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Validation of non-residential cold and hot water demand model assumptions

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Abstract

Existing guidelines related to the water demand of non-residential buildings are outdated and do not cover hot water demand for the appropriate selection of hot water devices. Moreover, they generally overestimate peak demand values required for the design of an efficient and reliable water installation. Recently, a procedure was developed based on the end-use model SIMDEUM to derive design rules for peak demand values of both cold and hot water during various time steps for several types and sizes of non-residential buildings, i.e. offices, hotels and nursing homes. In this paper, the assumptions of building standardisation, on which the design rules are based, are validated. This was done with measurements of cold and hot water demands on a per second base and with surveys. The good correlation between the simulated water demand patterns and the measured patterns indicates that the basis of the design rules, the SIMDEUM simulated standardised buildings, is solid. Surveys were held to investigate whether the construction of the standardised buildings based on the dominant variable corresponds with practice. Surveys show that it is difficult to find relations to equip the standardised buildings with users and appliances. However, the validation proves that with a proper estimation of the number of users and appliances in only the dominant functional room of the standardised buildings, SIMDEUM renders a realistic cold and hot water diurnal demand pattern. Therefore, the new design rules based on these standardised buildings lead to reliable and improved designs of building installations and water heater capacity, resulting in more hygienic and economical installations.

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Keywords: non-residential water demand; SIMDEUM; validation model assumptions; surveys.

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1. Introduction

Non-residential users form an uncertain factor in the design of drinking water infrastructure and in the management of water demand, due to the limited availability of information related to their expected water demand. We do know that non-residential users account for approximately 28% of the total distributed water in the Netherlands, and that their diurnal patterns are different from residential water demand patterns (Loureiro et al., 2010; Blokker et al., 2011; Baggelaar and Geudens, 2008). To enable a high water demand, pipe diameters in distribution networks are generally oversized. The overcapacity can cause water quality problems, especially discolouration (Vreeburg, 2007). The lack of information on non-residential water use also complicates the design of drinking water installations inside buildings and the lack of information on hot water demand disturbs the optimal selection of the type and capacity of heating systems. Badly designed systems can cause stagnant water with hygienic consequences, and are less energy efficient and therefore more expensive to operate. The occurrence of *Legionella* in non-residential buildings is an internationally recognised problem (Van der Kooij et al., 2005).

Guidelines can provide the essential information to design indoor plumbing and water heater capacity to obtain a hygienic and microbiological reliable drinking water installation. Peak demand values are important to select the appropriate pipe diameter for cold and hot water and the water meter. In addition to the peak demand of hot water, the hot water use in different time periods is required for the selection of type and size of hot water devices. The suitable time period depends on the type of water heater system (Scheffer, 1994).

In the Netherlands, existing guidelines that provide the peak demand values for non-residential buildings of various types and sizes are based on flow measurements carried out between 1976 and 1980 (Scheffer, 1994). Presumably, they are no longer suitable for modern utility buildings, that have altered considerably in appliances and user's number and behaviour in the past decades. For example, rest rooms are now provided with water saving plumbing fixtures and urinals; offices have replaced the coffee lady with machines. Moreover, the working habits have changed, with more flexibility in working hours, with open-plan offices and a difference in ratio of men and women and an aim at maximum occupancy. Hotels are more luxurious and in some cases are extended with facilities for a conference or theatre. Nursing homes have changed in the recent years, aiming at small-scale services and residents' independency. The residents have expectations concerning privacy and continuing their personal way of life, resulting in qualitative enhancement of facilities and equipment to improve quality of life. Measurements of the water demand in several non-residential buildings confirm this presumption, since they show that the guidelines do not give an accurate view of peak water demand. They predict a higher water demand than measured, leading to systems that are overdimensioned (Pieterse-Quirijns et al., 2011).

There are no Dutch guidelines that describe the hot water demand in non-residential buidlings. For the design of the heating system, the building's owner or designer has to rely on the dimensions proposed by the supplier of heating systems. In practice, it appears that especially in non-residential buildings, the suppliers propose heaters with very large capacities, both in volume and power that do not match with the actual hot water demand (Pieterse-Quirijns et al., 2012).

Because of the described problems with the existing guidelines and because no guidelines exist for the hot water demand, new models for characteristic values of cold and hot water for non-residential buildings are required. In 2010, a procedure was developed to derive design rules for the peak demand values of both cold and hot water for various types of non-residential buildings, i.e. offices, hotels and nursing homes (Pieterse-Quirijns, 2010). The design rules are based on water demand patterns simulated by SIMDEUM, an end-use model which simulates residential and non-residential water demand patterns (Blokker et al., 2011). In the procedure, SIMDEUM simulates diurnal water demand patterns, for a specific value of a dominant variable. This dominant variable characterises the size of a building, such as the number of employees in an office or the number of beds in a nursing home. A crucial part of the procedure is the standardisation of each type of building, meaning that for a specific value of the dominant variable, a building is constructed with the corresponding number and characteristics of appliances (like toilets, showers, etc.) and of users (like kitchen personnel, visitors, etc.). The relevant information is not easy to find, since there is much freedom in the design of sanitary installations. Moreover, the number and behaviour of present non-residential water users is barely known. In section 2 of this paper, the background is described more extensively.

Before the SIMDEUM based design rules can be applied in practice and replace existing guidelines, they need to be validated. The validation procedure consists of two steps. In the first step, the outcome of the design rules is compared with measured peak demand values of cold and hot water on a per second basis. In earlier papers, the outcome of this first step, i.e. the succesfull prediction by the design rules, is described and the consequences for design of indoor plumbing and heating systems are illustrated (Pieterse-Quirijns et al, 2011; Pieterse-Quirijns et al, 2012).

This paper focusses on the second validation step. In this step, the assumptions of how to standardise buildings, on which the design rules are based, are validated with measurements and surveys. The validation step consists of two phases. Firstly, average simulated diurnal demand patterns of the standardised buildings are compared with measurements of cold and hot water patterns on a per second base for 6 different buildings. Secondly, surveys will show whether the construction of the standardised buildings based on the dominant variable corresponds with practice. When correspondence is established between standardised buildings and reality, in both predicted water demand patterns and construction of the building, the solid base of SIMDEUM based design rules is proven by the proof of concept, i.e. when the construction is reliable, the prediction of the expected cold and hot water demand in the building will be reliable.

2. Background

2.1. Background of SIMDEUM for non-residential buildings

SIMDEUM stands for "**SIM**ulation of water **D**emand, an **E**nd-**U**se **M**odel." It is a stochastic model based on statistical information of end uses, including statistical data on water appliances and users (Blokker et al., 2010). SIMDEUM's philosophy is that people's behaviour regarding water use is modelled, taking into account the differences in installation and water-using appliances. This means that in each building, whether it is residential or non-residential, like an office, hotel or nursing home, the characteristics of the present water-using appliances and taps, like flow rate, duration of use, frequency of use and the desired temperature, are considered as well as the water-using behaviour of the users who are present (presence, time of use, frequency of use).

SIMDEUM for non-residential water demand follows a modular approach. Each building is composed of functional rooms, characterised by its typical users and water using appliances (Table 1). The characteristics of the users and the appliances are different for each type of building and are extensively described in Blokker et al. (2011). With this approach, water demand patterns over the day for cold and hot water demand can be simulated for a specific non-residential building. From these daily water demand patterns, the characteristic peak demand values of cold and hot water during various time steps can be derived, which form the basis for the design guidelines.

Table 1 Functional rooms and the type of user who take water in the functional rooms in three categories of non-residential buildings, office, hotel and nursing home

Functional room	**Type of users (and reason for variable occupancy)**		
	office	**hotel**	**nursing home**
Meeting area	Employees (fulltime / part-time working), visitors	Guests (meeting, conference, theatre), employees	Visitors, employees
Lodging	-	Hotel guests (tourists, business people)	Residents
Restaurant	Kitchen personnel	Kitchen personnel	Kitchen personnel
Fitness room	Employees using the fitness room	Hotel guests using the fitness room	-
Technical / other	Number of buckets filled for cleaning, washing machines, …		

2.2. Background of SIMDEUM based design rules for non-residential buildings

For three categories of non-residential buildings SIMDEUM based design rules were developed, i.e. offices, hotels and nursing homes. Within each category, different typologies of buildings were defined. The typologies can vary in types of appliances, like types of toilets, flow of showers, and in the type of users, like business or tourist hotel guests. In Table 2, the defined typologies within each category are presented. The definition of the typologies is arbitrary. In the presented various typologies, existing building types were used as reference, based on practical experiences given by Uneto-VNI, the Dutch association of installers

The aim of the design rules is to predict the peak demand values of cold and hot water for the various types of offices, hotels and nursing homes of any size. The new design rules predict the peak demand values as a function of a (dominant) variable. Blokker et al. (2011) presented a sensitivity analysis for SIMDEUM for non-residential water demand in each of the considered categories. The dominant variable was established from this sensitivity analysis. The dominant variable is the functional room or user in a building that contributes most to the pattern and total amount of water use in a building. In offices, the main contributor (80-90%) to water demand is the meeting area with the toilets. The dominant variable for offices therefore is the number of employees that use the toilets. In hotels, the main contributor is the hotel rooms (app. 80%) for hotels without conference and theatre facilities. The dominant variable for hotels is the number of rooms, which can be occupied by 1 or 2 guests, dependent on the type of hotel. In nursing homes, the water use is not determined by a single dominant functional room. The washing of the residents and the toilet use of personnel and visitors all largely determine the water use. Since the number of personnel and visitors is determined by the number of beds (all beds occupied), the latter is defined as the dominant variable. For each category the dominant functional room and the dominant variable is given in Table 2.

Table 2 Different typologies of non-residential buildings within the categories offices, hotels and nursing homes and the dominant functional room and dominant variable in each category.

category	typology			dominant	
	typology name	users	Discerning appliances	functional room	variable
office	office A	male:female = 65%:35%	toilet with 6 litre cistern and urinal	meeting area	number of employees
	office B	male:female = 65%:35%	toilet with flushing valve and urinal		
	office C	male:female = 65%:35%	toilet with 6 litre cistern and no urinal		
	office D	male:female = 90%:10%	toilet with 6 litre cistern and urinal		
hotel	business (incl. conference)	business guests	7 types of shower	hotel rooms	number of hotel rooms
	tourist (incl. theatre)	tourist guests	7 types of shower		
nursing home	A: individual room	care needed residents	3 types of intensity of use bedpan washer	lodging and meeting area	number of beds
	B: four persons per room	care needed residents	3 types of intensity of use bedpan washer		
	C: combination of single rooms and four persons per room	care needed residents	3 types of intensity of use bedpan washer		
	D: self-contained apartments / assisted living	independent residents			

The procedure to derive the design rules for the peak demand values of cold and hot water for non-residential buildings is extensively described in Pieterse-Quirijns et al. (2010). For a specific value of the dominant variable, a standard building was constructed, i.e. each functional room is equipped with appliances and users. For this purpose, the number of appliances and users is established as a function of the dominant variable for each type of non-residential building. An example for a standardised office is given in Table 3 for the number of users and in Table 4 for the number of appliances. From the stochastic demand patterns at different values of the dominant variable, the maximum peak demand values for cold and hot water were derived. These peak demand values for several buildings could be described by simple linear relations as a function of the dominant variable. These linear relations form the design rules.

3. Methodology for validation

3.1. Phase 1: Methodology to measure and compare cold and hot water demand patterns of non-residential buildings

For the measurement of cold and hot water demand an ultrasonic flow meter was used. The Proline Prosonic Flow meter is a clamp-on meter that can be installed without disturbing the water supply. To ensure an accurate

Table 3 Number of users and their water use probability in each functional room in a standardised office as function of the dominant variable, *x* the number of employees

Functional room	**Type of user**	**Number of users**	**Times of presence and water use probability in office**[a]			
			t1	***t2***	***t3***	***t4***
Meeting area	employees and visitors	*x* 10%·*x*	8:00	12:15	13:00	17:00
Restaurant	kitchen personnel	0.0052·*x*+2.24	8:30	12:30	13:30	15:00
Fitness room	employees using the fitness room	1,5%·*x*	7:30	-	-	18:30
Technical / other	cleaners	0.0265·*x*+0.027	17:00	-	-	18:30

[a] t_1 is starting time of water use probability, t_4 is the end. t_2 and t_3 characterise a peak in water use probability (Blokker et al., 2011).

Table 4 Number of appliances in each functional room of a standardised office as function of the dominant variable, *x* the number of employees

Functional room	**Appliance**		**Number of appliances as function of *x* (number of employees)**	**remarks**
Meeting area	toilet ladies	*x*≤300 *x*>300	*x*/12 *x*/18	60% of flushes use the water saving option, frequency = 4
	toilet gentleman	*x*≤300 *x*>300	*x*/12 *x*/18	frequency = 1, no use of water saving option
	urinal	*x*≤300 *x*>300	*x*/12 *x*/18	frequency = 3
	tap wash basin	*x*≤300 *x*>300	2·*x*/12 *x*/18	frequency = 4.5
	coffee machine		0.0232·*x*+4.5	frequency = 8
Restaurant	kitchen tap		0.0052·*x*+2.24	frequency of usage depends on number of kitchen personnel and number of guests in the restaurant
	dish washer *x*: 0-500 *x*: 501-1000 *x*: 1001-1500		 1 2 3	
Fitness room	shower		0.0132·*x*-0.49	with boundary condition >0
Technical / other	cold and hot water		0.0265·*x*+0.027	

measurement of peak demand and of the diurnal demand pattern, the logging frequency was set to 1 second. The logging precision was 0.5%. The water demand was measured during minimal 20 weekdays for hotels and nursing homes and 30 working days for offices.

In each category of non-residential users, two buildings of one typology were selected with different values of the dominant variable. It appeared to be very difficult to find suitable buildings for the measurements. Narrow installation environments, the presence of buffers in the hot water circulation system, not enough straight pipes to install the flow sensor with desired distance from fittings, such as valves, T-pieces, elbows, etc were the most encountered problems. Moreover, it appeared that Dutch offices are seldom equipped with a collective hot water system. Therefore, the measurement of hot water was not possible, and the developed design rules for offices can only be validated on cold water use. Since the hot water use in offices is very small, this is not a problem. The selected buildings are given in Table 5. For the measurements a full occupation time period was aimed for. However, this was difficult to achieve for the two hotels. The occupation varied between 4-100% during weekdays.

Table 5 Selected buildings for measurement of cold and hot water demand, to validate the developed design rules for offices, hotels and nursing homes

category offices	**number of employees (*x*)**	**category hotels**	**number of hotel rooms (*x*)**	**category nursing homes**	**number of beds (*x*)**
office I	255	business hotel I	80	nursing home I	124
office II	2000	business hotel II	192	nursing home II	260 212 (hot)[a]

[a]One wing of nursing home II has its own boiler. The measured hot water use concerns 212 beds.

For each building, the medians of the measured daily patterns of cold and hot water demand are compared with the corresponding medians of simulated patterns of the standardised building. For an objective evaluation, the coefficient of determination R^2 is applied as statistical parameter. R^2 is a measure for the similarity between the distributions and calculated as:

$$R^2 = 1 - \sum_{i=1}^{N} (y_i - x_i)^2 \Big/ \sum_{i=1}^{N} (x_i - \bar{x})^2 \qquad (1)$$

where x_i is the measured data, y_i is the simulated data and $\bar{x}$ is the mean of x_i. Good agreement between measurements and simulations is achieved when $R^2 > 0.70$ (Blokker et al., 2011).

3.2. Phase 2: Methodology to survey the construction of standardised buildings

In each category of non-residential buildings, extensive surveys were held in at least four buildings of different typology. In the surveys the number and characteristics of users and appliances were investigated and compared with the construction of the standardised buildings, as is given for offices in Table 3 and in Table 4. In Table 6, the number of investigated buildings, the requested information of users and appliances in each functional room (see Table 1) and the additional information in different categories is summarised.

It was very difficult to collect these data. In practice, no survey send out to selected building owners were returned. It was required to collect the requested information by interviews. This was a highly labor and time intensive process: finding cooperation was a lengthy process, the information could not always be given by one person, the information was of a too high level of detail.

Agreement between the outcome of the surveys and the construction of the standardised buildings, was established in graphs in a visual way, since statistical agreement was not possible due to the limited number of buildings.

Table 6 Number of interviewed buildings in each category of non-residential buildings and the requested information in the surveys.

category	typology	Number of buildings	users	appliances	additional
office		8	Number Time of presence	Number Flow Type	Behaviour employees (2 offices): Time and frequency of use (toilets, urinals, coffee machine) Type of use (saving options) Use of appliances in kitchen (1 office): duration and frequency
hotel	business	5[a]	Number Time of presence	Number Flow Type	Behaviour business hotel guest: Frequency and duration of shower and bath use
	tourist				Behaviour tourist hotel guest: Frequency and duration of shower and bath use
nursing home	care needed residents	5	Number Time of presence	Number Flow Type	Intensity of use bedpan washer Frequency of use toilet and shower of residents
	self-contained apartments	3			

[a]hotels were not fully business or tourist. Some hotels were characterised as business on week days and tourist in weekend or 70% business and 30% tourist hotel. In the construction of standardised buildings, this doesn't cause problems, since the difference in water use is mainly caused by the different behaviour of a tourist guest and business guest.

4. Results and discussion

4.1. Phase 1: validation of cold and hot demand patterns of standardised non-residential buildings

The simulated patterns of the standardised buildings are compared with the measured daily patterns of cold and hot water. The comparison of the median demand patterns, allows to test the assumptions in the standardised buildings, concerning the presence of the users and their probability of water use during the day (see Table 3). Moreover, the height of the demand patterns gives information on the assumptions of average water use per person, defined in for example the frequency and use of water saving options of the toilets (see Table 4).

In Fig. 1 an example is given for one building in each category. The visually good agreement between the daily patterns is confirmed by the values of R^2 which is larger than 0.70 for offices, for cold water in nursing home I and for both cold and hot water in the nursing home II (Table 7). The lower value for hot water in nursing home I, is caused by the cleaning of the wash bowls on one location and one specific moment in the afternoon, which was not applied in standardised nursing home. The lower value for hotels is most probably due to the varying occupation of the hotel. Another explanation might be the later appearance of the morning peak demand and the difference in evening peak.

This phase shows that the assumptions made for the presence of users, their probability of water use during the day and for average water use per user are reliable for offices and nursing homes. For hotels, the presence of hotel guests and their probability of water use during the day is not estimated very well, following from the differences in morning and evening peak demand. On the other hand, the average water use per user is estimated in a reliable way, following from the height of the demand patterns. This means that the predicted peak demands will be reliable, although occurring on another time during the day.

This phase also shows the advantage of using the physically based SIMDEUM for the development of design rules, since differences can be interpreted and explained.

Table 7 Statistics of the comparison between measured and simulated water demands for offices, business hotels and nursing homes and their corresponding standardised buildings

category offices	**R^2 cold**	**category hotels**	**R^2 cold**	**R^2 hot**	**category nursing homes**	**R^2 cold**	**R^2 hot**
office I	0.90	business hotel I	0.54	0.49	nursing home I	0.71	0.38
office II	0.96	business hotel II	0.45	0.50	nursing home II	0.82	0.71
			0.61	0.59			

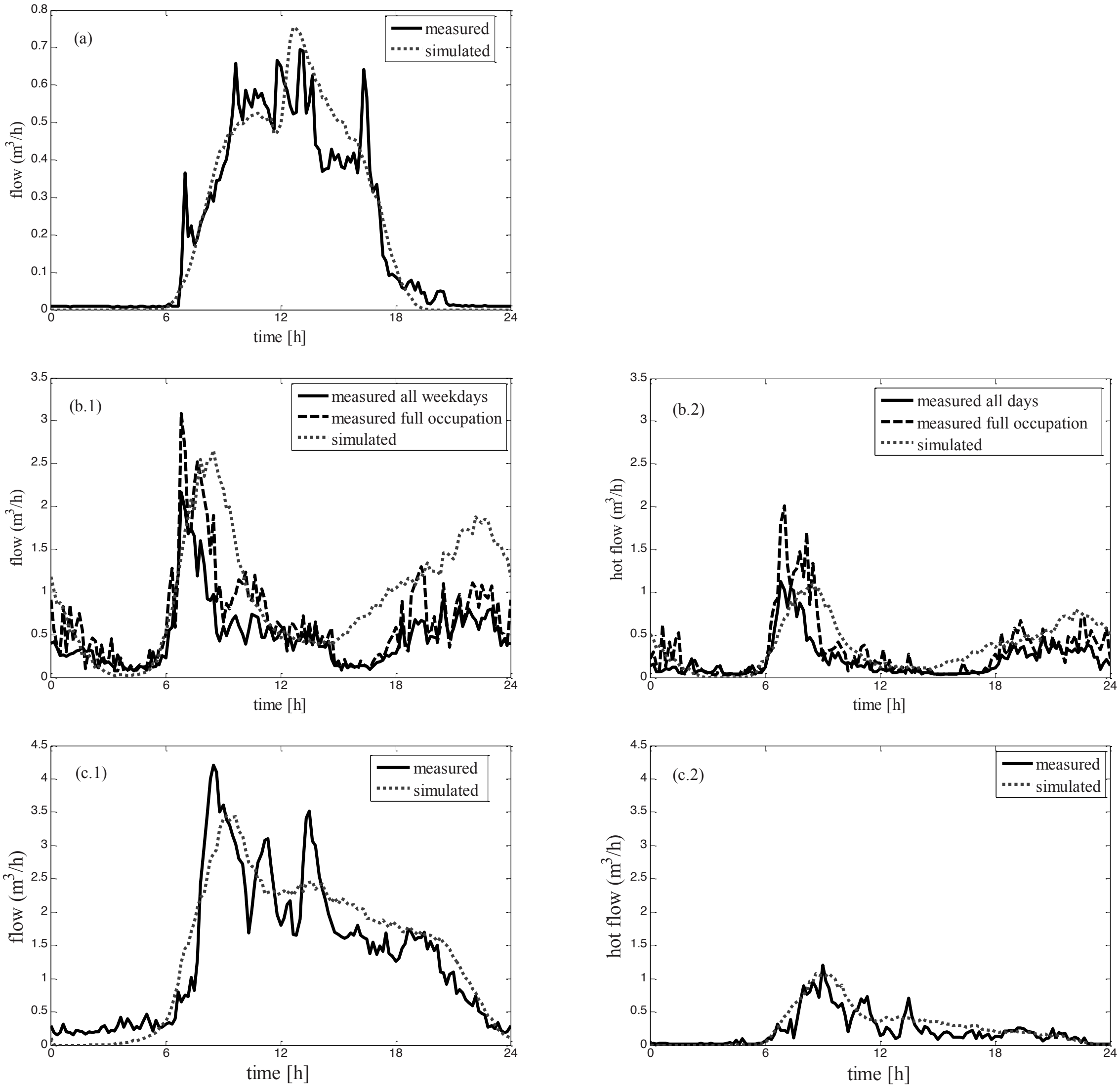

Fig. 1 Comparing average measured and simulated demand of cold water of office I (a), cold water (b.1.) and hot water (b.2.) of a business hotel (II) during weekdays and cold water (c.1.) and hot water (c.2.) of a nursing home (II) with care needed residents during weekdays.

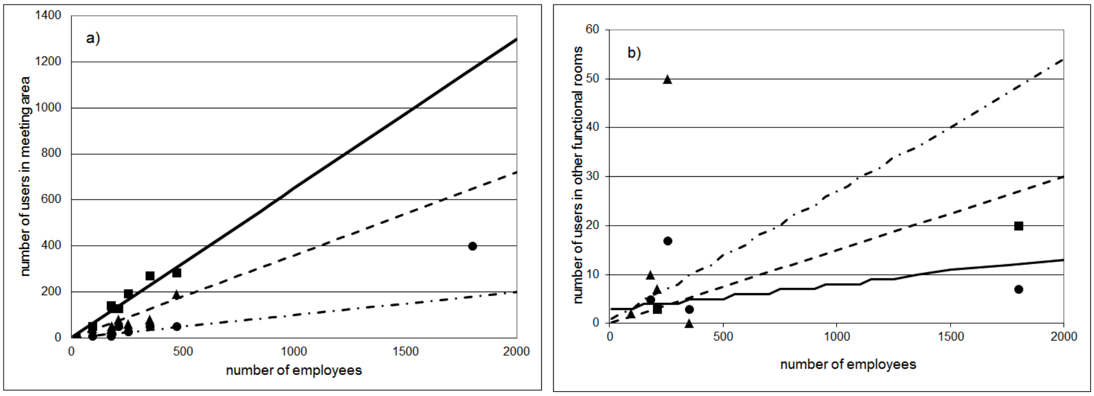

Fig. 2 Number of users in the standardised office of design rules (lines) and in surveyed offices (data points) in the dominant functional room of offices, meeting area (a) with male employees (- and ■), female employees (- - and ▲) and visitors (-.- and ●) and in other functional rooms (b) with kitchen personnel (- and ■), employees using the fitness room (- - and ▲) and cleaners (-.- and ●).

4.2. Phase 2: validation of construction of standardised non-residential buildings

The construction of the standardised buildings is validated by comparing the number and characteristics of appliances and users in all functional rooms (Table 1). The surveys mainly give information on the ratio between users and appliances. As illustration, the results for offices are presented in Fig. 2, where the outcome of the surveys for number of users are shown together with the relations of the standardised building (Table 3). Fig. 2a shows that the number of users in the dominant functional room, i.e. the meeting area (Table 2) corresponds well with practice. Also the behaviour of the users, like the frequency of toilet use, the use of coffee machine, the time of presence correspond well. In practice, the water saving options of the toilet flush are used less frequently than assumed in the standardised building. On the other hand, the number of users in the other functional rooms, as the restaurant, the fitness room and the technical room (Fig. 2b) show higher variations and are less accurate. Moreover, the data from the surveys show that it is not possible to extract a more appropriate standard from the available data. The same is true for the appliances: the number and types of appliances in the dominant functional room, like the number of toilets for men and women, the number of wash basins and the number of coffee machines correspond well with practice. Only the number of urinals is lower in practice than assumed in the standardised office. This means that in the standardised offices a higher simultaneous use of urinals is possible, which might result in a higher peak demand predicted by the design rules. The assumptions for the number of appliances in other functional rooms are reasonable. Sometimes, not enough information can be extracted from the surveys.

The surveys indicate that the equipment of the standardised office is reliable for the dominant functional room, the meeting area. The functional room, that contributes most to the pattern and total amount of water use in a building is equipped corresponding with practice: the number of users and their water using behaviour as well as the number of appliances correspond with the surveyed offices. The agreement between the simulated and measured demand patterns of $R^2 > 0.90$ (Fig. 1a) means that a reliable equipment of the functional room in the standardised office is sufficient for a realistic prediction of the water demand of a building. Moreover, it shows that as long as the ratio between users and appliances is not extreme, for example when there are not enough toilets for the users causing queues, the exact ratio is not crucial. This gives SIMDEUM the possibility to be less exact, while still predicting the water demand in a reliable way.

The same tendency is found for hotels and nursing homes. The dominant functional rooms in the standardised buildings, respectively the hotel rooms for hotels and the lodging and meeting area for nursing homes have a reliable equipment regarding the number of users and appliances. The other functional rooms are less accurate and it is not possible to find better relations to equip the other functional rooms in the standardised buildings with users and appliances from the surveys. The reliable equipment of the dominant functional rooms is sufficient for a reliable prediction of the expected cold and hot water demand in the building (Fig. 1b and c). In short, the proof of concept is established for all considered categories of non-residential buildings.

5. Conclusions

Recently, new SIMDEUM based design rules were developed for cold and hot water demand of non-residential buildings. In this paper, the assumptions of building standardisation, on which the design rules are based, were validated with surveys and measurements of both cold and hot water on a per second basis for six different non-residential buildings, offices, hotels and nursing homes. The validation shows that the model predicts the cold and hot water daily demand patterns reasonably well to good. The correlation of the simulated patterns with the measured patterns indicates that the basis of the design rules is solid.

Moreover, the construction of standardised buildings with users and appliances is validated with at least four surveys per category of non-residential buildings. The validation proves that with a proper estimation of the number of users and appliances in only the dominant functional room of the standardised buildings, SIMDEUM renders a realistic cold and hot water diurnal demand pattern.

With the correspondence between standardised buildings and reality, in both diurnal water demand patterns and construction of the building, the solid base of SIMDEUM based design rules is proven by the proof of concept, i.e. when the construction is reliable, the prediction of the expected cold and hot water demand in the building will be reliable. Therefore, the new design rules based on these reliable predictions result in reliable peak demand values of cold and hot water, required in the designs of buildings. The new design rules improve the design of the building installation, expressed as the selected pipe diameters, and of the heating system.

The paper shows that SIMDEUM forms a reliable basis to predict non-residential cold and hot water demand. Due to the modular approach of SIMDEUM, the procedure is easily applicable to other types of buildings (such as schools, restaurants or sporting facilities), or to other countries where specific information on users and appliances is available.

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