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ANALYSIS OF THERMAL ENVIRONMENT INDICES AND AIR QUALITY INSIDE A WOODEN HISTORIC CHURCH IN WIŚNIOWA

Summary

The paper presents a computational analysis of the PMV, PPD and PD thermal environment indices for indoor air quality (IAQ) inside a historic wooden church in the village of Wiśniowa. The study is based on annual measurements of indoor air parameters as well as data on the number of Sunday Mass attendees and indoor air quality. As the results point out, indoor thermal comfort during the majority of Sunday Masses, both in summer and winter, remains within category C while the indoor air quality, assessed by means of PD index, levelled at 100%, irrespective of time of year. The improvement of inside air comfort and hygienic standards is possible by means of installing an effective mechanical ventilation system adapted for use in a historic building of high value in terms of local material culture.

Key words: thermal environment indices, indoor air quality, indoor thermal comfort

INTRODUCTION

In non-air-conditioned churches, thermal comfort of the occupied zone is influenced by indoor air parameters (temperature, humidity, velocity). According to Fanger [2003], the sole maintenance of optimal air temperature and relative humidity inside a room does not guarantee that its occupants will sense thermal comfort; indoor air quality (*IAQ*) is an equally important factor here. With dense crowding and lack of ventilation, which is the case during Masses in Wiśniowa's church, it is important to answer the question about air quality in the context of indoor environment hygiene. The index of usable floor area and cubic capacity, expressed by the value of usable floor area and cubic capacity per 1 person, as well as lack of suitable ventilation both during Masses and afterwards can both point to poor indoor air quality in the occupied zone. According to a number of church attendees, the local parson as well as the authors of this publication, indoor air quality during Masses is definitively poor. Nevertheless, the mentioned parameters of thermal comfort and hygienic safety of people participating in Sunday services in Wiśniowa's church, which is a valuable object of local material culture, cannot be the only criteria justifying the use of a heating and ventilation system. What should be also taken into account is the adverse impact of such a system on wood, valuable polychromies, sculptures, furnishing, etc. Moreover, the church needs to be heated, ventilated or air-conditioned only during services and religious celebrations.

The paper analyses the impact of indoor air parameters on thermal comfort of service attendees and evaluates air quality inside a wooden historic church in Wiśniowa (the Małopolska region), in the context of the users' comfort.

METHODOLOGY

The wooden church of Saint Martin in Wiśniowa was built around 1730. It is a log church covered with larch clapboards (Fig. 1). During Sunday Masses, people gather in the spacious nave – 300 m^2 of usable floor area, yet with a large number of service attendees, the occupied zone also includes roofed vestibules adjoining the nave, particularly the wide (32m^2) western vestibule. Each Sunday, 4 Masses are held at the following times: 6:30 am, 9:00 am, 11:00 am, and 5:00 pm (in winter) or 6:00 pm (in summer). Most people, approx. 400 local inhabitants, participate in the noon service (from 11:00 to 12:00), which gives about 0.83 m^2 per person and 7.5 m^3 per person.

Figure 1. The church of Saint Martin in Wiśniowa as viewed from the southeast. Photo: K. Wąs.

Indoor temperature, relative air humidity and dew-point temperature were measured with the help of four USB-502 sensors and one HOBO sensor, which was installed on a campanile situated in the direct vicinity of the church. The measurements were conducted from 1st January to 31st December 2008. The USB 502 sensors were located near the longitudinal church axis at the following heights: 0.3, 2.5, 4.0, 6.0 m above the floor. The data was registered every 5 minutes (USB 502) and every 10 minutes (HOBO). The number of Sunday Mass attendees was recorded as well.

Indoor air quality was evaluated with the help of a survey carried out among 50 adult participants of a winter Sunday Mass, which provided information about the number of smokers: about 24%; cosmetic users (perfumes, after shaves, etc.): almost 90%; as well as personal opinions about the quality of indoor air.

Since church windows are placed only in the southern wall (during Masses, these are usually closed or slightly opened in the summer), whilst the nave and the chancel are separated from the outside by closed vestibules, it can be assumed that air movement in the occupied zone was minimal and did not exceed 0.1 m s^{-1}.

Due to the character of the building, only the results of Sunday measurements were taken into consideration in the course of the study. Sensor breakdowns in February, August and September made it impossible to include these months' results into the analysis.

Evaluation of indoor air parameters was conducted on the basis of thermal environment indices, that is: Predicted Mean Vote (*PMV*) and Predicted Percentage Dissatisfied (*PPD*) calculated according to the PN EN ISO 7730 [2006] standard with the help of included computer application designed for calculating these indices (the application calculating thermal comfort indices attached to PN-ISO 7730 standard contains certain errors which were corrected in the course of calculations, in accordance with the *PMV* equation included in this standard).

PMV is expressed in a 7 degree scale, subjective scale of thermal comfort evaluation (fig. 2) suggested by Fanger's research group [2003]. The index is affected by indoor air temperature, air relative humidity, physical activity and clothing thermal insulation properties for people present in the room.

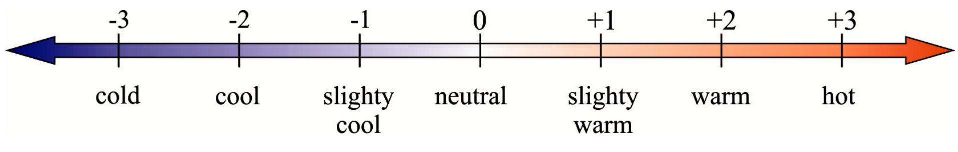

Figure 2. *PMV* assessment scale

Thermal comfort can be classified on the basis of *PMV* and *PPD* values. Table 1 presents a classification of indoor thermal environment categories, as by the PN EN ISO 7730 standard.

Table 1. Categories of thermal environment

Category	PMV	PPD, %
A	-0.2 < PMV < +0.2	< 5
B	-0.5 < PMV < +0.5	< 10
C	-0.7 < PMV < +0.7	< 15

Source PN EN ISO 7730 [2006]

Thermal comfort indices were calculated with the help of an arithmetic mean of temperatures measured at 0.3 m and 2.5 m above the church floor (with inconsiderable air velocities, vertical temperature distribution in the occupied zone is roughly linear).

Two values of physical activity were assumed for attendees of Sunday Masses: 1.2 met and 1.3 met (comparative limit value). These values refer to the rate of human metabolic activity of 69.84 $W \cdot m^{-2}$ and 75.66 $W \cdot m^{-2}$, relatively (sedentary activity, e.g., office, school).

Depending on time of year and outside temperature, the following clothing thermal insulation values have been assumed, based on applicable values from the PN EN ISO 7730 standard.

- 0.5 clo (underwear, short sleeve shirt, light trousers, light socks, shoes),
- 1.0 clo (underwear, shirt, trousers, socks, shoes),
- 1.5 clo (long leg and sleeve underwear, shirt, trousers, vest, jacket, coat, socks, shoes).

The PN EN ISO 7730 standard also defines optimal indoor air temperature parameters taking into consideration their influence on user's thermal comfort. For light physical activity, which includes participation in a Sunday Mass, the following relative air humidity values are recommended:

- for the heating season: 40 ÷ 50%, (min. 30%),
- for the cooling season 40 ÷ 55%, (max. 70%).

Optimal operative temperature and air velocity values for the activity of 70 $W \cdot m^{-2}$ and three categories of indoor thermal environment are presented in table 2.

Table 2. Design criteria for indoor air (activity 70 $W \cdot m^{-2}$)

Category of thermal envirnoment	Operative temperature °C		Maximum mean air velocity $m \cdot s^{-1}$	
	Summer (cooling season)	Winter (heating season)	Summer (cooling season)	Winter (heating season)
A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21

Source: PN EN ISO 7730 [2006]

RESULTS AND RESULT ANALYSIS

The distribution of indoor relative air humidity reveals that during church services relative air humidity usually remained at optimal levels. The minimum value was inconsiderably exceeded only in December with φ_i = 29% being recorded on 28 December 2008 at 8:00 pm. The number of measurements when relative air humidity during a Mass was lower than the minimum constitutes only 0.7% of the yearly data.

Maximum relative humidity value of φ_i = 81% was registered on 8th June 2008 at 7:00 am. Relative humidity values exceeding the optimum (70%) were generally recorded in June, July and August. Taking into consideration the total time when the church was occupied by people, these constituted 3.3% of all measurement results.

Air relative humidity during a Mass is mostly affected by people. More significant fluctuations caused by their presence occur in the winter season. The largest disparity between the maximum and minimum relative air humidity inside the church, which amounted to 23.9%, was noted in March, whilst the narrowest span of only 4.7% was registered in May.

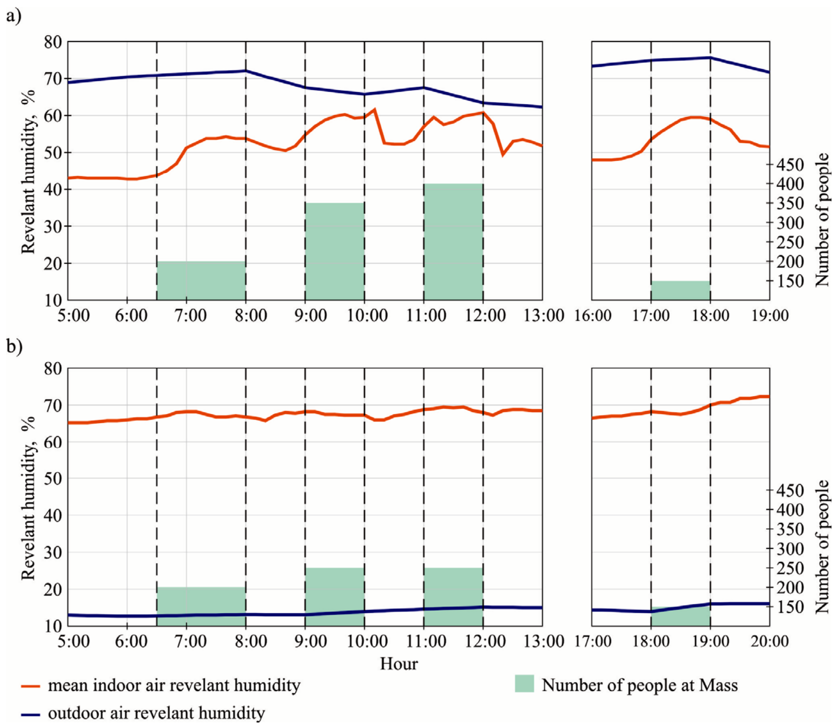

Figure 3. Relative air humidity distribution in the occupied zone and outside: a) 6th January 2008, b) 13th July 2008

Figure 3 illustrates an exemplary distribution of relative humidity fluctuations during church services and between them in the winter (6th January 2008) and the summer (13th July 2008) seasons. It reveals that even in the case of very low outside air relative humidity (13th July 2008), inside air humidity remained at a high level, which confirms high autonomy of the building with respect to humidity.

The highest average air temperature in the occupied zone of 26.5°C was recorded on 13th July 2008 at 12:30 pm, whilst the lowest, of 5.5°C, was registered on 17th February between 5:00 to 7:00 am. Minimal values were always noted at the beginning of the 6:00 am service, which can be explained by substantial cooling of the church interior. Throughout the investigated period, maximum daily outside air temperatures were registered around noon, just after the end of the 11:00 am Mass.

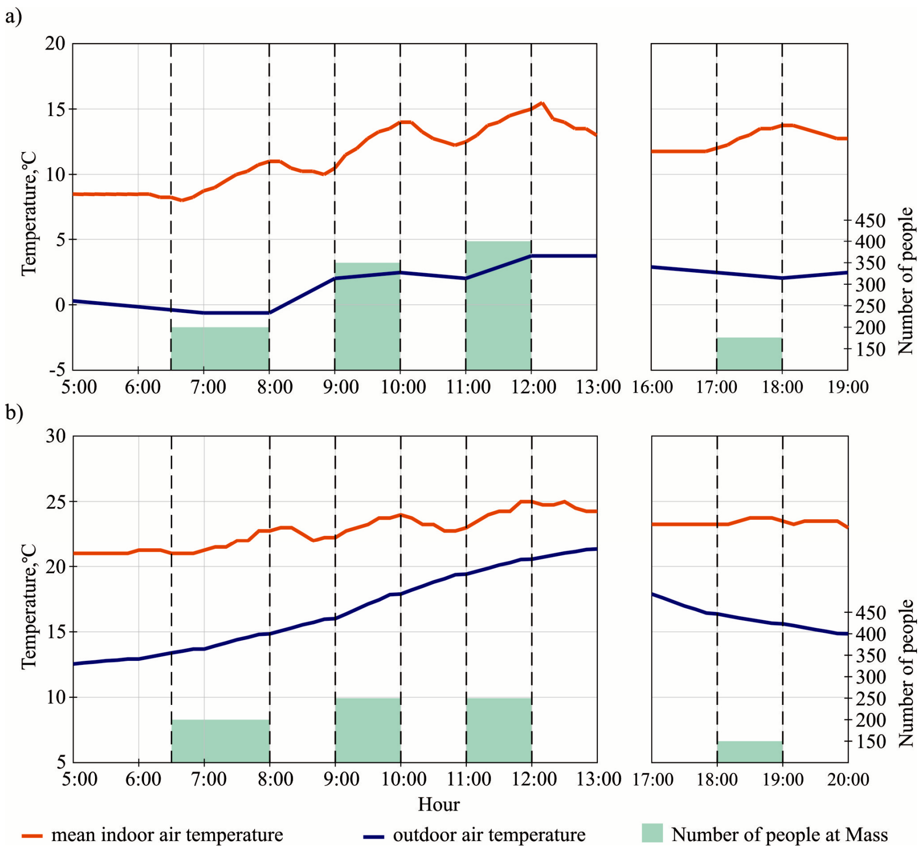

Figure 4. Temperature distribution in the occupied zone and the number of service attendees a) 6th January 2008, b) 13th July 2008

The analysis of results reveals that in the periods directly preceding and following Masses air temperature inside the church evidently decreased. This is related to a repeated procedure of opening entrance doors to the vestibules and nave whilst entering and leaving the building. In the course of the service, the temperature increased, frequently despite the decrease in outside temperature (fig. 4). The more people attended the church service, the more significantly the temperature increased.

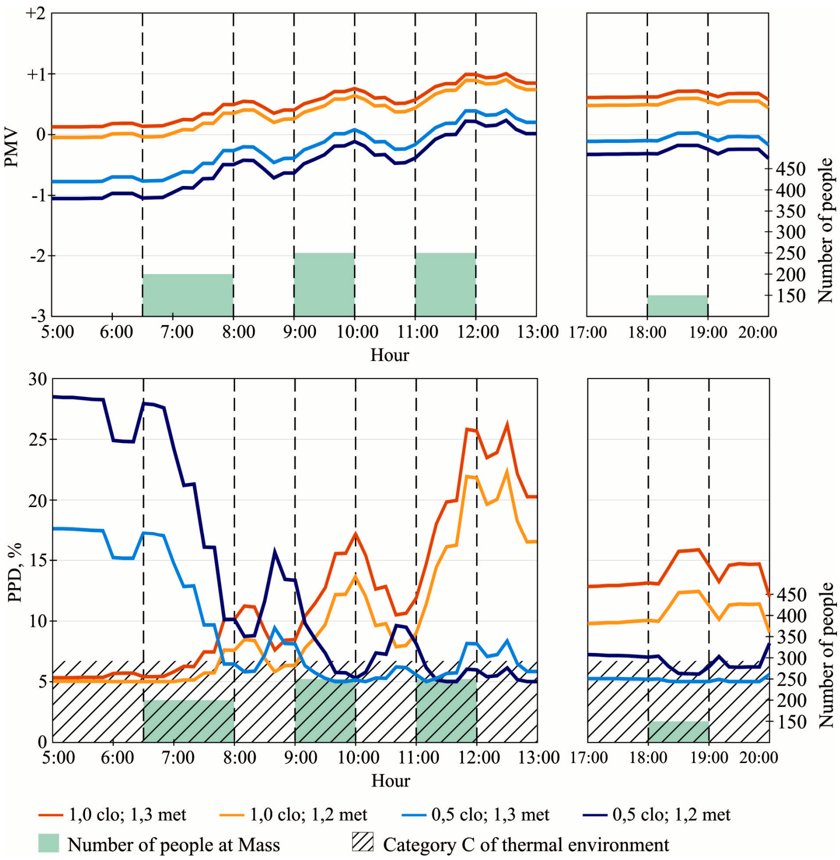

Figure 5. Predicted Mean Value and Predicted Percentage Dissatisfied for a Mass held on Sunday 13th July 2008

Similarly to relative humidity, most significant differences in inside air temperature, of approx. 7 K, were recorded with low outside temperature and high relative outside air humidity. Consequently, the smallest differences, of approx. 3 K, were recorded with high outside temperature and low relative outside air humidity.

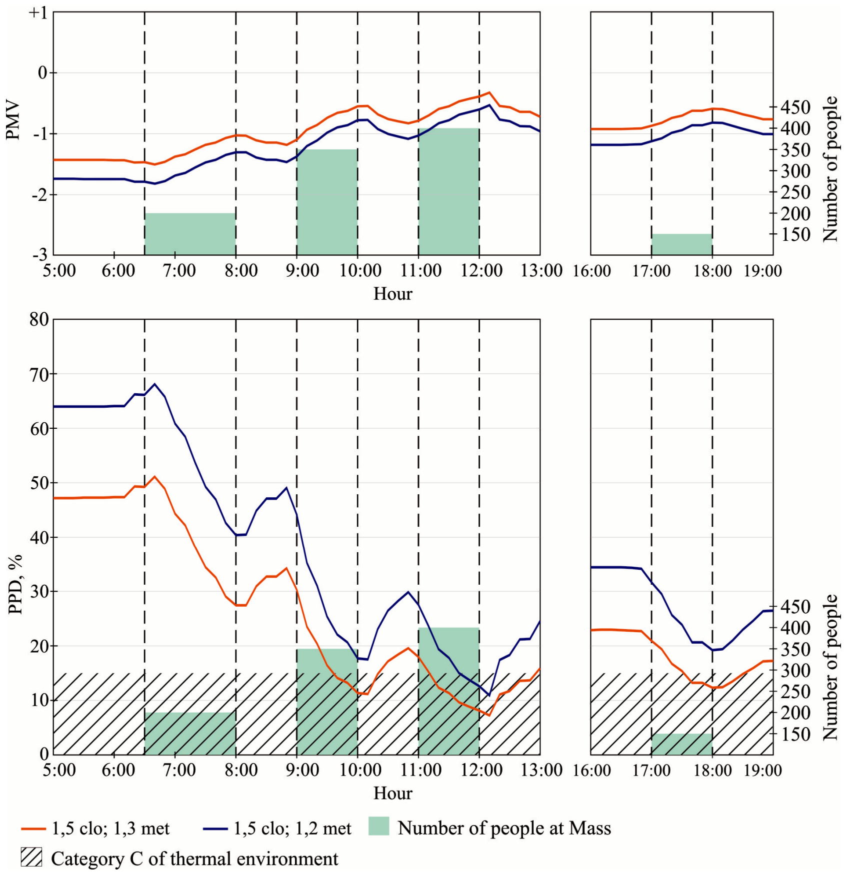

Figure 6. Predicted Mean Value and Predicted Percentage Dissatisfied for a Mass held on Sunday 6th January 2008

Based on conducted calculations, the influence of air velocity within the range defined by the PN EN ISO 7730 standard, and particularly velocities not exceeding 0.1 $m \cdot s^{-1}$, is negligible. Nevertheless, it needs to be noted that increased air velocity, especially at the floor level, could have occurred each time before the onset of service, when people were entering the church and the door to the nave was repeatedly opened. These could result in temperature decrease at the floor level and consequently significant momentary thermal discomfort caused by temporarily high air temperature gradient.

Based on obtained calculation results for the summer period, it can be concluded that temperature and humidity conditions inside the church of Wiśniowa were satisfactory. Assuming that insulation properties of human clothing differed depending on weather conditions, it can be maintained that the predicted mean value *PMV* would stay between -0.7 ÷ +0.7. Only during the morning service, people could evaluate inside temperature as "slightly low". At that time, the percentage of dissatisfied, apart from an insignificant number of cases, did not exceed 15% (*PPD* ≤ 15%). This means that in the summer period, the church can be classified as C category, which is a satisfactory result for a building not designed for permanent human residence.

In the transitory and winter period, even with the assumption of highest physical activity (1.3 met), thermal comfort assessment varied between "cool" and "slightly cool". The conducted analysis reveals that in marginal cases, particularly during morning services, *PMV* value could reach as low as -1.81 (thermal insulation of clothing 1.5 clo, activity 1.2 met). This means that thermal comfort assessments approximated to the "cool" level and the predicted percentage dissatisfied grew to over 86% (Fig. 6). Notably, outside temperatures did not fall below –3°C throughout the period under analysis. With colder winters, *PMV* values may turn out even less favourable. Therefore for the winter and transitory periods, the greatest number of temperature assessments lay beyond the categories of inside thermal comfort as defined by the PN EN ISO 7730 standard (in most cases, *PPD* exceeded 15%).

Irrespective of time of year, the feeling of thermal comfort in Wiśniowa's church increased gradually in the course of the morning service, through subsequent services until the last one at 17:00. Already during the noon Mass, the majority of attendees could evaluate thermal comfort as satisfactory. This was due to a significant growth of indoor temperature during successive services.

Indoor air quality involves the entirety of non-thermal parameters of this air which affect human well-being and health. The quality of air is experienced through the sense of smell. Not only does this depend upon chemical composition of inhaled air, but also on its temperature and humidity, conjoined in enthalpy [Fanger et al. 2003].

The quality of indoor air is measured by the percentage of dissatisfied PPD. A person is regarded as dissatisfied if upon entering the church he or she evaluates indoor air to be unacceptable. The *PD* tolerable limit value for air quality equals 20% [Recknagel et al., 2008].

It is generally believed that people are the main emitters of indoor olfactory pollution. However, in the case of churches another such source is construction materials (wood moisture, wood-decay fungi) as well as burning candles or frankincense. The total load of pollution as sensed by service attendees can be approximately a sum of pollution from various sources. Regular monthly visits to the church held on weekdays made the authors realize that the specific smell, emitted by wooden walls, furniture and tapestries, can be felt even when the building is empty. The smell acts as a strong background for pollution emitted by people and smoke produced by candles, frankincense and dust.

In the case of the church in Wiśniowa (taking into consideration wood saturation with smells, the building was classified as a strong pollution structure: 0.2 olf·m^{-2}) [Recknagel et al., 2008], the average load of pollution experienced by service attendees would amount to 1.03 olf·m^{-2}, assuming that all of them were non-smokers. Taking into account the influence of smokers (approx. 24%), the value will reach approx. 1.86 olf·m^{-2}. The percentage of people dissatisfied with air quality was measured with the help of a suitable *PD* equation [Fanger et al., 2003] with no mechanical ventilation, closed windows and doors. The result was 100% – irrespective whether smokers were taken into consideration or not. Individual air load with pollution was approx. 186 decipol·m^{-2}. Thus, Wiśniowa's church indoor air quality poses a serious threat to human health. Based on the results of a conducted survey, the percentage of dissatisfied was lower by approx. 30% than what the calculations yield. The difference can be explained by the fact that people usually stayed in the church for a relatively short time, approx. 1 hour. They did not have high expectations as to air quality inside (the majority of Wiśniowa's inhabitants work in agricultural production) and were rather focussed on service proceedings than evaluating the quality of indoor air. There is, nevertheless, a certain group of people who, due to poor indoor air quality, participate in the ceremonies standing in the vestibules (in winter) or outside (in warmer seasons of the year).

CONCLUSION

In small wooden churches, the changes of indoor air temperature are generated by both the flux of heat emitted by people and the outside temperature, especially as people enter and leave the building.

The feeling of thermal conditions inside the church of Wiśniowa during most seasons of the year can be defined as "slightly cool", irrespective of clothing thermal insulation and activity of service attendees. That is why church heating would be recommended only in winter during the morning Mass.

Thermal comfort and indoor air quality should be considered simultaneously. Definitely poor indoor air quality turns out to be the most significant problem of Wiśniowa's church. Thermal comfort of service attendees and their sanitary safety could be most positively improved with a system of mechanical ventilation, which in the case of the church in Wiśniowa would be a relevant answer to the growing number of high social expectations regarding air quality. Due to the specific character of a historic building, it is necessary to conduct an analysis of technological and organizational solutions that would be approved by the proper monument conservator and would ensure the provision of fresh air in suitable volumes and with accurate parameters.

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