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# Application of the Taguchi and ANOVA Methods to Optimize Ventilation Parameters for Infection Risk Based on the Wells-Riley Model


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**Abstract**

The coronavirus pandemic has caused many deaths and affected societies with social and economic problems as a consequence of its effects. Many different measures were taken to stop or reduce the spread of the virus, like wearing a face mask and reorganizing school activities, transportation, and meetings. As an alternative to these measures, ventilation is a critical engineering solution that can help reduce the infection risk in the indoor environment. In this study, the Taguchi method was used to investigate the effects of ventilation parameters t (volume, inlet velocity), and quanta emission rates on the Wells-Riley method-based infection risk probability. The orthogonal array was used to create the experimental design. Then, each parameter was analyzed according to the performance criterion (infection risk probability) using signal-to-noise (S/N) ratios, and the order of importance of the parameters was calculated. The contribution ratio of each parameter to infection risk was calculated with both the Taguchi method and the ANOVA method, and these results confirmed each other. Consequently, these data were used to identify worst-case and best-case scenarios to minimize the risk of infection in the indoor environment.


## 1. Introduction

The COVID-19 pandemic showed the importance of infection control measures, especially in indoor environments. The transmission of the SARS-CoV-2 virus, which causes COVID-19, can occur through respiratory droplets or close contact with infected individuals [1]. Many measures were taken by the governments around the world to prevent the spread during the pandemic process. Regulations were made for organizations in closed environments, masks became mandatory in many areas, and most closed areas were rearranged depending on social distance.

The Wells-Riley method is a method that quantifies the probability of infection risk and has been widely used to estimate the risk of infection transmission in indoor environments, as it considers a variety of factors that can influence the risk of infection, such as the room volume, ventilation rate, breathing rate, quanta emission rate, and exposure time. Many epidemic modeling studies have used the Wells-Riley equation as part of their mathematical model [2]. Some researchers modified the Wells-Riley equation, developed dose-response models, and used additional numerical modeling techniques to provide more comprehensive risk assessments [3]–[5]. The number of studies using the Wells-Riley method has increased with the Covid-19 pandemic, and many researchers used this method with the computational Fluid Dynamics (HAD) method [6]–[8].

However, this method has some limitations because it does not consider the effect of other variables that may affect the transmission of infection, such as the level of personal protective equipment (PPE), gender or physiological differences, etc. Many researchers have proposed ways to improve this model. In addition, the effect of


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each parameter used in the Wells-Riley model on infection risk probability is not clear. This is essential because it defines the strategies for decreasing infection risk in indoor environments.

To address these limitations and the challenges posed by the COVID-19 pandemic, a novel approach, the Taguchi optimization method, was used in this study to optimize the infection risk calculated using the Wells-Riley method. The Taguchi method involves the systematic variation of multiple parameters in a controlled experiment by means of a orthogonal array and the use of statistical analysis to determine the optimal combination of these parameters that results in the desired outcome, which in this case is minimized infection risk [9]. The contribution ratio of each parameter is also calculated with the Taguchi method, and these results were confirmed with another statistical method, ANOVA.

In this study, the levels of room volume, inlet velocity, and quanta emission rate values that will minimize the possibility of infection risk in the room were investigated. Each parameter was considered in a large range. The order of importance of the parameters and, accordingly, the best- and worst-case scenarios were obtained.

## 2. Material and Method

In this study, the effects of room volume, inlet velocity, and quanta emission rate on the risk of infection in the room were investigated using the Wells-Riley method. Parameters and their values are given in Table 1. All parameters were investigated over a large range. Inlet velocity values have a critical effect on infection risk; because of this reason a large range is also examined for this parameter. The quanta emission rates were determined as 3.1 (resting, oral breathing), 21 (heavy activity, oral breathing), and 42 quanta/h (light activity, talking) [10]. Room volume was also considered in the analysis, and its values were defined as 18, 42, and 60 m$^3$.

**Table 1.** Investigated parameters

| | Parameters | Levels 1 | 2 | 3 |
|---|---|---|---|---|
| A | Volume (m$^3$) | 18 | 42 | 60 |
| B | Velocity (m/s) | 1 | 2 | 3 |
| C | Quanta emission rate (quanta/h) | 3.1 | 21 | 42 |

### 2.1 Wells-Riley Method

The Wells-Riley method is used to model the risk of indoor airborne transmission of infectious diseases such as tuberculosis and Covid-19 and is based on quanta. Quanta was proposed as a hypothetical unit of infection dose in Wells' work [11]. Quanta is defined as the number of airborne infectious particles required to infect a person. [3]. In other words, it can be defined as the droplet nuclei in the air that can cause infection in 63% of the people in the environment [10]. The Wells-Riley equation was defined as [12]:

$$P = 1 - e^{-n} \tag{1}$$

In Equation 1, $P$ is the probability of infection risk and n is the inhaled quanta. The quanta calculation can be done according to Equation 2:

$$n = C_{avg} Q_b D \tag{2}$$

In Equation 2, $C_{avg}$ (quanta/m$^3$) represents the time-averaged quanta concentration, $Q_b$ the volumetric breathing rate of an occupant, and $D$ (h) occupancy time.

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \tag{3}$$

In Equation 3, $E$ (quanta/h) is the quanta emission rate (quanta/h), $V$ (m$^3$) is the volume of the room, $\lambda$ (1/h) is the first-order loss rate coefficient for quanta/h. $\lambda$ is sum of deposition onto surfaces $\lambda_{dep}$ (1/h), ventilation (ACH) $\lambda_V$ (1/h), virus decay k (1/h) ($\lambda = \lambda_{dep} + \lambda_V + k$). The surface deposition loss rate was considered to be 0.3 1/h [13], [14] and virus decay was considered averaged value of 0.32 1/h [15], [16] according to literature [10].

It is assumed that the quanta concentration is 0 at the initial state, and then after the equation (3) is solved, the average quanta concentration can be calculated as below:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda D}\right) \tag{4}$$

In Equation 4, $t$ (h) is the time.

$$C_{avg} = \int_0^D C(t)dt \ \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \tag{5}$$

## 2.2 Taguchi Method

Taguchi method, which was developed by Taguchi [9], was successfully applied to many disciplines [17]–[21]. Taguchi method uses signal/noise ratios (S/N) to obtain the importance order of parameters, contribution ratios, and best- and worst-case scenarios [22].

Yuce et al. [23] discussed the solution steps and advantages of the Taguchi method in detail. Details on the methodology can be accessed from the related study. Three parameters (volume, inlet velocity, and quanta emission rate) and 3 different values of each parameter were examined in this study. As a result of this, the L9 (33) orthogonal array was used. Since the objective function is infection risk in this study, the 'smaller the better' approach was used according to the assumption that the smallest value is the best, as shown in Equation 6:

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (6)$$

In the Taguchi method, the factors determining the order of importance are obtained by the delta values. Delta values are calculated by the difference between the maximum and minimum S/N ratios for each parameter. The parameter with the largest delta value represents the most effective parameter [23].

Table 2 shows the L9 (33) orthogonal array created for this study. Nine different scenarios were determined for this design. Infection risk calculations were made for each scenario. Then, using equation 6, S/N ratios were calculated.

**Table 2.** Taguchi L9 (33) orthogonal array and calculated infection risk and S/N values

| No. | Volume ($m^3$) | Velocity (m/s) | Quanta emission rate (quanta/h) | Infection Risk (%) | S/N |
|---|---|---|---|---|---|
| 1 | 18 | 1 | 3.1 | 4.35 | 27.33 |
| 2 | 18 | 2 | 21.0 | 14.27 | 16.89 |
| 3 | 18 | 3 | 42.0 | 18.68 | 14.56 |
| 4 | 42 | 1 | 21.0 | 24.73 | 12.15 |
| 5 | 42 | 2 | 42.0 | 25.83 | 11.77 |
| 6 | 42 | 3 | 3.1 | 1.48 | 36.48 |
| 7 | 60 | 1 | 42.0 | 42.02 | 7.54 |
| 8 | 60 | 2 | 3.1 | 2.13 | 33.56 |
| 9 | 60 | 3 | 21.0 | 9.50 | 20.45 |

## 2.3 Analysis of Variance (ANOVA)

ANOVA is a commonly employed statistical method that helps understand the impact of each variable on the experimental outcome. The procedure for ANOVA includes the following steps [23]:

The total sum of squares ($SS_T$) can be calculated as [24]:

$$SS_T = \sum_{i=1}^{N}(Y_i - \bar{Y})^2 \quad (7)$$

In equation 7, N represents the number of cases in the orthogonal array and $Y_i$ represents the result for the $i_{th}$ case,

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i \quad (8)$$

The overall sum of the squared deviations, $SS_T$, is made up of both the sum of the squared error, $SS_e$, and the sum of the squared deviations due to each process parameter, $SS_P$, hence $SS_P$ is defined as [24]:

$$SS_P = \sum_{j=1}^{t}\frac{(SY_j)^2}{t} - \frac{1}{N}\left[\sum_{i=1}^{N} Y_i\right]^2 \quad (9)$$

In equation 9, P represents a specific parameter, j is the level of that parameter, t indicates the number of times each level of the parameter is repeated, $SY_j$ represents the sum of the experimental results for the parameter P at level j, and $SS_e$ represents the sum of squares from the error parameters, as shown below [24]:

$$SS_e = SS_T - SS_A - SS_B - SS_C - SS_D - SS_E \quad (10)$$

The overall degree of freedom, $D_T$, is equal to N-1, and the degree of freedom for each evaluated parameter, $D_P$, is also equal to N-1. The variance of the tested parameter, $V_P$, is calculated as 〖$SS_P/D_P$. The F-value for each design parameter can be determined by dividing the variance of that parameter by the variance of the error, $F_P = V_P/V_e$. The percentage contribution, ρ, is calculated as [24]:

$$\rho_P = \frac{SS_P}{SS_T} \tag{11}$$

## 3. Results and Discussion

Infection risk and, accordingly, S/N ratio values for nine different conditions were obtained, and they are shown in Table 2. These S/N ratio values were used to calculate the average S/N ratio values for each level of each parameter. Average S/N ratio values are shown in Table 3. Delta values were also obtained according to the average values.

In Figure 1, the variation of the S/N ratios depending on the levels of the examined parameters is shown. Among the examined parameters according to the order of importance in Table 3 and the S/N ratio values in Figure 3, the most effective parameter on the infection risk probability is the quanta emission rate.

Figure 1 shows that the possibility of infection risk is significantly reduced by a low quanta emission rate (3.1 quanta/h). The inlet velocity is the second important parameter, and as the amount of fresh air given to the environment increases, the risk of infection decreases. The lowest probability of infection risk according to inlet velocity is at 3 m/s. The parameter that has the least effect on the risk of infection is the room volume, and the risk of infection decreases as the volume increases.

Delta values were calculated for each parameter as Volume$_{0.92}$$<$Inlet velocity$_{8.16}$$<$quanta emission rate$_{21.17}$. Contribution ratios of each parameter on infection risk probability were obtained with the delta values. The volume, inlet velocity, and quanta emission rate have contribution ratios on infection risk as 3.04, 26.98, and 69.98% respectively.

According to Figure 1, the parameter levels corresponding to the minimum infection risk are 60 $m^3$ for the volume, 2 m/s for the inlet velocity, and 3.1 quanta/h for the breathing rate. The best case is not within the orthogonal array shown in Table 2. The infection risk probability was calculated as 1.46% when the infection risk was calculated in the Wells-Riley equation according to these values and this result is lower than all the values in the orthogonal array. The closest value to this is 1.48% in the 6th scenario. Scenario 6 has the same values as the best-case scenario except for volume, and the reduction in infection risk was also small, as the room volume had a low impact on infection risk.

Figure 1 shows that the infection risk probability is the highest, and for the worst-case scenario, the volume is 18 $m^3$, the inlet volume is 1 m/s, and the quanta emission rate is 42 quanta/h. The worst case is not included in the scenarios within the orthogonal array as it is in the best case. The infection risk probability was calculated in the Wells-Riley equation according to these values as 45.23% and this result is higher than all the values in the orthogonal array. The closest situation to this scenario is seen in scenario 7 and the infection risk value is 42.02%. As similar to best case, the parameter that is different in this scenario is the volume value, and due to the small effect value of the volume, the difference between it and the highest value seen in scenario 7 is low.

**Table 3**. The order of importance of parameters according to mean S/N ratios

| Level | Volume ($m^3$) | Velocity (m/s) | Quanta emission rate (quanta/h) |
|---|---|---|---|
| 1 | 19.6 | 15.67 | 32.45 |
| 2 | 20.13 | 20.74 | 16.49 |
| 3 | 20.51 | 23.83 | 11.29 |
| Delta | 0.92 | 8.16 | 21.17 |
| Rank | 3 | 2 | 1 |
| Contribution (%) | 3.04 | 26.98 | 69.98 |

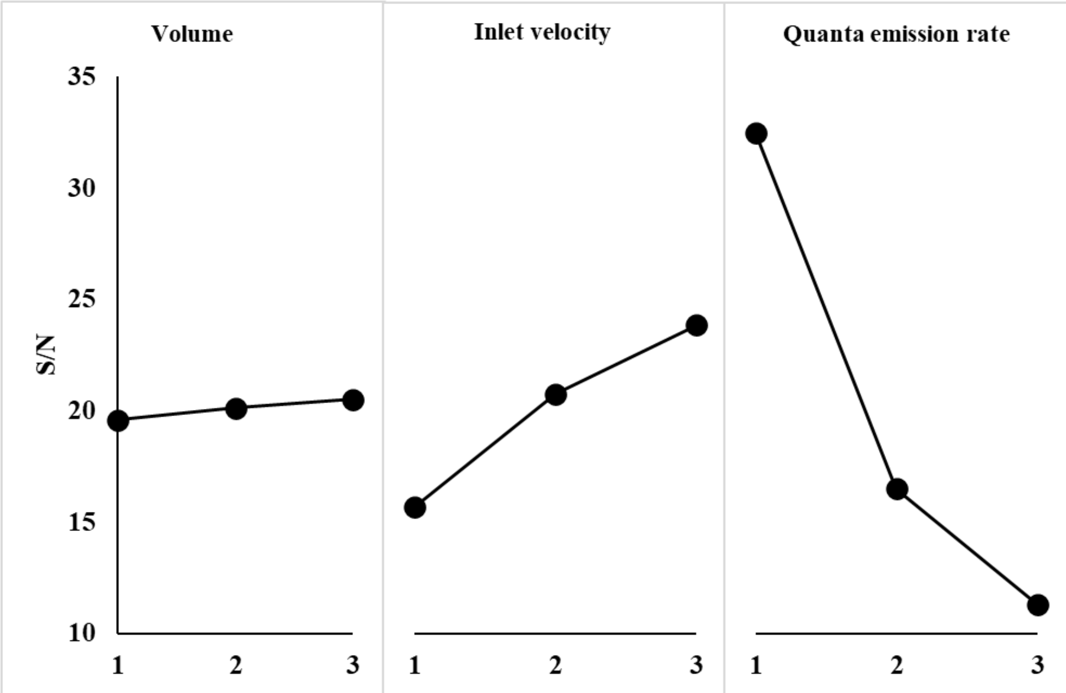


**Figure 1.** Variation of S/N ratios according to volume, inlet velocity, and quanta emission rate

ANOVA results are shown in Table 4. The results of the contribution ratios for each parameter are similar to those of the Taguchi analysis. The main difference between these statistical methods is based on the contribution ratio of the supply velocity, which corresponds to a 6% difference. Results of two methods are compared with each other in Figure 2.

**Table 4.** ANOVA results and contribution ratios of parameters on infection risk

| Parameters | DOF | SS | MS | F-Value | Contribution ratio |
|---|---|---|---|---|---|
| Volume ($m^3$) | 2 | 0.005 | 0.003 | 0.94 | 3.74% |
| Velocity (m/s) | 2 | 0.030 | 0.015 | 5.2 | 20.76% |
| Quanta emission rate (quanta/h) | 2 | 0.103 | 0.052 | 17.92 | 71.51% |
| Error | 2 | 0.006 | 0.003 | | 3.99% |
| Total | 8 | 0.144 | | | 100.00% |

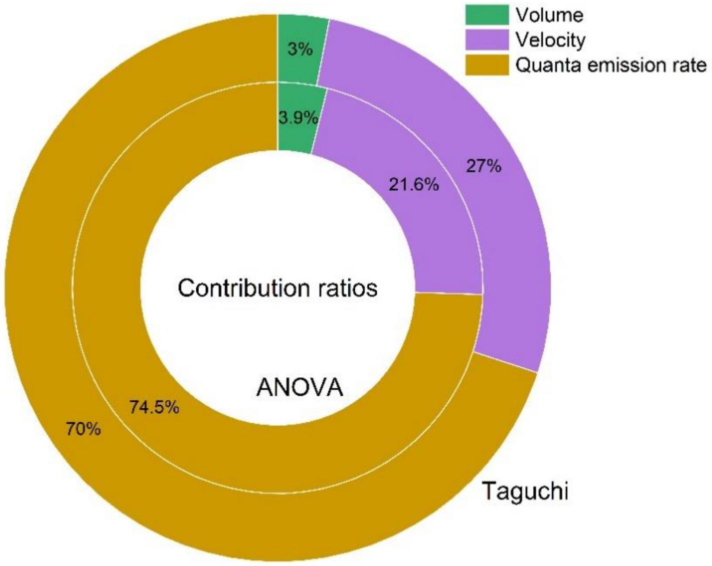


**Figure 2.** Comparison of contribution ratios of parameters obtained from Taguchi and ANOVA analysis.

## 3. Conclusion and Suggestions

In the study, the effects of different room volumes, inlet velocity, and the quanta emission rate on the infection risk probability calculated with the Wells-Riley equation were investigated by the Taguchi method. In the study, the best and worst-case scenarios were obtained, and the risk of infection was 1.46% in the best case and 45.23% in the worst case.

Among the parameters examined, the most effective parameter was found to be the quanta emission rate with an effect of 69.98%. Since this value changes depending on the person's activity (talking coughing, sneezing, etc.), it is possible to interpret that solutions such as the use of face masks will be effective in reducing the infection risk probability. The second important parameter is the inlet velocity. Ventilation is an important engineering solution that can reduce the risk of infection with its 27% contribution ratio. These values were also confirmed with ANOVA analysis with small differences. According to ANOVA analysis, the effect of the quanta emission rate is 71.51%, supply velocity is 20.76% and volume is 3.74% on infection risk.

It was seen that the room volume was the least effective parameter on the probability of infection risk and decreased the risk of infection (3%) with increasing values. This contribution rate is pretty low compared to others and this effect will be even smaller in real life, given that the room volume is a constant parameter and does not vary over a wide range of buildings. This situation can be interpreted as a positive output in the struggle against epidemics and allows to focus on other parameters that can be changed dynamically instead of fixed parameters such as room volume in buildings and can benefit the solution of the infection risk problem. In addition, these results carry studies that have volumetric differences on different room or space types, further than being a case study.

The limitations of this study rely on the limitations of the Wells-Riley method. Uniformity, the steady-state approach, neglecting gender and physiological differences are the main weaknesses of the model. This study can be improved in the future by coupling the CFD method and improving the equation with the help of the literature.

## Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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