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Energy, economic, and environmental impacts of enhanced ventilation strategies on railway coaches to reduce Covid-19 contagion risks

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ABSTRACT

In the last years, the Covid-19 outbreak raised great awareness about ventilation system performance in confined spaces. Specifically, the heating, ventilation, and air conditioning system design and operating parameters, such as air change per hour, air recirculation ratio, filtration device performance, and vents location, play a crucial role in reducing the spread of viruses, moulds, bacteria, and general pollutants. Concerning the transport sector, due to the impracticability of social distancing, and the relatively loose requirements of ventilation standards, the SARS-COV-19 outbreak brought a reduction of payload (up to 50%) for different carriers. Specifically, this has been particularly severe for the railway sector, where train coaches are typically characterized by relatively elevated occupancy and high recirculation ratios. In this framework, to improve the Indoor Air Quality and reduce the Covid-19 contagion risk in railway carriages, the present paper investigates the energy, economic and environmental feasibility of diverse ventilation strategies. To do so, a novel dynamic simulation tool for the complete dynamic performance investigation of trains was developed in an OpenStudio environment. To assess the Covid-19 contagion risk connected to the investigated scenarios, the Wells-Riley model has been adopted. To prove the proposed approach’s capabilities and show the Covid-19 infection risk reduction potentially achievable by varying the adopted ventilation strategies, a suitable case study related to an existing medium-distance train operating in South/Central Italy is presented. The conducted numerical simulations return interesting results providing also useful design criteria.

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1. Introduction

The role of ventilation in reducing the spread of airborne infectious agents, pollutants, bio effluents, etc. in enclosed spaces is well known and has been widely investigated in literature [1,2]. However, since the spread of the SARS-COV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) at the end of 2019, and the consequent outbreak of the Covid-19 (CoronaVirus Disease-2019) increasing interest regarding the relation between ventilation system performance and Covid-19 contagion risk increased [3,4]. Ensuring adequate outdoor air ventilation rates per person becomes essential [5] to reduce the Covid-19 infection risk [6]. This is an issue, especially for public and crowded enclosed spaces such as those of public transport means. In worth noticing that most of the carriers have experienced a not negligible reduction of the payload, and this was particularly severe for the railway sector (up to 50% reduction of the passengers). In this framework, the present paper aims at investigating the relationship between the outdoor ventilation rate per person and the Covid-19 contagion risk for railway coaches (to improve both Indoor Air Quality (IAQ) and safety), while also studying the related energy, economic, and environmental impact. To point up the current state of the art regarding this topic, in the following, a deep analysis of the existing literature is presented. Specifically, will be discussed first papers dealing with Indoor Air Quality (IAQ) and ventilation in the railway sector (and typically published before the Covid-19 outbreak), and then the ones investigating also the Covid-19 contagion risk (for a wider range of applications). Starting with papers regarding IAQ and ventilation in the railway sector, most of the works focus their attention on the infrastructures [7], such as stations and subway...
tunnels [8,9], rather than on the railway carriage. In fact, except for the works adopting a CFD approach, such as the one reported in Ref. [10] about a standard passenger coach, or those reported in works adopting a CFD approach, such as the one reported in study, the concentration of both particles <10 μm (PM10) and particle-bound polycyclic aromatic hydrocarbons (pPAH) are elevated in both smoker and non-smoker compartments. The concentration of Volatile Organic Compounds (VOCs) in metro carriages and the related health risk is instead assessed by the authors of the work reported in Ref. [14] investigating the IAQ of passenger trains focusing on ultrafine particle pollution. Another study focusing on suspended particulate matter in railway coaches is the one reported in Ref. [15] where the authors conclude that, for the considered case study, the concentration of both particles <10 μm (PM10) and particle-bound polycyclic aromatic hydrocarbons (pPAH) are elevated in both smoker and non-smoker compartments. The concentration of Volatile Organic Compounds (VOCs) in metro carriages and the related health risk is instead assessed by the authors of the work presented in Ref. [16] concluding that poor air circulation and ventilation lead to high VOC levels. The importance of ventilation in maintaining cleaner air in trains is underlined also in the work reported in Ref. [17], where the authors investigate the factors affecting the passenger exposure to airborne particles inside railway carriages, and in the work presented in Ref. [18], where the authors investigate physicochemical and microbiological pollutants in trains cabins. In particular, the latter underlines how fungi and bacterial loads, as well as airborne microbiota, are high in trains and busses due to high occupancy and that ventilation represents an effective manner to enhance IAQ. In general, it is possible to state that even if some papers investigate the impact of ventilation on the IAQ for railway carriages, almost all of them neglect the energy implications connected to the ventilation load variation. This is a severe lack since the high influence of ventilation systems on the energy demand. In this framework, the works presented in Refs. [19,20] are examples of the few exceptions. Specifically, in Ref. [19] the authors examine a novel low momentum ventilation concept for train compartments. This solution is studied from the thermal comfort and energy consumption points of view, neglecting however the IAQ one. Another contribution is given by Ref. [20] where the authors carry out studies (both numerical and experimental) on ventilation panel models for a subway passenger compartment. Also in this case, besides the interesting outcomes from the thermal and energy point of view, no IAQ analyses are conducted. Thus, it is possible to conclude that it is difficult to find contributions in literature simultaneously dealing with IAQ and energy consumption of railway conveyors. Concerning the manuscripts dealing with the Covid-19 contagion risk in enclosed spaces, diverse works already exist in the literature, starting from 2019, trying to assess such risk for diverse spaces typologies by adopting both qualitative and quantitative approaches. It is worth noticing that all the works quantitatively assessing the Covid-19 contagion risk share the same methodological approach. Specifically, the Covid-19 contagion risk assessment is performed by adopting the Wells-Riley model for the infection probability [21]. As an example, in Ref. [22] the authors developed a dynamic simulation tool to assess both the Covid-19 risk and the HVAC system energy demand, by which investigating a commercial building to provide useful design criteria. The role of mechanical ventilation is investigated also in Ref. [23] where the authors study a high rise institutional building located in Montreal. The analysis focuses on the assessment of the optimal outdoor airflow rate guaranteeing a Covid-19 contagion risk below 1% (assumed as a safe threshold), at the variation of quanta emission rate. The authors conclude that when the quanta emission rate increases from 28 h⁻¹ to 857 h⁻¹, the need for ventilation raises from 7.4 m³/s to 225.2 m³/s. An office building is instead investigated by the authors of reference [24]. Here the authors assessed the Covid-19 risk of infection during the working day for diverse scenarios, such as the adoption of 100% outdoor air and/or HEPA filtration systems. The authors conclude that the outdoor air increase returns a higher impact on the contagion risk rather than HEPA filters. The relation among Covid-19 protection and HVAC system is underlined also in Ref. [25], where the ventilation system operation modes are investigated under sanitary emergency scenarios. Also in this case, the authors underline how the increase in fresh air ratio is the most effective action to take to reduce covid-19 risk in enclosed spaces. The influence of ventilation strategies is investigated also in Ref. [26]. Here, the authors analyse the influence of ventilation system operation modes and of air cleaning technologies to reduce the Covid-19 aerosol particle concentration in a gym, concluding that a combination of both
actions could be the most effective solution. A prefabricated Covid-19 inpatient ward is instead studied in the work presented in Ref. [27]. Here, the authors numerically studied three diverse ventilation strategies to reduce respiratory droplets and aerosols. The study concludes that small particles are effectively removed from the environment by adopting higher ventilation, whereas larger ones cannot move with the airflow and usually deposit on solid surfaces. Diverse case studies are instead investigated in Ref. [28], where a design method to reduce respiratory infection risk in enclosed space is discussed. Here, the authors test, by using the Wells-Riley model, the ventilation flow rates recommended by the standard EN 16789–1. The results showed infection probabilities ranging from 2 to 14.5%, meaning that the standard should be updated aiming at reducing the Covid-19 contagion risk. Note that the authors state that due to the high difference among the investigated case studies, it is not easy to define a sole rule for the ventilation rate estimation. In the work presented in Ref. [29], the authors investigated diverse strategies to reduce the SARS-CoV-2 airborne infection risk in a variety of confined spaces. Specifically, for the reference case studies (e.g. without proposed solutions), the infection probability assessed by the authors is over 30%. The authors conclude that the infection risk could be substantially reduced by enhancing room ventilation (in terms of both external flow rate and vents position), adopting HEPA filters, and by wearing high filtration face masks. In Ref. [30] the authors investigate the influence of diverse parameters (e.g. occupants concentration and distribution, air changes per hour, etc.) on both energy consumption and Covid-19 infection risk for a university facility. Here, the authors underline the positive correlation existing between the occupant density and both the buildings' energy consumption and contagion risk. They prove that the adoption of an optimal controlled occupant distribution throughout the day could reduce both the contagion spread and the energy demand. In addition, the authors underline how a higher air exchange rate reduces Covid-19 contagion risk by up to 56%. However, an increase in energy consumption is also expected, requiring a trade-off solution to tackle both the problems. The same outcome is obtained in the work reported in Ref. [31], where the authors propose the adoption of ultraviolet-C (UV–C) and air disinfection device (RM3) to reduce the Covid-19 contagion risk. The authors conclude that the best strategy is the combination of disinfection devices and the use of 100% outside air, leading to a Covid-19 infection risk probability reduction from 27 to 3%. A school building is instead investigated in Ref. [32]. Here, the authors study the chance of reducing the Covid-19 contagion risk in schools by improving the ventilation rates. Specifically, two existing classrooms are experimentally tested by collecting data about indoor air temperature, relative humidity, and CO₂ concentration. These data are then adopted to perform, by exploiting the Wells-Riley model, a Covid-19 infection risk numerical analysis. From the performed investigations, by augmenting the outdoor air ventilation from 8 to 32 l/s, an R(t) drop from 23 to 7% has been obtained. Similarly, another work exploiting the Wells-Riley is the one reported in Ref. [33] investigating the waiting rooms of a hospital building. Here, the authors investigate the effectiveness of both face mask adoption and augmented ventilation in reducing the Covid-19 contagion risk. The results show that by improving the outdoor air ventilation a contagion risk decrease of up to 75% can be achieved. In general, many other works exist in literature, focusing on diverse case studies and indeed uses, proving the current importance of this topic. Nevertheless, besides the small spaces, the high occupancy rate, and the adoption of ventilation systems with high ARRs and low Air Changes per Hour (ACHs), few are the papers focusing on the railway sector. Examples are the ones reported in Ref. [34], and reference [35]. Specifically, the first one surveys the air exchange rate in trains assessing the related Covid-19 airborne infection risk, whereas the second paper assesses the Covid-19 infection probability for long-distance trains by adopting a Computational Fluid Dynamics (CFD) approach. Nevertheless, both manuscripts neglect the energy aspect. By the carried out literature review, it is possible to conclude that most of the existing works (regardless of the investigated sector) agree on the key role played by the ventilation system in reducing the Covid-19 contagion risk, especially in the case of the airborne suspended aerosol [36,37]. Specifically, three are the most commonly proposed actions to enhance indoor air safety: i) to increase the outdoor air ventilation rates per person to reduce the Air Recirculation Ratio (ARR); ii) to improve the performance of filtration systems (e.g. HEPA filters); and iii) to design the air distribution system with the scope of minimizing the horizontal air displacements [38]. From the considered literature, different conclusions can be made. First of all, it is difficult to find works examining both IAQ and energy performance of ventilation systems in the case of railway carriages: the energy and economic implications of diverse ventilation strategies are mainly investigated in studies focused on energy efficiency solutions rather than on IAQ [39,40]. This is a severe limitation considering the strong link between IAQ, ventilation strategies, and energy consumption [41]. Moreover, most of the investigated works are developed before the Covid-19 pandemic, thus neglecting the existing relation between the ventilation system performance (e.g. outdoor air ventilation rates per person, filtration efficiency, etc.) and the Covid-19 infection risk [42]. Concerning the latter point, the few existing papers on this topic and related to the railway sector (reference [34,35]), are focused only on the infection risk, neglecting the energy implications connected to a variation of the ventilation system operation strategies. Thus, aiming at facing the upcoming challenges imposed by the current pandemic, at improving the safety of the railway sector consciously, and at meeting the energy-saving expectation, it is possible to state that there is a huge need for comprehensive studies linking together, for the railway sector, the ventilation system performance, the Covid-19 risk, and the energy performance. In this framework, this paper aims to fill the above-mentioned lack of knowledge by presenting a novel dynamic simulation tool for the assessment of energy consumption, economic feasibility, and environmental impact, of diverse ventilation strategies for the IAQ enhancement and the Covid-19 contagion risk reduction on railway coaches. Specifically, the novel dynamic simulation tool, developed in the OpenStudio environment, can replicate the real train behaviour by considering the actual train stops, and the occupancy, lights, and equipment schedules. Aiming at quantifying the performance of the ventilation system and the IAQ level, the CO₂ concentration is adopted as widely done in literature as a proxy: tracking carbon dioxide levels is considered a promising way to monitor the IAQ level in enclosed spaces where the occupants are the only CO₂ emitters [43–45]. On the other hand, to assess the Covid-19 contagion risk at the variation of HVAC system layout and/or operating conditions the Wells-Riley model for the infection probability assessment [21] has been adopted. To prove the capabilities of the proposed approach and to investigate the ventilation strategies for the Covid-19 contagion risk reduction on railway coaches a suitable case study is considered. Specifically, it consists of an existing medium-distance train operating on a regional basis. For the considered train, supposed to operate in South/Central Italy, diverse ventilation strategies aimed at reducing the Covid-19 contagion risk are analysed by investigating their energy impact and the economic feasibility. Numerical simulations,
conducted by the developed model, return interesting results from the Covid-19 contagion risk, energy, and economic points of view. The achieved results could be useful to define novel criteria for the design of modern railway coaches with the aim of improving indoor air quality and safety (see Fig. 14).

2. Method and mathematical model

The method and the mathematical model adopted to perform the previously mentioned analyses are described in this paragraph. Concerning the adopted method, in Fig. 1 a schematic diagram of the adopted workflow is shown. Specifically, it allows for the simultaneous assessment of the train energy performance and the probability of infection of the passengers. As shown in the figure, the Matlab script manages both the inputs and outputs of the detailed simulation model of the railway coach or the infection risk calculation model.

Concerning the railway coach energy simulation, this is based on the coupling of a BIM (Building Information Modelling) software to a dynamic energy simulation one [46]. Specifically, the conceived workflow is schematically presented in Fig. 1. Here, it is possible to notice that three different tools are used: Autodesk Revit, OpenStudio, and Energy Plus. Autodesk Revit, a 3D-CAD/BIM software, is employed to detailly develop the 3D model of the train coach envelope, to define the thermal zone key features (e.g. set-point temperature, occupation and lights scheduling, etc.), and to set the system main thermophysical parameters. Once the 3D model is developed, this is imported, using gbXML file, in the OpenStudio suite, an energy simulation software based on the EnergyPlus calculation engine. In OpenStudio the adopted weather file [29, 47], the HVAC system features, etc. are implemented whereas more complex systems and/or control logics are modelled through code editing directly in Energy Plus [48, 49]. Please, note that the developed simulation tool can dynamically account the weather solicitation by considering the actual moving train location and orientation [50, 51]. Concerning the Covid-19 analysis, for the same railway coach and operating condition the contagion risk assessment is performed. Specifically, this is conducted into a purposely developed Matlab subroutine, based on the Wells-Riley model. Both the energy consumption and Covid-19 contagion risk assessment methods, and the related mathematical models, will be detailed described in the following.

2.1. HVAC system

The HVAC system is detailly modelled in an OpenStudio environment. Due to the software flexibility, a wide range of HVAC system layouts and control logics can be realized. In this framework, a schematic model of a generic air loop system, representative of most of the railway stocks HVAC systems, is shown in Fig. 2.

From Fig. 2, Node 1 and Node 7 represent the HVAC system fresh air inlet and the exhausted air outlet, respectively, whereas Node 2 is the mixing chamber of fresh and recirculating air, whose mix conditions are evaluated by a specific EnergyPlus psychrometric routine, as follow:

\[
\begin{align*}
\dot{m}_{\text{air,return}} + \dot{m}_{\text{air,outdoor}} &= \dot{m}_{\text{air,mix}} \\
\dot{m}_{\text{air,return}} \cdot \theta_{\text{air,return}} + \dot{m}_{\text{air,outdoor}} \cdot \theta_{\text{air,outdoor}} &= \dot{m}_{\text{air,mix}} \cdot \theta_{\text{air,mix}} \\
\dot{m}_{\text{air,return}} \cdot h_{\text{air,return}} + \dot{m}_{\text{air,outdoor}} \cdot h_{\text{air,outdoor}} &= \dot{m}_{\text{air,mix}} \cdot h_{\text{air,mix}}
\end{align*}
\]

where \( \dot{m}_{\text{air,return}} \), \( \dot{m}_{\text{air,outdoor}} \), and \( \dot{m}_{\text{air,mix}} \) are the recirculated air, fresh air, and mixed air mass flow rates, respectively. When no recirculation is considered (ARR set equal to zero), the psychrometric condition of air at Node 2 coincides with that of Node 1. Heating and cooling devices are instead schematically represented by Node 3 and can be detailed modelled by the real ones installed on the considered train (see case study section for further details). The investigated thermal zone is instead embodied by Node 5, which is linked to the considered train 3D model for the thermal analysis of the whole

![Fig. 1. Workflow of the adopted method.](image-url)
train carriage. Lastly, Node 4 and Node 6 represent the supply and return vent ducts.

2.2. CO2 concentration and Covid-19 contagion risk analysis

Using the presented tool it is possible, through a purposely conceived OpenStudio subroutine, to assess the CO2 concentration inside train carriages. Such parameter is adopted as an indicator of outdoor air ventilation rates per person and as a proxy of the IAQ level [52]. In OpenStudio, the transient air mass balance equation for the air carbon dioxide concentration is expressed, for each investigated thermal zone, as follows:

\[ \rho_{\text{air}} V_z \frac{d C_{z}^i}{dt} = \sum_{i=1}^{N_{\text{load}}} k_{\text{mass,CO}_2} \cdot 10^5 + m_{\text{inf}} \left( C_{\infty} - C_{z}^i \right) \]  \hspace{1cm} \text{Eq. (2)}

where \( \sum_{i=1}^{N_{\text{load}}} k_{\text{mass,CO}_2} \) is the sum of the internal CO2 loads, \( m_{\text{inf}} \) represents the air mass flow rate entering the thermal zone due to infiltration and/or ventilation, \( C_{\infty} \) and \( C_{z}^i \) are the outdoor and the thermal zone carbon dioxide concentration, \( \rho_{\text{air}} \) is the zone air density, \( V_z \) is the zone volume and \( C_{O2} \) is the carbon dioxide capacity. Using Equation (5), it is then possible to dynamically assess, for each timestep, the CO2 concentration level.

Concerning the assessment of the Covid-19 contagion risk, the model proposed by the authors of reference [43] has been applied. Specifically, the contagion probability, function of the virus concentration, can be assessed by the Wells-Riley infection model [21], as follows:

\[ P = 1 - e^{-n} \]  \hspace{1cm} \text{Eq. (3)}

Here, \( n \) is the number of inhaled “quanta”, representing the amount of virus which a susceptible person inhales. This, is expressed by the following equation:

\[ n = q_c \cdot b_r \cdot D \cdot (1 - \eta_{wm} \cdot \eta_{in}) \]  \hspace{1cm} \text{Eq. (4)}

where \( \eta_{wm} \) represents the face mask efficiency of filtration in case of exhalation, \( b_r \) represents the rate of breathing, \( \eta_{in} \) is the number of people (in %) who wear the mask, \( D \) is the time of exposition, and \( q_c \) is mean concentration of quanta in the considered environment, evaluated as:

\[ q_c = \left( \eta_{er} \right) \cdot \left( 1 - \frac{1}{l_r + D} \right) \cdot \left( 1 - e^{-l_r \cdot D} \right) \]  \hspace{1cm} \text{Eq. (5)}

where, \( V \) represents the volume of the considered space, \( \eta_{er} \) represents the emission rate of quanta, and \( l_r \) is the rate of the virus infectivity loss, which can be evaluated as:

\[ l_r = V_{\text{air}} + d_s + \lambda \]  \hspace{1cm} \text{Eq. (6)}

where, \( d_s \) is the amount of virus inactivated due to deposition on surfaces, \( V_{\text{air}} \) represents the virus inactivation connected to the outdoor air ventilation, and \( \lambda \) is the infectivity loss rate of the virus. The number of quanta emitted by the infectious passenger, \( \eta_{inf} \) is instead estimated as follow:

\[ n_{er} = E_p \cdot (1 - \eta_{ex} \cdot \eta_{wm}) \cdot p_{\text{inf}} \]  \hspace{1cm} \text{Eq. (7)}

where \( \eta_{ex} \) represents the face mask efficiency of filtration in case of exhalation, \( p_{\text{inf}} \) represents the number of passengers assumed as infected and infectious, and \( E_p \) is the emission rate of quanta, evaluated as:

\[ E_p = Q_{\text{act}} \cdot \left( E_{pb} \cdot Q_{\text{var}} \right) \]  \hspace{1cm} \text{Eq. (8)}

where \( E_{pb} \) represents the number of quanta emitted in case of the first Covid-19 variant, \( Q_{\text{var}} \) is an index to correct the emitted quanta number as a function of the passenger activity (speaking, talking, standing, seating, etc.), and \( Q_{\text{act}} \) is an index adopted to correct the emitted quanta as a function of the Covid-19 considered variant.

2.3. Economic and environmental assessment

Using the presented tool, both economic and environmental analyses can be performed. Specifically, the economic impact of the analysed systems can be assessed by evaluating the yearly cost of the consumed electricity, as follow:

\[ C_Y = E_e \cdot C_{el} \]  \hspace{1cm} \text{Eq. (9)}

where \( C_Y \) is the system operating cost on yearly basis, \( E_e \) is the electric energy required by the train on yearly basis, and \( C_{el} \) is the electricity purchase tariff. Concerning the environmental analyses, the amount of emitted CO2 is also assessed. Specifically, the CO2 environmental emission is evaluated as follow:
CO₂ = Eₜₐₜ * fₑₜ

Here, fₑₜ represents the CO₂ emission factor dependent on the considered case study location.

3. Case study

To show the capabilities of the developed tool, and aim at assessing the energy, economic and environmental impact of diverse solutions for outdoor air ventilation rates enhancement (to reduce indoor CO₂ concentration and Covid-19 contagion risk), a suitable case study is considered. It consists of an existing high-capacity double-deck train carriage, operating on regional bases: this type of coach runs within the same region or, in some cases, across contiguous regions. Starting from the selected railway coach, the envelope 3D model, developed in the Autodesk Revit environment, is shown in Fig. 3, whereas its main geometrical features are in Table 1.

From the figure, it is possible to notice that the central part of the coach consists of two passenger decks (lower and upper floors in Table 1), whereas the extremities consist of a single one (intermediate floor in Table 1). The investigated coach does not have any separation doors between the lower and upper floors, and there are no lobbies between doors and the passenger’s zone. Consequently, a single thermal zone (87.5 m², 169.7 m³) can be defined for the entire train. Concerning the envelope, the main thermophysical data of the opaque and transparent components are presented in Table 2.

Regarding the indoor thermal comfort conditions [53–55], these are ensured by an HVAC system made of two Direct Expansion (DE) devices, for space cooling, and Electric Resistances (ER), for space heating. Each DE device, equipped with 4 scroll compressors, has a total cooling capacity of 61.2 kW (for a total installed capacity of 122.6 kW) and can be partialized in four stages, as reported in Table 3. The heating system, consisting of a total installed capacity of 57 kW, can be instead partialized in three stages (Table 4).

Inside the carriage, a variable setpoint, function of the outdoor air temperature (Fig. 4), is adopted. Specifically, a fixed value of 21 °C is kept if the outdoor temperature is below 15 °C, then the setpoint temperature is linearly increased until the upper value of 28 °C, corresponding to an outdoor environmental temperature of 40 °C.

Regarding the HVAC system control logic, the diverse heating and cooling systems stages (Partial Load Ratios, PLR) are respectively activated by following the subsequent equations:

\[
PLR_{\text{Heating}} = \begin{cases} 
0.33 & \text{if } t_{\text{setpoint}} < t_{\text{zone}} \leq t_{\text{setpoint}} - \Delta t_{h,1} \\
0.66 & \text{if } t_{\text{setpoint}} - \Delta t_{h,1} < t_{\text{zone}} \leq t_{\text{setpoint}} - \Delta t_{h,2} \\
1.00 & \text{if } t_{\text{setpoint}} - \Delta t_{h,2} < t_{\text{zone}} \leq t_{\text{setpoint}} - \Delta t_{h,3} 
\end{cases}
\]

Eq. (11)

\[
PLR_{\text{Cooling}} = \begin{cases} 
0.41 & \text{if } t_{\text{setpoint}} + \Delta t_{c,1} < t_{\text{zone}} \leq t_{\text{setpoint}} \\
0.59 & \text{if } t_{\text{setpoint}} + \Delta t_{c,1} < t_{\text{zone}} \leq t_{\text{setpoint}} + \Delta t_{c,2} \\
0.82 & \text{if } t_{\text{setpoint}} + \Delta t_{c,2} < t_{\text{zone}} \leq t_{\text{setpoint}} + \Delta t_{c,3} \\
1.00 & \text{if } t_{\text{setpoint}} + \Delta t_{c,3} < t_{\text{zone}} \leq t_{\text{setpoint}} + \Delta t_{c,3} 
\end{cases}
\]

Eq. (12)

Here, \(t_{\text{zone}}\) (Node 5 in Fig. 2) represents the indoor air temperature, \(t_{\text{setpoint}}\) is the setpoint temperature (function of the outdoor one as shown in Fig. 4), and \(\Delta t_{h,x}\) and \(\Delta t_{c,x}\) represent respectively the heating and cooling temperature differences between the setpoint temperature and the indoor air temperature at which a certain PLR stage is activated (reported in Table 5).

Table 1
Investigated train main data.

| Length    | m  |
|-----------|----|
| Width     | m  |
| Height    | m  |
| Floor area| m² |
| Volume    | m³ |

Table 2
Coach envelope main data.

| Carriage envelope component | U-Value [W/m²K] | Solar fraction [-] |
|-----------------------------|------------------|--------------------|
| Wall                        | 0.87             | -                  |
| Roof                        | 0.87             | -                  |
| Floor                       | 1.8              | -                  |
| Windows                     | 1.3              | <0.3               |

Table 3
Cooling system features.

| Cooling Stage | Partial load ratio [%] | Total Cooling Power [kW] | Sensible Cooling Power [kW] | EIR = 1/COP [-] |
|---------------|------------------------|--------------------------|-----------------------------|-----------------|
| I             | 41                     | 25.20                    | 18.14                      | 0.867           |
| II            | 59                     | 36.00                    | 25.92                      | 0.700           |
| III           | 82                     | 50.40                    | 36.28                      | 0.539           |
| IV            | 100                    | 61.20                    | 44.06                      | 0.488           |
Concerning the ventilation, the HVAC system elaborates a total flow rate of 8800 m³/h with variable Air Change per Hour (ACH) and Air Recirculation Ratio (ARR). Specifically, the considered train exploits a Demanded Controlled Ventilation (DCV) strategy: by using CO₂ probes located inside the cabin, the actual number of passengers is estimated at any moment and the fresh outdoor air flow rate is accordingly regulated to maintain 20 m³/h per passenger (as required by EN 13129-1 standard). Consequently, the Air Change per Hour (ACH) ranges between 7 and 18 (depending on the passenger load), and the Air Recirculation Ratio (ARR) between 65 and 85%. For a better understanding, ventilation data for maximum and minimum coach occupancies are presented in Table 6.

3.1. Investigated itinerary

To simulate the investigated railway coach in its real operating conditions, a suitable itinerary referred to a daily inter-regional route between the cities of Naples (south of Italy) and Rome (centre of Italy), has been considered (Fig. 5). Note that the train path and the related stops scheduling (here not shown for sake of brevity) have been obtained by the real ones gathered from the Italian national railway company “Trenitalia”. Specifically, the train departs at 04:00 from “Napoli Centrale” station and arrives at 10:18 at “Roma Termini” station. Subsequently, after a stop of 20 min, the train leaves Rome to return to Naples. This round-trip is repeated during the day until the train arrives in Naples at 21:58. For passenger occupancy, a variable schedule is assumed throughout the day (Fig. 6). Note that the maximum occupancy has been supposed equal to the number of seats (see Table 1) plus 20% during the rush hours (the maximum passenger number is then equal to 154).

3.2. Investigated scenarios

To improve the investigated train IAQ, and to reduce the Covid-
19 contagion risk, diverse ventilation strategies consisting of Air Change per Hour (ACH) enhancement and Air Recirculation Ratio (ARR) reduction, are investigated. These solutions are detailly described in the following (note that the train described in the previous paragraph is considered as the Reference System - RS).

3.2.1. Proposed system 1 (PS1)

The reference system (RS) requires, following the EN 13129-1 standard, an outdoor air flow rate equal to 20 m³/h per person, resulting in a maximum and minimum external airflow rate of 3080 m³/h and 1240 m³/h, when the train operates at its full and minimum passenger loads, respectively (see Table 6). Therefore, the recirculation ratio ranges between 65 and 85% (corresponding to a recirculated airflow rate of 5720 m³/h and 7560 m³/h, respectively). To enhance the investigated railway coach air safety, in the case of Proposed System 1 (PS1) the amount of recirculated air is set equal to zero without varying the total flow rate elaborated by the HVAC system. Consequently, the outdoor air flow rate raises to 8800 m³/h (51 vol/h), with an expected increase in energy consumption. Note that, for PS1 (such as for the other following solutions) the DCV system is deactivated being unnecessary.

3.2.2. Proposed system 1.1 (PS1.1)

To counterbalance the expected energy demand increase, the PS1 system is enhanced by considering the installation of two air-to-air Heat Recovery (HR) devices (4400 m³/h each, one for each HVAC system). It is worth noticing that the available space on the roof of the train is usually small, for such a reason also the HR dimension should be limited (with consequent smaller heat recovery efficiencies and higher pressure drops than bigger HRs). By considering the actual available space on the train roof, evaluated by analysing the conveys technical drawings, a commercial heat

| Occupancy | Passengers | Fresh air flow rate (per person) | Fresh air total flow rate (total) | Total flow rate | ACH | ARR |
|-----------|------------|---------------------------------|----------------------------------|----------------|-----|-----|
| Maximum   | 154        | 20                              | 3080                             | 8800           | 18  | 65  |
| Minimum   | 62 (or less)| 1240                            |                                  |                 | 7   | 85  |
recovery system with a sensible efficiency equal to 0.6 has been adopted. All the data related to the selected device are presented in Table 7. Note that the existing fans (high-efficiency backwards curved radial ones) are capable to provide the desired flow rate at the higher static pressure (1300 Pa).

### 3.2.3. Proposed system 2 (PS2)

In the case of the previously described PS1 and PS1.1 systems, the outdoor airflow rate per person is notably higher than the one suggested by the standards (57 m³/h per person for PS1 and PS1.1 vs. 20 m³/h per person in the case of RS), with a consequent remarkable expected increase in energy demand. For such a reason, to increase the outdoor air ventilation rates with respect to RS while restraining the energy consumption increase, a reduction of the total airflow rate from 8800 m³/h to 5390 m³/h is proposed in the case of the PS2. Note that this value has been selected considering the typical outdoor airflow rate adopted on aircraft. Note also that, besides the considered reduction, due to the ARR equal to zero, the amount of outdoor air is still 75% higher than the RS one (30 ACH; 35 m³/h per person in case of PS2 vs. 18 ACH, 20 m³/h in case of RS).

### 3.2.4. Proposed system 2.1 (PS2.1)

Finally, Proposed System 2.1 (PS2.1) is derived from PS2 by adding (like PS1.1) two sensible Heat Recovery systems (HR) (see Table 7). It is worth noticing that, both PS2 and PS2.1 systems, proposed to reduce the impact of higher ventilation rate on the energy consumption, bring with them some issues related to the thermal comfort and IAQ aspects. The lower flowrate elaborated by the HVAC system could imply, during the summer (winter) season, a too low (high) supply air temperature, with consequent perceived discomfort increase. In addition, the lower air speed resulting from the airflow rate reduction could reduce the supply air speed, with a consequent lower performance of the ventilation system (in terms of capacity of the air to clean the entire environment without any stratification or areas of stagnation). Therefore, in the case of PS2 and PS2.1 systems adoption, a more accurate design phase should be required.

To sum up all the proposed scenarios, in Table 8 a recap of the examined case studies and the related features is presented (see Table 9).

### 4. Results and discussion

In this paragraph, the impact of the investigated scenarios on the CO₂ concentration levels, Covid-19 infection risk, energy consumption, HVAC system running cost, and environmental emissions, are separately presented, and discussed.

### Table 7

Heat recovery features.

| Parameter               | Value | Unit |
|-------------------------|-------|------|
| Plate spacing           | 2.13  | mm   |
| Plate length            | 549   | mm   |
| Plate height            | 549   | mm   |
| Plate thickness         | 0.13  | mm   |
| Casing outside length   | 567   | mm   |
| Casing outside height   | 567   | mm   |
| Nominal pressure drops  | 200   | Pa   |
| Nominal efficiency      | 0.6   | –    |

### Table 8

Recap of proposed ventilation strategies.

| Investigated system | Total flow rate [m³/h] | Recirculated air | Outdoor air | ACH [m³/h per person] | Heat Recovery |
|---------------------|------------------------|------------------|-------------|-----------------------|---------------|
| RS                  | 8800                   | 7560             | 20          | 7/18                  | No            |
| PS1                 | 8800                   | 0                | 57          | 51                    | No            |
| PS1.1               | 8800                   | 0                | 57          | 51                    | Yes           |
| PS2                 | 5390                   | 0                | 35          | 31                    | Yes           |
| PS2.1               | 5390                   | 0                | 35          | 31                    | Yes           |

### Table 9

Breathing rate and quanta emission rate for diverse activities.

| Activity     | IR [m³/h] | ER Oral breathing (ob) [quanta/h] | ER Speaking (sp) [quanta/h] |
|--------------|-----------|----------------------------------|-----------------------------|
| Sitting (s)  | 0.49      | 14.3                             | 16.5                        |
| Standing (st)| 0.54      | 15.8                             | 18.2                        |
4.1. CO2 concentration and Covid-19 contagion risk

In this section, the CO2 concentration and the Covid-19 contagion risk results are shown and discussed. Concerning the indoor CO2 concentration assessment, the outdoor air CO2 concentration level is assumed equal to 400 ppm [56] whereas the passenger’s CO2 generation rate is equal to 0.0045 l/s (typical value for a person between 30s and 40s with a mean body mass of 87 kg and a level of physical activity of 1.2 met [57,58]). In Fig. 7, the indoor CO2 concentration time histories for a typical day, evaluated by adopting the mentioned boundary conditions, are presented for all the investigated ventilation strategies. From the figure, it is possible to detect that, in the case of the reference system layout (RS, orange line), the CO2 concentration level reaches a peak value of 1200 ppm (daily mean value: 1183 ppm). Such CO2 concentration level is not negligible, being a lower value usually suggested for enclosed spaces [57–59]. By applying PS2 and PS2.1 system layouts (red lines), thanks to the higher outdoor airflow rate vs. RS (31 vol/h vs. 18 vol/h), a remarkable reduction of the CO2 concentration is detected, with a peak value of about 860 ppm (daily mean value 775 ppm). Even better results are obtained, as expected, by considering PS1 and PS1.1 system layouts (green line) returning a maximum CO2 peak concentration of 680 ppm (daily mean value: 624 ppm).

From the shown results it is possible to notice that the outdoor air ventilation rates per person suggested by the standards (RS) seem to be not sufficient to adequately dilute the indoor air (CO2 concentration is always above 1000 ppm level in case of RS). On the other hand, by increasing the outdoor airflow rate, interesting CO2 concentration reductions are always obtained. As previously mentioned, the CO2 level can be adopted as a metric for the overall IAQ evaluation, however, it should be considered that being the CO2 just one of the many airborne contaminants in indoor spaces, it is a better metric of the ventilation rate per person only [52]. It is worth also noticing that high indoor CO2 levels could also indicate a higher Covid–19 contagion risk [60–62]. To quantify such risk for all the investigated system configurations, the method proposed by the authors of reference [43], based on the previously described Wells-Riley infection model, was applied. Specifically, the following assumptions have been made:

- Only one passenger is considered infected and infectious over the 154 passengers (meaning a Covid–19 incidence of 0.6%, which is the typical statistical incidence for Italy at the time of writing);
- the rate of virus infectivity loss (\( \lambda \)) is considered equal to 2.8 h\(^{-1} \) [63];
- The breathing rate (\( b_t \)) is evaluated in accordance to Eq. (14) by considering the inhalation rate for sitting and standing people (\( IR_s \) and \( IR_{st} \), m\(^3\)/h, see Table 10) [32]. Note that for the considered case study 95% of the people have been considered as seated (\( n_s \), %) and the remaining 5% as standing (\( n_{st} \), %);

\[
b_t = IR_s \cdot n_s + IR_{st} \cdot n_{st}
\]

Eq. (14)

- a quanta emission rate (\( E_{ql,q} \), namely \( ER, \) quanta/h) equal to 13.4 quanta/h has been adopted. This value is estimated with Eq. (15) using the emission rate valued for breathing \( ER_{b} \) and speaking \( ER_{sp} \), gathered from Ref. [32]. Note that for the selected case study, the 80% of the occupants are considered as breathing, and the remaining 20% as speaking.

\[
ER = (ER_{ob,s} \cdot n_{ob} + ER_{sp,s} \cdot n_{sp}) \cdot n_s + (ER_{ob,sp} \cdot n_{ob} + ER_{sp,sp} \cdot n_{sp}) \cdot n_{st}
\]

Eq. (15)

- three different face mask scenarios have been considered: no face masks, surgical masks, and N95 masks. Masks filtration efficiencies during the inhalation (\( m_{in} \) in Eq. (7)) and exhalation (\( m_{ex} \) in Eq. (7)) phases have been set respectively equal to 30 and 50%, for the surgical mask, and to 90% for both the phases in the case of the N95 mask [64,65];
- an exposition time (\( D \) in Eq. (7)) corresponding to a full journey from Naples to Rome (or backward, see Case Study section) is considered;
- the number of quanta emitted by the infectious passenger is constant;
- at the starting of the simulation, the carriage is zero;
- a fully mixed model is considered for quanta aerosol;
- the infection risk due to the close-proximity is ignored.

By the above-mentioned assumptions, the Covid–19 contagion risk results shown in Table 11 are achieved.

![Fig. 7. CO2 concentration time histories for all the investigated systems.](image-url)
By analysing the obtained results, starting from the no mask case, it is possible to notice that, for a ventilation rate equal to 18 vol/h (RS), an infection probability of 2.38% is achieved, which is above the 1% threshold value considered as a safe one, as also specified in literature [23]. By rising the ACH to 31 vol/h (PS2 and PS2.1), an infection probability reduction equal to ~40% vs. RS is detected. Nevertheless, the contagion risk probability results to be still higher than 1%. Higher reduction (~60%) and a contagion risk below 1% are instead achieved by increasing the ACH to 51 vol/h (PS1 and PS1.1). Lower Covid-19 contagion risk values, below the 1% one, are instead generally detected in the case of all passengers wearing surgical masks. Yet, similar infection probability reductions are achieved by the ACH increase. Finally, a very low contagion risk is detected in the case of all the passengers wearing N95 masks regardless of the adopted ventilation strategy (further details are given in the following). Thus, by adopting the proposed ventilation rates, infection risk reductions ranging from 40% to 65% are achieved over the RS system. The obtained results prove, as also reported in the existing literature, the key role played by outdoor ventilation in reducing the Covid-19 contagion risk in enclosed spaces. Note that a comprehensive comparison with other works in literature is not possible due to the high differences occurring among the investigated case studies. Nevertheless, the achieved outcomes are consistent with the results presented by other works in literature that is not possible due to the high differences occurring among the investigated case studies. Nevertheless, the achieved outcomes are consistent with the results presented by other works on the same topic: by augmenting the outdoor airflow rate, Covid-19 contagion risk reduction up to 56% for a university facility [30], 30% for an office space [31], and 75% for an outpatient building [33] are obtained by other authors. It is worth noticing the occurring differences are mainly due to the very different case study geometry, indeed use, ventilation rates, etc. To carry out the previously shown analysis also in case of higher virus diffusion, a further study has been performed by assuming 5 infectious passengers (meaning a Covid-19 incidence of 3.2%, which is the highest Covid-19 incidence in some Italian regions at the time of writing), and the related results are presented in Table 11.

Here, considerations similar to those related to the 1 passenger case can be done (with, however, a higher magnitude in the contagion risk). Specifically, in both no mask and surgical mask cases, the contagion risk results to be always above the 1% threshold, whereas a “safe” condition is reached only in case of all passengers wearing the N95 mask. From the shown results it would be possible to state that no airflow rate increase seems to be necessary in case of all passengers wearing N95 masks. However, it should be considered that i) most of the time, a mix of surgical and N95 masks are worn; and ii) the adopted value of N95 filtration efficiencies (90% for both inhalation and exhalation) are estimated in case of new masks, properly worn. Thus, in the case of non-sanitary people, face masks actual efficiency could be lower, as stated in several studies [64], with a corresponding increase in the contagion risk. It is worth noticing that the Covid–19 infection risk absolute values shown in Table 11 are subjected to some level of uncertainty. Such uncertainty is mainly due to the adopted number of quanta, whose value is still under discussion in the scientific community. Nevertheless, the relative results achieved by the conducted analysis can be successfully adopted to develop design criteria for ventilation systems aiming at reducing the Covid-19 contagion risk.

### 4.2. Energy analysis

The ventilation strategies proposed to reduce the Covid-19 contagion risk and the CO2 concentration have a remarkable consequence on the train thermal behaviour and energy consumption. To evaluate such impact, in this section the thermal and energy results related to all the investigated case studies are presented. Starting from the RS, the indoor air temperatures are shown in Fig. 8 for a sample winter (Fig. 8, left) and summer (Fig. 8, right) days, over a 30 min period.

| Investigated system | ACH | No mask | Surgical mask | N95 mask |
|---------------------|-----|---------|---------------|----------|
| Probability of infection [%] |
| RS 18 | 11.35 | 4.13 | 0.12 |
| PS2/PS1.2 31 | 6.91 (−39%) | 2.48 (−39%) | 0.07 (−42%) |
| PS1/PS1.1 51 | 4.32 (−62%) | 1.53 (−63%) | 0.04 (−66%) |

**Table 11**

Covid-19 contagion risk probability (5 infectious passengers).

---

**Fig. 8.** RS temperature time histories for a typical winter (left) and a typical summer (right) days.
Specifically, the outdoor air (blue line), the indoor air (green line), the mix temperature (Node 2, Fig. 2, grey line), the setpoint temperature (red line); and the upper and lower setpoint dead bands (dotted orange lines) time histories are presented. From the figure, it is possible to notice that, in the case of RS, the HVAC system is capable to maintain the indoor air temperature close to the setpoint one in both winter and summer periods. Different outcomes are achieved in the case of the other investigated scenarios. Specifically, the same diagrams presented in Fig. 8 for RS are reported in Fig. 9 for PS1 (Fig. 9, top) and PS1.1 (Fig. 9, bottom). Note that for both PS1 and PS1.1 systems, the air mix temperature is not plotted being absent the recirculated air. Concerning the PS1 system (Fig. 9, top), it is possible to notice that the existing HVAC system is not capable of adequately maintain the indoor air setpoint in case of both winter (Fig. 9, top-left) and summer (Fig. 9, top-right) season. Such occurrence is due to the discrete on/off operating logic of the HVAC system and to the concurrent high outdoor air ventilation flow rate. Specifically, once the setpoint is reached, the heating (cooling) device went OFF and the high ventilation rate rapidly decreases (increases) the indoor air temperature below (above) the accepted dead band. Such occurrence leads to two different drawbacks: i) higher discomfort level vs RS system, and ii) increase in energy consumption (as will be shown in the following). Such an issue can be partially overcome by installing the Heat Recovery system (PS1.1 system), as shown in Fig. 9, bottom. Here, the purple line represents the fresh air temperature at the outlet of the heat recovery system. By analysing both winter (Fig. 9, bottom-left) and summer (Fig. 9, bottom-right) seasons, it is possible to notice that, differently from the PS1 system (Fig. 9 top), in the case of PS1.1 the temperature setpoints are easily maintained. Such occurrence already proves the advantages of adopting the proposed HR system. 

Fig. 9. PS1 and PS1.1 temperature time histories for a typical winter (left) and a typical summer (right) days.
The same considerations made for PS1 and PS1.1 systems can be also made for PS2 and PS2.1 (respectively Fig. 10, top and bottom).

Specifically, in the case of PS2 adoption, the HVAC system still struggles in guaranteeing the indoor air set-point for both summer and winter periods (respectively, top-right and top-left of Fig. 10). Such behaviour, similar to that noticed for the PS1 system (see Fig. 9, top), is however lower in magnitude due to the lower amount of outdoor airflow rate. This issue is instead totally solved when the HR is considered (PS2.1), as shown in Fig. 10, bottom. Here, it is possible to notice that, by coupling the reduction of the total elaborated flow rate to the adoption of the HR system, the indoor air temperatures are always kept close to setpoint one. Concerning the energy results, the thermal energy demands for space heating and space cooling for all the investigated scenarios are presented in Fig. 11 left and in Fig. 11, right respectively.

Starting from the winter season (Fig. 11, left), it is possible to notice that, as expected, PS1 and PS2 adoption (respectively orange and yellow bars) return energy consumption remarkably higher than that required by the RS (blue bar). Specifically, thermal energy demand for RS is equal to 9 MWh/y whereas 61 MWh/y (+52 MWh/y) and 38 MWh/y (+29 MWh/y) are required in the case of PS1 and PS2 systems respectively. Such increase is substantially reduced by HR adoption as shown for PS1.1 (18 MWh/y, +9 MWh/y) and PS2.1 (8 MWh/y, -1 MWh/y) (grey and red bars). Note that, in the case of PS2, the concurrent reduction of the elaborated flow rate (vs. PS1) and the HR adoptions returns thermal energy demand slightly lower than that required by RS.

Concerning the thermal energy demand for space cooling (Fig. 11, right), considerations similar to those made for the winter season can be made. By comparing the winter and summer seasons

![Fig. 10. PS2 and PS2.1 temperature time histories for a typical winter (left) and a typical summer (right) days.](image-url)
it is possible to notice that, in general, differences lower in magnitude can be detected during the summer season over the winter one. On yearly basis, the overall electricity demand for space heating and cooling is presented in Fig. 12, for all the considered case studies (see Fig. 13).

Here it is possible to notice that, following the thermal energy results shown in Fig. 11, PS1 and PS2 systems return remarkable electricity consumption increases (+54 and +33 MWhel/y, respectively). Smaller increases are instead detected for PS1.1 and PS2.1 cases (+12 and +2 MWhel/y, respectively). The results presented in Fig. 12 do not consider the energy consumption of ventilation fans (which increases in the case of HR adoption, due to the higher air ducts system static pressure). The overall electric energy demand (including fans) is instead computed in Table 12 where it is possible to notice that the fan energy demand (first row of the table) changes at the variation of the adopted system. Specifically, in the case of PS1 the energy required by the fan is the same as RS (same elaborated flow rate, same air ducts static pressure), whereas in the case PS1.1 higher energy needs are detected (9.2 MWhel/y, +1.0 MWhel/y with respect to RS) due to the higher air ducts static pressure caused by the HR installation (as reported in Table 7). Concerning the PS2 system, here, lower energy demand is detected with respect to RS (6.6 MWhel/y, -1.6 MWhel/y) due to the reduced elaborated air flow rate at the same air ducts static pressure. Finally, by considering the PS2.1 system, higher energy requirements vs. PS2 system (still lower than RS one) are detected (7.6 MWhel/y, -0.6 MWhel/y). By adding the consumption of the fans to the electricity demand for space heating and cooling, the total electric energy needs of the investigated systems are obtained, as reported in the last row of Table 11.

### 4.3. Economic analysis

All the investigated systems return, as expected, higher electricity consumption on a yearly basis if compared to the reference one. Consequently, it is not possible to assess a payback period. However, in this section, the higher expenses that would be faced by considering the proposed ventilation strategies are reported. In this framework, two different electricity costs ($c_e$), representative of the minimum and maximum cost of electric energy for the railway sector across EU Countries [66] have been considered: 0.06 and 0.16 €/kWh el. The initial price of the Heat Recovery (HR) system, obtained from manufacturer data, is equal to 1.2 k€ per device. The results of the economic analysis are then shown in Table 12, where the systems’ CAPEX (CAPital EXPenditures) and OPEX (OPERating EXPenditures) are shown. From the table, it is possible to notice that the HVAC system operating cost ranges between 2.5 and 5.7
reduce the COVID-19 contagion risk. To prove the capabilities of the proposed approach, a suitable case study consisting of an existing medium-distance train operating on a regional basis is considered. For the considered train, diverse HVAC system operating conditions and layouts are analysed by investigating their energy impact and economic feasibility. From the carried-out analyses, several considerations can be made:

- **Lower CO₂ concentration** is always achieved by augmenting the outdoor airflow rate, as expected. Specifically, the CO₂ concentration is remarkably reduced in the case of 51 vol/h (PS1 and PS1.1 systems - daily mean CO₂ concentration equal to 624 ppm) over 18 vol/h (RS case study - daily mean CO₂ concentration equal to 1183 ppm). By adopting 31 vol/h (PS2 and PS2.1 systems), higher CO₂ concentrations (daily mean CO₂ concentration equal to 775 ppm), still remarkably lower than that obtained by RS, are obtained. From these results it is clear that, from the CO₂ concentration point of view, the current standard doesn't provide an adequate amount of outdoor air;

- **Higher air ventilation rates per person** imply lower risks of Covid-19 contagion. Specifically, reductions of 40 and 60% of probability of infection are detected by increasing the ACH from 18 (RS) to 31 (PS1.1) vol/h, respectively. The adoption of the ventilation value from the standard (18 vol/h) results to be enough only in case of all passengers properly wearing an N95 face mask (or surgical one in case of only one passenger infected and infectious). However, the adopted values of surgical and N95 masks filtration efficiencies are estimated in case of new masks, properly worn, whereas in the case of non-sanitary people, face masks actual efficiency could be lower;

- **Due to the augmented air ventilation rates per person**, a remarkable increase in energy consumption (+54 kWhel), CO₂ emission (+26.0 t/CO₂) and HVAC system operating cost (+3.2/8.6 €/y, depending on the electricity cost) are noticed in case of the original HVAC system working with nominal flowrate and no recirculated air (PS1). These drawbacks could be slightly reduced by adopting a heat recovery system (PS1.1);

- **Reducing the total airflow rate elaborated by the HVAC system**: by maintaining the recirculating air to zero (PS2), still returns reduced CO₂ concentration and Covid-19 contagion risk while reducing the energy, environmental and economic impact of the revamping proposal. However, these values are still remarkably high (+31.1 kWhel, +15.9 t/CO₂, and +18/+4.9 €/y) making also this solution unviable. The adoption of air-to-air heat recovery coupled with a reduction of the total elaborated flowrate (PS2.1) reduces the energy, economic and environmental impact (+1.2 kWhel, +0.9 t/CO₂, and +0.07/+0.19 €/y). However, the reduction of the elaborated flow rate could cause some issues from the thermal comfort and IAQ points of view (in terms of the capacity of the air to clean the entire environment without any stratification or areas of stagnation). Therefore, a more accurate design phase should be required.

From the shown results, it is possible to conclude that the existing normative doesn’t suggest an adequate amount of outdoor air to ensure low CO₂ concentration level and low Covid-19 contagion risk on railway coaches. Consequently, the obtained findings underline the need of updating standards regarding ventilation in enclosed spaces. In this framework, the shown results can give useful insights on the new rates to be considered as standards. In this framework, the augmentation of outdoor air flowrate is proven to be a good solution to reduce both CO₂ concentration and Covid-19 contagion risk. Still, such action is highly energy consuming, requiring the adoption of heat recovery devices, otherwise, it would be unviable from the energy, economic, and environmental performance of railway coaches is presented. Through the developed tool, it is possible to investigate the feasibility of diverse ventilation strategies to improve railway coaches’ IAQ and

$k/€/y$ and between 6.6 and 15.2 $k/€/y$, for an electricity price of 0.06 and 0.16 $€/kWh$, respectively. In Fig. 13, the OPEX increases obtained by adopting the proposed systems vs. the reference one, are presented. Following the results shown in Table 13, the system returning the lower running cost increase vs. the RS (with however lower performance from the ventilation point of view) is the PS2.1, with a total growth of 72 and 192 $€/y$ in the case of 0.06 $€/kWh$ and 0.16 $€/kWh$, respectively. On the other hand, the system returning the best performance by the CO₂ concentration and Covid-19 contagion risk reduction (PS1.1), returns a total growth of 0.76 and 2.0 $€/y$ in the case of 0.06 $€/kWh$ and 0.16 $€/kWh$, respectively.

### 4.4. Environmental analysis

The energy results previously shown imply the environmental ones presented, for all the investigated ventilation strategies, in Fig. 14. Note that these results have been obtained by considering an emission factor ($f_{el}$) equal to 0.483 tCO₂/MWhel. From the figure, it is possible to notice, in accordance with the energy results shown in Fig. 12, that PS1 and PS2 systems adoption (respectively orange and yellow bars) return remarkable CO₂ emission increases (+26.0 and +15.9 t/CO₂ vs. RS). On the contrary, by adopting the PS1.1 and PS2.1 systems the environmental impact is strongly reduced to 21.7 t/CO₂ y (+5.7 t/CO₂ y vs. RS) and 16.9 t/CO₂ y (+0.9 t/CO₂ y vs. RS), respectively.

### 5. Conclusions

In the present paper, a dynamic simulation model purposely developed for the assessment of the energy, economic, and environmental performance of railway coaches is presented. Through the developed tool, it is possible to investigate the feasibility of diverse ventilation strategies to improve railway coaches’ IAQ and

| System  | CAPEX [€] | OPEX [€/y] |
|---------|-----------|-------------|
| RS      | –         | 2.5         | 6.6         |
| PS1     | 2.4       | 3.2         | 8.7         |
| PS1.1   | 2.4       | 4.3         | 11.6        |
| PS2     | 2.4       | 2.6         | 6.8         |
| PS2.1   | 2.4       | 3.2         | 8.7         |

### Table 13

Investigated scenarios economic results.
also environmental points of view. Finally, it is worth noticing that currently most trains are subjected to a remarkable reduction of payload (up to 50%). Thus, even with an unavoidable increase in the operating cost, the adoption of the proposed systems could help to restore the original payload more safely. In addition, the achieved results can be also useful in providing guidelines to train constructors to define novel HVAC systems design criteria. From a future perspective, the feasibility of other actions, such as the adoption of filtration and disinfection strategies, will be investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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