A comparison between the fixture unit approach and Monte Carlo simulation for designing water distribution systems in high-rise buildings

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Abstract

The fixture unit approach with an arbitrarily assumed reference flow rate is commonly used for the estimation of probable maximum simultaneous demand in many building water systems. This study evaluates such estimations for some high-rise buildings in terms of various reference flow rates. The estimation accuracies are analysed against Monte Carlo simulations with which no reference flow rate is assumed. The results reveal that the traditionally assumed reference flow rate (10 ℓ·s^{-1}) for demand analysis should be increased to 250 ℓ·s^{-1} for high-rise water systems in a dense built environment similar to Hong Kong.

Keywords: Demand analysis, water supply system, fixture unit approach, reference flow rate

Introduction

Demand overload is legitimate in some water plants and piping systems provided that its occurrence is very unlikely and a small failure probability corresponding to the theoretical maximum demand is allowed (Hassanein and Khalifa, 2006; Oliveira et al., 2009). To evaluate the probable maximum simultaneous demand problems in building water supply systems, the fixture unit approach is a simple and standard method to use. The approach is based on the fact that a simultaneous reference flow rate can be produced from different numbers of identical appliances characterised by their respective operating flow rates and operating probabilities (Plumbing Services Design Guide, 2002; Wise and Swaffield, 2002). The traditional reference flow rate of 10 ℓ·s^{-1} in the fixture unit approach was reported without significant problems in small-scale water supply systems, but water supply at an unsatisfactory low flow rate during peak demand periods was reported in some high-rise buildings (Mui et al., 2008; Wong and Liu, 2008). An underestimated simultaneous probable maximum demand resulted in excessive pressure variations in high-rise drainage stacks (Cheng et al., 2010). While the appliance characteristics are practically measured and updated in accordance with the local context, the choice of the reference flow rate, which is arbitrarily decided (and details of its sensitivity to the simultaneous demand variability are missing, particularly for dense built environment), is based on an assumption that needs to be examined for validity.

As Monte Carlo simulation can be employed to determine the system failure probability density function, this is another technique for instant water demand assessment (Courtney, 1972). For high-rise water systems, a stochastic model was developed on this basis, to acquire modelling parameters without the assumption of a reference flow rate (Wong and Mui, 2008). In this study, the variability of probable maximum simultaneous demands in water supply installations due to different choices of reference flow rate was investigated. Demands estimated via the fixture unit approach were compared with the Monte Carlo simulation results computed by the stochastic model. Appropriate alternatives regarding water supply systems in high-rise buildings were then discussed, and reference flow rates for demand analysis of high-rise water systems in a dense built environment similar to Hong Kong were recommended.

Simultaneous demand and fixture unit approach

In a water supply system, simultaneous operation for a group of appliances of the same type can be evaluated using the probabilistic approach (Hunter, 1940). During the repeat cycle operation, the operating probability of an appliance p at any time with a mean operating period τ_d (s) and a mean time interval between the start time of 2 consecutive operations τ_w (s) is:

$$p = \frac{\tau_d}{\tau_w} \qquad (1)$$

Assuming the appliance operations are binomially distributed, the probability p of N out of M (where M is the total count) identical appliances operating together in the system, ${}_M p_N$, is given by the following, where $(1-p)$ is the probability of appliances not in use and C_N^M is the binomial coefficient:

$${}_M p_N = C_N^M p^N (1-p)^{M-N}\ ;\ C_N^M = \frac{M!}{N!\,(M-N)!} \qquad (2)$$

Presently, some water plants and piping systems are designed to allow a number of N (out of M; e.g. M>30) appliances to operate simultaneously for a maximum acceptable risk of failure, in order to minimise water supply system costs. They might be 'overloaded' when serving all of the M appliances concurrently at the theoretical maximum simultaneous flow rate. Regarding the acceptable level of system performance in terms

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of reliability, an unsatisfactory engineering state happens if more than N appliances are in use. The failure rate λ (i.e. occurrence of 'failure' as a percentage of time during peak demand periods) is determined by the sum of probabilities while this state takes place:

$$\lambda = p(N+1) + p(N+2) + ... + p(M-1) + p(M) = \sum_{i=N+1}^{M} p_i; \quad N < M \tag{3}$$

The selection of an acceptable failure rate is based on professional judgment, with or without verification (Mui et al., 2008). The probable number N (i.e. the number of appliances in simultaneous operation), approximated by the Sterling's formula for an 'engineeringly acceptable' limiting failure rate λ = 1% (recommended in some designs), can be expressed with z = 1.82255 as follows (Wong and Mui, 2007):

$$N = Mp + z\sqrt{2Mp(1-p)} \tag{4}$$

The corresponding probable maximum simultaneous demand q_d ($\ell \cdot s^{-1}$) for an installation of M appliances can then be calculated via Eq. (5), where q ($\ell \cdot s^{-1}$) is the operating flow rate of an appliance:

$$q_d = Nq = q\left[Mp + z\sqrt{2Mp(1-p)}\right] \tag{5}$$

Using the fixture unit approach, Eq. (5) can also be employed to determine the design operating flow rate for an installation with two or more appliance types. In this study, a reference simultaneous flow rate q_{ref}($\ell \cdot s^{-1}$), e.g. 10 $\ell \cdot s^{-1}$, was produced from a number of base case appliances A_b with their respective usage characteristics. The level of q_{ref} was professionally estimated and its sensitivity to the probable maximum simultaneous demand was evaluated.

Each appliance A_i is defined by 2 characteristics, namely, the operating probability p_i and operating flow rate q_i, i.e. $A_i(p_i,q_i)$. Since q_{ref} ($\ell \cdot s^{-1}$) applies to both an installation of M_i number of A_i and an installation of M_b number of A_b, by taking the fixture unit of A_b as U_b = 1, the fixture unit U_i for A_i is:

$$U_i = \left.\frac{M_i}{M_b}\right|_{q_{ref}} \tag{6}$$

Figure 1 illustrates the notion of using the characteristics of a base case appliance $A_b(p_b,q_b)$ to approximate those of an appliance A_i with $A_i(p_i = 2p_b, q_i = q_b)$ or $A_i(p_i = p_b, q_i = 2q_b)$. Ideally, 2 base case appliances should not be simultaneously discharging or discharging exactly in phase in order to achieve the absolute approximation as shown in Fig. 1(ii). Probable cases where a number of base case appliances discharge in random patterns are not excluded in the fixture unit approach and additional occurrence information is needed to eliminate them via mathematical treatment. These non-ideal approximations are exhibited in Fig. 1(iii). Indeed, the existing fixture unit approach depends not only on the appliance attributes p_i and q_i, but also on the choice of q_{ref}.

Results and discussions

The characteristics of a base case appliance $A_b(p_b,q_b)$~[0.0282, 0.15] with the corresponding base case fixture unit U_b = 1 at a reference flow rate q_{ref} = 10 $\ell \cdot s^{-1}$, as stated in an existing design guide, were employed for the use of discussion (Wise and Swaffield, 2002; Galowin, 2008). In order that influences of the q_{ref} choice on the sensitivity of the fixture units could be fully demonstrated, operating probabilities and operating flow

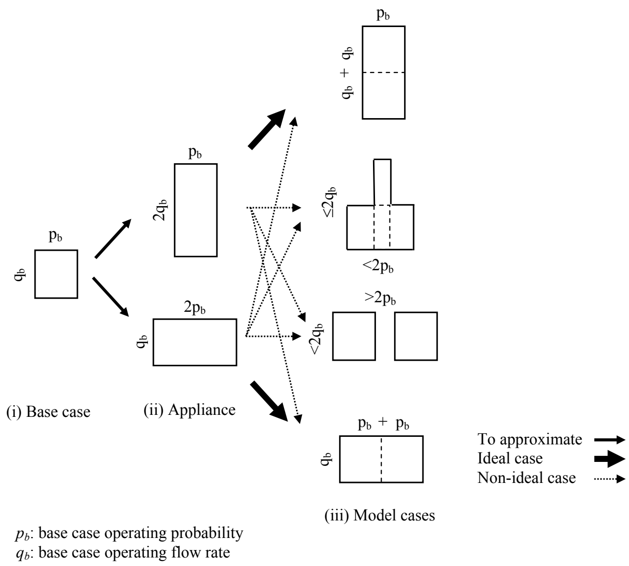

Figure 1
Models of appliance $A_i(p_i,q_i)$ using a base case appliance $A_b(p_b,q_b)$

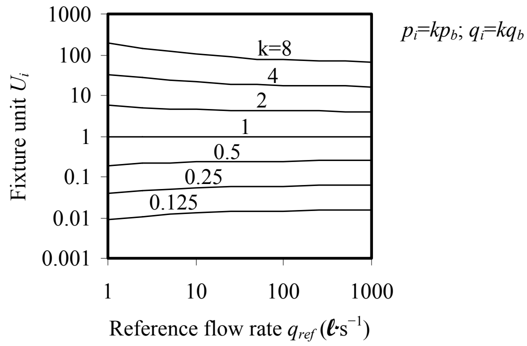

Figure 2
Fixture units in reference to a base case appliance $A_b(p_b,q_b)$~[0.0282, 0.15]

rates ranging from 0.125 to 8 times the base case attributes were considered, i.e. $A_i = A_i(p_i,q_i)$, where $p_i = kp_b$, $q_i = kq_b$ and k∈[0.125, 8].

Figure 2 shows the fixture units U_i of A_i with reference to A_b in the q_{ref} range between 1 $\ell \cdot s^{-1}$ and 1 000 $\ell \cdot s^{-1}$. It was noted that a unity fixture unit U_b was defined for all q_{ref}. For k = 0.125, 0.25, 0.5, 1, 2, 4 and 8, U_i were 0.009, 0.04, 0.193, 1, 5.6, 33 and 200 at q_{ref} = 1 $\ell \cdot s^{-1}$; 0.013, 0.054, 0.229, 1, 4.5, 21 and 101 at q_{ref} = 10 $\ell \cdot s^{-1}$; and 0.015, 0.06, 0.243, 1, 4.2, 18 and 74 at q_{ref} = 100 $\ell \cdot s^{-1}$, respectively. The reference flow rate choice was found to have some influences on the fixture unit values.

The fixture unit ratio $\phi_{i,q_{ref}}$ indicates the variation in U_i at a selected reference flow rate q_{ref} as compared with the base case q_{ref} = 10 $\ell \cdot s^{-1}$:

$$\phi_{i,q_{ref}} = \frac{U_{i,q_{ref}}}{U_{i,10}} \tag{7}$$

For k = 0.125, 0.25, 0.5, 1, 2, 4 and 8 times the base case attributes, $\phi_{i,q_{ref}=1}$ = 0.67, 0.74, 0.84, 1, 1.24, 1.57, 1.98 at q_{ref} = 1 $\ell \cdot s^{-1}$, and $\phi_{i,q_{ref}=100}$ = 1.14, 1.11, 1.06, 1, 0.92, 0.83, 0.74 at q_{ref} = 100 $\ell \cdot s^{-1}$, respectively. In the ideal case, $\phi_{i,q_{ref}}$ is very close to unity over a range of q_{ref} to which the fixture unit values are not sensitive. Apparently, the choice of a smaller reference flow rate, e.g. q_{ref} = 1 $\ell \cdot s^{-1}$, resulted in a larger variation of ϕ_i.

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Figure 3 exhibits the fixture unit ratios ϕ_i for appliances $A_i = A_i(p_i, q_i)$, where $p_i = kp_b$, $q_i = kq_b$ and k∈[0.125, 8]. Fixture unit ratios determined from the results presented in Fig. 2 are illustrated in Fig. 3(a). Once again, a smaller variation of ϕ_i was found when a larger reference flow rate was selected (e.g. $q_{ref} \geq 100$ ℓ·s^{-1}).

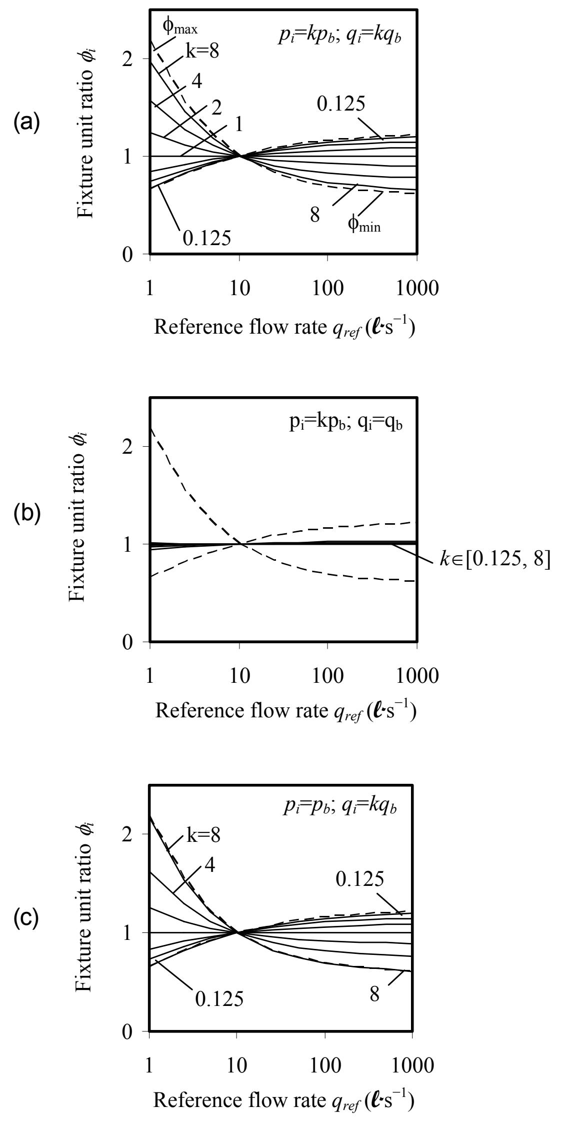

Figure 3
Fixture unit ratios ϕ_i for appliances $A_i(kp_b, kq_b)$, k∈[0.125, 8]

For an appliance running at the base case operating flow rate, i.e. $q_i = q_b$, ϕ_i was less sensitive to the operating probability $p_i = kp_b$. This finding is shown in Fig. 3(b) and the corresponding range of ϕ_i was from 0.94 to 1.03. For an appliance running under the base case operating probability such that $p_i = p_b$, on the contrary, ϕ_i was sensitive to the operating flow rate $q_i = kq_b$. Figure 3(c) displays the corresponding ϕ_i ranges: ϕ_i = 0.67 to 2.17 at q_{ref} = 1 ℓ·s^{-1}; ϕ_i = 0.69 to 1.15 at q_{ref} = 100 ℓ·s^{-1}; and ϕ_i = 0.61 to 1.20 at q_{ref} = 1 000 ℓ·s^{-1}.

The fixture unit ratios were further evaluated in 2 conditions expressed by:

$$\phi_{i,q} = \frac{U_{i,q_i}}{U_{i,q_b}} \quad (8)$$

$$\phi_{i,p} = \frac{U_{i,p_i}}{U_{i,p_b}} \quad (9)$$

where $\phi_{i,q}$ is the ratio of an appliance fixture unit over the fixture unit of the appliance running under the base case operating flow rate q_b (ℓ·s^{-1}) and operating probability $p_i = kp_b$, k∈[0.125, 8]. Similarly, $\phi_{i,p}$ is the ratio of an appliance fixture unit over the fixture unit of the appliance running under the base case operating probability p_b and operating flow rate $q_i = kq_b$, k∈[0.125, 8]. As either p_i or q_i was assumed constant in each of the 2 cases for the sensitivity study, the fixture unit ratio and the ratio of either p_i or q_i would impeccably vary by the same amount over the base case value at a preferred reference flow rate q_{ref}.

Figure 4 presents the fixture unit ratios $\phi_{i,p}$ and $\phi_{i,q}$ against k∈[0.125,8]. Generally, the ratios and the values of k varied by the same amount. Compared with $\phi_{i,p}$, $\phi_{i,q}$ showed good agreement with the k values. It was obvious as the fixture unit ratios were more sensitive to the appliance operating flow rate q_i than to the appliance operating probability p_i.

At a chosen reference flow rate q_{ref} (ℓ·s^{-1}), the relative deviations of the response of $\phi_{i,q}$ and $\phi_{i,p}$ can be expressed by $\delta_{i,q}$ and $\delta_{i,p}$, respectively:

$$\delta_{i,q} = \frac{\phi_{i,q_i}}{k_i} \quad (10)$$

$$\delta_{i,p} = \frac{\phi_{i,p_i}}{k_i} \quad (11)$$

$\delta_{i,q}$ and $\delta_{i,p}$ against k_i∈[0.125,8] at q_{ref} = 1 ℓ·s^{-1}, 10 ℓ·s^{-1}, 100 ℓ·s^{-1} and 1 000 ℓ·s^{-1} are shown in Figs. 5 and 6. A larger q_{ref} was associated with a smaller variation in the relative deviation. When q_{ref} increased from 1 ℓ·s^{-1} to 1 000 ℓ·s^{-1}, the maximum average deviation was reduced from 0.1 to 0.004 at the base

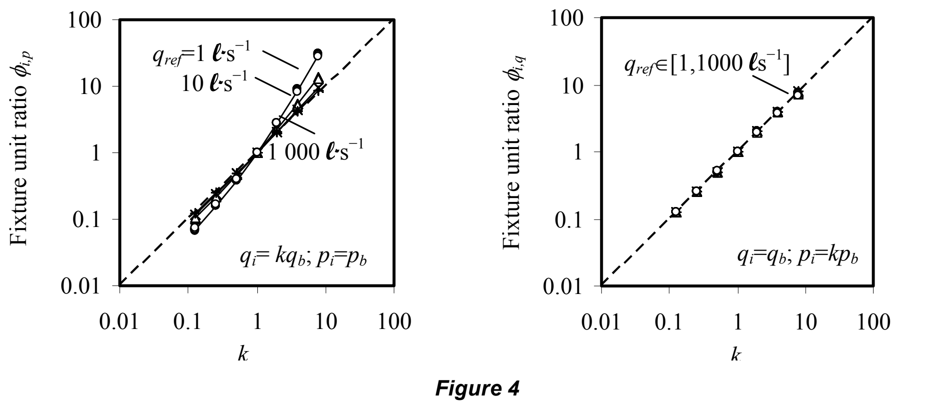

Figure 4
Fixture unit ratios $\phi_{i,p}$ and $\phi_{i,q}$

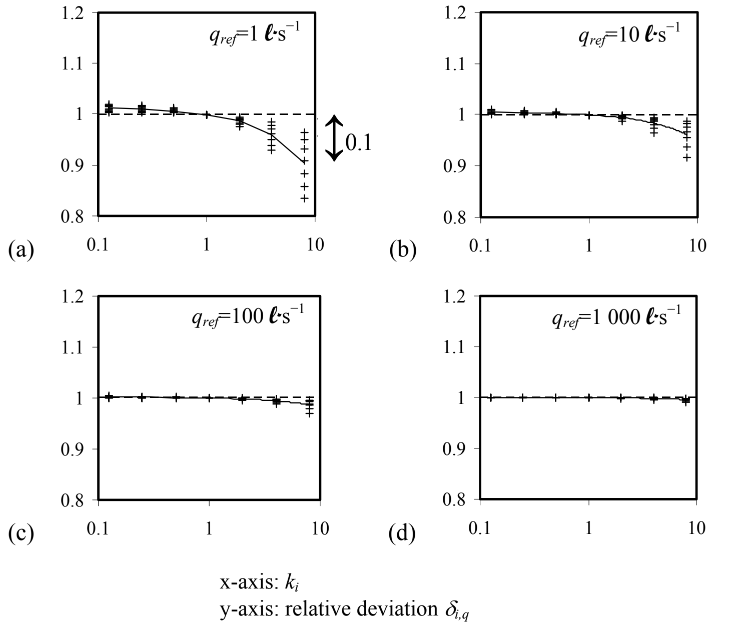

Figure 5
Relative deviations $\delta_{i,q}$ at the base case operating flow rate q_b

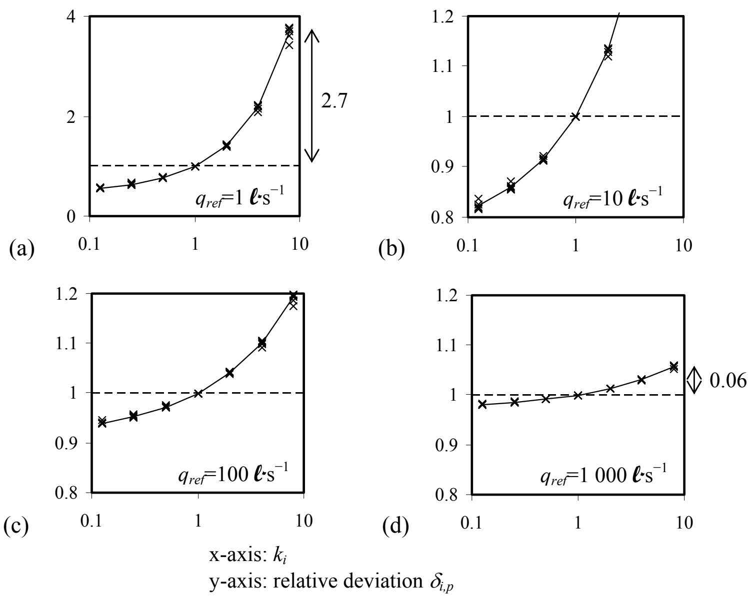

Figure 6
Relative deviations $\delta_{i,p}$ under the base case operating probability p_b

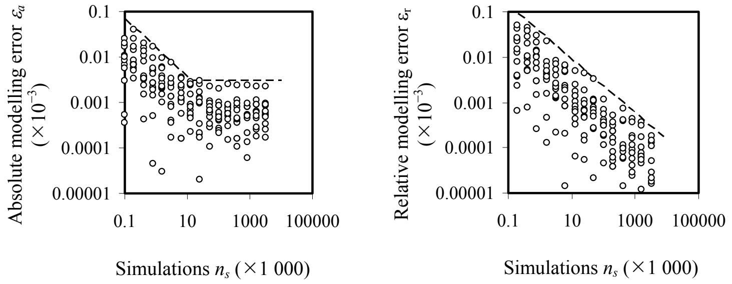

Figure 7
Stochastic model errors ε_a and ε_r versus simulation runs

case operating flow rate q_b (Fig. 5), and from 2.1 to 0.06 under the base case operating probability p_b (Fig. 6). The results also demonstrated that the variations were more sensitive (about 15 to 30 times) to the appliance flow rate q_i than to the corresponding reference flow rate q_{ref}.

Comparison with a stochastic model

For comparison, the probable maximum simultaneous water demand of an installation with a number of appliances was also evaluated by a stochastic model whose parameters can be identified from the descriptive distribution functions using a Monte Carlo sampling technique (Wong and Mui, 2008). This model has been applied to assess domestic washrooms where the usage patterns were complex.

Based on the operating probability p_i and operating flow rate q_i (ℓ·s^{-1}), as defined in the fixture unit approach, the operation of an appliance $A_i = A_i(p_i,q_i)$, where $i = 1...n_i$, is described by a random process with a random number $p^* \in [0,1]$:

$$q_i = \begin{cases} 0\ ; p^* > p_i \\ q_i\ ; p^* \le p_i \end{cases} \quad (12)$$

In each simulation j, the simultaneous operating flow rate $q_{d,j}$ (ℓ·s^{-1}) is computed by:

$$q_{d,j} = \sum_{i=1}^{n_i} q_i \quad ; i = 1...n_i; \quad (13)$$

The probable maximum simultaneous demand q_d^* (ℓ·s^{-1}) is determined by the distributions of all simulated simultaneous operating flow rates $\tilde{q}_d$ (ℓ·s^{-1}) from all simulations $j = 1...n_s$, where the allowable failure rate is $\lambda = 1\%$ as adopted in some common practices:

$$q_d^* = F(\lambda);\ \lambda = 1 - \int_0^{q_d^*} \tilde{q}_d dq_d \quad (14)$$

Via further simulation steps, the required number of simulations n_s can be resolved through error fine tuning using 2 error terms. The first term is the absolute modelling error ε_a which is quantised by the modelled number of appliances in simultaneous operation for 99% of N^*cases, i.e. corresponding to $\lambda = 1\%$ in Eq. (4):

$$\varepsilon_a = \left| \frac{N^* - N}{N^*} \right|;\ N = Mp + z\sqrt{2Mp(1-p)} \quad (15)$$

The second term is the relative modelling error ε_r calculated by the change of model output due to 1 simulation increment:

$$\varepsilon_r = \left| 1 - \frac{N^*_{n_s - 1}}{N^*_{n_s}} \right| \quad (16)$$

Figure 7 presents the modelling errors ε_a and ε_r versus n_s simulations for installations with 1 000 to 30 000 appliances whose operating probability range set was $p \in [0.01,0.05]$. It was reported that the maximum absolute modelling error ε_a would remain unchanged for n_s>10 000, at n_s = 10 000, the relative modelling error ε_r would be 0.008 x 10^{-3}.

At a reference flow rate $q_{ref} \in [1,1000]$, the fixture unit approach was applied to determine the probable maximum simultaneous demands $q_{d,ref}$ (ℓ·s^{-1}) of M installations. Each of the installations was composed

Table 1 **Appliance attributes**				
Applications	**A_1: Washbasin**		**A_2: WC**	
	p_1 (-)	q_1 (ℓ·s^{-1})	p_2 (-)	q_2 (ℓ·s^{-1})
(a) Commercial	0.055	0.15	0.1	0.1
(b) Residential	0.028	0.15	0.05	0.1
(c) Public	0.11	0.15	0.2	0.1

p: operating probability; q: operating flow rate

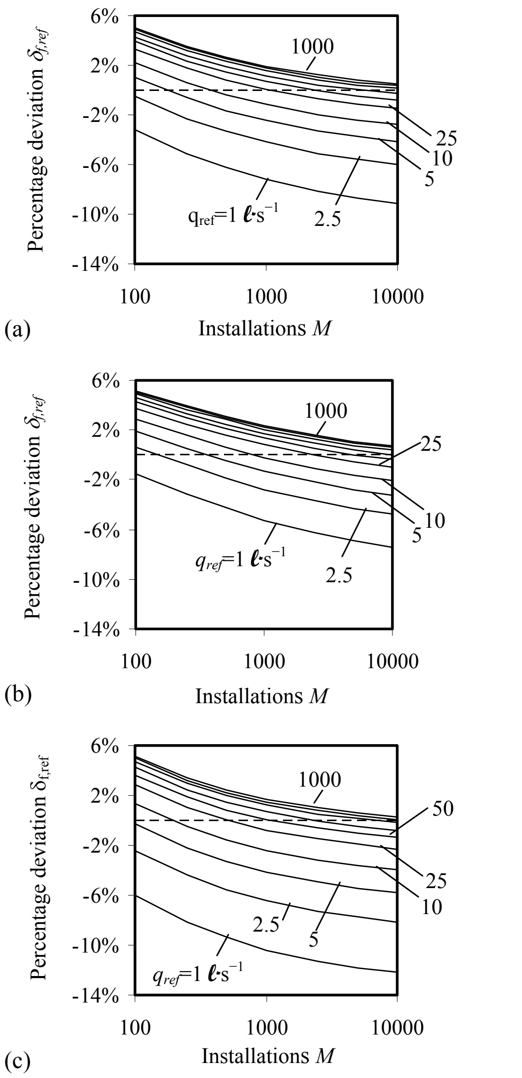

Figure 8
Percentage deviations $\delta_{f,ref}$ for (a) commercial, (b) residential, and (c) public demand patterns

of 2 different appliance types, A_1 and A_2, and operating in 3 demand patterns, namely, commercial, residential and public, as listed in Table 1. The picked installation sizes ranged from 100 to 10 000 washbasin-WC pairs and the resulting $q_{d,\,ref}$ (ℓ·s^{-1}) were compared with the q_d^* (ℓ·s^{-1}) values obtained from the stochastic model. The percentage deviation $\delta_{f,\,ref}$ between $q_{d,\,ref}$ and q_d^* is given by:

$$\delta_{f,ref} = \left(\frac{q_{d,ref}}{q_d^*} - 1 \right) \times 100\% \qquad (17)$$

Figure 8 exhibits the percentage deviations estimated for the 3 demand patterns. In the figure, a positive value indicates an overestimation of the probable maximum simultaneous demand and should be considered as satisfactory under the maximum allowable failure rate condition, i.e. $\lambda = 1\%$. The outcome showed that the choice of a reference flow rate had a significant influence on the predicted demand values. A wide range of deviations $\delta_{f,ref}$ were thus reported. The deviations varied from −9 to 5%, −7 to 5% and −12 to 5%, in the commercial, residential and public installations, respectively.

Taking a reference flow rate of 10 ℓ·s^{-1} (a common practice) as an example, the results of the fixture unit approach would give satisfactory maximum simultaneous demand predictions (i.e. overestimation within 2%) for installation sizes of 400, 900 and 200 washbasin-WC pairs, in commercial, residential and public applications, respectively. However, the installation sizes for an 80-storey residential building and a housing estate of 40-storey buildings in Hong Kong are about 1 200 and 10 000 washbasin-WC pairs, respectively. Besides, a high-rise commercial building of 80 storeys will require 2 000 pairs and a commercial shopping complex over 1 000 pairs. In other words, for water supply systems in high-rise buildings, the reference flow rate should be increased to meet the 1% failure allowance. This study demonstrated that for an installation size of up to 10 000 washbasin-WC pairs, reference flow rates of 100 ℓ·s^{-1} and 250 ℓ·s^{-1} would be adequate for high-rise residential and commercial buildings, respectively. Correspondingly, for the public applications, these 2 rates would be adequate for installation sizes up to 1 000 and 5 000 washbasin-WC pairs, respectively. Table 2 gives some example fixture units for appliances operating at a reference flow rate of 250 ℓ·s^{-1}. Illustrative examples for the probable maximum simultaneous demands for typical residential buildings and commercial buildings with both reference flow rates (10 ℓ·s^{-1} and 250 ℓ·s^{-1}) are shown in Appendix 1. Underestimates of 2-4% of the probable maximum simultaneous demands were illustrated in the examples. Existing fixture units used for some buildings are shown for comparison. The differences revealed why the fixture unit approach should be revised for high-rise water systems.

Table 2 **Example fixture units**				
Applications	**q_{ref} = 10 ℓ·s^{-1}**		**q_{ref} = 250 ℓ·s^{-1}**	
	Wash-basin	**WC**	**Wash-basin**	**WC**
(a) Commercial	2	2.2	2	2.3
(b) Residential	1	1.1	1	1.2
(c) Public	3.9	4.4	3.9	4.7

Conclusion

The fixture unit approach, based on a reference flow rate of 10 ℓ·s^{-1}, has been used to estimate the probable maximum simultaneous demands in building water systems for many years. Despite the finding that it would give good estimates (at a failure rate of 1%) for installations of 400, 900 and 200 washbasin-WC pairs in commercial, residential and public applications, respectively, this study reports that the selection of a reference flow rate did have significant influence on the demand estimates, and the existing choice would underestimate the actual demands in high-rise buildings of larger installations, commonly found today. Therefore, the traditionally assumed reference flow rate should be increased for high-rise water systems in a dense built environment. This study illustrated that a reference flow rate of 250 ℓ·s⁻¹ is adequate for typical residential and commercial buildings with installations of up to 5 000 washbasin-WC pairs.

Acknowledgments

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Appendix 1
Illustrative examples

Examples showing the simultaneous probable maximum demands using the fixture unit approach with the reference flow rates of 10 ℓ·s⁻¹ (traditionally assumed reference flow rate) and 250 ℓ·s⁻¹ (suggested value for high-rise water systems in a dense built environment) are presented. The base case operating probability p_b is 0.0282, and the base case operating flow rate q_b is 0.15 ℓ·s⁻¹ for the base case appliance assigned with a fixture unit of 1.

Example 1:
For an 80-storey residential building with an installation size of 1 200 washbasin-WC pairs

Traditional approach (at the reference flow rate of 10 ℓ·s⁻¹):
Fixture units of a washbasin-WC pair = 1+1.1 = 2.1
Total fixture units of a building (reference to the base case appliance) M = 1 200 × 2.1 = 2520
The simultaneous probable maximum demand, q_d =13.9 ℓ·s⁻¹

Suggested approach (at the reference flow rate of 250 ℓ·s⁻¹):
Fixture units of washbasin-WC pair = 1+1.2 = 2.2
Total fixture units of a building (reference to the base case appliance) M = 1200 × 2.2 = 2640
The simultaneous probable maximum demand, q_d =14.5 ℓ·s⁻¹

Example 2:
For a high-rise commercial building of 80 storeys with an installation size of 2 000 washbasin-WC pairs

Traditional approach (at the reference flow rate of 10 ℓ·s⁻¹):
Fixture units of a washbasin-WC pair = 2+2.2 = 4.2
Total fixture units of a building (reference to the base case appliance) M = 2000 × 4.2 = 8400
The simultaneous probable maximum demand, q_d = 41.4 ℓ·s⁻¹

Suggested approach (at the reference flow rate of 250 ℓ·s⁻¹):
Fixture units of washbasin-WC pair = 2+2.3 = 4.3
Total fixture units of a building (reference to the base case appliance) M = 2000 × 4.3 = 8600
The simultaneous probable maximum demand, q_d = 42.3 ℓ·s⁻¹