurses outside of Nottingham. At the time of writing this article there were 123 respondents.

The survey asks several different types of questions. General questions (about age, gender, ethnic background, their own assessment of a disability, where they work and which area of the hospital/healthcare organization they work in and their position), what type of gown they wear and what they wear underneath. We enquired about the textile composition, details the size they normally wear.

As far as possible the answers to the questions were prepared in multiple-choice illustrated groups (Fig. 2) to make the process expedient, but with space for descriptive answers. We also incorporated the possibility of choosing between contrasting positive/negative responses to specific aspects of the gown (e.g. feelings of comfort and safety) with 5 possible marks; Number 1 referring to the first parameter (very comfortable) and Number 5 the opposite parameter (uncomfortable), with the choice of three marks in between, the middle score (3) denoting a neutral response. In this article we focus mainly on the percentages accrued for 1, 2 and 4, 5, and disregard 3.

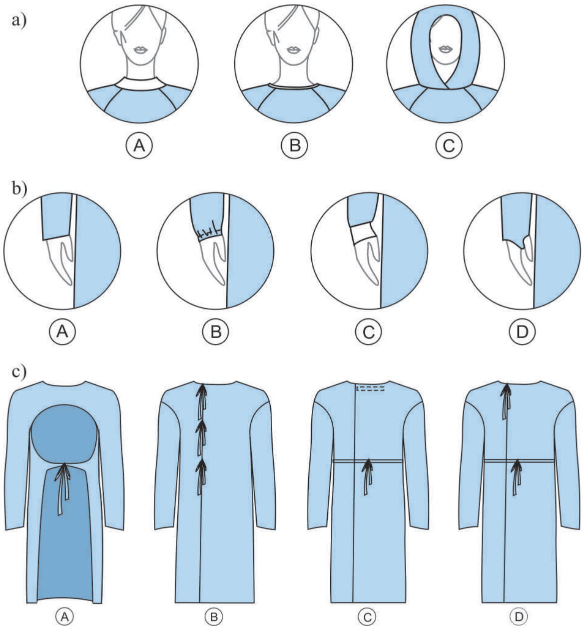

Fig. 2. *Examples of the illustrated multiple-choice approach to questions about a) necklines; b) cuffs and c) waist fastenings.* [20]

2.2.1 General Survey Questions and Answers

In common with many surveys, the first two general questions cover information about the age and gender of the respondents. The highest percentage (36.4 %) were between 25 years and 34 years and between 35 years and 44 years old (28.9 %) with 19 % between 45 years and 54 years old. Fewer than 10 % were aged 55 to 64 and the smallest number (4.1%) between 18 and 24. A ratio of 81.8 % females and 17.4 % males replied. This latter statistic is in keeping with press articles about poor PPE performance and generic sizing, putting females who make up 75 % of health staff at greater risk than males [4].

In terms of ethnicity, 76.9 % of the respondents were white, 7.4 % from other Asian backgrounds; 4.1 %, black or black British-African and the same percentage Asian or Asian British-Indian, with 1 % identifying as being from different mixed ethnicity backgrounds. These figures are not representative of the NHS workforce which is much more ethnically diverse than these percentages suggest (Ref) and an important consideration for future PPE design and PPE procurement policy. 4.1 % considered themselves to have a disability, and 1.7 % prefered not to say.

Initially, the majority of the survey participants worked for our project partners, Nottingham University Hospital Trust (NUHT) and Diaverum, UK. However, following publicity about the project in late November 2021 we received replies from nurses working across the UK, including in Scotland, England, Wales and Northern Ireland.

Nearly 81.5 % of all respondents worked in ‘high-risk environments’ and defined themselves as working with covid patients in various nursing roles including in: dialysis, critical care, mental health, intensive care, theatres and recovery, as healthcare assistants, clinic managers, in a Hot Zone in an Emergency Department and Intensive Care Unit (ICU) involving respiratory and aerosol generating procedures (AGP).

In the following sections we analyse the survey responses in relation to the themes of ‘wearability, comfort, fit and sustainability’.

2.2.2 Disposable and Reusable Gowns, Donning and Doffing

The majority of surveyed respondents, 75 % confirmed they wear disposable gowns and 25 % reusable gowns 25 % (Fig. 3). In terms of duration, 26.5 % generally wearing these protective garments for 8 h to 12 h, 23.6 % wear them for between 1 h and 2 h or 3 h and 4 h, and 13 % for 4 h to 8 h. 12.2 % of the respondents highlighted ‘other’ timescales (Fig. 4) supported by comments about wearing multiple, single-use PPE during shifts, depending on the medical treatment: “New gown with each patient or entry to a room - sometimes for as short a time a few minutes sometimes for 1 h to 2 h.”.

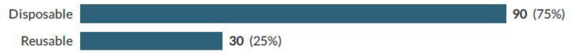

Fig. 3. *Survey answers to Question 7: Are the gowns you wear disposable or reusable?*

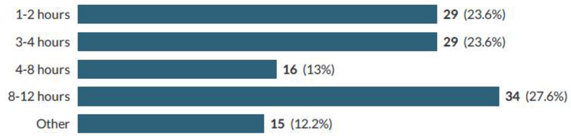

Fig. 4. *Survey answers to Question 8: How many hours do you generally wear your isolation gown for?*

In response to Question 9: What do you wear under your gown? the healthcare workers generally cited scrubs (80.2 %), undergarments (3.3 %), or 18.2 % non-uniform clothing such as a tunic and trousers, skirt and top or dress.

Question 10: Is your gown easy to put on (don) and take off (doff)? The respondents had very different experiences, depending on the type and fabrication of the gown they wear (e.g. disposable/polyurethane), how experienced they are, and how much time they have to put it on or take it off. Some reported ‘no problems’ while others suggested that ‘proper training is required.’

With reference to donning, we discussed two parameters: Easy to put on (score 1) vs. difficult to put on (score 5). Some respondents said they needed help to cross the back and/or fasten the ties. Those with experience of wearing hooded gowns or hazard suits experienced greater difficulty in getting dressed. Similarly, with undressing or doffing: Easy to take off (score 1) vs. Difficult to take off (score 5), The answers demonstrated that 47.1 % of the respondents can easily remove their gowns (score 1) and 20.7 % (score 2). A total of 19.8 % of the respondents chose score 3 and only a minority of the respondents confirmed difficulties in doffing taking off the gowns, namely 9.9 % (score 4) 2.3 % scoring 5.

This result was unsurprising, as most respondents wearing disposable gowns, just pull or rip them off at the end of use because the paper-like composite fabric tears quite easily, although, the velcro fastenings can pull on the neck, as reiterated: ‘Sometimes the gowns tear whilst donning using closed glove method. Sometimes the ties disconnect whilst donning and sometimes they are difficult to undo or pull apart to remove.’ Some nurses also need help removing gowns carefully to avoid cross-contamination.

2.2.3 Impact of Fabrication on Wearer Experience

In our gown review we found that most disposable gowns were fabricated in non-woven spunbonded polypropylene. The reusable gowns were fabricated in PU (polyurethane/plastic) coated polyester. With the exception of one polythene and one traditional surgeon’s gown in polyester/cotton, all these PPE products met EN 13795-1 [19] safety standards required for surgical gowns or drapes.

To undertake in-depth analysis of the gown’s fabrication and its impact on the wearer, we sub-divided some of the questions to gain insights into the positive and negative aspects of the materials as ‘active participants’ in the study [5].

We discussed many parameters: fit (good (score 1) vs poor (score 5), feel (cool (1) vs warm (5), textile quality (good (1) vs poor (5), manufacturing quality (good (1) vs poor (5), fastenings practicality (practical (1) vs impractical (5), lightness of material (light

(1) vs heavy (5), softness (soft (1) vs stiff (5), water repellency (waterproof (1) vs absorbency (5) and breathability (breathable (1) vs non-breathable (5).

Regarding the fit of the gowns, 19.3 % of healthcare workers agree that the gowns are good fit with a score of 1, 14.3 % chose a score of 2, 29.4 % a neutral rating of 3. Another 16 % gave a rating of 4 and 21 % gave a rating of 5. If we add the first and last two scores, this equates to 33.6 % being comfortable and 37 % being uncomfortable, which is over one third of the workforce.

For feeling cool vs warm, many more respondents confirmed that the gowns are too warm, causing discomfort [14]. As illustrated in Fig. 5, only 14.5 % (scores 1 and 2) found their garments cool, while 76.1 % (scores 4 and 5) suggested that their gowns were heat inducing, with 54.7 % scoring 5, evidencing the seriousness of this issue (Fig. 5).

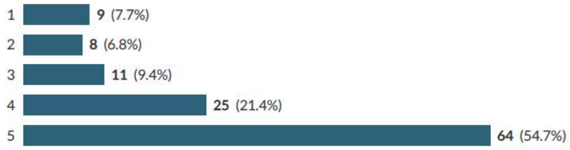

Fig. 5. *Survey answers to Question 11.2: What are the positive/ negative aspects about wearing the gown: cool vs warm?*

In Question 11.3: Good vs poor textile quality, the prevailing opinion was negative, with 9.2 % and 16.8 %, respectively scoring 1 and 2. 34.5 % (score 3) and 12.6 % (4) and the highest, 26.9 % scoring 5 (poor quality).

For manufacturing quality, the balance tilted slightly in a more positive direction, with 9.2 % (1) 21.8 % (2), 37 % neutral (3), but 14.3 % (4) and once again the highest figure of 17.6 % (5) denoting poor manufacturing quality. This result was reiterated by our gown review, where we noted that some disposable gowns were overlocked, incorporated internal and external waist/ neck ties, Velcro fastenings, ribbed cuffs and in one case a ribbed neckline (e.g. SubMed, Table 1).

Responses to Question 11.5, regarding the practicality of fastenings were very evenly distributed; the prevailing opinion being that fastenings are practical rather than impractical; 15.8 % (1), 21.7 % (2), 23.3 % (3) in contrast with 18.3 % (4) and 20.8 % scoring them as impractical.

If we look at the parameters in Question 12.1 light vs heavy, we immediately see that the majority of respondents estimate that gowns are light with 42.4 % (1) and 28 % (2), and only 5.1 % (4) and 2.5 % (5) considering them heavy. Almost half of the respondents to Question 12.2 soft vs stiff said their gowns were soft: 20 % (1) and 26.1 % (2) rather than stiff; 9.6 % (4) and 9.6 % (5). This is logical, as the disposable gowns are generally fabricated in non-woven spunbond polypropylene, such as the SubMed gown (Table 1). Over half the respondents to Question 12.3 waterproof vs absorbency (44.1 % score 1 and 21.2 % score 2) confirmed that their gowns were waterproof, rather than absorbent 8.5 % (4) and 1.7 % (5) which is to be expected in compliance with EN 13795 safety standards.

Q. 12.4 Breathability vs Non-breathability garnered a majority response of 69.9 % (38.5 % score 5 and 21.4 % score 4) compared with only 15.1 % confirming that their gowns were breathable; 9.4 % (2) and 7.7 % (1). (Fig. 6).

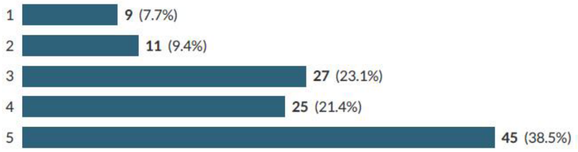

Fig. 6. *Survey answers Question 12.4: What are the positive/ negative aspects about wearing the gown: Breathable vs non-breathable?*

2.2.4 Feelings of Protection and Risk

Of all the respondents to Question 13: Do you feel protected wearing your gown? 76.9 % felt safe when wearing their isolation gown, although 28 % did not. Those who felt protected described that the gowns covered all parts of the scrubs, their whole body, to at least knee-length, preventing the spread of microorganisms between patients and staff. They also noted the prevention of liquids from getting onto the uniform and body, as they are water repellent, as confirmed earlier (Q. 12.3). However, being "So plastic nothing can get through!"; "Very thin material that tears easily" and "It feels like clingfilm" were less positive in relation to safety.

Other comments relating poor protection included references to: "poor fit"; "too big and uncomfortable"; "arms are not protected" One person said that "arms got wet from the liquid used", another noted that the gown was "too short and not covering the back" or "the whole body". Other comments stated that their gown "Gets caught on things"; some "Some [reusable] gowns were very old" and "They do not cover the neck area, they are loose round the neck area. Very sweaty, sometimes seemed lined with polythene on arms which sticks and irritates skin over forearms. Just awful."

2.2.4 Sizes of Isolation Gowns and Their Impact on Performance

We were interested to discover what gown and dress size the survey participants usually wear, to make connections between the two wearing systems and the problems individuals face when wearing a gown size that is inappropriate.

The female participants indicated which (UK dress) sizes they wear, with the most common size, 33 % being 12 to 14 (M), followed by size 8 to 10 (S), worn by 24.1 %. Size 16 to 18 (L) is worn by 16.1 %, size 20 to 22 (XL) by 8.9 %, size 6 (XS) by 5.4 % of respondents, with the lowest number being 24 to 26 (XXL) at 1.8 %. As "Other" noted answers (10.7 %) are not important for the survey (e.g. I am a man; I do not wear women's clothes) (Fig. 7).

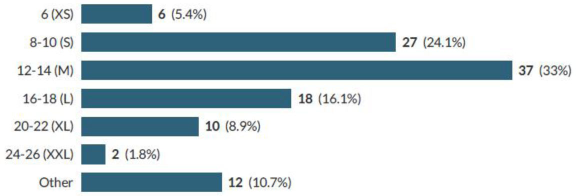

Fig. 7. *Survey answers to Question 14: What womens' (UK dress) size do you normally wear?*

Another question, 14b asked which men's (UK dress) sizes they usually wear. The most common size was 40 to 42 (M) at 27.9 %, followed by size 44 to 46 (XL) worn by 18.6 % of survey participants. Size 42 to 44 (L) is worn by 14 % of, size 36 to 38 (XS) by 11.6 %, with sizes 38 to 40 (S) and 46 to 48 (XXL) each being worn by 7 % of the respondents. Other answers (14) are not important for the survey (e.g. I do not wear men's clothes) (Fig. 8).

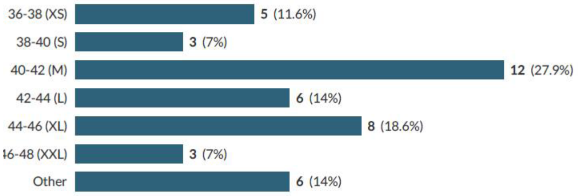

Fig. 8. *Survey answers to Question 14b: What mens' (UK dress) size do you normally wear?*

Although Medium was the most popular dress size for both women and men, large and one-size both scored 31 % in response to Question 15 (Fig. 9). Other data relating to which size of isolation gown the healthcare workers wear included: M (23.3 %), XL (20.8 %), S (6.7 %), XXL (4.2 %) and XS (0.8 %).

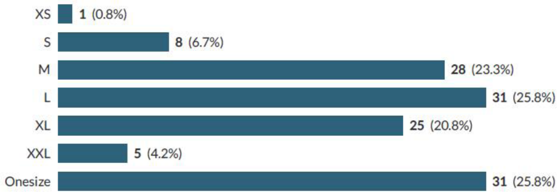

Fig. 9. *Survey answers Question 15: What size is the isolation gown you normally wear?*

If we compare the data for UK dress size 6 (XS) (Fig. 8) and 36 to 38 (XS) (Fig. 9) we can see that normally 6 women and 5 men wear this size. However, only 1 person, 0.8 % of the 123 women and men surveyed, wears a gown of that size (Fig. 10). Hypothetically, this suggests that 10 of the people who usually wear XS are wearing gowns too big for them. This situation was confirmed in the interview we had with the Clinic Manager from Diaverum, who stated that while most staff found the SubMed disposable gown comfortable in one-size, this was problematic for the smallest member of his team, who usually wore XS.

In reply to Question 16: "Do you feel that wearing this size of gown affects your performance?", 53.8 % of the respondents answered yes and 46.2 % answered no, which they were asked to explain in 16a. Most comments were linked to discomfort during long shifts, of feeling too hot because of the gowns made them: "very hot and sweaty, causing dehydration!"

Predominantly reasons were linked to poor fit, due to only 'large' 'XL' or one-size being available although in one comment the issue was about the gown being too small. The excess volume of oversized garments was referred to by many, as was the length which proved hazardous in terms of tripping up the wearer. The following comment reflected on both extremes: "If they (gowns) are too tight, movement is restricted, and if they are too long, they are a tripping hazard."

Other responses related to the impact on bodily movement, included: "The gown is too long" (as are the sleeves) "it is way too big"; "the gown interferes with work"; "sizes that sweep across the floor"; "made of too much material"; "is quite restrictive"; "some sizes are not available"; "can be baggy", "Cumbersome", "Usually too short in sleeve, but larger means too low at neck" and "It is the only size we have, it is very uncomfortable and difficult to move in as it is so large."

2.2.5 The Relationship between the Shape of the Body and the Fit of Insulating Clothing

Question 17 asked "What body shape are you?" providing a link to sketches showing differences and emphasis of the body postures (Fig. 10). Most of them (34.2 %) are hourglass, rectangle (26.5 %) and oval (17.1 %). The fourth most common posture is triangle (8.5 %). Less common are trapezoid (5.1 %) diamond (4. 3%), and inverted triangle (4.3 %).

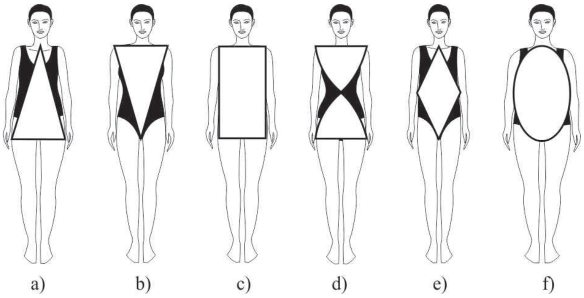

Fig. 10. *Survey answers Question 17: What body shape are you? Example for women body postures: a) triangle; b) inverted triangle; c) rectangle; d) hourglass; e) diamond; f) rounded.* **[20]**

Answer about their height gives 103 people (out of 123 respondents). From these 103 validly filled questionnaires, we calculated that 6.8 % of the respondents have a height of 150 cm. Between 151 cm and 160 cm have 29.1 % of the respondents. Between 161 cm and 170 cm are 36.9 %, between 171 cm and180 cm are 16.5 %, between 181 cm and 190 cm are 8.7 % and between 191 cm and 200 cm are 1.9 % of the respondents.

Replies to Question 19 indicated gown length preferences as: calf-length (38 %), knee-length (33.9 % each), slightly less (28.1 %) like full-length. Question 20 around 'fit', confirmed that only 11.5 % (scores 1 and 2) of respondents rated their isolation gowns as being too small. 38.8 % of them say that they fit well but significantly, almost half, 49.6 % considered their gowns to be 'too big' comprising 33.1 % (4) and 16.5 % (5) (Fig. 11).

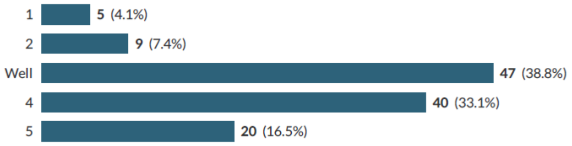

Fig. 11. *Survey answers to the question How does the isolation gown fit you: too small vs too big?*

2.2.6 Design Details

Details are very important. We can find many different variants of them on the market and the questionnaire particularly exposed necklines, cuffs and fastenings.

Cuff and sleeve: A cuff with thumb loop was the most desired variant (32.5 %), as well as elastic (30 %) and knitted rib (28.3 %). To the question "Is your cuff lose fitting vs tight fitting", 56.8 % of respondents said it was comfortable, 23.7 % said it was too loose and 19.5 % said it was too tight. To the question "Is your sleeve too long or too tight?" 48.3 % of all responses are comfortable, 36.5 % are too long, and 15.2 % are too tight (Fig. 12). Our gown review reinforced these observations, with the predominantly one-size garments being generally designed to fit a male over the height of 6 foot, resulting in sleeves and overall gown length being proportionately too long.

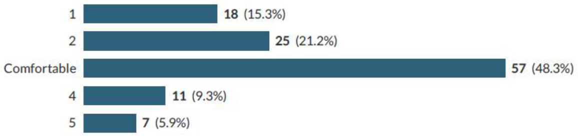

Fig. 12. *Survey answers to the question: Is your sleeve too long vs too tight?*

Neckline. The respondents' gowns had a neckline finished with wide binding (27.9 %) or narrow binding (52.1 %) and no one wore a gown with a hood. In response to "Is your neckline gaping vs tight?" 48.7 % wrote that it was comfortable, 37 % are gaping and 14.3% found them tight.

Fastenings. When asked "What kind of fastenings does your gown have?" most (35.1 %) said they tie it at the neck, tie around the waist, or hidden inside the gown, at the waist. 33.3 % of respondents have a Velcro fastening at the back-neck, 28.1 % of respondents wear an open-back gown. Only 6.1 % wear three ties at the centre back.

Ease of movement across back vs restrictive movement across back; 65 % of respondents wear gloves with easy movement on the back. 21.4 % choose neither easy movement nor restrictive movement. 13.6 % find movement across the back restrictive.

Easy movement vs restrictive underarm movement; 58.1 % wear gowns with easy movement from underarm, 14.5 % perceive restrictive underarm movement, and another 27.4 % are neutral (Note 3).

Easy movement at the waist vs restrictive movement at the waist; 61.8 % feel easy movement at the waist and 10.4 % perceive only restrictive movement at the waist. The remaining 27.8 % chose a value of 3 between these two options.

2.2.7 Further Comments from Participants: Free Text Responses

Finally, we asked for any other comments on the daily experience of wearing the PPE isolation gown and invited suggestions for improving the design. Most of their responses have already been mentioned as comments on specific questions. What they revealed must be highly irritating to our respondents. We highlighted the most disturbing observations as follows: "Hot feeling." / "Too warm in hot weather." / "Too hot." / "Uncomfortable in warm weather." / "Very sweaty – stick to you." / "Too plastic." / "Can become very hot and sticky if the room is warm." / "Make them less tearable and less warm." / "They are so hot and sweaty! Would love to wear more breathable gowns!"

Breathability. They want to have breathable fabric, possibly with stretch. / "Make breathable especially form elbows down uniform scrubs tend to absorb sweat but elbow down doesn't as gown directly touches bare skin." / "It can get very warm wearing a plastic gown however I do like that it's waterproof." / "The plastic gowns are unbearable when it's hot. I sweat so much in them and then become dehydrated; They are also terrible for the planet." / "Breathable material appreciated as gown can get quite hot the longer, they are worn."

Improved fabrication for cuffs. "Replace wrist cuff material that irritates the skin."

Size. "Poor choice of sizing. Bigger size needed vs overall length too long" / "too long sleeves." / "Sleeve with thumb loop always to short." / "Would like to have different sizes available other than extra-large at the time." / "Because of excess fabric I can the gown on drawers, handles and the like. If small gowns are unavailable, I risk tripping up whilst wearing large gown. Gowns are not designed for petite wearers." / "Sometimes they are a little to long for short people, I sometimes trip over them."

Style. "I like the theatre style gowns."

Disposable vs reusable. Some prefer disposable, so it goes straight in the bin. / "Disposable rip easily." / "Prefer to wear plastic ones despite being hot all the time." Persons like to wear these through rather that the reusable one as the reusable ones when exposed to liquids it gets soaked and it may be difficult to untie the ties at the back. / "I find much more comfortable wearing the fabric gowns to plastic & they are better for the environment." / "A breathable material is very important. Since the pandemic started, we have been using reusable washable fabric gowns rather than disposable plastic gowns and I much prefer the environment consequences of this." / "We just have to use what is available. Majority of the time is reusable but sometimes we have to use disposable which are not nice to wear due to being sweaty, hot and non-breathable." /

Neckline. "Adjustable neck." / "They are loose round the neck area."

Fastening. "The tie fastening at the back isn't practical it just comes apart, not secure enough." / "I would prefer adjustable Velcro tabs rather that ties." / "Remove the tie at the back maybe have Velcro." / "Could have bigger ties as being big and tall makes it hard to tie."

Other comments. Two persons exposed the problem of pockets. From the reason of equipment (radios, phones, keys, algorithm cards) that they use, the gowns they have does not support them by works need. They would like to have "Some sort of pocket or waistline access who prevent us having to lift whole gown down." Other respondents wrote: "There is nowhere to attach a pen or pen torch."

3 RESULTS

Analysis of research from articles, models on the market, interviews with clinical and procurement leaders, and surveys was important in identifying key design issues.

Based on findings from all the methods but particularly 'wearer experience' as identified by the survey participants, we discovered both the positive and negative aspects of the gowns on the market based on different criteria. These include: the specifics of the workplace; the posture and height of the person; the length of time the gown is worn; the different qualities of construction and the materials, and personal opinions based on the experiences of our respondents. Some of the responses were a little contradictory, reflecting contrasting gown provision and working hours/ conditions, but there was consensus on key issues which informed our further design work.

The most common issues were: 1. the issue of heat stress due to non-breathable fabrication; this problem is related to the use of water repellent materials, also revealing the dilemma of using disposable or more sustainable solutions in reusable gowns; 2. inappropriate sizing; 3. garment details causing discomfort, donning or doffing issues.

3.1 How to Design Gowns That Prevent Overheating?

The strongest consensus regarding the gowns in use was their heat inducing properties. One respondent said of the fabric, "The plastic gowns are unbearable when it's hot. I sweat so much in them and then become dehydrated. They are also terrible for the planet." This finding, borne out by the literature [14] requires serious consideration of materials. In our further work we want to offer a better, more sustainable solution. The aim is to source a lighter weight textile, that still provides the necessary protection against fluid. There is also the possibility that the material for the back of the gown could be lighter than for the front. We are considering polyester/ carbon (99 % / 1 %) textiles with special fluorocarbon coatings, which can be washed in temperatures (71 °C) to thermally disinfect the garment by killing off all viruses and bacteria. With washing and reusing we can help reduce the impact on the environment. Another challenge to enhance breathability and lightness lies in the design, which can also be explored to reduce discomfort.

3.2 How to Improve Sizing Problems

Sizing is problematic, particularly with regard to the most commonly available "one-size-fits-all" gown. According to a review of the models we procured, the large (L) gown is the most common equivalent to One-size and as we can see, the One-size is the most common size worn by the survey participants (31 %). "Large" offers the best fit is for a person with a height of 170 cm to 180 cm, as highlighted in Fig. 13. Based on the survey responses, we drew the other heights of the respondents, which are indicated below each picture in cm.

To better imagine the kind of problem caused by sizing, especially for smaller-sized users, two models corresponding to the shortest (106 cm - model 1) and longest (129 cm - model 4) length of gowns, are shown in Table 1.

Through sketches we have simulated the same dress on different body heights; the shortest model marked as sketch line a) and longest marked as line b).

We can see that the smallest model length of 106 cm (Table 1) shown in Fig. 13a, is a suitable size/ length for a body height of 161 cm to 180 cm, but too big/ long for the shorter (150 cm to 160 cm) and too short for the taller (181 cm to 200 cm) individuals. The comparison is more extreme (Fig. 13b) when illustrating the longest model length of 129 cm, (Table 1). Users indicated in the survey that the gowns are obstructive during work. When we look at the longer models on smaller sizes, they extend to the floor. This evidences the need for a wider range of sizes to meet the different physiological characteristics of users.

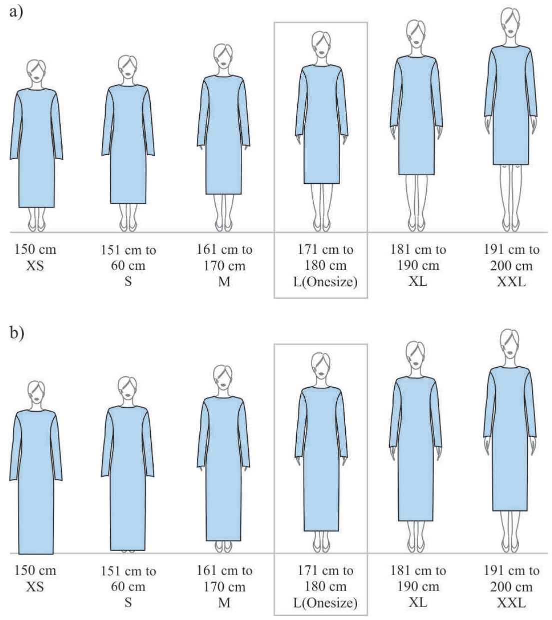

Fig. 13. *Sketches of the most common sizes of users and visualization of the problem of wearing one-size gowns, based on data in Table 1; a) the shortest model (length of gown 1) 106 cm and; b) the longest model (length of gown 4) 129 cm*

3.3 Details That Can Improve User Comfort and Practicality

Gown details such as necklines, fastenings, cuffs can be considered for potential improvements. For example, tight or loose necklines can irritate or protrude from the body; simple gown fastenings for easier donning and doffing are desirable and variations to cuffs, incorporating straps, Velcro or snaps should be considered.

A few respondents would like a pocket: "Some sort of pocket or access to prevent us having to lift whole gown up [to access scrubs]" Another respondent wrote: "There is nowhere to attach a pen or pen torch."

Findings from all the information referenced in the article influenced the further design development stage of the research.

3.4 Design and Development of Gowns

3.4.1 Analysis of Information and Design

Once all the qualitative and quantitative information was analysed and defined, we began developing the gown concepts.

Key issues influencing the design were identified as:

- the positive and negative aspects of gowns on the market,
- different roles and workplace scenarios,
- the posture and height of the person,
- size/ length of the gown,
- the varying quality (disposable/ reusable) of material, and
- personal opinions based on the experiences of our participants.

Some of the information was contradictory (e.g. sleeves too short / long), but in general we were able to concentrate on how the key issues could be mitigated through redesign.

The priority was to be more sustainable **[17]**, so we decided to develop only reusable gowns, in more breathable fabrications. The planet is dealing with a huge amount of clinical waste. And while it is understandable that at the beginning of the pandemic, disposable gowns offered the most expedient solution to the needs of healthcare organizations, we now need to consider a more sustainable approach for the future use of PPE, including gowns **[17]**.

In the design stage we particularly paid attention to the development of the functional form and details. The process of designing and developing functional clothing is based on the results of an objective evaluation of the user's requirements, and therefore tends to be complex and iterative **[21]**. Gupta **[21]** also highlights that in addition to the primary requirement of functionality, the wearer's needs are also related to the physiological, biomechanical, ergonomic, and psychological properties of the garment, which have different correlations depending on the intended use. An ergonomic design process involves the following steps: "selection of materials, determination of size and fit, pattern making, assembly and finishing" all of which were adhered to in our own methodology. This approach is relevant for the design of surgical, PPE gowns and clothing worn by healthcare workers in general to support protection, comfort and wellbeing. As evidenced in the survey analysis, the length of the gown and sleeves, availability of sizes, fastenings and feeling hot in composite, non-breathable textiles were commonly mentioned as hindering the daily working experiences of healthcare workers.

Initial sketches (Fig. 14) included some useful elements for further development of the selected models. Ideas for the neckline, front closure and various cuff solutions are being sampled and tested as details and part of gown prototypes.

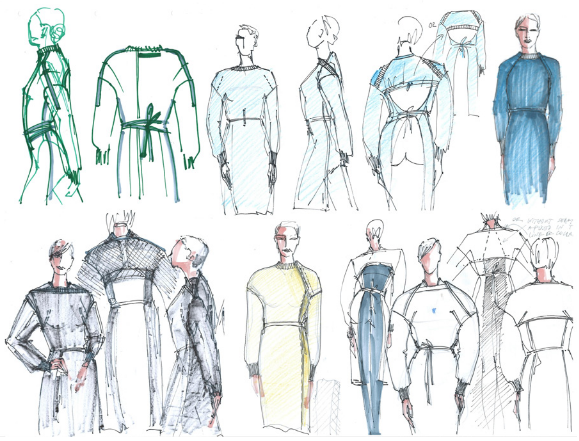

Fig. 14. *Initial sketches of gown design concepts*

Different design approaches to necklines (Fig. 15), cuffs (Fig. 16), gown fastenings (Figs. 17 and 18) an inner pocket (Fig. 17c) are illustrated below.

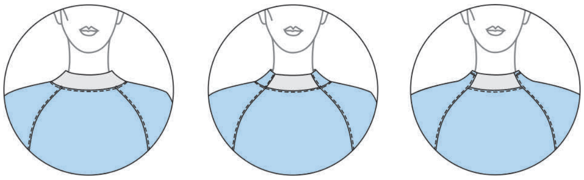

Fig. 15. *Initial sketches of neckline finishes*

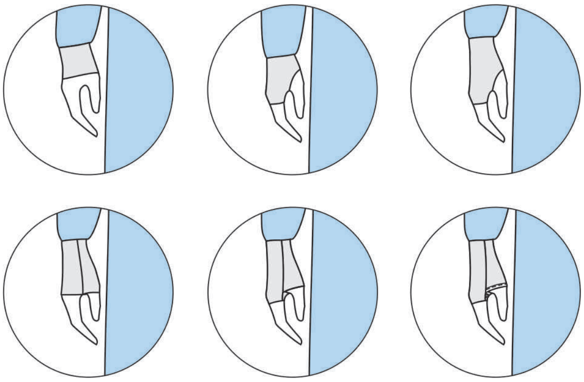

Fig. 16. *Technical sketches of different cuff solutions*

The development of pattern and detail designs is encompassing pattern cutting using traditional approaches informed by standard body measurements body shape index (BSI) and existing gown dimensions. The iterative sampling of cuffs, necklines and fastenings is also being undertaken.

The combination of a knitted rib neckline and cuff is common to all models, based on issues relating to comfort and safety. The style of the sleeves differs between the models e.g. set-in (Fig. 17) and raglan sleeves (Fig. 18) and fastening details on the centre-back (Figs. 17a and 18a) and left-back (Figs. 17b and 18b).

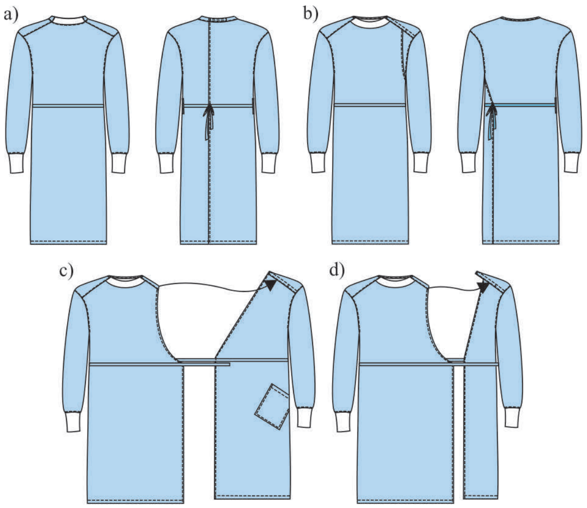

Fig. 17. *Variations of Prototype 1 and 2 with set-in sleeve; a) Velcro back-neck closure and waist-tie at centre-back; b) front closure with side fastening and double-layer front; c) fastening variations and inner pocket; and d) double-layer front with narrower under-layer*

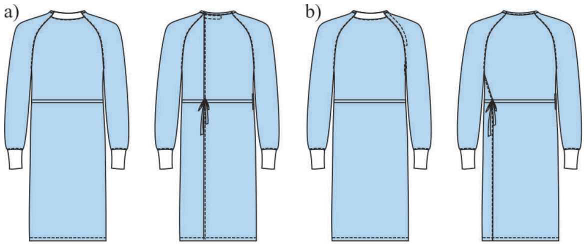

Fig. 18. *Variations of Prototype 3 with raglan sleeve; a) back closure with neck Velcro and waist tie at centre-back; b) front closure with waist tie at back-left side*

4 CONCLUSIONS AND FURTHER WORK

Since the outbreak of COVID-19, a shortage of suitable PPE has resulted in healthcare workers wearing disposable, "one-size-fits-all" isolation gowns, compromising comfort and safety. Oversized, ill-fitting gowns impede freedom of movement and increase body temperature and the risk of viral transmission. Clinical procurement and acute care leaders have expressed the need for more sustainable, reusable, individual-size PPE gowns fabricated from washable textiles to enhance the experience of healthcare workers while mitigating infection risk and reducing clinical waste.

The main purpose of this research was to identify the issues experienced by healthcare workers experience when wearing disposable, "one-size-fits-all" PPE isolation gowns when treating patients with coronavirus. The research findings, together with detailed product information, informed the design and development of prototypes. All results will be used as the basis for the next step.

We have developed various details and models that represent a range of possible solutions in practice.

The use of the information disclosed in this study is important for further work. The "one-size-fits-all" sizing system needs to be considered for all users, who often suffer from working in inappropriate gowns. Additional size options (e.g. XL to 3XL) should be more widely available and are being developed and trialed through this research.

We designed closures, cuffs and necklines with more options (some presented in sketches). By prototyping these solutions as creative experimental research, employing range of scientific and material methods and data [5], [13], [14], [17] and [19] to enhance the ergonomic and technological sustainability of future gowns [9] and [21].

By designing reusable gowns from a textile developed specifically for surgical high performance textiles heat-reducing, breathable solutions are possible.

A range of alternatives are offered that add both utility and protective value to the designs. Details added value in the form of soft knit on the collar, an extended knitted rib with a thumb loop, a hidden pocket that is not directly visible, variations in closures and lengths offered.

The further development of the prototyping and production models is currently being undertaken with a PPE manufacturer, ensuring the gowns are EN 13795 compliant and CE accredited. A laundry provider will coordinate the testing of the multiple sized reusable prototypes (washed/worn up to 70 times) with different nursing teams treating patients with COVD-19 across various healthcare organizations in the UK.

6 ACKNOWLEDGEMENTS

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The key data underpinning the paper are published within it. The online survey remains open, the results of which will be available with the entire data set at the end of the project on 05/01/2023, DOI: 10.5281/zenodo.6394461.

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The Prevalence of COVID-19 Among Health Care Personnel in a University Hospital by the End of 2020, and Ambient Air CO_2 in Hospital Rooms Ventilated by Window-Opening in 2021/22

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In autumn and winter 2020/21 and again in 2021/22 Slovenia has ranked among countries with the highest incidence of COVID-19 per million inhabitants and high excess mortality over the average of previous years. Many patients on non-COVID-19 hospital wards were in fact infected by SARS-CoV-2. Health care personnel at the University Medical Centre Ljubljana (UMCL) were falling ill by Covid-19 in large numbers despite wearing surgical masks and eye protection when dealing with patients. We compared the prevalence of COVID-19 among health care personnel of the Division of Internal Medicine, UMCL by the end of December 2020 with the national average of Slovenia. After instructions had been issued to increase room ventilation by opening windows every hour for at least 10 minutes, ambient air CO_2 *was measured in an intensive care room and in an outpatient clinic room during a 10-month period, from April 2021 to February 2022. The prevalence of COVID-19 by the end of December 2020 was 42 % among nurses, 21 % among registered nurses and 17 % among medical doctors, whereas the national of average of the population was significantly lower at 5.5 %. Between April 2021 and February 2022, the average* CO_2 *(ppm) in the intensive care was 633 (standard deviation 198, range 376 to 1540), while in the outpatient clinic the average was 552 (standard deviation 199, range 380 to 1910). During 2020, before the instructions for the use of personal protective equipment were up-graded and before regular window-opening was advised, the prevalence of Covid-19 among health care personnel at the Division of Internal medicine, UMCL exceeded the national average by 3- to 8-fold. After regular window-opening was advised, the peak* CO_2 *levels still often exceeded the recommended "safe" level of 750 ppm.*

Key words: COVID-19, prevalence, airborne spread, room ventilation, CO_2 **level**

Highlights

- *The importance of airborne transmission of SARS-CoV-2 has been recognized by the World Health Organization rather late into the pandemic.*
- *During the second wave of the pandemic by the end of December 2020, the prevalence of COVID-19 was 3 to 6 times higher among nurses at the Division of Internal Medicine, UMCL, than the national average, indicating that airborne transmission in poorly ventilated hospital rooms with infected patients had been taking place.*
- *Relying on improving ventilation by instructing personnel to open windows for at least 10 minutes every hour does not work consistently, as evidenced by* CO_2 *measurements at the Department of Vascular Diseases, UMCL.*
- *Airborne virus transmission should be recognized as a serious public health threat that should be systematically addressed, just as contaminated water and food have been addressed and successfully dealt with in the past.*

0 INTRODUCTION

During the second wave of the COVID-19 pandemic in the autumn and winter 2020/21, Slovenia reported one of the worldwide highest incidences per million inhabitants. In November 2020, Slovenia suffered a more than 100 % increase in all-cause mortality compared with the monthly average of previous years (Fig. 1) [1]. To a slightly lesser degree, the situation repeated itself in the autumn and winter 2021/22, a year after effective anti-Covid-19 vaccines had already been available.

More than a year into the COVID-19 pandemic, the World Health Organization (WHO) still considered Covid-19 to be spreading mainly by droplet transmission – through "large" (> 5 µm in diameter) infective droplets, exhaled, sneezed of coughed out by an infected person, reaching the respiratory tract or eyes of the susceptible next person in close contact, at distances of up to 1.5 m to 2 m. The WHO long acknowledged airborne (aerosol) transmission only under special circumstances of aerosol-generating procedures, such as noninvasive high-flow oxygenation, and added transmission by aerosols in poorly ventilated or crowded rooms to their website at the end of April 2021 [2]. Accordingly, until the end of December 2020, the recommendations to health care personnel of the University Medical Centre Ljubljana (UMCL) dealing with "non-Covid" patients, many of whom were in fact infected with SARS-CoV-2, only advised on wearing a surgical mask and eye protection - goggles or a face shield. However, a surgical mask

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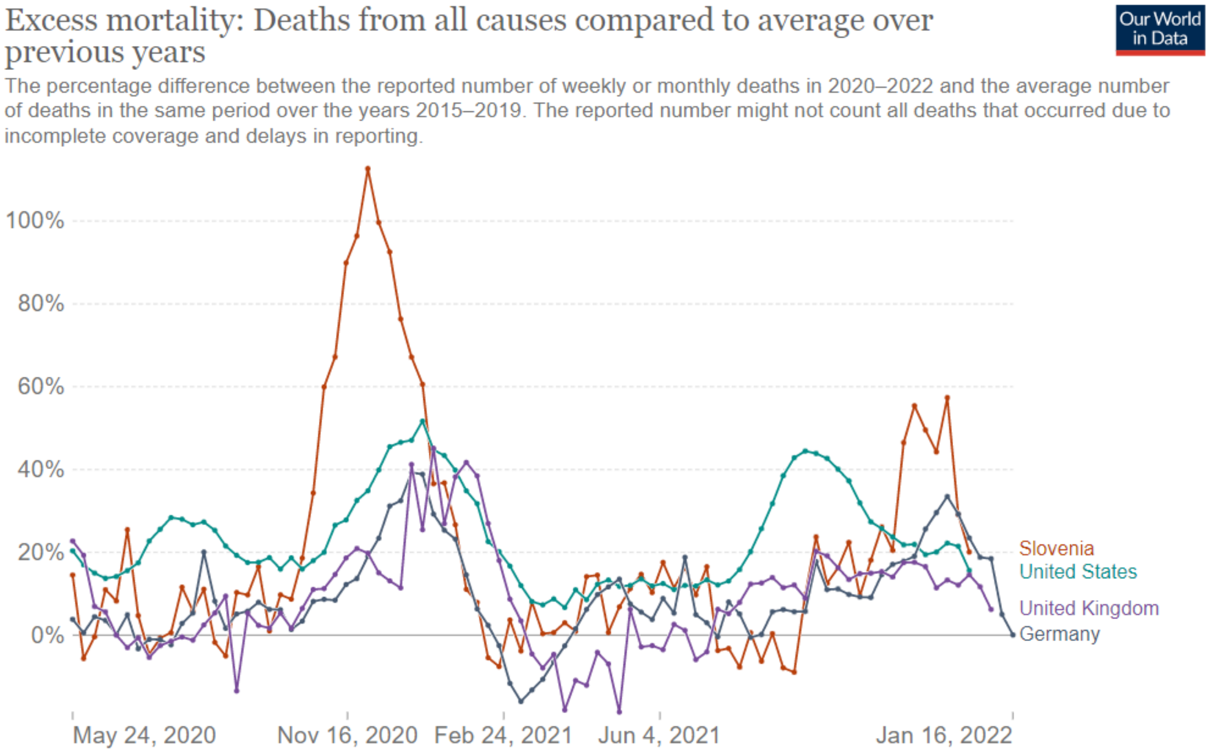


Fig. 1. *Excess mortality in November 2020 and January 2022 in Slovenia exceeded that of the United States of America, United Kingdom and Germany* [1]

only shields others against droplet transmission from the wearer, but not the wearer against inhaling infective aerosols. By the end of December 2020, all medical personnel at the UMCL were encouraged to wear FFP2 masks when dealing with possibly infected patients, and instructions were given to improve hospital room ventilation by opening windows for at least 10 minutes every hour.

In this paper, we provide the comparison of Covid-19 prevalence among health care personnel at the Division of Internal Medicine of the UMCL with the prevalence among the general population of Slovenia by December 24, 2020. As a surrogate marker of the adequacy of room ventilation in the UMCL, we present data on CO_2 content in ambient air of two hospital rooms between April 2021 and February 2022.

1 MATERIALS AND METHODS

1.1 Prevalence of Covid-19

Data on the number of employees who took a mandatory sick-leave because of confirmed infection by SARS-CoV-2 from January 1 to December 24, 2020, before instructions on up-grading of personal protective equipment and instructions on regular window-opening were issued, were obtained from the records of the Division of Internal Medicine, UMCL.

The prevalence of confirmed infection by SARS-CoV-2 in the general population of Slovenia by December 24, 2020, was calculated from data obtained from [3].

The prevalence of confirmed Covid-19 among nurses, registered nurses and medical doctors of the Division of Internal Medicine, UMCL, was compared with the prevalence of Covid-19 among the general population of Slovenia in the same period by the chi-square test.

1.2 CO_2 Content in Ambient Air

Air-quality sensors WAVEplus (Airthings, Norway) were kindly provided by MIK d.o.o., Slovenia, and installed in selected rooms of the Department of Vascular Diseases, Division of internal Medicine, UMCL. Data from the sensors were obtained from [4].

In the Intensive Care Unit (ICU) of the Department of Vascular Diseases the CO_2 content of ambient room air was measured between April 4, 2021, and February 18, 2022, and 91,048 measurements were taken. The ICU room had an area of about 36 m^2, a ceiling height of about 3.6 m, housed up to 4 patients and up to 3 nurses or medical doctors, was connected via a large opening in the wall to a symmetrical ICU room, and was equipped by air-conditioning. The ICU had windows that could be opened.

In the Outpatient Angiology Clinic of the Department of Vascular Diseases the CO_2 content of ambient room air was measured between April 15, 2021, and February 18, 2022, and 87,192 measurements were taken. The Outpatient Angiology Clinic room had an area of about 20 m^2, a ceiling height of about 3.6 m, housed up to 1 patient, 1 nurse and 1 medical doctor, did not have air-conditioning, but had windows that could be opened.

2 RESULTS

The prevalence of Covid-19 by December 24, 2020, among personnel of the Division of Internal Medicine, UMCL, compared with the general population of Slovenia is presented in Table 1.

The average, standard deviation, minimum and maximum values of CO_2 in ambient air of the ICU and Outpatient Angiology Clinic are given in Table 2.

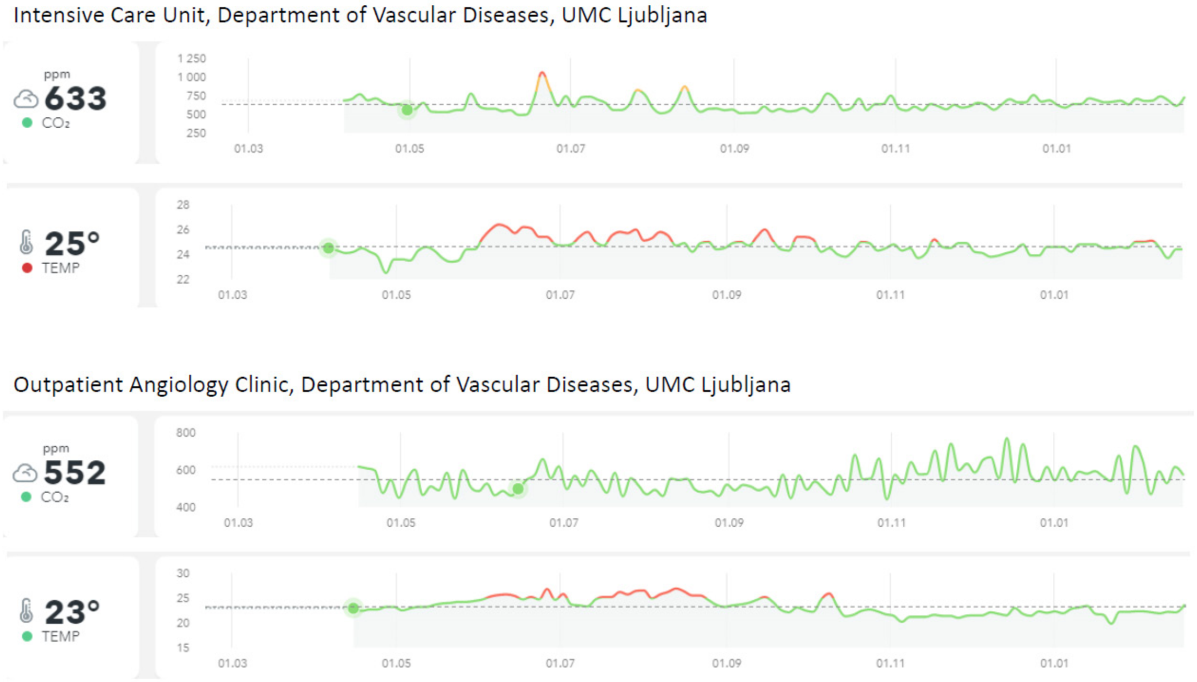
Table 1. *The prevalence of Covid-19 by December 24, 2020, among nurses, registered nurses and medical doctors at the Division of Internal Medicine, UMCL, compared with the general population of Slovenia* [3]

	Total number	Confirmed cases of Covid-19	Prevalence of Covid-19 (%)	*p*-value (compared to the population of Slovenia)
Nurses	292	122	42	< 0.00001
Registered Nurses	471	99	21	<0.00001
Medical Doctors	282	47	17	0.0008
Population of Slovenia	2,079,000	113,886	5.5	-

Table 2. *CO_2 [ppm] measured between April 2021 and February 2022 in the Intensive Care Unit and in the Outpatient Angiology Clinic of the Department of Vascular Diseases, UMCL*

CO_2 [ppm]	Intensive Care Unit (ICU)	Outpatient Angiology Clinic
Average	633	552
Standard deviation	198	199
Minimum	376	380
Maximum	1540	1910

Large-scale graphs of the 10-month measurements of CO_2 and room temperature are shown in Fig.


Intensive Care Unit, Department of Vascular Diseases, UMC Ljubljana

Outpatient Angiology Clinic, Department of Vascular Diseases, UMC Ljubljana

Fig. 2. *10-month measurements of CO_2 [ppm] and room temperature [°C] in the Intensive Care Unit and the Outpatient Angiology Clinic of the Department of Vascular Diseases, UMCL*

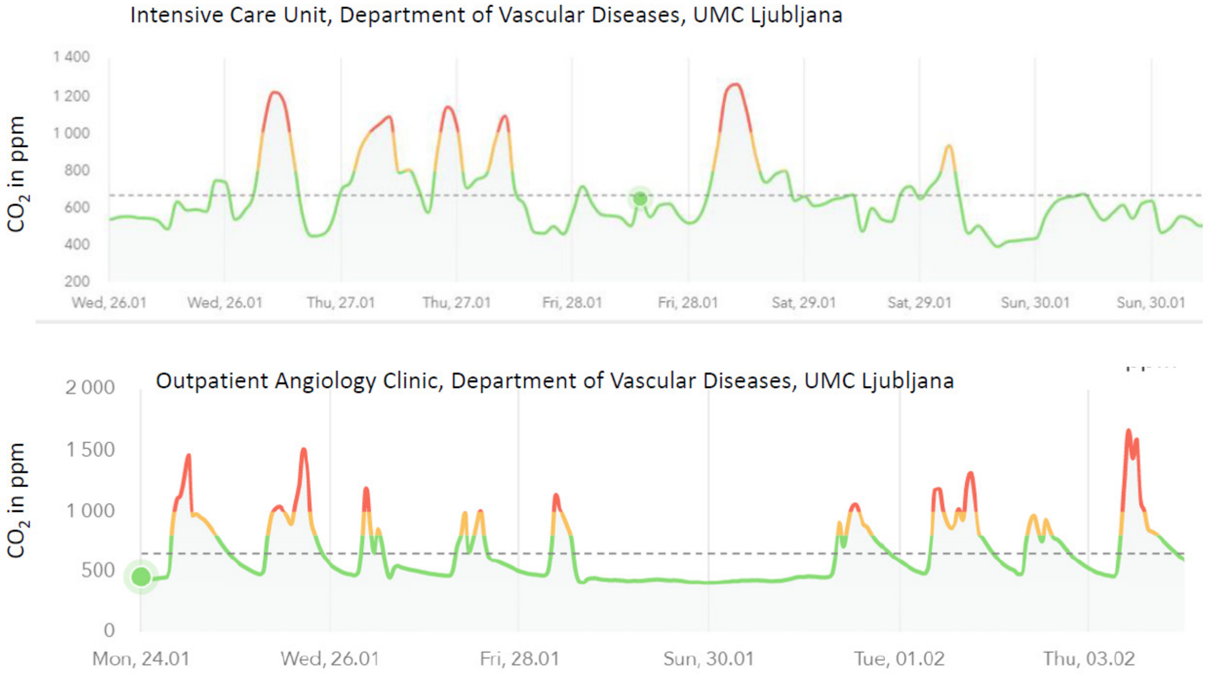


Fig. 3. *Day to day measurements of CO_2 [ppm] in the Intensive Care Unit and the Outpatient Angiology Clinic of the Department of Vascular Diseases, UMCL*

2. Since occasional peaks of CO_2 cannot be seen on the large-scale graph, an example of day-to day measurements is presented in Fig. 3.

3 DISCUSSION

The prevalence of COVID-19 by December 24, 2020 was 3- to 8-times higher among health-care personnel of the Division of Internal medicine than among the general population of Slovenia. It seems unlikely that lack of adherence to protective protocols has been the only reason for the high infection rates. The highest prevalence of COVID-19 among nurses, who spend the most time in patient rooms, speaks in favor of airborne transmission of SARS-CoV-2 in hospital rooms with infected patients. Aerosol scientists have long known that there is no clear boundary between droplet transmission and aerosol transmission **[5]**. People exhale droplets with a continuous distribution of sizes, most of which are smaller than 1 µm in diameter **[6]**. With air-flow velocities typical of indoor spaces, droplets up to 5 µm in diameter may travel several tens of meters before falling to the ground **[7]**. An invited commentary for Clinical Infectious Diseases by Morawska and Milton **[8]**, endorsed by 239 scientists from all over the world, summarized these facts in July 2020, explicitly warning of SARS-CoV-2 transmission in poorly ventilated indoor spaces. Their message was presented to the lay public by the New York Times **[9]** and to the scientific community by Nature **[10]**. In October 2020, airborne transmission of SARS-CoV-2 was addressed by a letter published in Science **[11]**, claiming that droplets not only up to 5 µm but up to 100 µm in diameter contributed to infective aerosols, and that airborne transmission was the major route of spreading COVID-19 **[11]**. Poorly ventilated indoor spaces where an infected individual resides for a longer time are prone to become sites of airborne COVID-19 transmission **[11]** and **[12]**. A review of studies testing air samples from hospitals for the presence of SARS-CoV-2 RNA found the highest concentrations in toilets, bathrooms, inner rooms for personnel and in hallways /waiting rooms without windows **[13]**. Weighing the evidence for and against the probability of airborne transmission has given SARS-CoV-2 a high probability score of 8- on a 9-point scale, together with tuberculosis and influenza **[14]**.

Authors from the Massachusetts Institute of Technology (MIT) **[15]** have developed a mathematical model predicting the probable time to airborne infection in confined spaces with an infected individual, considering the number and activity of other people in the room, the volume of the confined space, ventilation, air filtration, air humidity and some other variables. Based on this model, an interactive internet application was developed [16]. The authors assumed an infective dose of a few tens of SARS-CoV-2 virus particles [15] and [16], which is in accordance with recent estimates [17] and [18]. Admittedly, we do not know the precise infective dose of SARS-CoV-2 in humans, since all assumptions rely on animal data and on modeling [17]. However, our experience at the Department of Internal Medicine, UMCL, agrees with predictions of the MIT model: in a poorly ventilated room, where an infected individual has resided log enough to create stationary conditions of the infective aerosol, another person entering the room without protective equipment becomes infected after only 3 minutes on average [15].

At the request of the Medical Director of the UMC Ljubljana, a lecture on airborne transmission of SARS-CoV-2 was presented to the Medical Board of the UMCL on December 21, 2020 [19]. The lecture was summarized in [20], and a mini-review has been published [21].

Immediately following the lecture to the Medical Board of the UMCL, all medical personnel were encouraged to wear FFP2 masks when dealing with possibly infected patients, and instructions were given to improve hospital room ventilation by opening windows for at least 10 minutes every hour. However, the initial interest in improving room ventilation and installing air- filtration systems in the UMCL decreased immediately after effective COVID-19 vaccines became available.

Paralleling developments in the community, efforts were mainly focused on promoting vaccination, which was important and commendable, but not sufficient to bring the COVID-19 pandemic under control. In the autumn of 2021, the numbers of SARS-CoV-2 infected residents of Slovenia, hospital patients and personnel at the UMCL rose again sharply. Especially with the overwhelming wave of the omicron variant, vaccination against the original Wuhan strain of SARS-CoV-2 no longer protected against symptomatic infection, although it still strongly protects against severe illness requiring hospitalization [22].

In parallel with the decreasing efficacy of existing anti- Covid-19 vaccines against symptomatic infection, the enthusiasm for ventilating patient rooms by regularly opening the windows every hour also decreased, as evidenced by the occasionally excessive concentrations of CO_2 at the Department of Vascular Diseases of the UMCL (Fig. 3). The concentration of CO_2 in indoor air approximates the concentration of exhaled aerosols and the recommended "safe level" of CO_2 in the air is less than 750 parts per million [23] and [24].

Vaccines against SARS-CoV-2 have been developed in record time and especially mRNA vaccines have proven to be very safe and effective against the early strains of SARS-CoV-2 [25] and [26]. Unfortunately, at first due to the limited supply of vaccines, and later due to vaccine hesitancy, vaccination has been proceeding much too slowly to result in herd immunity. Vaccination rates in many parts of the world remain very low, which creates the opportunity for infectious mutant virus strains, such as omicron, to rapidly spread around the globe [27]. Additionally, there are other respiratory pathogens besides SARS-CoV-2 that are transmitted by aerosols, among which influenza is the most well-known [28] and [29]. It is therefore prudent to address prevention of airborne spread of infective respiratory diseases in addition to promoting large-scale vaccination against Covid-19.

From the public health perspective, it is wise to promote outdoor activities, which however is not a reasonable alternative for hospitals and nursing homes that urgently need adequate ventilation and air filtration systems. Morawska and co-workers [30] have appealed in their science paper that airborne virus transmission should be recognized as a serious public health threat which should be systematically addressed, just as contaminated water and food have been addressed and successfully dealt with in the past.

4 CONCLUSIONS

During 2020, before the instructions for the use of personal protective equipment were up-graded and before regular window-opening was advised, the prevalence of Covid-19 among health care personnel at the Division of Internal medicine, UMCL exceeded the national average by 3- to 8-fold. We have not proven a causal relationship between airborne transmission and the high number of Covid-19 cases because many potential confounding factors have not been accounted for. However, the association remains highly suggestive. After regular window-opening was advised in UMCL, the peak CO_2 levels still often exceeded the recommended "safe" level of 750 ppm. Adequate ventilation /air filtration systems should be installed and maintained in hospitals, nursing homes and other densely populated public buildings in order to assure good air quality and minimize airborne hazards to human health.

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Correlation between Air Pollution and the Spread and Development of COVID-19 Related Disease

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Potential correlation of exposure to polluted air and the spread and co-development of COVID-19 and severe acute respiratory syndrome, caused by SARS-CoV-2, was examined. The emphasis was given on polluted air in the form of suspended particulate matter or liquid particles in gas or air (so-called dust particles). This study was structured as a systematic literature review of multiple research projects carried out across the globe. Impact of the polluted air particles on the virus spread was examined from the temporal and spatial spread. Furthermore, overall impact of particulate matter and COVID-19 disease on human health human was investigated on a microbiological level.

Despite some ambiguity, through systematic literature review effect of the polluted air on the increased spread of various viruses was demonstrated. Longer exposure to contaminated airborne dust particles has a negative effect on the human immune system and in the case of infection with COVID 19, may even overload it. This can lead to serious consequences for human health or even cause death.

This review article also provides an insight into a more comprehensive analysis of possible correlation between the spreading the virus (SARS-CoV-2) by means of particulate matter and other meteorological variables (such as air temperature and humidity, weather events and climate).

Keywords: air pollution, coronavirus (COVID-19), particulate matter, morbidity, meteorological parameters, air quality

Highlights

- *A strong relationship was found between air pollution and the spread of COVID-19 pandemic in the EU, China and the US.*
- *Particulate matter was found to contribute to morbidity and mortality due to COVID-19.*
- *Higher temperature and humidity have a negative effect on the spread of the SARS-CoV-2.*

0 INTRODUCTION

Coronaviruses are a family of enveloped positive-stranded RNA viruses, which cause a variety of diseases, from mild colds to severe respiratory problems [1]. New SARS-CoV-2, causing COVID-19 disease, was identified on 7th of January 2020. On 11th of March 2020, the World Health Organization announced a pandemic of global dimensions [2]. From the very beginning of the novel virus identification a great emphasis was given on the investigation of virus characteristics and transmission by various research groups, with goal of limiting the virus spread.

Past studies researching the transmission of respiratory virus (RSV) [3] and acute respiratory syndrome (SARS-CoV) [4] in the air, have found that various viruses spread in the form of drip aerosols transmitted by coughing, sneezing, talking or breathing and by physical contact and transmission through contaminated surfaces.

Research of transmission of respiratory viruses based on ribonucleic acid as a genetic material (RNA) has shown that the virus expelled by coughing is present in both larger drip aerosols (> 5 μm) and smaller particles (< 5 μm) [5]. In exposed people, the (previously exhaled or coughed) drip aerosol of larger dimensions (> 5 μm) is lodged in the upper airways (areas of the nose and throat), while drip aerosol of smaller dimension (< 5 μm) can penetrate all the way to the lower respiratory tract (bronchi and alveoli in the lungs) [6].

SARS-CoV-2 is mostly transmitted from a distance of a few centimeters if there are larger aerosols present, to few meters if there are smaller aerosols. If there are drip aerosols of larger size (> 5 μm) it can take a few minutes for them to land on the ground. Aerosols of smaller sizes (< 5 μm) can remain in the air for several hours before they are deposited in the human body or on another surface in the area where the infected subject moves [7]. The distance of transmission of the virus and the persistence of the virus and its infectivity depends on the force of the individual person coughing or sneezing, the transmission procedure (the size of the coughed air cloud) [8], parameters of the internal or external environment and the type of surface [9] on which the drip aerosols are retained, before the infected person passes them on or they enter into another host body through his/her activity. The survey [10] showed that under similar meteorological conditions (air temperature from 21 ºC to 23 ºC and relative humidity 40 %) different types of surfaces can affect the temporal and effective stability of SARS-

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CoV-2: plastic (up to 72 h), stainless steel (up to 48 h), cardboard (up to 24 h) and copper (up to 4 h).

However, the recent review [11] showed that outdoor SARS-CoV-2 concentrations are very low and often under detection limits so that airborne transmission could eventually be limited to crowded sites and small indoor environments with poor ventilation. On the other hand, that one of the first paper [12] addressing the problem of studying correlations among COVID-19 cases and mortality with pollution mentioned that long-term exposure could eventually make susceptible individuals more prone to have strong effects of COVID-19 and even mortality. The correlation with number of cases is not indicating a causal relationship because there are a large number of confounding factors that needs to be taken into account such as population density, transmissibility that induces spatial autocorrelations, movement of people that influence both probability of contagion.

1 IMPACT OF METEOROLOGICAL PARAMETERS

The spread of coronaviruses in the external environment is influenced by several meteorological parameters (air temperature, air humidity, air movement and solar radiation).

1.1 Air Temperature

Survey of meteorological variables and disease rates for COVID-19 in 190 countries [13] showed a clear association of air temperature with the spread of viruses. When temperature rises from 5 ºC to 11 ºC, the risk of COVID-19 disease is reduced by up to 28 %. In their time series study (carried out between 23rd January 2020 and 13th April 2020 at 415 locations in 190 countries) an increase of air temperature from 7 ºC to 22 ºC was associated with the decrease of 25 % in the cumulative risk of the COVID-19 incidence over a 14-day period [14]. The study [14] found that with the formation of seasonal influenza and the lowering of temperatures, the lipid-containing virus envelope (including SARS-CoV-2 [15]) stabilizes and contributes to the persistence of the virus. Low air temperature inhaled through the nasal canal by cooling the nasal epithelium (avascular tissue) inhibit the production and transport of mucus. Low temperature reduces phagocytic ability of cells in the upper respiratory system, which may increase the amount of virus in the body [16].

1.2 Air humidity

Various studies have shown a clear association between air humidity and the spread of viruses, which is not unique. As the relative humidity of the air increases by up to 72 %, the risk of COVID-19 disease also increases [13].

When the virus is clinging to a drop of water, lowering relative air humidity leads to the crystallization of the salt, which consequently lowers the salt concentration in the water thereby stabilizing ineffective virus (virion) [17]. transmission rate will be increased due to lower air humidity levels and evaporation, which retains the virus in/on smaller particles in the liquid state and makes it harder for particles to drop on the floor. A review of viability of the virus in different climates [9] came to a similar conclusion. It says that at the same time lower temperatures (6 ºC) and relative humidity (50 %) of the air (moderate climate belt) virus is nevertheless more stable than in higher temperatures (20 ºC) and relative humidity (80 %) of the air.

1.3 Wind Speed

When the wind blows faster (above 6 m/s), the virus's ability to spread is reduced [13]. In outside spaces, the virus is more easily dispersed due to its own low weight and stronger movement of the air mass.

1.4 Solar Radiation

Stronger solar radiation is credited for a faster rate of virus decay in/on the medium through which it is transmitted. The survey [18] concluded that the average virus decomposition time, found in the medium (saliva), is halved when compared with the intensity of the simulated light between early autumn/ winter/summer. The theory [19] assumes, that only UV-B spectrum of electromagnetic radiation from sunlight hits the RNA of the virus and damages it, is not sufficient enough to justify results [20] thus leaving space to a greater role of UV-A spectrum of light.

2 IMPACT OF AIR POLLUTION

Air pollution is caused by releasing gaseous, liquid or solid pollutants into the air naturally or due to human factor. Viruses are most easily spread by particulate matter that can differentiate based on the state of matter, chemical composition, size and shape. Particulate matter (dust particles) most commonly originate from bare surfaces (e.g. deserts), by transmission of seawater by natural fires [21]. They can also originate from anthropogenic activity as a by-product of the following activities: the production of electricity and heat from fossil fuels and wood chips, transport based on fossil fuels and industrial activities such as petrochemical, metallurgical, ceramic, pharmaceutical and other activities as evidenced by reports from Slovenia [22] and the EU [23]. Particulate matter polluted air is found in urban centers, where most of the industrialized world population lives, which is also credited with the highest share of emissions in history [24] next to recently emerging large countries (China and India), as shown in a survey [25].

Study [26] examined the impact of particulate matter concentration in Italian municipalities, where it argued that prolonged pre-COVID exposure to, and contemporary levels of particulate matter can play a positive and significant role. Particulate matter concentration impact on daily deaths between the first COVID-19 outbreak in Italy and the previous five years was studied and the findings showed a positive and significant effect of botch components.

The virus-laden aerosol particles eventually present in atmosphere are dry residual of evaporated droplets (i.e. droplet nuclei) rather than agglomerate with pre-existing particles. There is a small, but not negligible, probability that virus-laden aerosol could act as a sink of ultrafine particles (around 0.01 µm in diameter). However, this will not change significantly the dynamics of the virus particles or their permanence time in atmosphere. Therefore, the probability of airborne transmission due to respiratory aerosol is very low in outdoor conditions, even if it could be more relevant for community indoor environments [27].

Weather and climatic conditions favorable for increased deposition of submicron aerosols (and infectious aerosols) due to supersaturation in the airways, can be linked to seasons of respiratory infections and an increase in the respiratory symptoms of asthma and chronic obstructive pulmonary disease (COPD). Thus, while all available evidence in favor of the critical role of air humidity, and decrease in air temperature, and supersaturation in the airways increasing the risk of developing respiratory symptoms is circumstantial [28].

Unfortunately, premature and unsubstantiated claims that SARS-CoV-2 coagulates (creates clusters) with outdoor particulate matter (PM_{10}) in the air, and that SARS-CoV-2 can be transported by air pollutants, have been widely circulated and cited by many researchers as fact, as a result of the misinterpretation of statistical data and misuse of specific terminology. The current work shows that these mistakes have resulted in the creation of a new epidemiological myth [29].

2.1 Particulate Matter

Particulate matter transport different chemical components and micro-organisms and may be inhaled through the mouth or nose and, due to their different sizes, are deposited in different areas of human body (Fig. 1).

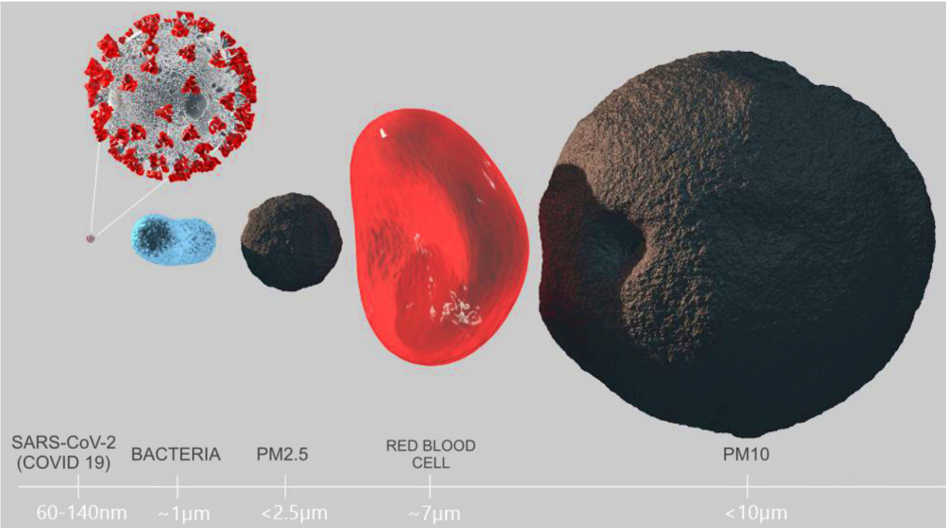

Fig. 1. *Comparison of particles (PM2.5 and PM10) sizes and SARS-CoV-2 virus size* [30]

Larger particulate matter (> 10 µm) are usually deposited in the oral and nasal cavity and throat. Breathing through the nose is usually safer due to the successful filtering of particulate matter because of nose hair and greater change in direction through which inhaled air flows and consequently stops particles. Bigger particles which do not stop in these parts of the respiratory system may also penetrate the trachea. There they can be removed through mucus, or they enter the body. Smaller particles can penetrate all the way to the pulmonary follicles. Only 1 % of 10 µm particles can access the pulmonary follicles, according to the World Health organization (WHO) [31], while particles of 2 µm have a higher chance of penetration. Particles of less than 2 µm (about 0.5 µm) on average do not exceed 10 % to 15 % ability due to the respiratory system exhalation. Meanwhile, ultrafine particles (0.1 µm) are much more likely to remain in the system. They enter the bloodstream and internal organs via diffusion [32].

Exposure to particulate matter in polluted air is in itself are problematic from the standpoint of the impact on the human health in the form of diseases [31], [33] and [34] such as:

- lung disease caused by accumulation of dust in the lungs,
- cancer that may develop due to inflammation of the lung tissue,
- cardiovascular disease,
- blood, kidney and central nervous system poisoning due to body absorbing toxic,
- chemicals that trigger reactions in other organs,
- infectious diseases,
- skin reactions,
- neurodegenerative disorders,
- deterioration of other diseases such as asthma.

Burnett et al. estimate that in 2015 there was around 8.9 million deaths due to long-term exposure to particulate matter in ambient air and subsequent development of the aforementioned diseases [35] requiring assumptions about equivalent exposure and toxicity. We relax these contentious assumptions by constructing a $PM_{2.5}$-mortality hazard ratio function based only on cohort studies of outdoor air pollution that covers the global exposure range. We modeled the shape of the association between $PM_{2.5}$ and nonaccidental mortality using data from 41 cohorts from 16 countries - the Global Exposure Mortality Model (GEMM). The number of deaths is comparable to 10.3 million due to nutrition and 6.3 million smoking-related deaths (as a separate parameter) which are two of the largest causes of death respectively. As a result, many describe the consequences of air pollution as a 'silent epidemic' of large dimensions [36].

3 PARTICULATE MATTER AND SARS-CoV-2

3.1 Temporal and Spatial Impact of Particulate Matter

The likelihood of interactions of pre-existing particulate matter in the atmosphere and virus-laden aerosols was studied in the cities in Italy [27] but the relative importance of airborne transmission is still controversial. Probability of outdoor airborne transmission depends on several parameters, still rather uncertain: virus-laden aerosol concentrations, viability and lifetime, minimum dose necessary to transmit the disease. In this work, an estimate of outdoor concentrations in northern Italy (region Lombardia. The maximum probability of particulate matter merging with viral aerosols is when particles are approximately 0.01 µm (ultrafine particulate matter) in size. However, due to the reduced overall presence of concentrations of genetic material in ambient air (excluding crowds of people) this would not contribute to the significant spread through space and time. Chemical analyses of PM_{10} concentration samples from Bergamo in Italy [37], confirmed the presence of SARS-CoV-2 genetic material, but did not confirm infectiveness. A similar study was conducted in the Lombardy region in Italy [38], where they analyzed the relationship between PM_{10} concentrations and the number of cases of infected cases in different regions. Direct correlation could not be established as the maximum number of cases appeared in some provinces that did not have the highest PM_{10} concentrations. Due to the uncertainty of faster virus spread, focus was given on studies which investigated correlation of long-term exposure to particulate matter and the negative impact of COVID-19 disease on human health.

3.2 Impact on COVID-19 Disease and Mortality

Research review [39] of negative effects of particulate matter on human health and the exploitation of them by SARS-CoV-2 showed that the virus at the cellular level typically exploits the vulnerability of cells that have been damaged by long-term exposure to air pollution (different sizes and chemical compositions) through oxidative stress and inflammation of cells.

Oxidative stress occurs when harmful substances are present in the organism. These substances cause a state of imbalance between free radicals (chemically reactive molecules containing oxygen with free electrons) and antioxidants in the human body. The right amount of these compounds (free radicals) occurs with normal oxygen metabolism and contributes to the defense mechanism against different microbes. Harmful substances cause production of free radicals in large quantities which, when neutralization has not been successful, cause damage to cellular structures in the human body or limit the defense mechanisms against harmful viruses [40].

Particulate matter shows an intrinsic oxidant generating capacity that is correlated with the physical-chemical characteristics of the particles, such as their surface properties and their chemical composition. In [41] the analysis of the oxidative potential of PM_{10} was integrated with PM_{10} characteristics. These results support the idea that the oxidative potential of PM could be an indicator of cytotoxicity of PM. When acellular and cellular assays of oxidative potential are compared, it seems that cellular assays are more representative of cytotoxicity. However, these results should be validated with further studies done in different seasons (at the same site) and different sites (for example urban and industrial areas).

Cell inflammation due to particulate matter exposure eventually weakens the immune system response and causes impairment of the ability of white blood cells, such as macrophages to successfully perform phagocytosis process to disable microorganisms [42]. In [43] it was shown, that the human immune system responds to COVID-19, also by producing interleukin (e.g., Interleukin-6, IL-6), which contributes to the defense by stimulating a more vigorous immune response. If the immune system response is too strong (as in the case of cytokine storms) and immune cells produce too much interleukin (IL-6) the effect is the reverse. Immune system response is so vigorous that it starts to attack or harm microbes as well as healthy cells through various products that should eliminate attack of microbes. In patients with severe symptoms of COVID-19, inflammation can be limited by inhibiting interleukin access (IL-6) to IL6R receptors and limit the development COVID-19 disease itself [44] but after review, treatment was liberalized to patients with lower oxygen requirements. Patients were divided into two groups: those requiring ≤ 45 % fraction of inspired oxygen (FiO_2). The immune system responds similarly to particulate matter i.e., by secreting IL-6 [45]. Due to these processes, it is evident that a long-lasting presence of particulate matter in the human body and a consecutive infection with COVID-19 disease, may overload the human immune system. In a longitudinal study [46] it was also suggested that particulate matter further stimulates the response of the immune system when already dealing with COVID-19 and can overload it, which can result in higher mortality.

In [47] the contribution of air pollution to COVID-19 disease in England, while taking into account socio-economic, demographic and health-related characteristics of the population, it was determined that the increase in long-term exposure to concentrations of $PM_{2.5}$ to 1 $\mu g/\mu m^3$ was associated with a 12 % increase in the number of COVID-19 cases. When examining the correlation between air pollution and the increase in COVID-19 deaths in three French cities [48], the researchers were able to establish the levels of particulate matter concentrations ($PM_{2.5}$ and PM_{10}) above which the number of deaths due to COVID-19 could be significantly increased. To mitigate the number of deaths related to COVID-19, the concentration level should be lower than 17.4 $\mu g/\mu m^3$ for $PM_{2.5}$ and 29.6 $\mu g/\mu m^3$ for PM_{10} in Paris, from 15.6 $\mu g/\mu m^3$ for $PM_{2.5}$ and 20.6 $\mu g/\mu m^3$ for PM_{10} in Lyon and from 14.3 $\mu g/\mu m^3$ for $PM_{2.5}$ and 22.04 $\mu g/\mu m^3$ for PM_{10} in Marseille. Study in Germany [49] confirmed the link between environmental pollutants ($PM_{2.5}$, PM_{10}, O_3, NO_2), meteorological indicators and cases of disease and death due to COVID-19. Germany presents an unique case as it at the time faced a relatively high number of infectious cases of disease, but very low COVID-19 mortality. The concentration between particulate matter ($PM_{2.5}$ and PM_{10}) present in Germany has a high compliance with the number of cases of disease but does not have such significant association with the number of deaths due to COVID-19. Data analysis thus supports the fact that a lower level of environmental pollution presents a known contribution to the fight against coronavirus, as Germany has high quality health services, with a high proportion of renewable energy sources in the electricity generation sector [50].

Similar link was established in a study in the United States where research was conducted [51] across more than 3,000 counties. Very strong correlation between long-term exposure to air contaminated was shown with $PM_{2.5}$ particles and death by COVID-19. The study further highlights that COVID-19 mortality also depends on other variables such as: population size, age of population, population density, socioeconomic status of people, number of hospital beds available, behavioral patterns.

In China an extensive survey of 49 cities [52] and 14 cities [53] the extent of this effect requires further investigation. This study was designed to investigate the relationship between long-term exposure to air pollution and the case fatality rate (CFR demonstrated that long-term exposure to contaminated air with $PM_{2.5}$ and PM_{10} increases the vulnerability of the population to the SARS-CoV-2 and the impact of the development of COVID-19 disease. Negative impact of long-term exposure to different pollutants in the air and its connection to COVID-19 morbidity was also demonstrated in the **[54]**. Statistical analysis showed that increases in $PM_{2.5}$, PM_{10}, NO_2 and O_3 by 1 $\mu g/\mu m^3$ may result in 1.95 %, 0.55 %, 4.63 % increase and 2.05 % reduction in morbidity for COVID-19. Whereas the analysis did not show a morbidity increase due to the combined impact of COVID-19 and particulate matter, significant association between COVID-19 morbidity and long-term exposure to SO_2 and CO was observed.

In India results of air pollution study related to COVID-19 pandemic in 741 counties studies **[55]** indicated that a 1 % increase in long-term exposure to solid particles ($PM_{2.5}$) leads to increase in COVID-19 deaths by 5.7 %. However, a survey in Chennai (India) **[56]** especially the particulate matter (PM found that the areas of cities exposed to prolonged excessive concentrations of PM particles ($PM_{2.5}$ and PM_{10}) also present the highest (initial) proportion (including up to 90 %) of COVID-19 sufferers. Later measures against the COVID-19 pandemic (reduction in industrial production, transport) lowered concentrations of air pollution (including by 80 %), which moderated the effects of SARS-CoV-2.

Based on the presented studies, we can observe that particulate matter together with SARS-CoV-2 disease pose an additional hazard. The particulate matter itself causes damage and have adverse effects on human health.

4 DISCUSSION AND CONCLUSION

Various studies **[39]** show that increased exposure to air polluted by particulate matter has a negative effect on a person's immune system and may, while fighting COVID-19 disease, overload immune system. Overloading the immune system can lead to serious consequences for human health or even to death. In order to better understand the development of the disease itself, it would be necessary to further study how various disease development mechanisms function in relation to other with other factors mentioned. Due to the proven correlations between polluted air, which in itself harms human health and the spread of the virus and the development of COVID-19 diseases, there is also an urgent need for air quality control. This could be done by performing air quality measurements at a large number of locations in cities and rural areas, regular improvement of atmospheric dispersal models and building more effective communication routes, thus making the public more aware of current air quality and expected air quality in the near-future. In order to improve air quality, it would make sense to perform short-term solutions such as: limiting containment around the source of pollution, technical systems to improve the quality of internal **[57]** however, were debated, especially regarding quantitative recommendations. The answers to \"what is the safe distance\" and \"what is sufficient ventilation\" are crucial to the upcoming reopening of businesses and schools, but rely on many medical, biological, and engineering factors. This study introduced two new indices into the popular while perfect-mixing-based Wells-Riley model for predicting airborne virus related infection probability - the underlying reasons for keeping adequate social distance and space ventilation. The distance index Pd can be obtained by theoretical analysis on droplet distribution and transmission from human respiration activities, and the ventilation index Ez represents the system-dependent air distribution efficiency in a space. The study indicated that 1.6 m to 3.0 m (5.2 ft to 9.8 ft and ambient air, the use of fuels with lower emissions of particulate matter for heating households and propelling individual and public transport. Long-term measures to address the reduction of air pollution include investments in installations that are not based on fossil fuel for the production of heat and electricity in households, refurbishment of the external layer of buildings making them more energy-saving, investment projects for the technologies that have low or zero particulate emissions in transport and major energy promoting activities which are not based on excessive air pollution.

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Public Handling of Protective Masks from Use to Disposal and Recycling Options to New Products

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A study was conducted on the waste of disposable surgical masks and their problematic impact on the environment. The studies examined have shown the negative effects on the environment that are likely to occur and those that have already occurred. In this article, society's relationship to the potential recycling of disposable surgical masks is considered and projected onto the possibilities of the cradle-to-cradle design approach. The development of a product from recycled surgical masks is driven by two different surveys. The first focuses on wear and disposal habits, and the second on the relationship to recycling. As a result, the flooring was developed with thermally treated recycled surgical masks replacing the filler layer. The goal of the product design was to improve the long-term life cycle analysis of a waste surgical mask.

Keywords: masks, medical waste, environment, recycling added-value product, life-cycle-analysis

Highlights

- *Disposable surgical masks have been shown to have a high carbon footprint.*
- *Disposable surgical masks are the most commonly used protective masks in the Slovenian population.*
- *10 % or more of users incorrectly dispose of the protective masks they wear, regardless of the type of mask.*
- *Disposable masks are used longer than specified in the instructions for use in 84 % of cases, in contrast to respirators, which are disposed of correctly after 6 hours in 86 % of cases.*
- *92 % of survey participants would use products made from recycled face masks.*
- *A soil solution made from used surgical masks was developed.*

0 INTRODUCTION

The COVID-19 pandemic changed everyday life around the world. In response, many countries have enacted various regulations to prevent the spread [1] to [3]. The safety guidelines have brought many side effects, especially for the environment. The biggest positive side effect is the improvement in air quality [4], but the negative effects are alarming. Along with quarantines, online shopping and delivery has increased, leading to an increase in packaging waste. In addition, the amount of medical waste has increased dramatically [5] and [6], while the increased production of medical waste has increased CO_2 emissions [7] and [1].

While some safety guidelines differed from country to country, most countries required the use of face masks, which, along with gloves and surgical gowns, accounted for the majority of medical waste. Medical waste is often infectious and must be properly handled before disposal or recycling. However, due to the increasing volumes during the pandemic, where millions of disposable face masks and gloves were disposed of daily, many disposal centres are unable to process sufficient quantities [5] and [2]. At the height of the pandemic, Wuhan alone generated 240 tons of medical waste in a single month [8]. The UNEP report states that 400 million tons of plastic waste were produced daily worldwide during the pandemic [2]. As a result of the immense amounts of face masks and the waste generated, a new environmental crisis is emerging with many challenges [6].

Face masks are made of polymeric materials that degrade over time. Macroplastics break down into smaller fragments, first into microplastics and later into nanoplastics. Both microplastics and nanoplastics were one of the most problematic environmental pollutants even before the pandemic [5] and [6]. Studies [6] have shown that a disposable surgical mask can produce up to 147,000 micro- and nano-particles during three cycles of the ageing process. The fact that waste masks have already been found in the ocean is of concern [8], as marine life is already suffering from pollution. Studies [7] have also revealed several cases of animals getting caught in the rubber bands of the masks and suffocating. In addition, it has already been shown that many animals mistake the masks for food. Surgical masks have been shown to be ecotoxic, and improper handling can result in colossal amounts of micro- and nano-plastics after use ends [7].

The purpose of this article is to present a study on waste disposable surgical masks (WDSM) and their problematic effects on the environment. The most important consideration at the starting point is to understand society's relationship to potential recycling and the possibilities of the cradle-to-cradle design

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approach. Two different surveys were conducted. The first focused on the wearing and disposal habits of the Slovenian population in relation to protective masks, while the second focused on the relationship of Slovenians to face mask recycling and the acceptance of different product categories made from recycled face masks.

1 METHODS

The first part of the study consisted of a literature and paper search on the topic of face masks and environmental impacts of waste face masks. The research focused on categorising different types of face masks, understanding the life cycle analysis of a disposable surgical mask, including long-term impacts, and investigating available and potential disposal solutions. Based on the information gathered, two different questionnaires were created to define the disposal habits of the respondents, their attitudes toward recycling, and their attitudes toward products made from recycled face masks. The answers were then crucial for the design and development of a socially acceptable product made from used surgical masks.

2 FACE MASKS RESEARCH

2.1 Types of Facial Masks Used during the Pandemic of COVID-19

Textile face masks are the first category. They are made of variable textile material, are inexpensive and reusable. There are several types of textile masks, which differ in the number of layers and the material of the layers. Approval of such masks varies by country and is limited because they provide only basic protection, having been shown to be less effective against SARS-CoV-2 than, for example, N95. However, they provide adequate protection against air contaminants and were used in several Asian countries prior to the pandemics [9].

The second category is surgical or medical masks, also called disposable surgical masks (DSM), which are used to protect against droplets. Surgical masks usually consist of three, sometimes four, layers: the inner layer, which absorbs water and moisture; the middle layer, which serves as a filter and is made of melt-blown polypropylene; and the outer layer, which is hydrophobic. The inner and outer layers are made of non-woven fabric. Four-layer masks also have an activated carbon filter. An essential component of a surgical mask is also a flexible nasal strip made of plastic or metal [9].

Respirators are the third category of face masks. They include filtering facepiece (FFP) masks, full-length face shields and SCBA (self-contained breathing apparatus). FFP masks are filtered by a variety of complex polypropylene microfibers and electrostatic rates. There are three types of FFP masks: FFP1, FFP2 and FFP3, and they differ in the number of pleats of the filtering material. A full facepiece consists of a clear polycarbonate shield that runs across the face. It provides direct plastic containment and protects against droplets [9].

2.2 Life Cycle Analysis of Disposable Surgical Mask

The focus of current research [8] is to understand the long-term environmental impact of disposable surgical masks. To understand the impacts as comprehensively as possible, nine categories were considered: climate change, fossil fuel depletion, metal depletion, water depletion, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, marine eutrophication, and human toxicity. In each category, emissions were calculated for raw material procurement, production, transportation, use, and end-of-life. The disposable surgical mask was found to have high emissions for raw material procurement in all categories, but especially for carbon footprint, fossil fuel degradation, metal degradation, freshwater ecotoxicity, and marine ecotoxicity. The emission levels are also problematic for end-of-life condition in terms of carbon footprint, metal depletion, freshwater ecotoxicity, and marine ecotoxicity.

Some research [10] focused on two different scenarios for end-of-life masks: non-sanitary landfill and sanitary scenario. The following impact categories were considered and studied: non-carcinogenic toxicity to humans, carcinogenic toxicity to humans, marine ecotoxicity, freshwater ecotoxicity, mineral resource scarcity, stratospheric ozone layer depletion, land use, fossil resource scarcity, terrestrial acidification, global warming, terrestrial ecotoxicity. The first scenario showed that DSM has a lower environmental impact than FFP2 masks, especially because of the fossil resource scarcity factor, but a significantly higher environmental impact than washable masks. The most problematic impacts of DSM are stratospheric ozone depletion, soil acidification, and fossil resource scarcity. When considering the landfill disposal scenario, the results are similar, mainly because the production of a mask is the most problematic environmental impact. However, a difference can be seen in the factor for stratospheric ozone depletion, which is significantly lower. In both scenarios, the highest values are given for the terrestrial acidification category. This impact factor life cycle analyses (LCA) is described [11] as negatively affecting terrestrial ecosystems by lowering soil pH through atmospheric deposition of acidifying substances such as Sulphur oxides, nitrogen oxides, and ammonia. Decreased soil pH can lead to a deficiency of essential metal ions for plant growth and exposure of roots to toxic metal ions.

2.3 Disposable Surgical Masks (DSM)

Medical waste must be properly treated to eliminate all pathogens. The commonly used treatment technologies are thermal (autoclaving, incineration, plasma treatment, and microwave treatment) [5]. Prior to the pandemic, medical waste was excluded from medical personnel and facilities. During the pandemic, medical facilities were instructed to separate masks worn by an infected person from other masks used in a particular facility. The separated masks were then to be labelled. During the pandemics, the use of masks expanded to the entire population. With the wrong instructions on how to handle mask waste, the problem of inappropriate and unorganized mask collection or disposal began [7] and [12]. On the other hand, there is research [3] indicating that masks, as a layered composite material, can be a safe hotspot for antibiotic resistance gene colonization when disposed into the marine ecosystem. Decontamination of masks is challenging due to susceptibility to filtration [13]. However, studies [14] have shown that decontamination of previously used surgical masks is possible. The following categories were considered: optical integrity, air permeability, burst resistance, pressure differential, and particle filtration efficiency. Decontamination methods (oven, thermal drying, autoclave, hydrogen peroxide plasma vapor) were tested and evaluated for both performance and safety. The results showed that all tested methods successfully decontaminated a mask after only one cycle. In addition, the properties of a surgical mask were maintained for at least five cycles. Overall, the oven decontamination method (75 °C for 45 min) was found to be the simplest. The general guidelines [13] for reuse of facial masks state that the filtration efficiency of masks contaminated with fluids may be compromised and therefore they should not be reused, that each mask should be separated and labelled to avoid mixing the masks and avoiding direct contact with the metal surface or other masks, surgical masks should not be used when in contact with a potential COVID-19 positive person (coronavirus is much smaller than the pores in surgical masks).

Studies show that many different potential DSM recycling options can be considered, e.g. pyrolysis [15]. Crushed face masks were evaluated along with recycled concrete aggregate for civil engineering field, aggregate with mask showed good compressive strength (216 kPa) and resilient modulus (314.35 MPa). Similarly, the effect of surgical mask fibres (polypropylene) on the mechanical properties of concrete was evaluated. The mechanical properties improved. Polypropylene from surgical face masks was treated and converted into cathodes for supercapacitors.

Based on LCA [10], a disposable surgical mask could be improved by changing the position and attachment system of the nasal wire and rubber ear band to facilitate disassembly from the core of the mask. It would be even more efficient to manufacture the entire mask from a single polymer, which would allow for easier recycling. The most efficient solution would be to manufacture and use reusable masks with replaceable filters.

3 SURVEY RESEARCH

3.1 Survey on the Current Use of Protective Masks in Slovenia

A survey was conducted to collect data on the wearing habits of various protective masks and face coverings of Slovenians. It was conducted between March and June 2021. During this period, 670 correctly completed questionnaires were collected and analysed. 69 % of the participants were female and 31 % were male. All participants were 16 years of age or older, and 91% were between 16 years and 55 years of age. It was found that in the period from March 11, 2020 (declaration of the pandemic by WHO and introduction of measures requiring the wearing of protective masks) to March 8, 2021 (start of the survey), 98 % of Slovenians had used one of the following protective masks: DSM, FFP2 or FFP3 protective mask, or textile mask (TM). 81 % of respondents had used a DSM at least once during this period, and 63 % of respondents had used a TM at least once (Fig. 1). 3 % of respondents who answered otherwise referred primarily to other textiles such as a scarf, route, bandana, or buff, or they answered that they had not used protective masks or face coverings during the first year of the pandemic. When respondents were asked what type of mask they used most often, we obtained the results shown in Fig. 2.

From these results, it appears that Slovenians used DSM most often.

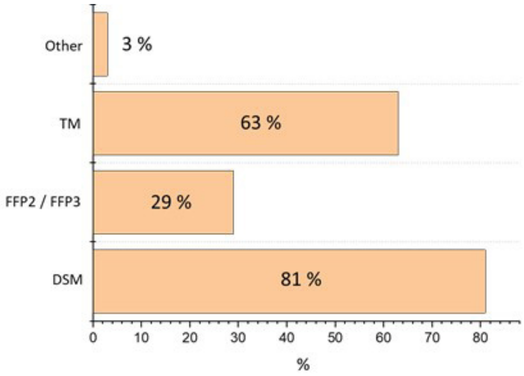

Fig. 1. *Survey answers to Question 1: Which face mask have you used since start of pandemic?*

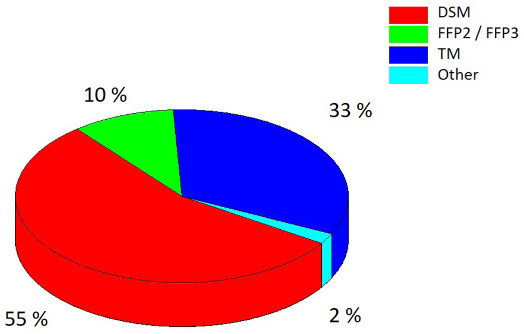

Fig. 2. *Survey answers to Question 2: Which face mask do you use most often?*

When asked how many masks you use per month, respondents answered an average of 16 masks, with a minimum of 0 mask and a maximum of 150 masks. When asked how much money they spend on buying masks for themselves, respondents answered an average of €51.6, with a minimum of €0 and a maximum of €500.

The population of Slovenia older than 16 years in the first half of 2021 was 1,791,246, so, using these data we can roughly estimate that in the first year of the pandemic in Slovenia, about 344 million protective masks were used, on which Slovenians spent €92.5 million of their personal money. In addition, companies and the government spent much more money to provide a sufficient amount of masks in schools, hospitals, industry etc.

An analysis of the handling of each type of mask was also performed. On this subject, we obtain the following results.

3.1.1 Disposable Surgical Masks

Only 16 % of respondents use DSM correctly - they use each mask only once for a maximum of 2 hours. This means that 84 % of the population uses DSM more than once. When asked how often you use the same DSM, they responded as shown in Fig. 3.

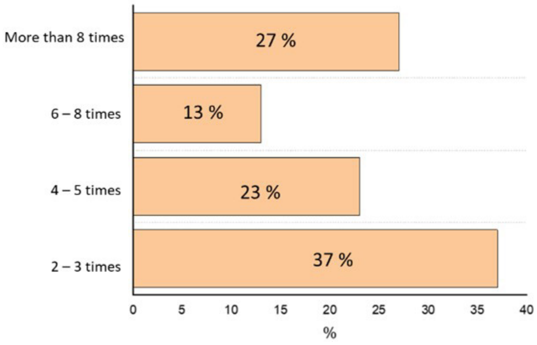

Fig. 3. *Survey answers to Question 3: How often do you use the same DSM?*

Since it has been determined that the DSM is the most commonly used type of protective mask, it is also extremely important how are they threated after use. As recommended by the Slovenian National Institute of Public Health, waste DSM should be placed in mixed municipal waste or, if possible, in infectious waste. Two-thirds of Slovenians adhere to this recommendation (Fig. 4), while 17 % have an even better solution at hand and dispose of waste DSM in infectious waste containers. 4 % of respondents who chose the other option indicated that they collect waste DSM in special bags or containers and do not throw it away yet. 12 % of respondents do not properly dispose of waste DSM according to current recommendations, as they dispose of it in plastic or paper waste.

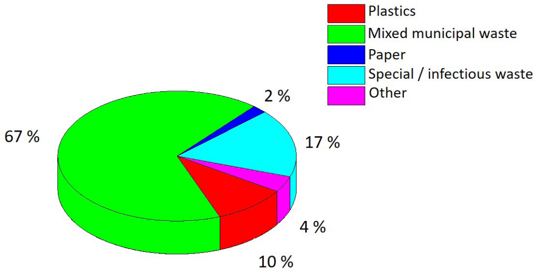

Fig. 4. *Survey answers to Question 4: Where do you dispose of waste DSM?*

3.1.2 Filtering Face-Piece Masks (FFP2/FFP3)

Users of FFP2 or FFP3 protective masks were asked the same questions as DSM users. It was found that most users of FFP2 or FFP3 masks use the masks correctly according to the instructions of the Slovenian National Institute of Public Health. 28 % of the respondents use the masks only once, and 86 % of the respondents do not use the same mask for more than 6 hours. The answers of those who wear the same mask more than once are shown in Fig. 5.

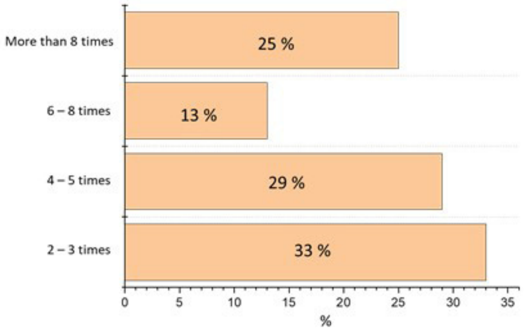

Fig. 5. *Survey answers to Question 5: How often do you use the same FFP2/FFP3 protective mask?*

A survey was also conducted on the disposal of waste FFP2/FFP3 mask. The recommendations of the Slovenian National Institute of Public Health for waste FFP2/FFP3 masks are the same as for waste DSM. 56 % of Slovenians follow this recommendation (Fig. 6), while 28 % have an even better solution ready and dispose of waste FFP2/FFP3 mask in containers for infectious waste. Better result compared to DSM users is to be expected, as 57 % of FFP2/FFP3 mask users are from the medical sector, while only 13 % of DSM users are from that sector. Only 5 % of respondents who selected the option other, indicated that they collect waste FFP2/FFP3 in special bags or containers and do not yet dispose of it. 11 % of respondents do not dispose of waste FFP2/FFP3 mask according to current recommendations.

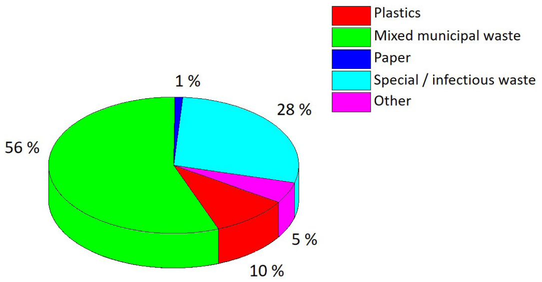

Fig. 6. *Survey answers to Question 6: Where do you dispose of waste FFP2/FFP3 masks?*

3.1.3 Textile Masks (TM)

A customized survey of TM users was also conducted. It was found that there was a wide variation in the duration of use of TMs before washing. The distribution of the duration of use is shown in Fig. 6.

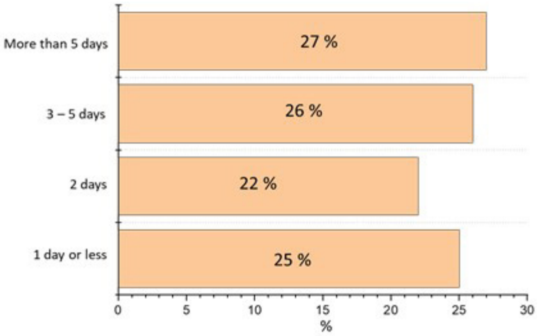

Fig. 7. *Survey answers to Question 7: How long do you use TM before you wash it?*

It was also studied how people deal with used TM. When asked how many times do you wash your TM before disposing of it, the most common response was that they did not dispose of any TM in the first year of the pandemic. 11 % responded that they disposed of TM after 6 to 10 washes and 13 % after more than 10 washes (Fig. 8). Those who already disposed of TMs were asked where they disposed of them. The responses are shown in Fig. 9. 80 % of respondents dispose of their TMs according to the current regulations for textile waste in Slovenia, which state that textile waste should be placed in mixed municipal waste or in special containers for textile waste. Those who answered with the option other still collect textile waste at home in special bags or containers and have not disposed of it yet.

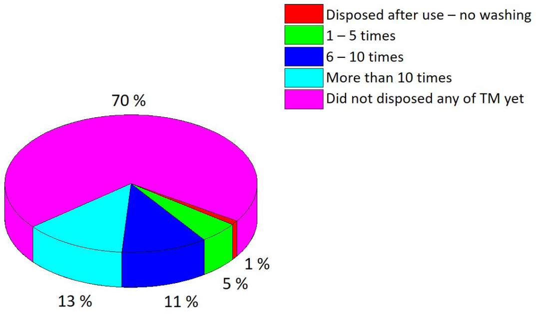

Fig. 8. *Survey answers to Question 8: How many times do you wash TM before disposal?*

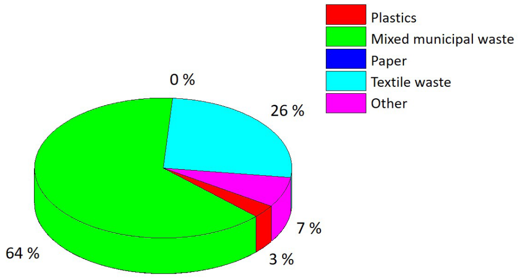

Fig. 9. *Survey answers to Question 9: Where do you dispose of used TMs?*

3.2 Survey on the Reuse of Used Face Masks

The second questionnaire contains 21 questions. Over a two-week period, 218 completed responses were collected (the response rate was 56 %). 71 % of the participants were female and 29 % were male. All participants were 16 years of age or older, and 99 % were between 16 years and 65 years of age.

The questionnaire was designed to obtain information on society's relationship to recycled products from DSM waste. From the introductory question and their answers, it appears that the majority of respondents separate their waste (97 %) and already consciously use products made from recycled materials (88 %). About 91 % of them would choose a reusable product if they had the choice between disposable and reusable. The main reasons for choosing reusable products are environmental awareness and convenience. The 9 % who would choose a disposable product cited price as the main influence on their decision, but also indicated that this decision varied from product to product.

3.2.1 Recycling of DSM

The majority of respondents would be willing to collect DSM waste separately (96 %), while the remaining 4 % do not consider DSM waste problematic and would dispose of it in the residual waste garbage can or the plastic garbage can. Fewer respondents would be willing to pay more for the mask that can be 100 % recycled (66 %). 48 % of them would be willing to pay 10 % more, 45 % would be willing to pay 10 % to 30 % more and the remaining 7 % would be willing to pay more than 30 % more.

DSM waste can be disinfected and recycled into other products. 92 % of respondents would use products made from recycled face masks. They also stated that such a decision would be more environmentally friendly, as it would result in less waste entering the natural environment, and overall stated that they do not care about the origin of the product and only care about usability. The other 8 % stated that they have doubts about the safety and hygiene standards of such products, others are concerned that such products cost more and are not as high quality. As shown in Fig. 10, when asked which type of recycling they would prefer, 25 % of respondents answered that they would prefer products made from thermally recycled DSM, 8 % answered that they would prefer products made from mechanically recycled DSM, 62 % would prefer both equally, and 5 % would use neither.

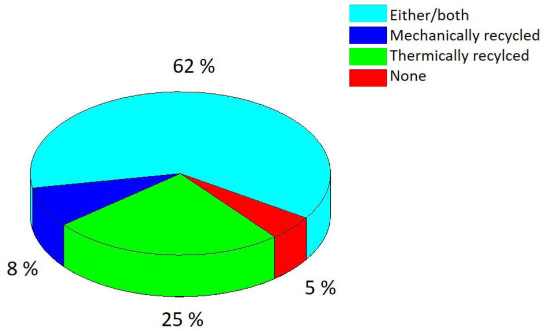

Fig. 10. *Survey answers to Question 10: Products from which mask recycling process would you prefer?*

3.2.2 Products Made of Recycled DSM

Respondents were asked how likely they were to use a product from a particular product category that was made from DSM waste. Responses were ranked on a scale of 1 to 7, where 1 means I would never use it, while 7 means I would definitely use it. The product categories were: clothing, shoes, jewellery, bags, other fashion accessories, decor, lighting, furniture, bulkheads, flooring, packaging, and insulation (Fig. 11).

More than 50 % of respondents would definitely use bulkheads, flooring, packaging and isolation. They would be most likely to use Insulation made from DSM waste. 66 % of respondents chose 7, and 2 % chose 1. About 1 % chose 2, 4 % chose 3, 6 % chose 4, 7 % chose 5, and 13 % chose 6. Respondents would be least likely to use clothing, jewellery and other fashion accessories.

3.2.3 Added-Value Product from DSM

For 79 % of respondents, products made from recycled material have added value. When asked if products made from recycled DSM had added value, 70 % answered yes, stating that their decision was based on the environmental impact of recycled products. They

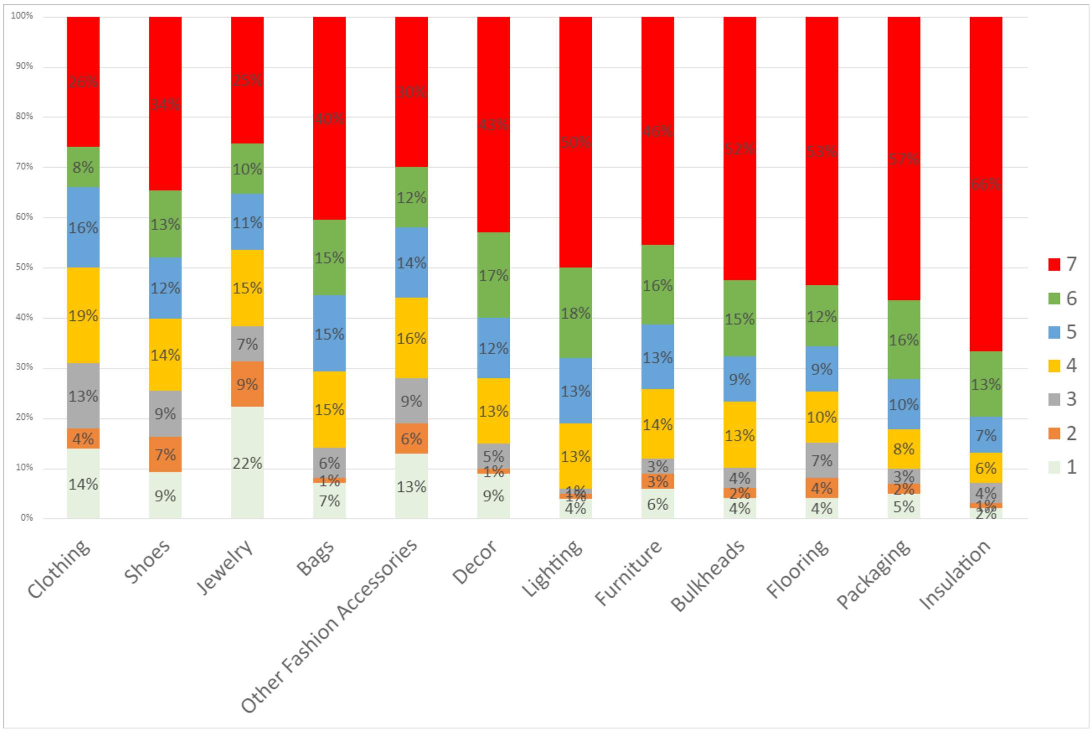

Fig. 11. *Survey answers to Question 11: Which products made from recycled face masks would you use, on a scale of 1 to 7?*

also pointed out that the feeling of doing something good for the environment plays a big role in decision making. 30 % of respondents answered in the negative, further explaining that they associate masks with unsanitary material or that they judge products only by quality and not by material.

The majority of respondents (65 %) believe that society is willing to accept products made from DSM waste.

4 RESULTS AND DISCUSSION

The designed product prototype is the result of research findings and surveys. The answers of the survey participants to the first questions were promising: 97 % already separate waste and 88 % consciously use products made of recycled material. The majority of respondents would be willing to collect used face masks separately, which is critical for product development because separating face masks in a landfill would not be efficient or even possible in some cases and could also be hazardous due to the characteristics of some wastes. The majority of responses also indicated that respondents would be willing to use products made from recycled DSM because they are aware of the environmental issues and see added value in a product made from recycled material. This kind of environmental awareness was an important confirmation for our design process.

In considering what types of masks we would use in the design process, we initially focused on a single type. The initial survey helped us understand what type of masks are most commonly used. It turned out that the majority of respondents use DSM the most and, on average, the frequency of discarding a mask is also highest for DSM. Since DSMs consist of different components and layers made of different materials, recycling is problematic because such a mask should be disassembled, and each group of materials should be recycled separately. Due to this construction of a face mask, our goal was to develop a product where the entire face mask can be used without any prior handling.

Particular attention was paid to respondents' answers about preferred product categories made from recycled face masks. We decided to focus on the flooring category since the only two categories that received a higher percentage of agreement were packaging and insulation. The goal was to create flooring similar to vinyl flooring.

Overall, it was critical to us and to respondents during the survey that proper sanitation be implemented. It also appeared that although the highest percentage of respondents would use both mechanically and thermally recycled products, a higher percentage would use thermally recycled products because they associate them with a higher level of disinfection. We studied the examples of already successful decontamination of such masks and considered how the procedures could be implemented when creating a prototype. It turned out that heating the masks to a certain temperature for a certain period of time is the most effective and simple procedure. In the research, which involved destroying pathogens but preserving the functions of a face mask, the waste masks were heated to 56 °C for 30 minutes. We set the temperature of 56 °C as the minimum temperature for our further work. Our waste mask bottom plate should consist of several layers, and we decided that the middle layer should be waste masks. The middle layer in floor plates usually represents the filling and provides additional thickness. Our surgical masks were therefore poured into a mould, which was then pressed in a high-pressure press at a temperature of 180 °C for 20 minutes. As the masks were melted, the mould was pressed for several hours to allow it to cool and harden into a plastic-like sheet. Between the melted polypropylene layer, we could see the ear band and the nose wires, which are now "glued" into the whole (Fig. 12).

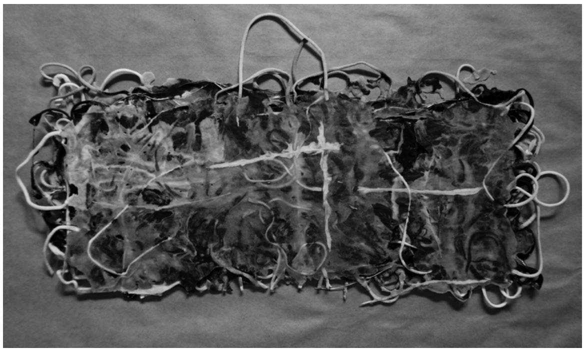

Fig. 12. *Testing the melting and cooling process of WDSM*

The entire plate was cold pressed together in a high-pressure press. The bottom part was the “backing layer” which is IXPE foam (radiation cross-linked polyethylene), the outer part is a decorative layer, a clear backing layer (which provides compressive strength and wear resistance) and the top layer is ultraviolet (UV) protection. Fig. 13 shows a sectional view of the designed WDSM flooring, and Fig. 14 shows a sample of the composite layers.

Considering the LCA, we wanted to ensure that as little energy as possible was used in the production of the middle layer, while completely avoiding the pollution of fresh water. The only possible disadvantage of such a flooring production would be the transport of the collected waste of surgical masks from the assembly centre to the factory/production line.

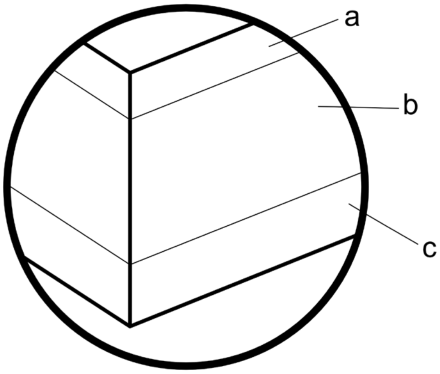

Fig. 13. *Graphical representation of the layers in a WDSM flooring; a UV protection, backing and decorative layer, b filling/WDSM layer, and c bottom backing layer*

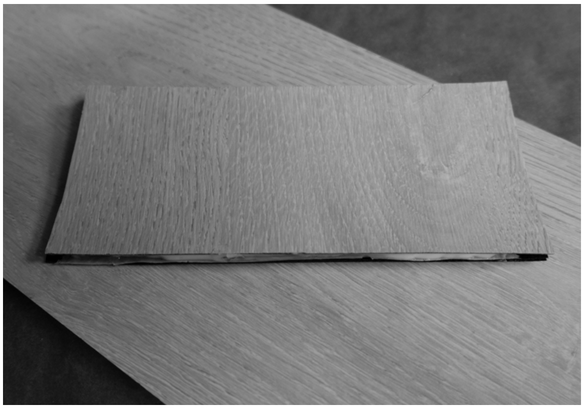

Fig. 14. *Sample of pressed layers of WDSM flooring*

5 CONCLUSIONS

Since the COVID-19 pandemic, the use and disposal of DSM has increased dramatically, resulting in DSM waste being thrown into landfills and the natural environment. Of particular concern is the breakdown of DSM into microplastics, which are already among the most damaging to the environment. The need to reuse and recycle facial masks has arisen even though the composition of DSM does not support a traditional recycling process.

The main objective of this research was to understand the environmental impact of DSM and to develop a product from used surgical masks. The research results combined with two different surveys helped us to design a prototype for a floor plate.

We changed the middle layer of a typical floor slab and replaced it with pressed and melted surgical masks. This layer provides enough stiffness and flexural strength to be used as flooring.

6 ACKNOWLEDGEMENTS

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Measurements of Air Quality in Kindergartens and Schools in the Republic of Slovenia before the COVID-19 Epidemic

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This article presents measurements of air quality in school and kindergarten facilities, which were carried out in 311 spaces throughout the Republic of Slovenia, before taking measures to improve energy efficiency of measured buildings. During the measurements, the internal dimensions of the spaces were also measured, as well as data on the energy efficiency of buildings and weather data at the time of the measurements. The measurements focused on indoor carbon dioxide concentration levels and air temperature and relative humidity of indoor air. The performed statistical analysis of measurements shows a large dispersion of measured parameters in buildings, which cannot be statistically significantly related to the analyzed quantities. During the occupancy of the spaces, a statistically significant difference in the concentration of carbon dioxide in the indoor air between the spaces of schools and kindergartens was found. The results of the measurements were also evaluated from the point of view of the Corona virus disease (COVID-19) pandemic. The average value of measured carbon dioxide value during occupancy of the spaces was compared with the results of a model that predicts an airborne transmission risk. The measured average value of relative humidity in kindergartens shows that relative humidity was 37 %, where is the highest infection risk according to recent studies. The measured average carbon dioxide concentration in classrooms and playrooms significantly exceeds the safe concentration, predicted by the model, to prevent COVID-19 spread at the expected six-hour exposure.

Keywords: natural ventilation, carbon dioxide monitoring, COVID-19, indoor air quality, schools, kindergartens

Highlights

- *Indoor air quality was measured in 311 mostly naturally ventilated spaces in years 2017, 2018, 2019 and 2020, before taking measures to improve energy efficiency of measured buildings.*
- *The statistical analysis of measurements shows a large dispersion of measured parameters.*
- *Measured CO_2 concentration level in the space during occupancy does not exceed the recommendations.*
- *The results of the measurements were evaluated from the point of view of the COVID-19 pandemic with model which predicts airborne transmission risk in connection with carbon dioxide concentration level.*
- *Measured average carbon dioxide concentration in classrooms and playrooms exceeds the safe CO_2 concentration to prevent COVID-19 spread at the expected six-hour exposure.*

0 INTRODUCTION

Indoor air quality is an issue that has recently received a great deal of attention. The primary reason is the emergence of coronavirus disease, which has further highlighted the often neglected subject matter in recent years. In the past, some attention in the Republic of Slovenia has been dedicated to air quality studies. The first researches in Slovenia, which described the basic parameters of the thermal environment, were carried out in the 1990s for various types of buildings [1]. The first results of the measurements indicated that people expressed a poor sense of well-being in enclosed spaces [2]. Subsequent research [3] has confirmed that people are not happy with the indoor environment [4] to [9]. Recently, it has not been possible to find data on systematic research of the internal environment in the Republic of Slovenia. Slovenia lies a great stress on rational energy use in buildings. This directly means that recently a lot of attention has been paid to the airtightness of buildings, and less to the quality of indoor air.

In the standards and recommendations that were implemented abroad in the 1990s [10] and [11], a lot of attention was given to the amount of air. Studies conducted at the time showed that many people expressed dissatisfaction with the indoor environment [12] and [13], and that people preferred a naturally ventilated environment, or that sick building syndrome related symptoms were lower in naturally ventilated buildings [14], as was also shown in the mentioned studies carried out in the Republic of Slovenia.

Indoor air quality is also directly related to health, as people are exposed to substances in the indoor environment that can also affect health. Numerous studies show that air quality in buildings with natural ventilation can be poor, which also has a negative effect on the intellectual abilities of individuals [15] and [16]. Studies show that exposure to carbon dioxide (CO_2) in the indoor environment generally has no effect on health, but some research shows that

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*Corr. Author's Address: Institute for Renewable Energy and Efficient Exergy Use, INOVEKS, d.o.o., Cesta 2. grupe odredov 17, 1295 Ivančna Gorica, Slovenia, simon.muhic@inoveks.si exposure to low concentrations of CO_2 (1000 ppm) already has a direct impact on the cognitive abilities of individuals [17]. On the other hand, other studies, such as [18] and [19] show completely different results, which may lead to the conclusion that the results of studies of the impact of CO_2 on the cognitive abilities of individuals are quite inconsistent [20].

Humans emit into the internal environment many substances called human bioeffluents that can be exhaled and dermally emitted. Studies have shown that exhaled bioefluent can contain over 600 substances [21] and dermally emitted almost 900 [22]. In doing so, dermally emitted bioeffluents have a greater impact on the perceived indoor air quality [23].

Even before the COVID-19 pandemic, the issue of air quality in naturally ventilated school spaces was given due attention [15] and [24], and with the emergence of the pandemic, studies are also being directed from spontaneous to strategic natural window ventilation [25] which improves air quality in naturally ventilated areas.

The subject research of indoor air quality in the Republic of Slovenia focused on air quality measurements before taking measures to improve energy efficiency of measured buildings in 2017, 2018, 2019 and 2020.

1 METHODS

During the research, air quality was measured in 481 spaces located in 161 buildings in different parts of the Republic of Slovenia as shown in Fig. 1. The type of facilities that were measured were schools, kindergartens, offices, cultural facilities, sports facilities and health facilities. This article presents only measurements in the spaces of kindergartens (playrooms) and schools (classrooms). In total, air quality was measured in 311 school and kindergarten spaces, 218 of which were school spaces and 93 kindergarten spaces. As part of the research, 24- or 48-hour monitoring of randomly selected spaces in the building was performed.

Measurements were performed in four sets. Table 1 shows the basic data on the time course of measurements in the performed terms.

During the measurements, three spaces were generally measured in each building. Monitoring was carried out on single place in the space throughout the period of measurements. Measurement equipment measured CO_2 concentration in the air in the space, the temperature of the air in the space and the relative humidity of the air in the space. Data was acquired every 60 seconds. The measuring accuracy of the measuring equipment used for measurements of CO_2 concentration was ±(5 % of the measured value +50 ppm) in the measuring range from 0 ppm to 9999 ppm, measuring accuracy of the air temperature was ±0.6 °C in the measuring range from –10 °C to 60 °C and measuring accuracy of the relative humidity was ±3 % in the range of 10 % to 90 % or ±5 % in the range of <10 % and >90 % respectively. Measurements were made in different annual seasons (winter, spring). For each space, data on the internal dimensions of the space was also obtained with accuracy ±0.05 m.

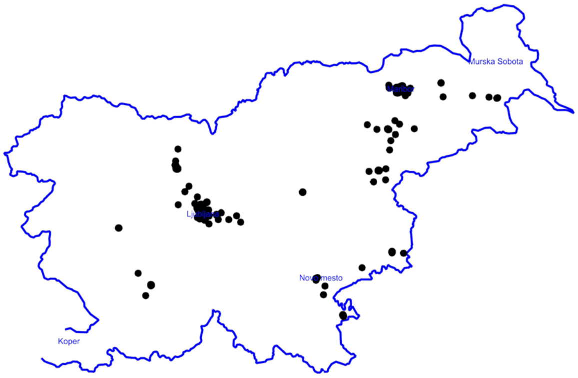

Fig. 1. *Locations of objects that were included in the measurements*

Table 1. *Sets of air quality measurements*

Set	Term of measurement
1.	2017-03-07 to 2017-04-19
2.	2018-03-24 to 2018-05-16
3.	2018-12-11 to 2019 -06-20
4.	2020-02-10 to 2020-03-13

After the measurements, the basic indicators of the measured parameters in the space during occupancy were calculated. Due to the way the space was used, the occupancy time was defined between 8 am and 12 noon for schools and between 8 am and 2 pm for kindergartens. In the case of 24-hour measurements, the average value was calculated for one day of measurements, and for 48-hour measurements, the average value represents the average for both days of measurements. Also, typical weather data for the selected measurement period were related to the weather data for the Ljubljana Bežigrad weather station, where the average value of air temperature at 2 m was taken as a reference, namely the average and the minimum value of outside air temperature at the time of measurements. Data on the energy efficiency of buildings were also obtained from public records.

2 RESULTS AND DISCUSSION

Table 2 shows the basic data of the measured spaces. Of the 311 spaces analyzed, only 9 spaces were mechanically ventilated. Fig. 2 shows the average outdoor air temperature (T_AVER) and the minimum outdoor air temperature (T_MIN) at the height 2 m at the meteorological station Ljubljana Bežigrad during all four sets of measurements on the day of installation of the measuring device. From the Fig. 2 it could be seen that the majority of measurements were performed during the heating period.

Table 2. *Basic data of measured spaces*

	School	Kindergarten	Sum
Natural ventilation	215	87	302
Mechanical ventilation	3	6	9
Sum	218	93	311

Table 3 shows the measured internal average air temperature during occupancy (*t*), the measured internal relative humidity (RH) in the space during occupancy and the calculated standard deviation for both parameters. The measured average air temperature is slightly higher in kindergartens, while the RH is slightly lower. The measured values are in accordance with RH values as defined by existing building regulations design criteria for humidity in Europe (20 % < RH < 70 % per EN 16798-1 **[27]**). The COVID-19 epidemic has also stimulated research of the impact of the RH on the spread of the virus. The impact of RH on infection risk was found to be dependent on the ventilation rate and the size range of droplets **[28]**. It was found that within the RH range of 20 % to 53 % the highest mean and maximum infection risk was always seen at an RH of 37 %, while it was lower at different levels of RH. Measured values of relative humidity in playrooms in kindergartens show that RH was exactly 37 %, at the highest infection risk.

Table 3. *Measured average temperature and relative humidity in spaces*

	Schools	Kindergartens
t [°C]	22.4	22.6
STDEV t [°C]	1.29	1.02
FI [%]	42.0	37.1
STDEV FI [%]	8.94	7.43

Table 4 shows the maximum of measured CO_2 concentration in indoor air during measurements by ventilation type. As expected, higher maximum

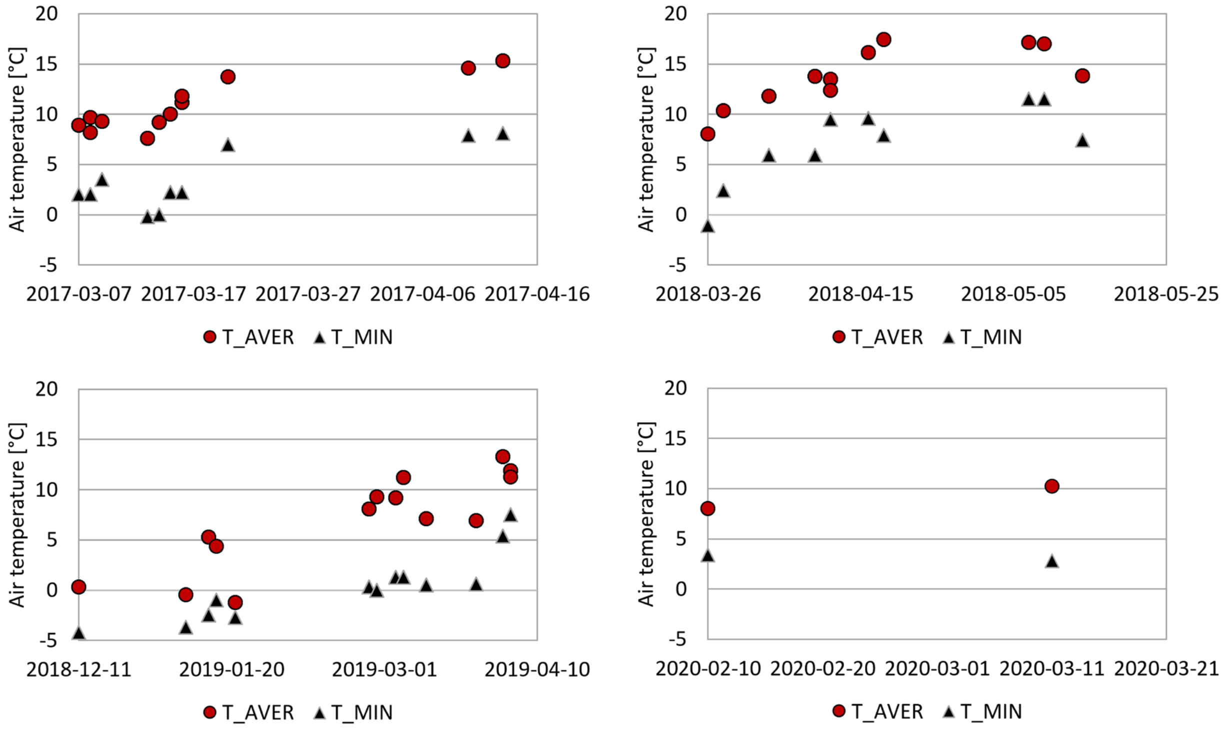

Fig. 2. *Outdoor air temperature during measurements* **[26]**

concentrations of CO_2 in indoor air were measured in naturally ventilated buildings.

Table 4. *Measured maximum CO_2 concentration in ppm*

Ventilation type	Maximum CO_2 concentration	
	Schools	Kindergartens
Natural ventilation	5179	3494
Mechanical ventilation	2190	2866

Fig. 3 shows the relationship between the average of measured CO_2 concentration in the spaces during occupancy of the spaces and the specific annual energy for heating obtained from the Energy performance certificates (EPC). EPC for 264 spaces was issued on the measured rating system basis, for 24 spaces EPC was issued by the calculated rating, for 24 spaces there was no EPC available in public records. Fig. 3 shows that the average of measured concentration CO_2 level during occupancy was lower in buildings with higher energy use than in buildings with lower energy use, which can be related to the airtightness of buildings. In more energy-efficient buildings, especially schools, the measured average CO_2 concentration is generally higher.

Fig. 4 shows the scatterplot of the maximum measured CO_2 concentration in indoor air and the average outdoor air temperature during measurements with marked types of facilities and type of ventilation system (natural, mechanical). It can be concluded that there is no clear relationship between the maximum measured CO_2 concentration and the average outdoor air temperature during measurements. Fig. 5 similarly shows the scatterplot of the maximum measured CO_2 concentration in the indoor air and the minimum average outdoor air temperature during measurements with the indicated types of facilities and ventilation type. It can be concluded that there is again no clear connection between the maximum measured CO_2 concentration and the minimum outdoor air temperature during measurements.

Figs. 6 and 7. show the relationship between the average measured CO_2 concentration during occupancy of the spaces and the average and the minimum outdoor air temperature. It can be concluded that there is also no clear connection between the measured average CO_2 concentration during occupancy and the average or minimum outdoor air temperature.

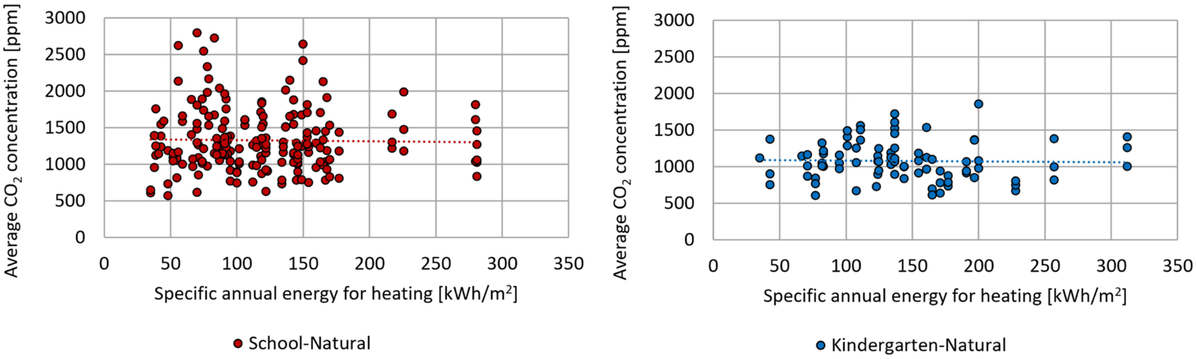

Fig. 3. *Scatterplot of average CO_2 concentration vs specific annual energy for heating*

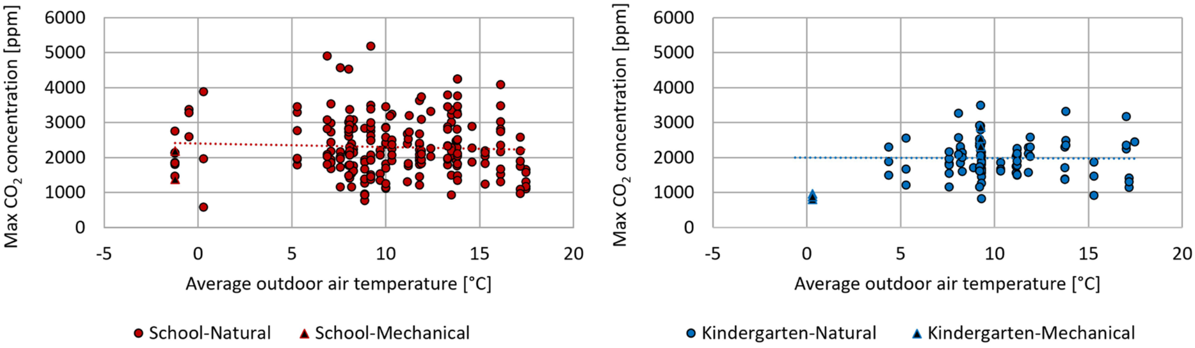

Fig. 4. *Scatterplot of maximum CO_2 concentration vs average outdoor air temperature*

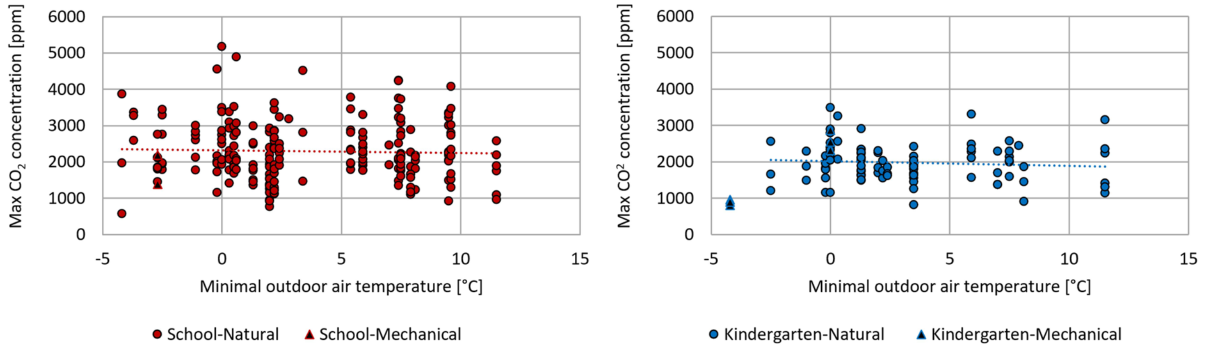

Fig. 5. *Scatterplot of maximum CO_2 concentration vs minimal outdoor air temperature*

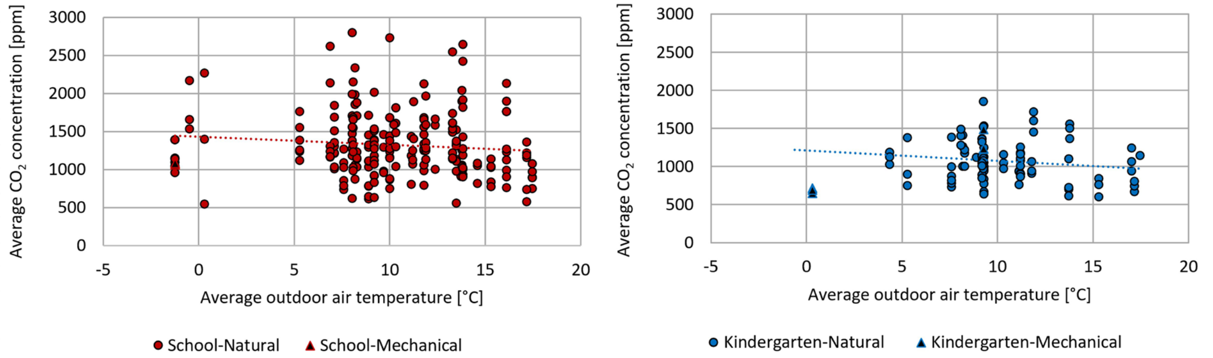

Fig. 6. *Scatterplot of average CO_2 concentration vs average outdoor air temperature*

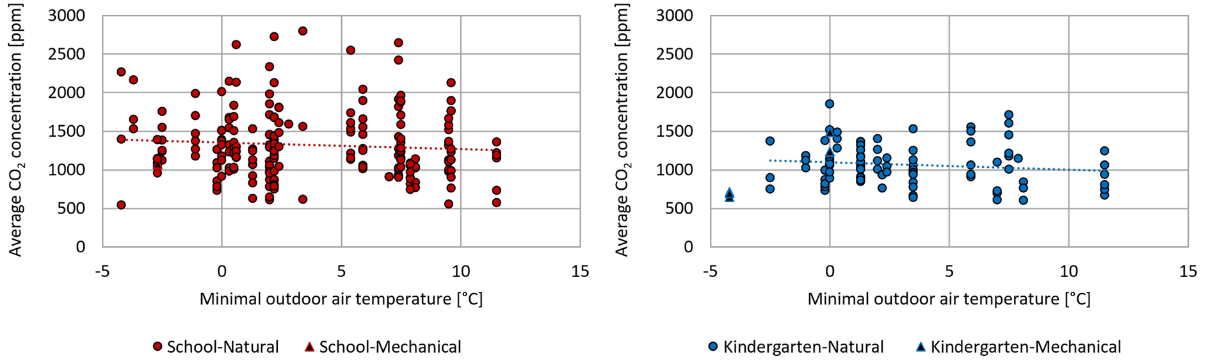

Fig. 7. *Scatterplot of average CO_2 concentration vs minimum outdoor air temperature*

From the above it can be concluded that the weather conditions do not have a major impact on the indoor air quality. Table 5 shows the average value of the measured maximum concentrations for all spaces ($CO_{2,\ max}$), the standard deviation of the measured maximum concentrations, the average value of the measured average concentrations during occupancy ($CO_{2,\ ave}$) and the standard deviation of the measured average CO_2 concentrations during occupancy in spaces. The data show that the average value of measured CO_2 concentrations is highest in naturally ventilated school buildings. The calculated standard deviation, however, indicates a similar dispersion in all buildings, regardless of the type of building or the method of ventilation. The table also shows that a lower CO_2 concentration was measured in mechanically ventilated spaces (School Mechanical, Kindergarten Mechanical), which cannot be confirmed statistically significantly due to the sample size (only 9 mechanically ventilated spaces).

Table 5. *Average value of measured maximum CO_2 concentrations in ppm*

	$CO_{2,max}$	STDEV $CO_{2,max}$	$CO_{2,ave}$	STDEV $CO_{2,ave}$
School Natural	2277	829	1310	442
School Mechanical	1789	843	1072	450
Kindergarten Natural	1979	843	1068	450
Kindergarten Mechanical	1732	838	1001	449

Analysis of variance (ANOVA) is a type of analysis that tests the difference among means of different groups [29]. The analysis performed, where we tested the null hypothesis that the measured maximum concentration and the measured average CO_2 concentration during occupancy are the same in schools and kindergartens, shows a statistically significant difference, so we can say that the measured CO_2 concentration in kindergartens was different from the measured CO_2 concentration in schools (Tables 6 and 7).

Table 6. *Analysis of variance for the maximum measured CO_2 concentration*

	Between Groups	Within Groups	Total
Sum of Squares	7086267	1.66E+08	1.73E+08
df	1	306	307
Mean Square	7086267	543580.5	
F	13.0363		
Sig.	0.000357		

Analysis of variance shows also that there is a statistically significant difference between the volume of measured spaces in schools and kindergartens. The average volume of schoolroom was 189.3 m^3, and the average volume of playroom in the kindergarten was 138.1 m^3. Analysis of variance shows that there is a statistically significant difference between the area of spaces in schools and kindergartens. The average area of the school space was 56.2 m^2, and the average area of the kindergarten space was 44.7 m^2. There is also a statistically significant difference between the height of spaces in schools and kindergartens. The average height of the school space was 3.36 m, and the average height of the space in the kindergarten was 3.08 m. Figs. 8 to 10 show the relationship between the average measured CO_2 concentration during occupancy and the dimensions of the measured spaces. Figures shows that there is again no clear relationship between the volume, area or height of the space with the measured average concentration of CO_2 during occupancy in the space.

Table 7. *Analysis of variance for the average value of the measured CO_2 concentration during occupancy*

	Between Groups	Within Groups	Total
Sum of Squares	4279101	45153467	49432568
df	1	306	307
Mean Square	4279101	147560.4	
F	28.999		
Sig.	1.45E-07		

In the period since the outbreak of the COVID-19 pandemic, special attention has also been given to the possible links between CO_2 concentrations and the risk of virus exposure, based on the finding that CO_2 concentrations are a measure of pathogens in the internal environment, which enables use of Wells-Riley model for determination of airborne transmission in an indoor space that is well-mixed [30]. Various models have also been developed that describe infection risk based on CO_2 level for typical indoor environments [31] and [32], where special attention was given to evaluate critical time spent in a space with infected person. Based on the models, a guideline to limit indoor airborne transmission of COVID-19 was developed [33], with an online

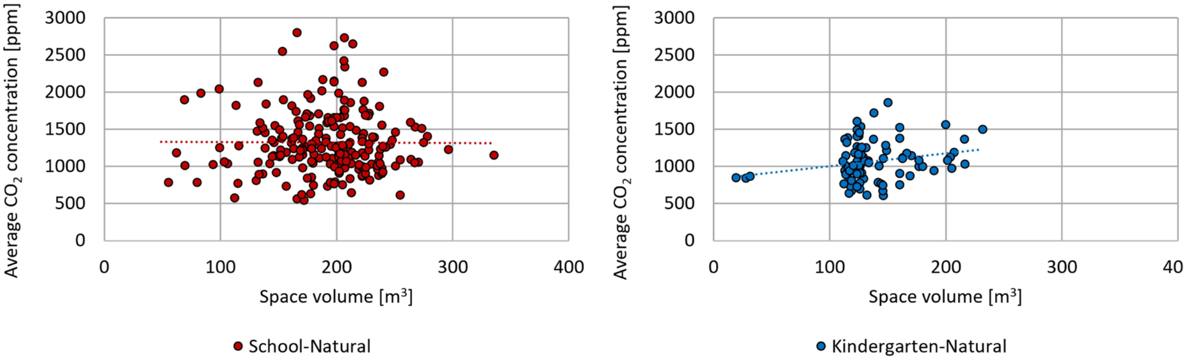

Fig. 8. *Scatterplot of average CO_2 concentration vs space volume*

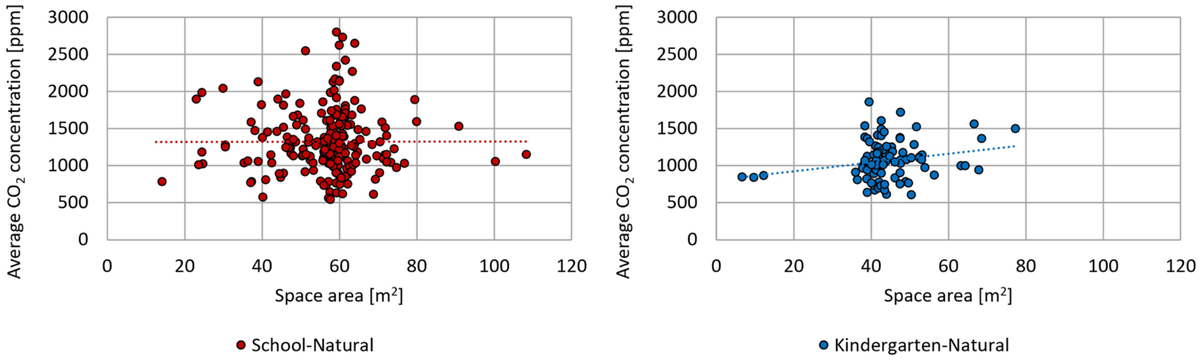

Fig. 9. *Scatterplot of average CO_2 concentration vs space area*

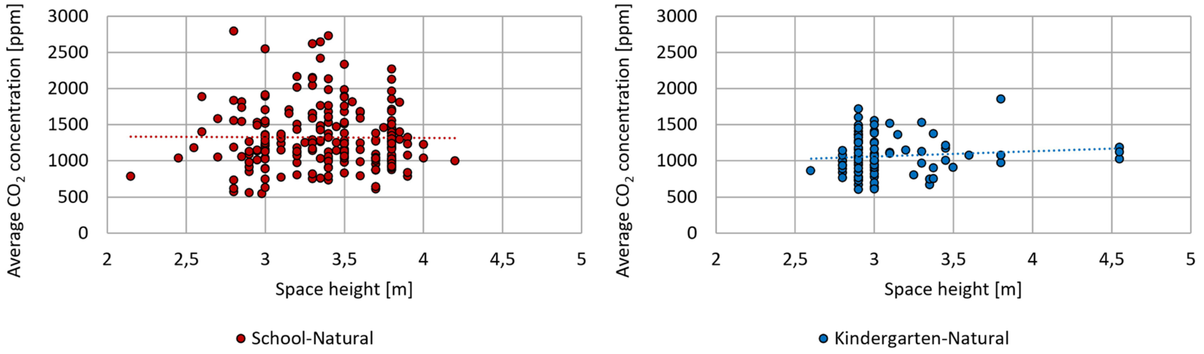

Fig. 10. *Scatterplot of average CO_2 concentration vs space height*

evaluation application [34]. The model [33] predicts airborne transmission risk from the real-time CO_2 measurements. This model was used to evaluate our measurement results where we evaluated the possibility of virus spread to populations under 15 years of age.

If we take into account the parameters collected in Tables 8 and 9 in the model, in the case when users do not wear masks in school spaces, we can find COVID-19 transmission for Delta variant of virus occurs after 19 min, and in the case of Omicron variant after 14 min. If users wear properly installed masks with an efficiency of 90 %, the prediction of the model indicates that the transfer of COVID-19 with Delta variant of virus occur after 4 hours, and in the case of Omicron variant of virus after 3 hours.

Table 8. *Basic input parameters for model [33] from measurements*

	School	Kindergarten
Area [m^2]	56.2	44.7
Height [m]	3.36	3.08
RH [%]	42	37.1
$CO_{2,ave}$ [ppm]	1310	1068
Persons in the space	28	22

The model predicts also the safe concentration of CO_2 at the assumed activity. In the case of the Delta variant of virus, if we do not wear masks, the safe CO_2 concentration for six hours of exposure is 837 ppm, and in the case of the Omicron variant of virus, this limit is 792 ppm. This means that the measured average concentration of 1310 ppm significantly exceeds the safe concentration of CO_2 as a measure of possible COVID-19 virus transmission. However, if users wear properly fitted masks with an efficiency of 90 %, the model predicts that a safe CO_2 concentration for six hours of virus exposure is more than 2000 ppm, regardless of the virus variant. This means that the measured average concentration of 1310 ppm is lower than the recommended one for six hours of exposure.

If we take into account the parameters collected in Table 9 in the model with the data for total floor area and ceiling height, represented in Table 10 for kindergartens, we can find that COVID-19 transmission with Delta variant of virus occurs after 18 min, and in the case of Omicron variant of virus after 13 minutes. If there were only 10 users instead of 22 in the same space, then the COVID-19 transmission with Delta variant occurs after 29 minutes, and in the case of the Omicron variant of virus after 22 minutes. Both results were calculated for the case when users do not wear masks in kindergarten spaces.

Table 9. *Basic input parameters for model [33] for school*

Parameter	Without mask	With mask
Total floor area [m^2]	56.2	56.2
Average ceiling height [m]	3.36	3.36
Ventilation [h^{-1}]	0.3	0.3
Recirculation rate [h^{-1}]	0	0
Filtration system (MERV)	0	0
Relative humidity [%]	42	42
Breathing flow rate [m^3/h]	0.49	0.49
Infectiousness of exhaled air [quanta/m^3]	72	72
Mask efficiency	0	0.9
Mask fit	0	0.95
Risk tolerance	0.1	0.1
Age group	0.23	0.23
Viral strain for Delta variant	2.5	2.5
Viral strain for Omicron variant	4	4
Percentage immune	0	0
Effective aerosol radius (at RH = 60 %) [μm]	2	2
Maximum viral deactivation rate [h^{-1}]	0.6	0.6
Outdoor air fraction	1	1
Aerosol filtration efficiency	0	0
Effective aerosol radius (at RH = 60 %), [μm]	2	2
Mask passage probability	1	0.145
Prevalence	0	0
Percentage susceptible, ps	1	1
Age factor	0.23	0.23

Table 10. *Input parameters for model [33] for kindergarten*

Parameter	Without mask
Total floor area [m^2]	44.7
Average ceiling height [m]	3.08

As it was already mentioned, the model also calculates the safe concentration of CO_2 at the assumed activity. In the case of the Delta variant of virus and if masks are not used, the safe CO_2 concentration for six hours of source exposure is 951 ppm, and in the case of the Omicron variant of virus this limit is 914 ppm. This means that the measured average concentration of 1068 ppm significantly exceeds the safe concentration of CO_2 as a measure of possible COVID-19 virus transmission at six-hour exposure.

4 CONCLUSIONS

In our research, which was conducted before the COVID-19 pandemic, we focused on the indoor air quality in school and kindergarten facilities and tried to connect it with selected facility parameters. It turns out that the dispersion of measured parameters in buildings is large and that there is no statistically significant relationship between measured parameters, selected facilities parameters and the energy efficiency of the building. Due to the small sample of mechanically ventilated spaces, it cannot be statistically significantly stated that the air quality parameters in mechanically ventilated spaces are better, but the results clearly show that both the maximum value and the average value during occupancy are lower in mechanically ventilated spaces than in naturally ventilated spaces. We proved that the measured maximum as well as the measured average CO_2 concentration during the time of occupancy is statistically significantly different between kindergarten and school spaces. All this shows the great influence of the users of the spaces on the air quality in them or in other words: the users of naturally ventilated spaces are the ones who have to take care of the air quality in the buildings. This is often difficult without the help of special devices or sensors, as the user of the space adapts to the air quality when one is indoors for a long time.

The results were also analyzed in the light of the COVID-19 pandemic. It was found that the measured average relative humidity in kindergartens at the time of occupancy was 37.1 %, where the maximum infection risk occurs. Analysis of the measured average CO_2 concentration during occupancy in schools with prediction of the model which predicts airborne transmission risk shows that the measured average concentration in classrooms at 1310 ppm significantly exceeds the safe level of CO_2 concentration as a measure of COVID-19 virus transmission at six-hour exposure, for Delta or Omicron variant of virus if users don’t wear masks. However, if users wear properly installed masks with an efficiency of 90 %, the model's prediction shows that the safe CO_2 concentration for a six-hour exposure is more than 2000 ppm, regardless of the virus variant. The analysis of the measured average concentration of CO_2 in kindergartens shows that the measured average concentration in playrooms with 1068 ppm also significantly exceeds the safe concentration of CO_2 as a measure for the transmission of COVID-19 virus at six hours of exposure, for Delta or Omicron variant of virus if users don’t wear masks.

All of the above shows that naturally ventilated spaces are ventilated relatively stochastically. Although the measured air quality in buildings, before taking measures to improve energy efficiency of buildings, does not exceed the recommendations from the point of view of CO_2 concentration in the space, in light of the COVID-19 pandemic in naturally ventilated buildings it is necessary to ensure adequate ventilation with help of appropriate sensors.

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Robusten in intuitiven model epidemije COVID-19 v Sloveniji

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Glavni cilj modeliranja epidemije je podpora obvladovanju epidemije z napovedmi njenega razvoja in analizami preteklih dogodkov. Pri modeliranju razvijajoče se epidemije smo omejeni s podatki v realnem času, ki niso vedno optimalni in katerih kvaliteta in dosegljivost se lahko s časom močno spreminjata. S tem v mislih smo razvili robusten in intuitiven model tipa SEIR (Susceptible-dovzetni, Exposed-izpostavljeni, Infectious-kužni, Recovered-ozdraveli) ter ga uporabili in preverili na valovih epidemije COVID-19 v Sloveniji po februarju 2020. Parametri modela temeljijo na splošnih značilnostih bolezni COVID-19, dostopnih v literaturi globalno za celoten planet, ter agregiranih dnevnih podatkih za Slovenijo, kot so na primer število potrjenih primerov, hospitaliziranih bolnikov, hospitaliziranih bolnikov v enotah intenzivne terapije in umrlih. Slovenski agregirani podatki so bili uporabljeni tudi za oceno stopnje imuniziranosti zaradi preteklih okužb in cepljenja, kar zmanjšuje število dovzetnih za bolezen.

Model smo razvili v integralni obliki, ki je intuitivna in ne povzroča numerične difuzije. Tako postanejo rezultati intuitivno razumljivi in predvidljivi, kar poveča zanesljivost interpretacije in s tem tudi točnost napovedi. V takšnem modelu je namreč mogoče negotovosti v podatkih, kot so npr. spremembe režimov testiranja, omejene zmogljivosti testiranja, spremembe meril za hospitalizacijo, spremembe v poročanju podatkov in manjkajoči podatki do neke mere nadomestiti s kvalitativnimi pristopi, kot sta na primer strokovna presoja modelarja in celosten pogled na epidemijo. Napovedi smo pripravljali na sledeči način. Če v bližnji prihodnosti ni bilo pričakovati večjih sprememb v vedenju ljudi, ki bi lahko vplivale na širjenje bolezni, smo predpostavili stacionarne parametre modela. V takih razmerah na razvoj epidemije vplivajo le spremembe v dovzetnosti oz. imunosti populacije zaradi cepljenja in preteklih okužb. Načrtovano uvajanje ali sproščanje nefarmakoloških ukrepov, kot npr. obvezno uporabo mask in prepoved združevanja ali gibanja, ter pomembne spremembe v vedenju ljudi, kot je na primer začetek ali konec počitnic, pa smo predvideli s spremembo reprodukcijskega števila R, ki je temeljila na strokovni presoji preteklih izkušenj v Sloveniji oz. v drugih državah. V največji možni meri smo poskušali upoštevati tudi mehke podatke, torej informacije, ki niso podane v obliki števil, kot na primer (ne)dosledno izvajanje nefarmakoloških ukrepov.

Predstavljeni so primeri uporabe modela, ki ponazarjajo njegovo robustnost in intuitivnost tako v napovedih kot pri analizah preteklega razvoja epidemije. S pomočjo analiz preteklega razvoja smo ocenili specifične vrednosti modelskih parametrov za Slovenijo ter ovrednotili učinke farmakoloških in nefarmakoloških ukrepov ter različnih dogodkov na razvoj epidemije, ki smo jih merili preko reprodukcijskega števila R. Te empirično pridobljene informacije smo nato uporabili v napovedi za različne obravnavane scenarije, ki dajejo dragocen kvalitativen in kvantitativen vpogled v možen prihodnji razvoj epidemije. Napoved števila hospitaliziranih bolnikov in hospitaliziranih bolnikov v enotah intenzivne terapije je bila zelo točna tudi v zahtevnih razmerah, ko so vzporedno potekali različni kompleksni procesi, ki vplivajo na širjenje bolezni (uvajanje nefarmakoloških ukrepov, naraščanje deleža bolj kužne različice virusa, prekuževanje, cepljenje). To dokazuje robustnost in ustreznost predlaganega modela. Točne napovedi so odločevalcem nudile dragoceno podporo pri upravljanju epidemije in načrtovanju ustreznih ukrepov, bolnišnicam pa omogočile, da so se pravočasno ustrezno pripravile.

Ključne besede: epidemija, COVID-19, modeliranje, SEIR, reprodukcijsko število, javnozdravstveni ukrepi

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Določanje učinkovitosti bakterijske filtracije različnih tipov mask

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Potrebe po zaščitni opremi so se v času pandemije bolezni COVID-19 znatno povečale, kar je vodilo v globalno pomanjkanje zaščitnih mask. Kot odziv na to so se na trgu pojavili novi tipi mask in materiali za njihovo izdelavo, ki zaradi potrebnega hitrega odziva pogosto niso bili primerno testirani. Vse zaščitne maske in njihovi materiali morajo namreč biti testirani za varnost in učinkovitost filtracije, kot to določajo standardi, relevantni za posamezno regijo. Pri tem je ozko grlo pogosto pomanjkanje akreditiranih laboratorijev, ki zahtevana testiranja izvajajo.

V članku je opisan postopek vzpostavitve metode testiranja učinkovitosti bakterijske filtracije (ang. *bacterial filtration efficiency*, BFE) zaščitnih mask, kot to določa evropski standard EN 14683:2019. Vzpostavljeni testni sistem vključuje šeststopenjski Andersonov vzorčevalnik (ang. *Andersen Cascade Impactor,* ACI), ki omogoča zbiranje aerosoliziranih bakterijskih delcev na agarnih ploščah in posledično njihovo kvantifikacijo ter določanje BFE testirane zaščitne maske. Testiranih je bilo skupaj 52 vzorcev kirurških mask in mask iz blaga, respiratorjev, materialov in filtrov, pri čemer je vsak vzorec obsegal tri do pet podvzorcev.

Sedeminštirideset vzorcev je doseglo učinkovitost filtracije nad 75 %, kar glede na slovensko tehnično specifikacijo SIST-TS 1200:2020 predstavlja minimalno zahtevano učinkovitost za polobrazne maske. Od tega je 16 vzorcev doseglo BFE med 75 % in 95 %, trije med 95 % in 98 %, kar 28 pa je doseglo učinkovitost nad 98 %. Rezultati določanja BFE kažejo, da večina testiranih vzorcev obrazne zaščitne opreme nudi minimalno zahtevano zaščito in so tako primerni za slovenski trg. Več kot polovica teh dalje ustreza strožjim evropskim zahtevam in omogočajo uvrstitev v skupino zaščitnih mask Tipa I oziroma Tipa II.

Poleg določanja BFE, standard EN 14683:2019 zahteva še dokazila o sledljivosti, testiranje biološke združljivosti oziroma citotoksičnosti, zračne prepustnosti in preverjanje čistosti zaščitnih mask, kar dodatno poudarja potrebo po večjem številu in dostopnosti akreditiranih testnih laboratorijev. Poleg tega je skupina 52 testiranih vzorcev heterogena in poleg kirurških mask, mask iz blaga ter materialov za njihovo izdelavo vključuje še filtre in respiratorje, katerih postopki testiranja in zahteve niso določene s standardom EN 14683:2019. Slednji podobno opisuje zgolj postopek določanja učinkovitosti bakterijske filtracije zaščitnih mask in ne tudi njihove stopnje zaščite pred virusnimi delci (ang. *viral filtration efficiency*, VFE), kar je v času pandemije COVID-19 ključnega pomena pri omejevanju širjenja okužb z virusom SARS-CoV-2.

Kljub poudarku na določanju BFE testiranih vzorcev, študija nudi številne pomembne informacije za vzpostavitev postopka testiranja zaščitnih mask v skladu z evropskim standardom EN 14683:2019. Podroben opis aparature, zasnove poskusa in postopka določanja BFE lahko testnim laboratorijem služi kot dodatek k standardu, kar je ključno predvsem z vidika pomanjkanja literature s tega področja. Ta obenem predstavlja osnovo za vzpostavitev sistema za določanje učinkovitosti virusne filtracije in s tem nadaljnjo obravnavo pomena uporabe zaščitnih mask v namen omejevanja širjenja virusnih okužb.

Ključne besede: učinkovitost bakterijske filtracije, zaščitne maske, respiratorji, EN 14683:2019, SIST-TS 1200:2020, šeststopenjski Andersonov vzorčevalnik

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Analiza ustreznosti prezračevanja izobraževalne ustanove z vidika preprečevanja širjenja koronavirusa (SARS-CoV-2)

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Učinkovito prezračevanje prištevamo med glavne inženirske ukrepe za preprečevanje aerogenega prenosa mikroorganizmov v prostoru. Pravilno načrtovanje sistemov za ogrevanje, prezračevanje in klimatizacijo (HVAC) ter njihovo učinkovito obratovanje in vzdrževanje so postali še posebej pomembni po izbruhu COVID-19. Namen raziskave je bil preveriti učinkovitost prezračevalnega sistema in izračunati verjetnost okužbe zaradi širjenja koronavirusa (SARS-CoV-2) po zraku v učilnicah izobraževalne ustanove v Sloveniji, pri čemer smo želeli odgovoriti na dve vprašanji in sicer: (i) ali obstoječi prezračevalni sistem izpolnjuje najnovejše smernice Zveze evropskih združenj za ogrevanje, prezračevanje in klimatizacijo (REHVA) za preprečevanje širjenja SARS-CoV-2, in (ii) kako določimo verjetnost okužbe glede na zasedenost učilnic, pretok zraka in delež maksimalne zmogljivosti prezračevalnega sistema.

Prezračevani sistem dovaja v stavbo svež zrak preko prezračevalnih naprav. V tej študiji je bilo analiziranih šest naprav za prezračevanje šestih večjih učilnic v pritličju in ena naprava za prezračevanje šestih manjših učilnic v kleti. Analiza prezračevanja je vključevala: (i) sistematski pregled prezračevalnega sistema skladno z metodologijo rednih pregledov klimatskih sistemov v Sloveniji, in (ii) izračun verjetnosti okužbe zaradi širjenja kužnih aerosolih delcev po učilnici za štiri sete scenarijev prezračevanja, upoštevajoč stopnje zasedenosti prostorov, pretok zraka in delež maksimalne zmogljivosti prezračevalnega sistema.

Verjetnost okužbe in reprodukcijsko število smo izračunali s kalkulatorjem prezračevanja REHVA COVID-19. Upoštevali smo stopnjo zasedenosti učilnic, pretok zraka, dimenzijske značilnosti prostorov in preventivne ukrepe (minimalna varnostna razdalja med učenci 1,5 m, obvezna uporaba zaščitne maske). Izračune smo izvedli za štiri sete scenarijev prezračevanja, kjer smo spreminjali delež maksimalne zmogljivosti prezračevalnega sistema (50 % in 80 %) in stopnjo zasedenosti učilnic (od 30 % do 100 %). Na osnovi analize smo določili ukrepe, s katerimi v učilnicah zagotovimo zadostno količino svežega zraka na učenca in obenem odvedemo kužne aerosolne delce.

Pregled prezračevalnega sistema izobraževalne ustanove je pokazal, da za učinkovito preprečevanje in obvladovanje bioloških tveganj, mešalni način prezračevanja ni ustrezen. Boljše je izpodrivno ali batno prezračevanje. Vsekakor pa zvišanje zmogljivosti prezračevalnega sistema s 50 % na 80 % zmanjša verjetnost okužbe z 0,40 % na 0,27 %, kar je pokazal primer velike učilnice. Pri tem se zmanjša tudi reprodukcijsko število z 0,11 na 0,07, kar se smatra kot sprejemljiva vrednost (vrednosti pod 0,1 so sprejemljive).

Upoštevajoč 1,5 m varnostne razdalje med učenci in obvezno uporabo zaščitnih mask, je bila verjetnost okužbe med predavanji nižja od 1 %. V obdobju večje pojavnosti respiratornih okužb se največja zasedenost učilnic v analizirani stavbi odsvetuje. Maksimalna zmogljivost prezračevalnega sistema zagotavlja zadostno količino svežega zraka za stopnjo zasedenosti 30 %, preračunano glede na zakonske zahteve in priporočila.

Izboljšanje delovanja prezračevalnega sistema obravnavane izobraževalne ustanove smo predvideli na osnovi dejanske zmogljivosti prezračevalnega sistema in nismo vključili njegove nadgradnje v smeri večje zmogljivosti. Verjetnost okužbe zaradi širjenja SARS-CoV-2 preko aerogenega prenosa smo ocenili z izračuni s kalkulatorjem REHVA COVID-19. Ugotovitve raziskave bi bilo koristno nadgraditi z mikrobiološkimi analizami zraka.

Metodološki pristop, ki smo ga predstavili v članku za izobraževalno ustanovo, ima veliko uporabno vrednost za presojo sistemov prezračevanja tudi v stavbah drugačne namembnosti.

Ključne besede: prezračevanje učilnic, kalkulator REHVA COVID-19, verjetnost za okužbo, reprodukcijsko število, HVAC sistem

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Primerjalna študija štirih komercialnih hitrih antigenskih testov SARS-Cov-2: karakterizacija posameznih komponent

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Med pandemijo Covid-19 se je ekstremno povečala potreba po diagnostičnih testih, ki bi lahko hitro in zanesljivo odkrili prisotnost virusa SARS-CoV-2 ali njegovih protiteles. Pomembno vrsto v skupini diagnostičnih testov predstavljajo hitri antigenski testi, krajše LFIA testi, ki delujejo na osnovi imuno-kromatografskega principa v kontaktu z analitom. Klinična praksa je v zadnjem letu pokazala, da so tovrstni diagnostični testi lahko učinkoviti pri preprečevanju širjenja virusa SARS-CoV-2. V tej študiji smo primerjali štiri komercialno dostopne hitre teste z uporabo najsodobnejših karakterizacijskih tehnik za posamezne komponente, z namenom identifikacije njihove kemijske sestave in drugih lastnosti, ki so ključne za delovanje teh testov.

Na razvoj in s tem izdelavo hitrih testov vplivajo številni dejavniki, ki posredno določajo njihovo občutljivost in točnost. Ti dejavniki so neposredno odvisni od vrste analita oziroma proizvedenega protitelesa, ki nastane kot imunski odziv ob okužbi z virusom. Izdelava hitrih antigenskih LFIA testov je tako povezana z ustrezno izbiro osnovnih komponent, ki določajo vrsto in kakovost teh testov. Najsodobnejše tehnike karakterizacije za posamezne komponente testov predstavljene v tem članku so vključevale: metode SEM, ICP-OES, ESEM/EDX in FTIR/ATR analize.

Pristop je sledil eksperimentalnemu delu, ki se je osredotočal na identično izvedene karakterizacije na vseh štirih izbranih komercialnih hitrih antigenskih testih za SARS-Cov-2, z namenom identifikacije tistih razlik v komponentah, ki so lahko posredno ključnega pomena za občutljivost in natančnost testa. Raziskava je bila usmerjena v pridobitev osnovnih podatkov o strukturi posameznih komponent komercialnih LFIA testov, ki so predstavljale osnovo za razvoj lastnega LFIA testa.

Hitri antigenski testi so kompleksni, saj imajo posamezne komponente različno kemijsko sestavo in morfološke značilnosti, kar rezultira v njihovih različnih lastnosti. Preiskave kažejo, da se v hitrih testih za blazinice uporabljajo različni materiali, od steklenih vlaken, poliestra, celuloze in nitro-celuloze. Naslednja ugotovitev je, da izbira kromatografskih membran z večjimi porami ne vpliva bistveno na občutljivost hitrih antigenskih LFIA testov. Na osnovi opravljene preiskave lahko zaključimo, da je za natančno poznavanje delovanja hitrih antigenskih LFIA testov potrebno vključevati različne karakterizacijske tehnike in eksperimente, s katerimi se lahko postavijo modeli njihovega delovanja in s tem napoved za zanesljivo uporabo v kliničnem okolju.

Omejitev raziskav ni bilo.

Ta prispevek predstavlja podroben vpogled v strukturo hitrih testov in prikaz, kako izvesti mikrostrukturno in strukturno karakterizacijo posameznih komponent hitrega testa. Vrednost prispevka je v tem, da je bila na štirih hitrih testih različnih proizvajalcev izvedena podrobna analiza materialov posameznih komponentah. Pri tem je treba poudariti, da so bili materiali natančno identificirani s pomočjo najsodobnejših metod t.i. State-of-the-art karakterizacije, tako, da je v okviru tega prispevka prvič predstavljena uporabljena metodologija. Vrednost prispevka je zelo pomembna, saj so takšni podatki neznani ali pa niso prosto dostopni, ker jih proizvajalci zelo dobro skrivajo. Članek tako predstavlja nove podatke in znanja za raziskovalce, ki se ukvarjajo z razvojem sorodnih testov na drugih področjih. To je tudi osnova za morebitne izboljšave v procesu optimizacije izbire ustreznejših materialov za posamezne komponente, s ciljem, da bi hitri testi v prihodnosti dosegli najvišjo možno stopnjo natančnosti in občutljivosti v klinični uporabi.

Ključne besede: SARS-CoV-2 virus, hitri antigenski testi, komponente, karakterizacija, mikrostruktura, primerjalna analiza

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Anketiranje zdravstvenih delavcev za izboljšanje dizajna, izkušenj uporabnikov in trajnostnega vidika zaščitnih halj kot osebne zaščitne opreme

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Projekt oblikovanja zaščitnih halj za zdravstvene delavce je odziv na nujno potrebne raziskave o preoblikovanju zaščitnih halj kot osebni zaščitni opremi, da bi bolje ustrezala svojemu namenu – zaščiti zdravstvenih delavcev in da bi bilo halje mogoče ponovno uporabiti. Raziskava je bila izvedena v okviru projekta 'Redesigning PPE: enhancing the comfort and safety of healthcare workers wearing isolation gowns to treat patients with COVID-19'. Od izbruha bolezni covid-19 so mnogi zdravstveni delavci zaradi pomanjkanja ustrezne osebne varovalne opreme nosili zaščitne halje za enkratno uporabo. Ker je bila večina zaščitnih halj v enotni velikosti, so neustrezne velikosti zaščitnih halj ogrožale udobje in varnost pri delu, kar velja predvsem za manjše uporabnike.

Cilj članka je poudariti povezavo med težavami, opaženimi v praksi, pomenom raziskav in vključevanjem uporabnikov z informacijami o njihovih praktičnih izkušnjah, ki so ključne za razvoj oblačil, ki podpirajo potrebe ljudi pri delu. V raziskavo smo najprej vključili vodje nabave medicinske opreme in osebje s področja akutne oskrbe, ki so izrazili potrebo po bolj trajnostnih zaščitnih haljah kot delu osebne varovalne opreme za večkratno uporabo. Izkazali so interes, da bi bile zaščitne halje izdelane iz pralnih tekstilij, s čimer bi izboljšali izkušnje zdravstvenih delavcev ter hkrati zmanjšali tveganje okužb in klinične odpadke.

V drugem delu raziskave smo želeli preveriti ponudbo zaščitnih halj na trgu. Pregledali smo modele ter opravili kontekstualno in senzorično analizo halj za enkratno in večkratno uporabo, vključno z izdelki, ki jih dobavljajo NHS in industrijski partnerji. Premerili smo dvanajst modelov, katerih dimenzije kažejo na to, da dolžine variirajo med 106 cm in 129 cm spredaj in med 110 cm in 125 cm zadaj. Šest od sedmih modelov, za katere podajamo meritve, so modeli enotne velikosti, ki po dimenzijah odgovarjajo velikostni številki »L«. Izmerjeni modeli se medsebojno zelo razlikujejo tudi po prsnem obsegu, saj variirajo med 69 cm in 139 cm v polovici prsnega obsega.

Kot tretji del raziskave je sledila kvalitativna analiza intervjujev in odgovorov na anketo, pri čemer so nas zanimale povratne informacije zdravstvenih delavcev NHS v Nottinghamu in okolici, od katerih se jih je 81 % opredelilo, da delajo pretežno s covidnimi bolniki, torej na področjih visokega tveganja za okužbo. Skupno 123 anketirancev je ocenilo izkušnje pri nošenju in izpostavilo probleme, s katerimi se srečujejo. 75 % jih nosi modele za enkratno uporabo. Vsaj 35 % naših anketirancev je visokih do 160 cm in običajno nosijo oblačila v velikosti M (33 %), S (24 %) ali XS (5 %). Tako pisni odgovori anketirancev kot tudi navedeni podatki kažejo, da so več kot polovici anketirancev zaščitne halje zelo predolge in prevelike, saj iz predhodne raziskave lahko razberemo, da večina dolžin in obsegov razpoložljivih modelov ne ustreza velikostim oseb, ki so visoke 165 cm ali manj. Posledično so uporabniki na trgu še posebej nezadovoljni z omejitvijo uporabe enotnih velikosti halj za enkratno uporabo. Prevelike in neprilagojene zaščitne halje so problematične in ovirajo svobodo gibanja, pogosto se zaradi neprimerne dolžine vlečejo po tleh in delavce še dodatno ovirajo pri delu. K slabemu počutju v teh haljah prispevajo še neustrezni materiali, ki ne dihajo in zvišujejo telesno temperaturo, zaradi česar še dodatno povečajo tveganje prenosa virusov.

Naše angažiranje pri pregledu literature in zaščitnih halj na trgu, analizi intervjujev ter raziskava in povratne informacije iz anket predstavljajo ustvarjalen, sodelovalen in komplementaren način za postavitev in opredelitev temeljev za nadaljnje preoblikovanje osebne varovalne opreme. Na podlagi pridobljenih podatkov smo oblikovali zaščitna oblačila za večkratno uporabo kot trajnostno rešitev, ki upošteva ključne elemente, ki bi lahko izboljšali uporabniško izkušnjo zaščitnih halj kot delom osebne varovalne opreme. Oblikovali smo vrsto alternativ v detajlih, ki temeljijo na uravnoteženju potreb uporabnikov in izvajalcev nujne medicinske pomoči ter hkrati upoštevajo predpise, zaščito, udobje, trajnost in stroške.

Ključne besede: zdravstveni delavci, anketa, zaščitna halja, osebna varovalna oprema za večkratno uporabo, izkušnje uporabnikov, kvalitativna raziskava

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Razširjenost Covid-19 med zdravstvenim osebjem Univerzitetnega kliničnega centra Ljubljana do zaključka leta 2020 in koncentracija CO_2 v zraku bolniških sob, prezračevanih skozi okna, v letu 2021/22

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Jeseni in pozimi 2020/21 ter ponovno 2021/22 se je Slovenija uvrstila med države z najvišjo pojavnostjo Covid-19 na milijon prebivalcev in z veliko presežno umrljivostjo glede na povprečje preteklih let. Pred cepljenjem so množično obolevali in umirali oskrbovanci domov starejših občanov, zelo pogosto pa so obolevali tudi bolniki in osebje na bolnišničnih oddelkih, kjer naj ne bi bilo okužb. Osebje je pri delu z bolniki nosilo predpisane kirurške maske in zaščito za oči, ki jih je ščitila pred neposrednim kapljičnim prenosom, ne pa tudi pred aerogenim prenosom virusa. Vse do konca leta 2000 navodila za preprečevanje okužb niso govorila o zračenju prostorov, zato se zdi, da je k širjenju okužb z virusom SARS-CoV-2 prispeval tudi aerogeni prenos.

Ugotoviti smo želeli, v kolikšni meri se je pogostost Covid-19 med zdravstvenim osebjem Interne klinike Univerzitetnega kliničnega centra Ljubljana (UKCL) razlikovala od povprečja prebivalcev Slovenije do konca decembra 2000. Dodatno smo želeli ugotoviti, ali se je po objavi navodil o obveznem prezračevanju prostorov v UKCL v zraku še vedno občasno kopičil CO_2, ki je indikator izdihanega zraka oz. nevarnosti za aerogeno virusno okužbo.

Razširjenost prebolelega ali aktivnega Covid-19 med zdravstvenim osebjem Interne klinike UKCL smo zbrali iz podatkov o bolniških dopustih zaradi potrjene okužbe s SARS-CoV-2 med 1. januarjem in 24. decembrom 2020. Podatke o prebolevnikih in aktivno okuženih prebivalcih Slovenije do 24. decembra 2020 smo pridobili s spletne strani COVID-19 sledilnika. Razlike v razširjenosti okužb med zdravstvenimi delavci in splošno populacijo smo preverili s testom hi-kvadrat. Kvaliteto zraka smo merili s senzorji WAVEplus (Airthings, Norveška), ki jih je posodilo podjetje MIK d.o.o., Slovenija. Meritve smo izvajali v Enoti intenzivne terapije Kliničnega oddelka za žilne bolezni (KOŽB) Interne klinike UKCL v času od 4. aprila 2021 do 18. februarja 2022 in v Angiološki ambulanti KOŽB Interne klinike UKCL v času od 15. aprila 2021 do 18. februarja 2022. V Enoti intenzivne terapije (s površino približno 36 m^2 in višino stropa 3,6 m, v kateri so bili nameščeni 3 do 4 bolniki, za katere so skrbeli v povprečju 3 zaposleni) smo opravili skupno 91.048 meritev. V Angiološki ambulanti (s površino približno 20 m^2 in višino stropa 3,6 m, v kateri so bile med delovnim časom povprečno 3 osebe) smo opravili skupno 87.192 meritev. Obe sobi sta imeli zunanja okna. Osebju je bilo naročeno, naj okna odpirajo vsako uro za vsaj 10 minut.

Do 24. 12. 2020 je Covid-19 prebolelo 42 % medicinskih sester, 21 % diplomiranih medicinskih sester in 17 % zdravnikov Interne klinike UKCL, kar se je značilno razlikovalo od 5,5 % prebolevnikov med prebivalci Slovenije. Med aprilom 2021 in februarjem 2022, po objavi priporočil o zračenju z rednim odpiranjem oken, je znašala raven CO_2 v delcih na milijon (ppm) v Enoti intenzivne terapije povprečno 633 ppm (standardni odklon 198, razpon 376 ppm do 1540 ppm), v Angiološki ambulanti pa 552 ppm (standardni odklon 199, razpon 380 ppm do 1910 ppm). Do preseganj priporočene dopustne koncentracije 750 ppm je v Enoti intenzivne terapije prihajalo najpogosteje ponoči, v Angiološki ambulanti pa okrog poldneva, ob vrhuncu delovnega procesa. V letu 2020, pred posodobitvijo navodil za uporabo osebne zaščitne opreme in pred svetovanjem rednega odpiranja oken, je razširjenost Covid-19 med zdravstvenim osebjem na Interni kliniki UKCL presegla državno povprečje za 3- do 8-krat. Čeprav nismo dokazali vzročne zveze med aerogenim prenosom in velikim številom primerov Covid-19, saj nismo mogli upoštevati potencialnih motečih dejavnikov, se povezava zdi zelo verjetna. Potem ko je bilo v UKCL svetovano redno odpiranje oken, so najvišje ravni CO_2 še vedno pogosto presegle priporočeno »varno« raven 750 ppm.

V bolnišnice, domove starejših občanov in druge gosto obljudene javne zgradbe je treba namestiti kvalitetne sisteme za prezračevanje/filtracijo zraka, ki bodo zagotavljali ustrezno kakovost zraka in zmanjševali nevarnosti za zdravje ljudi zaradi onesnaženega zraka.

Ključne besede: Covid-19, razširjenost, aerogeno širjenje, prezračevanje prostorov, koncentracija CO_2

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Povezava med onesnaženostjo zraka ter širjenjem in razvojem bolezni, povezane s COVID-19

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V članku je raziskana potencialna korelacija med izpostavljenostjo onesnaženemu zraku in smrtnostjo zaradi sočasnega razvoja bolezni COVID-19 s hudim akutnim respiratornim sindromom, ki je povzročena s koronavirusom SARS-CoV-2. Poudarek je na onesnaženemu zraku v obliki suspendiranih trdnih ali tekočih delcev v plinu oz. zraku (t.i. prašnih delcev).

Prikazali smo vpliv večih meteoroloških parametrov na širjenje koronavirusov v zunanjem okolju (temperatura zraka, vlažnost zraka, gibanje zraka in sončno sevanje). Poleg tega je prikazana povezava med onesnaženim zrakom, ki že sam po sebi škoduje človekovemu zdravju, ter širjenjem virusa in razvojem bolezni COVID-19. Onesnažen zrak pripomore k časovnemu in prostorskemu širjenju različnih virusov. Iz različnih raziskav je razvidno, da daljša izpostavljenost onesnaženemu zraku s prašnimi delci negativno vpliva na imunski sistem človeka in lahko ob sočasnem razvoju bolezni, kot je COVID-19, tega preobremeni. Preobremenjenost lahko vodi k posledicam za človekovo zdravje ali celo k smrti. Za boljše razumevanje samega razvoja bolezni bi bilo potrebno poglobiti razumevanje o delovanju različnih mehanizmov razvoja bolezni v povezavi z drugimi omenjenimi faktorji.

Analiza podatkov tako podpira dejstvo, da nižja stopnja onesnaževanja okolja znatno prispeva k boju proti pandemiji koronavirusa. Ob upoštevanju socio-ekonomskih, demografskih in z zdravstvenim stanjem povezanih karakteristik prebivalcev so ugotovili, da je bilo znižanje dolgoročne izpostavljenosti koncentracijam PM2.5 za 1 µg/µm3 povezano z 12-odstotnim zmanjšanjem števila primerov obolelosti za COVID-19. Poleg tega je potrjena domneva, da je presežek dnevnih priporočenih vrednosti za koncentracije onesnaženosti zraka s PM10 dober napovedovalec za večje širjenje obolelosti za COVID-19.

Različne študije so pokazale, da povečana izpostavljenost onesnaženemu zraku negativno vpliva na imunski sistem ljudi in lahko preobremeni imunski sistem. Za izboljšanje kakovosti zraka s stališča obolelosti za SARS-CoV-2 bi bilo smiselno izvajati tako kratkoročne kot tudi dolgoročne ukrepe. Kratkoročne rešitve so omejene predvsem na omejevanje zadrževanja v bližini vira unseasonal ter priporočila za delovanje tehničnih sistemov za prezračevanje prostorov. Dolgoročni ukrepi za reševanje zmanjšanja onesnaženosti zraka vključujejo naložbe v tehnologije, ki ne temeljijo na fosilnih gorivih, investicije v razvoj tehnologij z nizkimi ali ničnimi emisijami trdnih delcev ter spodbujanje rabe energije, ki ne temelji na čezmernem onesnaženju zraka.

Ključne besede: onesnaževanje zraka, koronavirus (COVID-19), trdni delci ($PM_{2,5}$ in PM_{10}), odziv imunskega sistema, obolevnost, umrljivost, meteorološki parametri, kakovost zraka

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Uporaba in odlaganje zaščitnih mask ter potencial recikliranja v nove izdelke

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Pandemija COVID-19 je po celem svetu spremenila vsakdanje življenje ljudi. V mnogih državah so bili sprejeti ukrepi z namenom preprečitve širjenja okužb. Zdravstvene usmeritve se od države do države razlikujejo, je pa večina držav enotnih pri uvedbi obveznega nošenja obraznih mask. Odpadne maske skupaj z zaščitnimi rokavicami in zdravniškimi zaščitnimi haljami, predstavljajo večinski delež medicinskih odpadkov. Odpadki iz zdravstva so pogosto kontaminirani, zato morajo biti ti odpadki pred odlaganjem ali recikliranjem ustrezno obravnavani. Zaradi povečanih količin medicinskih odpadkov med pandemijo, ko je bilo dnevno zavrženih na milijone obraznih mask in rokavic, sistem ni bil zmožen pravilno tretirati vseh nastalih odpadkov, ki so končali na odlagališčih odpadkov ali pa celo v naravi. Obrazne maske so izdelane iz polimernih materialov, ki začnejo pod okoljskimi vplivi po določenem času razpadati na mikroplastične in nanoplastične delce. Nastali mikro/nanoplastični delci predstavljajo velik okoljski problem.

Analiza življenjskega cikla kirurških mask upošteva devet različnih kategorij vplivov na okolje na različnih stopnjah cikla. Poleg visokih vrednosti v času pridobivanja materiala, se visoke vrednosti vplivov na okolje pojavljajo po končanem življenjskem ciklu mask. Še posebej visoke so vrednosti ogljičnega odtisa ter ekotoksičnosti sladko vodnega in morskega ekosistema.

Raziskava sovpada z razvojem koncepta produkta, ki omogoča porabo zavrženih obraznih mask. Ključnega pomena je razumevanje odnosa družbe do potencialnega recikliranja odpadnih mask, zato sta bili poleg raziskave že objavljenih literaturnih virov izvedeni dve ločeni anketi. Prva je ugotavljala navade nošenja mask in kakšno je ravnanje s temi maskami po njihovi uporabi. Druga anketa se je osredotočila na odnos do recikliranja mask in naklonjenost oziroma nenaklonjenost različnim kategorijam izdelkov narejenih iz recikliranih zavrženih mask.

Oblikovani produkt je rezultat raziskave in izsledkov obeh anket. Večina anketirancev bi bila pripravljena zbirati odpadne maske ločeno, zato bi bilo oblikovanje produkta iz takšnih mask smiselno. Prav tako bi večina anketirancev uporabljala izdelke narejene iz recikliranih odpadnih mask. Ker je vsaka maska sestavljena iz različnih materialov, je recikliranje oteženo, saj bi bilo potrebno vsako masko posebej razstaviti in reciklirati vsako komponento posebej. Cilj raziskave je bil, da bi lahko za oblikovani produkt porabili cele odpadne maske, brez kakšnih koli predhodnih postopkov predobdelave in ločevanja. Prva anketa je pokazala, da največ anketirancev uporablja kirurške maske, zato je bilo nadaljnje delo osredotočeno izključno na reciklažo kirurških mask. Še posebej velika pozornost je bila namenjena na odgovore anketirancev na vprašanje o naklonjenosti uporabi izdelkov določene kategorije iz recikliranih odpadnih mask. Anketirancem so bile za izbiro ponujene naslednje kategorije: oblačila, obutev, nakit, ostali modni dodatki, dekorativni izdelki, luči, pohištvo, embalaža, izolacija in pregradne stene. Večina anketirancev bi odpadne maske reciklirala v embalažo oz. v izolacijski material. Tako so se nadaljnje raziskave osredotočile na razvoj talnih oblog. Vseskozi je bila higiena in neoporečnost izdelka ključna smernica razvoja. V literaturi smo zasledili, da se uporabljene maske dezinficirajo že pri temperaturi 56 °C pri izpostavitvi enemu 30 minutnemu ciklu segrevanja.

V sklopu študije je bil razvit koncept kompozitne talne obloge, kjer srednji sloj (polnilo) sestavljajo odpadne kirurške maske, ki so bile v toplotni visokotlačni stiskalnici stisnjene v kalup. Po izpostavitvi visoki temperaturi, je staljena masa ostala stisnjena še nekaj ur, da se je le-ta strdila v ploščo. Skupaj s spodnjim nosilnim slojem, dekorativnim slojem, zgornjim nosilnim slojem in UV zaščitnim slojem, polnilni sloj iz mask tvori celoto, ki je bila skupaj hladno stisnjena v panel. Novo ustvarjeni koncept talnih oblog podaljšuje življenjsko dobo zavrženih kirurških mask. Pri procesu predelave odpadnih mas se ne dodajajo dodatne kemikalije, se ne onesnažujejo vodni viri, poraba električne energije je minimalna.

Ključne besede: maske, medicinski odpadki, okolje, recikliranje izdelkov z dodano vrednostjo, analiza življenjskega cikla

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Meritve kakovosti zraka v prostorih vrtcev in šol v Republiki Sloveniji pred epidemijo COVID-19

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Kakovost zraka v notranjih prostorih je problem, ki se mu v zadnjem času posveča izjemno velika pozornost tudi v Republiki Sloveniji. Primarni razlog je pojav koronavirusne bolezni, ki je še dodatno izpostavila v zadnjih letih žal pogosto zapostavljeno problematiko. Prve raziskave v Slovenskem prostoru, ki so popisovale osnovne parametre kakovosti zraka in toplotnega okolja, so bile izvedene v devetdesetih letih prejšnjega stoletja. V zadnjem času pa ni moč zaslediti podatkov o sistematičnih raziskavah notranjega okolja. V Republiki Sloveniji se sicer posveča veliko pozornosti učinkoviti rabi energije v stavbah, manj pa s tesnimi stavbami povezani kakovosti zraka v prostorih. Predmetna raziskava se je fokusirala na meritve kakovosti zraka pred izvedbo energijskih sanacij stavb v letih 2017, 2018, 2019 in 2020. Tekom raziskave smo izmerili kakovost zraka v 481 prostorih, ki so se nahajali v 161 stavbah po Sloveniji. V članku podajamo rezultate v 93 igralnicah vrtcev in 218 učilnicah šol. Od 311 analiziranih prostorov je bilo le 9 prostorov mehansko prezračevanih. Po izvedbi meritev koncentracije ogljikovega dioksida (CO_2), temperature in relativne vlažnosti zraka v prostorih smo izračunali osnovne kazalnike izmerjenih parametrov v prostoru, ki smo jih povezali z vremenskimi podatki ter s podatki o energijski učinkovitosti stavb.

Izmerjena povprečna temperatura notranjega zraka je v vrtcih nekoliko višja kot v šolah, relativna vlažnost pa nekoliko nižja. Izmerjene vrednosti relativne vlažnosti zraka so sicer v skladu s priporočili veljavne zakonodaje. Epidemija COVID-19 pa je vzpodbudila tudi raziskave o vplivu relativne vlažnost zraka na širjenje virusa. Izmerjene vrednosti relativne vlažnosti v igralnicah v vrtcih kažejo, da je bila relativna vlažnost v času zasedenosti 37 %, kjer so raziskave pokazale največjo verjetnost prenosa virusa.

Analiza variance je pokazala statistično značilno razliko med izmerjeno koncentracijo CO_2 v šolah in vrtcih. Ugotovili smo, da ni izrazite povezave med izmerjeno koncentracijo CO_2 v prostorih in zunanjo temperaturo zraka. Iz navedenega lahko zaključimo, da vremenske razmere nimajo večjega vpliva na način prezračevanja prostorov oziroma na kakovost zraka v prostorih. Vse navedeno tudi kaže, da se naravno prezračevane prostore prezračuje relativno stohastično. Prav tako smo ugotovili, da ni statistično signifikantne povezave med volumnom, površino ali višino prostora z izmerjeno koncentracijo CO_2 v prostorih.

V času od pojava pandemije COVID-19 se posveča posebna pozornost tudi možnim povezavam koncentracije CO_2 in tveganju izpostavljenosti virusu, ki bazira na ugotovitvi, da je koncentracija CO_2 merilo patogenov v notranjem okolju. Ta ugotovitev je osnova za različne modele, ki so uporabljeni tudi v aktualnih smernicah v povezavi s preprečevanjem prenosa virusa COVID-19 v zaprtih prostorih. Analiza izmerjene povprečne koncentracije CO_2 v šolah kaže, da je izmerjena povprečna koncentracija v učilnicah šol bistveno višja od meje varne koncentracije CO_2 kot mere za prenos virusa COVID-19, različice omikron ali delta, pri šesturni izpostavljenosti. Če pa uporabniki nosijo pravilno nameščene maske z učinkovitostjo 90 %, pa predikcija uporabljenega modela kaže, da je izmerjena koncentracija nižja kot je varna koncentracija CO_2 za šesturno izpostavljenost, ne glede na različico virusa. Analiza izmerjene povprečne koncentracije CO_2 v vrtcih pa kaže, da je izmerjena povprečna koncentracija tudi v igralnicah vrtcev bistveno višja od meje varne koncentracije CO_2 kot mere za prenos virusa COVID-19, različice omikron ali delta, pri šesturni izpostavljenosti. Čeprav izmerjena kakovost zraka v analiziranih objektih pred energijskimi sanacijami praviloma ne presega priporočil s stališča koncentracije CO_2 v prostoru, pa je v luči pandemije COVID-19 v naravno prezračevanih objektih nujno potrebno poskrbeti za ustrezno prezračevanje s pomočjo senzorjev.

Ključne besede: naravno prezračevanje, meritve koncentracije ogljikovega dioksida, COVID-19, kakovost zraka v prostorih, šole, vrtci

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Prof. dr. Peter Novak

18. marca letošnjega leta nas je presenetila žalostna vest, da nas je zapustil karizmatični profesor, nekdanji dekan Fakultete za strojništvo, Univerze v Ljubljani, mednarodno priznani strokovnjak in prijatelj prof. dr. Peter Novak. Vest nas je presenetila toliko bolj, ker je bil prof. Novak do zadnjega vitalen pri spremljanju dogajanj na področju energetike v domačem in mednarodnem okolju, njegova široka razgledanost in pronicljiv in vizionarski pogled na razvoj energetike in njeno vlogo v gospodarstvu in družbi nasploh, predvsem pa njegova edinstvena karizma, mu je na široko odpirala vrata v strokovnih krogih, pa tudi v javnosti, kjer se ga je prijel pomenljivi vzdevek »Sončni Peter«. Ta vzdevek ni govoril zgolj o Soncu, kot o obnovljivem viru energije, ki ga je daleč pred svojim časom fasciniralo, ampak o brezmejni energiji, volji in tudi človeški toplini, ki jo je izžareval in je bila esenca njegove karizme.

Profesor Novak se je rodil 27. 4. 1937 v Novem mestu, kjer je preživel mladost in maturiral leta 1955. Študij strojništva je zaključil na Univerzi v Ljubljani leta 1961. Doktoriral je leta 1975 na univerzi v Beogradu pri prof. dr. Popoviću, uglednem profesorju na Fakulteti za strojništvo, Univerze v Beogradu. Leta 1984 pridobil naziv rednega profesorja. Vrsto let je vodil Katedro za toplotno in procesno tehniko. Zasnoval je Laboratorij za ogrevalno, sanitarno in solarno tehniko. V zgodnjih letih profesorske kariere je raziskoval na področju ogrevalne in klimatizacijske tehnike, konec sedemdesetih let pa ga je pritegnilo izkoriščanje sončne energije. Znal se je povezati z raziskovalci interdisciplinarnih ved na način, da so njegove zamisli privedle do uporabnih tehnoloških rešitev na področju selektivnih in veliko-panelnih sprejemnikov sončne energije, sezonskih hranilnikov toplote, hranilnikov toplote z ohranjanjem eksergije. Vse to so rešitve, ki jih danes srečujemo v naprednih stavbah in so še vedno predmet nadaljnjih raziskav – aktualne teme v današnji znanstveni periodiki. Med študenti je bil zelo priljubljen, predavanja so bila jasna in so odražala njegovo vizionarsko usmerjenost k trajnostni energijski oskrbi, z rešitvami, ki so bile mnogokrat daleč pred njegovim časom. Med letoma 1991 in 1995 je bil dekan Fakultete za strojništvo Univerze v Ljubljani. Ob odhodu v pokoj koncem leta 1997 je pustil imenitno zapuščino: več kot 300 diplomantov, 25 magistrov znanosti in 20 doktorjev znanosti.

Tudi po njegovi upokojitvi smo se še srečevali na različnih strokovnih srečanjih, bili smo partnerji na raziskovalnih projektih. Kot predsednik razvojnega sveta za JV Slovenijo je vzpodbudil idejo in neposredno pripomogel k temu, da se je leta 2006 ustanovila Visoka šola za tehnologije in sisteme VITES, katere dekan je bil od njene ustanovitve do septembra leta 2012. Za doprinos k razvoju fakultete v Novem mestu mu je bil v letu 2012 podeljen naziv zaslužni profesor. Vsa leta pa je profesor Novak ostal velik ambasador svoje matične fakultete.

Brez profesorja Novaka si ne moremo predstavljati Godoviškega inštituta za gretje, hlajenje in klimatizacijo, v katerem deluje 12 laboratorijev in povezujejo industrijo v Sloveniji, kot panogo z velikim gospodarskim potencialom. S prenosom znanja na inženirje je nesebično usmerjal veliko raziskovalnih oddelkov v industriji in si s tem ustvaril veliko spoštovanje v gospodarstvu.

Kot cenjen strokovnjak, še posebej pa zaradi svoje človeške odprtosti in topline do drugih, je spletel številne vezi v mednarodnem okolju. Že v sedemdesetih letih prejšnjega stoletja je povezal kolege s področja celotne Jugoslavije. Je ustanovni in častni član Slovenskega društva za sončno energijo, kot tudi mnogih drugih nacionalnih združenj: SITHOK, ZSIS in KGH. V letu 1999 je profesor Novak postal zaslužni član American Society for Heating, Refrigerating and Airconditioning Engineers (ASHRAE). Skoraj deset let, do leta 2003 je bil predsednik komisije za klimatizacijo in član Znanstvenega sveta v Mednarodnem inštitutu za hlajenje (IIR), svetovni organizaciji z več kot stoletno tradicijo. Leta 1999 je postal član upravnega odbora in leta 2003 tudi časni član IIR. Kot vrhunski strokovnjak je bil imenovan v Znanstveni odbor Evropske agencije za okolje, en mandat, med leti 2012 in 2016 je bil podpredsednik tega odbora ter član Usmerjevalnega komiteja za okoljske nagrade EU. Evropska organizacija za gretje in hlajenje REHVA mu je leta 2010 podelila Zlato medaljo REHVA, kot najvišje evropsko priznanje za življenjsko delo v stroki za njegov prispevek k afirmaciji in izobraževanju tega področja strojništva. V zahvalo za profesorjev prispevek slovenskemu inženirstvu, mu je Zveza strojnih inženirjev Slovenije leta 2011 podelila najvišje priznanje, nagrado za življenjsko delo.

Življenjska moč profesorja Petra Novaka je pošla, njegova bogata zapuščina pa bo vedno obsijana z njemu in nam tako ljubim – Soncem.

Prof. dr. Mihael Sekavčnik,
dekan Fakultete za strojništvo Univerze v Ljubljani

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[1] Hackenschmidt, R., Alber-Laukant, B., Rieg, F. (2010). Simulating nonlinear materials under centrifugal forces by using intelligent cross-linked simulations. *Strojniški vestnik - Journal of Mechanical Engineering,* vol. 57, no. 7-8, p. 531-538, DOI:10.5545/sv-jme.2011.013.

Journal titles should not be abbreviated. Note that journal title is set in italics.

Books:

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[2] Groover, M.P. (2007). *Fundamentals of Modern Manufacturing*. John Wiley & Sons, Hoboken.

Note that the title of the book is italicized.

Chapters in Books:

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[3] Carbone, G., Ceccarelli, M. (2005). Legged robotic systems. Kordić, V., Lazinica, A., Merdan, M. (Eds.), Cutting Edge Robotics. Pro literatur Verlag, Mammendorf, p. 553-576.

Proceedings Papers:

Surname 1, Initials, Surname 2, Initials (year). Paper title. Proceedings title, pages.

[4] Štefanić, N., Martinčević-Mikić, S., Tošanović, N. (2009). Applied lean system in process industry. *MOTSP Conference Proceedings*, p. 422-427.

Standards:

Standard-Code (year). Title. Organisation. Place.

[5] ISO/DIS 16000-6.2:2002. *Indoor Air – Part 6: Determination of Volatile Organic Compounds in Indoor and Chamber Air by Active Sampling on TENAX TA Sorbent, Thermal Desorption and Gas Chromatography using MSD/FID.* International Organization for Standardization. Geneva.

WWW pages:

Surname, Initials or Company name. Title, from http://address, date of access.

[6] Rockwell Automation. Arena, from *http://www.arenasimulation.com,* accessed on 2009-09-07.

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