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Assessment of Simultaneous Heating Demands for Consumer Groups

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Abstract

The paper presents the determination of the simultaneity factor in district heating systems based on the simultaneous heat demand level of a group of consumers. The simultaneity factor is formed on a probability theory basis, involving a prescribed risk. The simultaneity factor is a ratio that indicates the proportion of the aggregated nominal heat demand of consumers that occurs at a specific time. As known, the simultaneity factor is less than one. Knowledge of the simultaneity factor allows us to uncover performance reserve capacity in a district heating system. This way, there are often opportunities for expanding district heating systems, connecting new consumers, and improving the economic efficiency of operation.

Keywords

simultaneous factory, district heating, consumers, distribution

1 Introduction

Approximately 67 million people in Europe live in homes which form part of district heating systems [1]. Central and Eastern Europe have relied on district heating for over a century. These systems typically burn fossil fuels – predominantly natural gas and coal – and operate at higher temperatures. Unfortunately, the region continues to be slow in taking advantage of technologies such as industrial-scale heat pumps, solar heating, and thermal energy storage. Furthermore, most of the region's district heating systems still operate at high temperatures, which are incompatible with these renewable heating technologies [2]. However, there is a renewable heating technology – geothermal power – which has significant potential to be widely deployed in the region, even within existing high-temperature systems. One of the areas with the greatest potential for deep geothermal heating is the Pannonian Basin. In Szeged, a city in southern Hungary with around 162 000 residents, one of Europe's largest district heating projects is underway [3]. The project involves transitioning from a natural gas-based system to a geothermal-powered one. European district heating systems represent an environmentally friendly approach, as 43.1% of total consumption is based on renewable energy sources.

Modern district heating and cooling systems are commonly designed and operated using mathematical modelling [4, 5], measurements [6, 7], and optimization methods. The combined application of these principles and tools enables designers and engineers to create efficient, energy-effective, and optimized systems that minimize pollutant emissions while maximizing energy efficiency.

In our research, the concept and application of the simultaneity factor, which represent the main research objective and are discussed on a probability theory basis, are not yet widespread, and the literature available in this field has been scarce. Within the framework of ASHRAE RP-1093, "diversity factors" have been developed to create various individual load profiles based on measured data, to be applicable in energy simulations.

The aim of the research [8] is to compile a library of schedules and diversity factors for energy and cooling load calculations in various indoor office environments in

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the United States and Europe. Two sets of diversity factors were developed: one for peak cooling load calculations and another for general cooling load calculations. Similar to Zhou et al. [9], the goal of this research is to enhance the efficiency of centralized HVAC systems by using the Gini coefficient to identify variations in load curves among different zones. The load function examines how load requirements are distributed across zones and change over time, impacting energy consumption and system efficiency. Describing load characteristics is conventionally challenging, but this paper employs the Lorenz curve and the Gini index to investigate and reveal their effects on HVAC systems. Various Gini indices, associated with different load characteristics, are compared to highlight their impact on supply, distribution, and adjustment processes. A higher Gini index indicates uneven load distribution, which can lead to oversupply, power losses, transient dissipation, and reduced heating/cooling source efficiency. Following the same principle, Winter et al. [10, 11] determined a 'simultaneity factor' for comparing district peak loads and the aggregated individual building peak loads in two district heating systems comprising a total of 558 buildings in Austria. They also developed a formula for estimating simultaneity based on the number of buildings in the district, examining the simultaneity behavior depending on the number of customers served. This simultaneity factor provides a fundamental basis for sizing heat distribution networks and heat production systems for small to medium-sized local heating systems. A mathematical approach was developed for the nPro tool [12], enabling the conversion of diversity-free annual profiles into annual profiles with a specified diversity factor. With this transformation, the maximum power demand in the demand profile decreases according to the determined diversity factor, while the total annual demand (the area under the annual profile) remains unchanged. This is a necessary condition, as considering diversity does not lead to changes in total demand but only to a reduction in peak load. Neglecting diversity in district heating networks could result in oversizing production capacities at the energy center. They [13–17] empirically formed a probability factor, but a probabilistic approach is not mentioned or proven.

2 Materials and methods

It is known that when multiple consumers are present in a district heating system, the combined simultaneous heat demand to be satisfied from the heat source is less than the sum of the individual nominal heat demands of consumers. The simultaneity factor describes/expresses this phenomenon. Heating demands are also probabilistic variables typically exhibiting a normal distribution with an expected value and variance, as introduced in our papers [18–20].

The design heat demand of each consumer is related to a prescribed level of risk. In a probability theory sense, the simultaneity factor is defined as follows: if the heat demand of (n) individual consumers is given in the form of normal distributions with known expected values (m) and variances (σ), then our task is to determine the combined prescribed heat demand as

$$\dot{Q}_h = \dot{Q}_{1,h} + \dot{Q}_{2,h} + \ldots + \dot{Q}_{n,h}. \tag{1}$$

Assuming that $\dot{Q}_{1,h}$, $\dot{Q}_{2,h}$, ..., $\dot{Q}_{n,h}$ are all normal distribution values, the next is to consider the standardized normal distribution variables formed from these:

$$\xi_1 = \frac{\dot{Q}_{1,h} - m_{1,h}}{\sigma_{1,h}}, \xi_2 = \frac{\dot{Q}_{2,h} - m_{2,h}}{\sigma_{2,h}}, \ldots, \\ \xi_n = \frac{\dot{Q}_{n,h} - m_{n,h}}{\sigma_{n,h}}, \tag{2}$$

where $m_{i,h}$ is the expected value of one consumer's heating demand, $\sigma_{i,h}$ is the variance of one consumer's heating demand.

From these expressions, the values of consumer heat demands $\dot{Q}_{1,h}$, $\dot{Q}_{2,h}$, ..., $\dot{Q}_{n,h}$ can be considered as the prescribed values of random variables.

$$\dot{Q}_{m\rightleftarrows 1,h} = m_{1,h} + \xi_1\sigma_{1,h}, \dot{Q}_{m2,h} = m_{2,h} + \xi_2\sigma_{2,h},.. \\ \ldots, \dot{Q}_{mn,h} = m_{n,h} + \xi_n\sigma_{n,h}. \tag{3}$$

Let it be $\xi_1 \equiv \xi_2 \equiv ... \equiv \xi_n \equiv \xi$.

Utilizing the correlations

$$m = m_1 + m_2 + \ldots + m_n, \tag{4}$$

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2, \tag{5}$$

in case of n consumers, the following can be stated for calculating simultaneous heat demand at a given reliability level:

$$\dot{Q}_{m,h} = \left(m_{1,h} + m_{2,h} + \ldots + m_{n,h}\right) \\ +\xi \cdot \left(\sqrt{\sigma_{1,h}^2 + \sigma_{2,h}^2 + \ldots + \sigma_{n,h}^2}\right). \tag{6}$$

Heat demand at a reliability level of 99%

$$\dot{Q}_{m,h} = \left(m_{1,h} + m_{2,h} + \ldots + m_{n,h}\right) \\ +2.33 \cdot \left(\sqrt{\sigma_{1,h}^2 + \sigma_{2,h}^2 + \ldots + \sigma_{n,h}^2}\right). \tag{7}$$

The simultaneity factor is to be defined as the ratio of the heat demand obtained by the simple summation of individual indicative heat demands as determined by Eq. (6):

$$e = \frac{\dot{Q}_{m,h}}{\sum_{i=1}^{n} \dot{Q}_{m,i,h}} = \frac{\sum_{i=1}^{n} m_{i,h} + \xi \cdot \sqrt{\sum_{i=1}^{n} \sigma_{i,h}^2}}{\sum_{i=1}^{n} \left(m_{i,h} + \xi \cdot \sigma_{i,h} \right)}. \tag{8}$$

Let the consumers be identical and let us examine how the simultaneity factor evolves if $n \to \infty$.

From expression Eq. (8), as

$$m_{1,h} = m_{2,h} = \ldots = m_{h,n} = m_h \tag{9}$$

$$\lim_{n\to\infty} e = \frac{n\, m_h + \xi \sqrt{n} \sigma_h}{n\left(m_h + \xi \sigma_h \right)} = \frac{m_h}{m_h + \xi \sigma_h} + \frac{\xi \sigma_i}{\sqrt{n} \left(m_h + \xi \sigma_h \right)} = \frac{m_h}{m_h + \xi \sigma_h}. \tag{10}$$

Eq. (10) clearly illustrates that if the number of consumers is very large, theoretically as it approaches infinity, the limit of the simultaneity factor is the ratio of one consumer's expected value to one consumer's prescribed value.

3 Evolution of the simultaneity factor with the inclusion of a standard consumer intake, as a function of the value and variance of consumer heat demand

Let us assume that we know the heating demand of an apartment ($\dot{Q}_1$) with its expected value (a_1) and standard deviation (σ_1) being known.

$$a_1 = 5000 [W], \tag{11}$$

$$\sigma_1 = 250 [W]. \tag{12}$$

Let us determine the simultaneity factor to be calculated when there are 100, 500, 1000, and 10 000 apartments characterized by the above data, respectively.

To solve this, the standardized normal distribution of the heat demand is to be used, where the probability variable is

$$\xi = \frac{\dot{Q} - a}{\sigma}, \text{ and from this } \dot{Q} = a + \xi \cdot \sigma. \tag{13}$$

The level of supply security is to be determined by setting the probability of ξ to be 95% and 99%.

$$P(\xi) = 0.95, \quad P(\xi) = 0.99. \tag{14}$$

In this case, the value of the probability variable for standardized normal distribution is:

$$\xi = 1.645 \quad \text{and} \quad \xi = 2.33 \tag{15}$$

It is known that for several normally distributed probability variables

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2 \quad \text{and} \quad a = a_1 + a_2 + \ldots + a_n. \tag{16}$$

Thus, for n identical apartments

$$\sigma^2 = n \cdot \sigma_1^2 \quad \text{and} \quad a = n \cdot a_1, \tag{17}$$

From which the prescribed heat demand of n apartments

$$\dot{Q}_m = n \cdot a_1 + \xi \cdot \sqrt{n} \cdot \sigma_1. \tag{18}$$

In our case, the simultaneity factor (e) can be expressed as

$$e = \frac{\dot{Q}_m}{n \cdot \dot{Q}_1}. \tag{19}$$

Substituting the above expressions for $\dot{Q}_m$ and $\dot{Q}_1$ into this and inserting the numerical values for n = 100 and P(ξ) = 0.95, will result in:

$$e = \frac{n \cdot a_1 + \xi \cdot \sqrt{n} \cdot \sigma_1}{n \cdot \left(a_1 + \xi \cdot \sigma_1 \right)} = \frac{100 \cdot 5000W + 1.645 \cdot \sqrt{100} \cdot 250W}{100 \cdot \left(5000W + 1.645 \cdot 250W \right)} = 0.9316. \tag{20}$$

Substituting the further values of n, following values will be obtained:

$$e_{n=500} = 0.9274, \tag{21}$$

$$e_{n=1000} = 0.9264, \tag{22}$$

$$e_{n=10000} = 0.9248. \tag{23}$$

If its value is examined at the limit transition as $n \to \infty$, then the resulting value will be

$$\lim_{n\to\infty} e = \frac{a_1}{a_1 + \xi \cdot \sigma_1} = \frac{5000W}{5000W + 1.645 \cdot 250W} = 0.924. \tag{24}$$

The simultaneity factor is presented as a function of n in Fig. 1.

By calculating the simultaneity factors for the case $P(\xi) = 0.99$ and examining how these values change with a standard deviation $\sigma = 500$ W, the summarized results presented in Table 1 below will be yielded.

Evolution of the simultaneity factor is shown in Figs. 2–5 as a function of the standard deviation, reliability level, and the number of apartments.

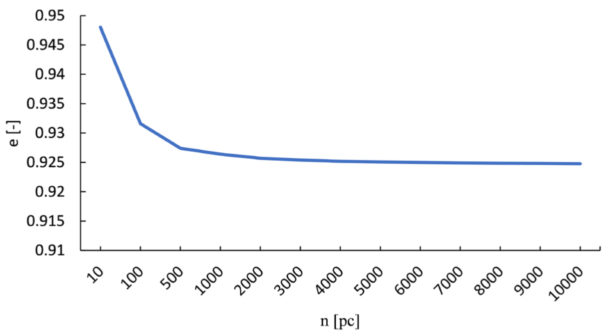

Fig. 1 Evolution of the simultaneity factor as a function of the number of apartments for a = 5000 W and σ = 250 W

Table 1 Correlations for heat transfer coefficient

	$P(\xi) = 0.95$		$P(\xi) = 0.99$	
	σ_1 = 250 W	σ = 500W	σ_1 = 250 W	$\sigma 1$ = 500 W
n =100	0.9316	0.8729	0.9061	0.8299
n = 500	0.9274	0.8651	0.9003	0.8195
n = 1000	0.9264	0.8632	0.8990	0.8170
n = 10 000	0.9248	0.8602	0.8967	0.8129
$n \to \infty$	0.9240	0.8587	0.8957	0.8110

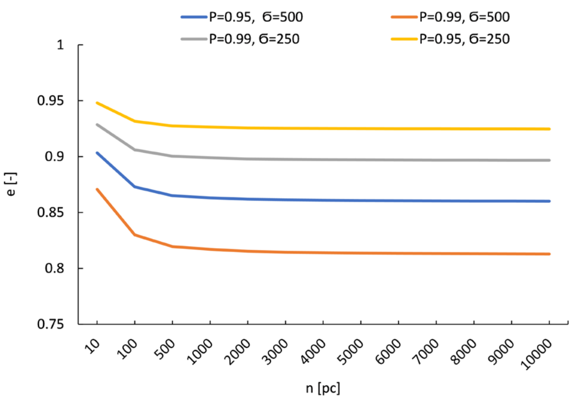

Fig. 2 Evolution of the simultaneity factor as a function of the number of apartments at various reliability levels for different standard deviations

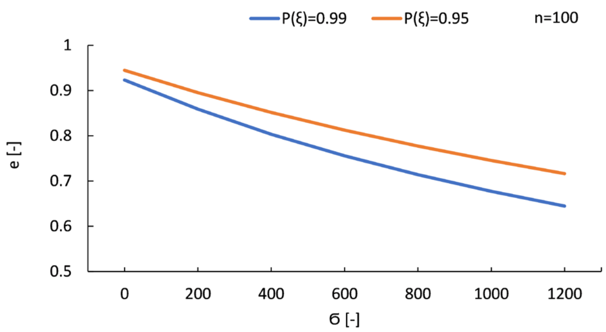

Fig. 3 Evolution of the simultaneity factor as a function of the standard deviation at various reliability levels for n = 100 apartments

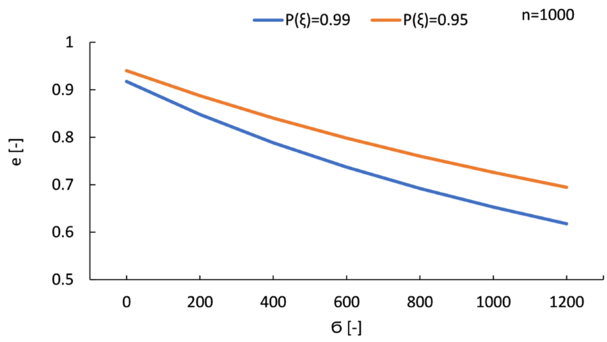

Fig. 4 Evolution of the simultaneity factor as a function of the standard deviation at various reliability levels for n = 1000 apartments

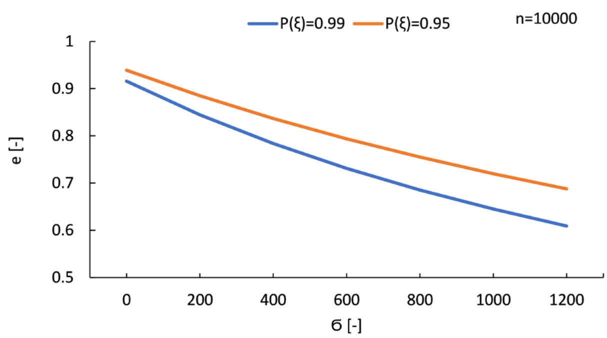

Fig. 5 Evolution of the simultaneity factor as a function of the standard deviation at various reliability levels for n = 10 000 apartments

4 Conclusions

In our research, we have demonstrated that the simultaneity factor is a random variable, derived from uncertainties in consumers' heat demands. These uncertainties are described probabilistically by the density function, the probability distribution function, and the moments of these functions, including the standard deviation and the expected value. We assigned reliability levels to heat demands and determined indicative values. By evaluating the rate values for each consumer, we established the resultant indicative value for the entire consumer group. Ideally, the reliability level is consistently applied to both individual consumers and the entire consumer group. The simultaneity factor is calculated as the quotient of the resultant standard value and the summed nominal value. In our thesis, the expected value and standard deviation of a standard consumer's heat demand were considered as key parameters. It was illustrated in diagrams how the simultaneity factor varies with the number of apartments, based on these parameters. The usefulness of the simultaneity factor is particularly evident when a consumer, especially a standard consumer, exhibits significant uncertainty in their heat demand, i.e., a large variance. In such cases, the district heating system can be significantly expanded with minimal risk, facilitating the identification of supply reserves within the system.

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