I.3 Application of fuzzy logic to the assessment of design flow rate in water supply system of multifamily building

L. H. Oliveira (1), L. Y. Cheng (2), O. M. Gonçalves (3), P. M. C. Massolino (4)
(1) Department of Construction Engineering of Escola Politécnica, University of São Paulo, Brazil, e-mail: lucia.oliveira@poli.usp.br
(2) Department of Construction Engineering of Escola Politécnica, University of São Paulo, Brazil, e-mail: cheng.yee @poli.usp.br
(3) Department of Construction Engineering of Escola Politécnica, University of São Paulo, Brazil, e-mail: orestes.goncalves@poli.usp.br
(4) Department of Construction Engineering of Escola Politécnica, University of São Paulo, Brazil, e-mail: pedro.massolino@poli.usp.br

Abstract

The traditional approaches to determine the design flow rates of water supply system of buildings are empirical and probabilistic ones. In Brazil, the empirical formulations are the most used because its application is recommended by Brazilian standard NBR 5626/1998. On the other hand, the probabilistic methods have been considered more suitable because they take into account more realistic conditions of each design, which is represented as random variables intervening in the use of the water inside the buildings. Nevertheless, as the usage of some sanitary appliances may depend on the subjective behaviors of the users, the aim of this work is to present a model that uses Monte Carlo simulation for random variables and fuzzy logic for fuzzy variables to achieve a more accurate assessment of design flow rate in water supply system of multifamily buildings. As the first stage of the study the results of the application of fuzzy logic to determine the duration of showers, which affects remarkably the flow rate, is shown here in. For the validation of the model, all fixtures of an apartment with three students were monitored during a period of 20 days with the use of a water measurement system in real time. The comparison of the time of shower of one student, obtained by fuzzy logic with that collected in real time measurement is carried out, and show good agreement between the calculated and the measured duration of shower.

Keywords

Design flow rate; water supply system; fuzzy logic; Monte Carlo simulation.

1. Introduction

The traditional approaches to determine the design flow rates in building water supply system can be classified into empirical and probabilistic ones [1]. The empirical formulations are the most used. However, the probabilistic ones are more suitable because they take into account more realistic conditions of each design, which is represented as random variables intervening in the use of the water inside the buildings. Nevertheless, the probability theory only considers random variables, which depend on future events. It does not treat fuzzy variables that better represent the behavior of the user, which is required in a more accurate assessment of flow rates in the feeding branches.

On the other hand, amount all the sanitary appliances used in multifamily buildings the shower generates the largest impact in the value of the design flow rate of the apartment's feeding branch, in case of water submetering system. This is because of its longer duration of usage and its larger unitary flow rate. Moreover, the duration of usage of shower is strongly affected by subjective behavior of the users, which may be modeled by means of fuzzy approach, instead of the probabilistic ones.

In this way, the aim of this work is purpose a model that applies Monte Carlo simulation and Fuzzy Logic to establish the design flow rate for the water system of the residential buildings. While fuzzy logic deals with subjective variables, in especial, to assess the duration of the shower usage, the Monte Carlo simulation uses the distributions of the variables for the determination of the instant of use of the sanitary appliances.

As it is very difficult to carry out flow rate measurements for a typical family, the approach present herein is validated by using the measurements obtain from the apartment of three students. For the sake of simplicity, only the morning shower is considered because the peak period clearly defined and the instant of usage is more critical due to time to leave the apartment for work or study.

2. Models for the determination of design flow rates in Brazilian water supply system

According to Gonçalves [1], the empirical models commonly used for the assessment of the design flow rates in the cold water supply system include those technique based on the use of tables, graphs and empirical formula established from the experience and judgment of its authors. Meanwhile, the probabilistic models are based on the weights, graphs and mathematical expressions derived from probabilistic concepts.

In the following sections, an overview of these two models is presented as well as the basic concepts of Fuzzy Logic, which is an approach adopted proposed herein to development a more accurate model for the assessment of design flow rates of water systems.

2.1 Deterministic model

The Brazilian standard NBR 5626/1998 [2] recommends the use of a deterministic method for the assessment of the design flow rates in cold water system, whose expression is given by Equation (1):

$$Q = 0{,}3\sqrt{\sum P} \tag{1}$$

Where:
Q is the design flow rate in a given section, L/s.
$\sum P$ is the sum of the relative "fixture units" of all the fixtures, installed downstream of the pipe section.
Despite of its simplicity, this method does not take into account the influence of the users' activities, which, in turn, are function of:

- the type of the building and the characteristics of the user;
- the characteristics of the building, which is defined for the size and the distribution of the population and,
- the characteristics, flow rates and intensity of use of the sanitary appliances.

2.2 Probabilistic model

In order to consider the real conditions of each design situation Gonçalves [3] proposed a model for the determination of the water demands in the water supply systems, which is briefly shown as what follows.

In building water supply systems the flow rates depends on the interaction between the user and the sanitary equipment system, and are affected by the following factors:

- activities of the users, which is a function of:
  - the type of building (residential, school, hotel etc.);
  - the characteristics of the users, determined for physiological, regional, cultural, social and climatic aspects;
- characteristics of the building, which is a function of:
  - the population (size and distribution) and
  - the space organization;
- characteristics of the set of sanitary appliances, which is a function of the types and the number of sanitary appliances.

The intervening variables, which consider the above mentioned factors are grouped in the model as follows:

- intensity of use of the set of sanitary appliances;
- unitary flow rates of each type of sanitary appliance.

The intensity of use of the set of sanitary appliances is considered in the model by using the following variables:

- duration of the discharge of a sanitary appliance, **t**;
- interval of time between consecutive discharges of a sanitary appliance, **T**;
- number of sanitary appliances installed downstream of the pipe section, **n**.

The unitary flow rate of a type of sanitary appliance is denoted by **q**.

The duration of the discharge of an appliance (**t**) consists of the period between the beginning of the discharge and the end of the water supply for the discharge. It can be determined by *in loco* measurements and calculation mean and the variance of a set of data or by the three points estimative method: a minimum value (t_{min}), a most probable (t_{prov}) and a maximum (t_{max}), using the Gamma distribution, according to Gonçalves [3], the mean (μ_t) and the variance (σ^2_t), may be determined by Equation (2) and (3), respectively.

$$\mu_t = \frac{t_{mín} + 3 \cdot t_{prov} + t_{máx}}{5}$$

(2)

$$\sigma_t^{\,2} = \frac{(t_{máx} - t_{mín})^2}{25}$$

(3)

Similarly, the unitary flow rate of each appliance (**q**) can also be determined by means of field surveys and its mean value and variance might also be calculated by using the three points estimative method.

The interval between two consecutive usages (**T**) depends on several factors, and can be represented by the following variables:

- number of appliances of the considered type installed in the sanitary room, **n**;
- number of usages *per capita* of a type of appliance during the peak period, **u**;
- population served at the sanitary room in which the appliance is installed, **P**.

The number of uses *per capita* of each type of sanitary appliance in the peak period (**u**) can be determined similarly to the ones presented for the unitary flow rate and for the duration of the discharge.

Despite the probability model gives more precise results than deterministic ones, the usage of sanitary appliances is strongly dependant on the users, whose subjective behavior may be better modeled as fuzzy variable [4]. Therefore, beside the deterministic and probabilistic models, approaches based on the Fuzzy Logic might be effective for the assessment of the flow rates, especially of the showers, whose usage is highly subjective.

In this way, in order to develop a more reliable and accurate method to estimate the duration of the usage of the sanitary appliances, the present work applies the Monte Carlo simulation to model the random variables such as the instant of usage of sanitary appliances and applies Fuzzy Logic to model the behavior of the users as a set of fuzzy inference rules for the usage of shower, which is particularly related to the instant of usage and air temperature. The approach adopted herein is presented in the following sections.

2.3 Monte Carlo simulation

Monte Carlo simulation [5] is considered in the present research to take into account random events of the use of the sanitary appliances such as the wash basin, water closet, sink, sink laundry and washing machines. Different from the shower, as will be shown in the next sections, the use of these sanitary appliances does not show clear relation to some intervening variables.

2.4 Fuzzy logic

Of all the sanitary appliances used in residential buildings, the shower generates greater impact in the value of the design flow rate of a section, due to the longer duration of use and relatively high unit flow rate. Moreover, the behaviors of its users are quite subjective, which might be better modeled by using Fuzzy Logic. This fact motivated the authors of this work to use the fuzzy logic to determine the duration of use of the shower during the bath of users.
According to Von Altrock [6], fuzzy logic is a technology that translates natural language descriptions of decisions policies into algorithm using a mathematical model. It is a reasoning system that involves fuzzy propositions and the procedure of the fuzzy inference consists of three major steps: fuzzification, inference and defuzzification, as presented in Figure 1.

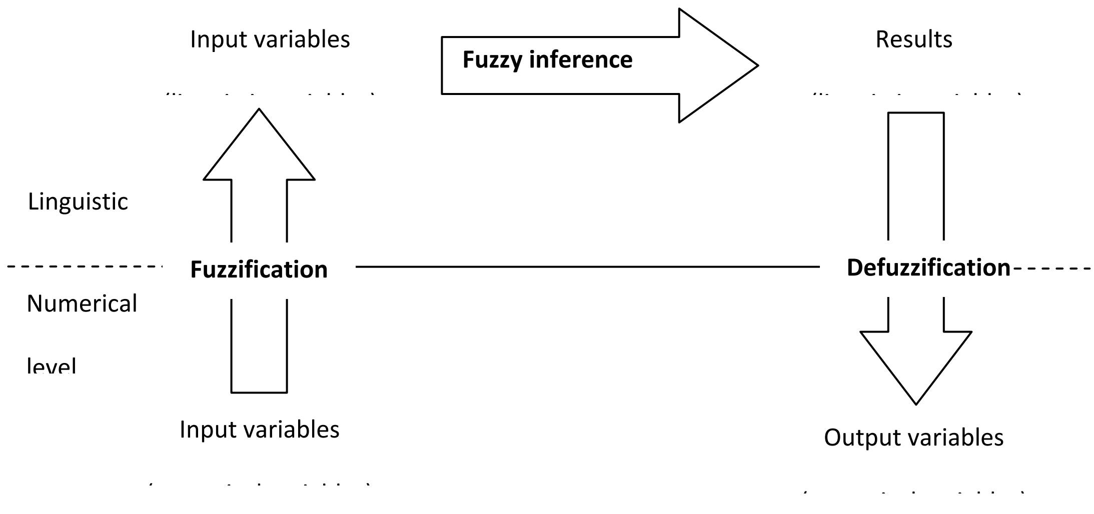

Figure 1: Structure of a fuzzy logic system [6]

Fuzzification: It is the initial step, where the fuzzy sets are used to translate numerical variables into linguistic variables, and the membership degree of the associated linguistic values are obtained.

Fuzzy inference: After translating all input numerical values into linguistic variable values, the fuzzy inferences are carried out by applying the if/then fuzzy rules that define system behavior. This step yields a linguistic value for the linguistic variable. For example, the linguistic result for "duration of shower" (linguistic variable) could be "very fast" (linguistic value).

Defuzzification: In this step, the fuzzy variable obtained by the inference rules is converted into a discrete numerical value that better represents the inferred values of the linguistic variable, which is the output of the fuzzy inference. There are many desfuzzification methods available in the literature. However, according to Cox [7], method of baricentre and method of average of the maximum are the most used ones. In this work the method of baricentre has been adopted.

3. Methodology

This section shows the methodology and the fuzzy approach adopted herein. The data obtained in the apartment of the students will be used for the establishment of the distribution of the following variable: average values of flow rates, average duration of use and schedule of the beginning of use of the sanitary appliances. It is highlighted that the duration of the showers is obtained by fuzzy logic.

Since it is very difficult to obtain authorization to install the measurement equipments *in loco* because the cabling and the sensor bother the users, as an alternative, measurements have been carried out in an apartment where three students live.

3.1 Model using Monte Carlo simulation and Fuzzy logic

Figure 2 shows the flowchart of the model to be developed. The following variables will be used:

- **deterministic** – quantity of sanitary appliances (**n**);
- **random** – average flow rate of sanitary appliances ($\mathbf{q_m}$); average duration of use of sanitary appliances ($\mathbf{t_m}$) except the electric shower, which will be obtained by fuzzy logic; instant of beginning of the activities related to the water use.
- **fuzzy** – linguistic values of the variable "instant of shower", "air temperature" and "duration of shower".

By means of the fuzzy logic determines the duration of the shower and with the use of Monte Carlo simulation is determined the start of use of the sanitary appliance.

Based on the quantity and type of sanitary appliances and the users, Monte Carlo simulation is carried out to determine the instant of usage of all sanitary appliances by each user. The duration of usage is also determined by Monte Carlo simulation, except in the case of shower. Because of its longer duration and the influence of the users´ behaviour, the duration of shower is determined by using fuzzy logic as explained in the section 3.2. In the case of overlapping of the shower usage (more than one user at the same time), a strategy that establishes the priority amount the users is adopted to solve the conflict.

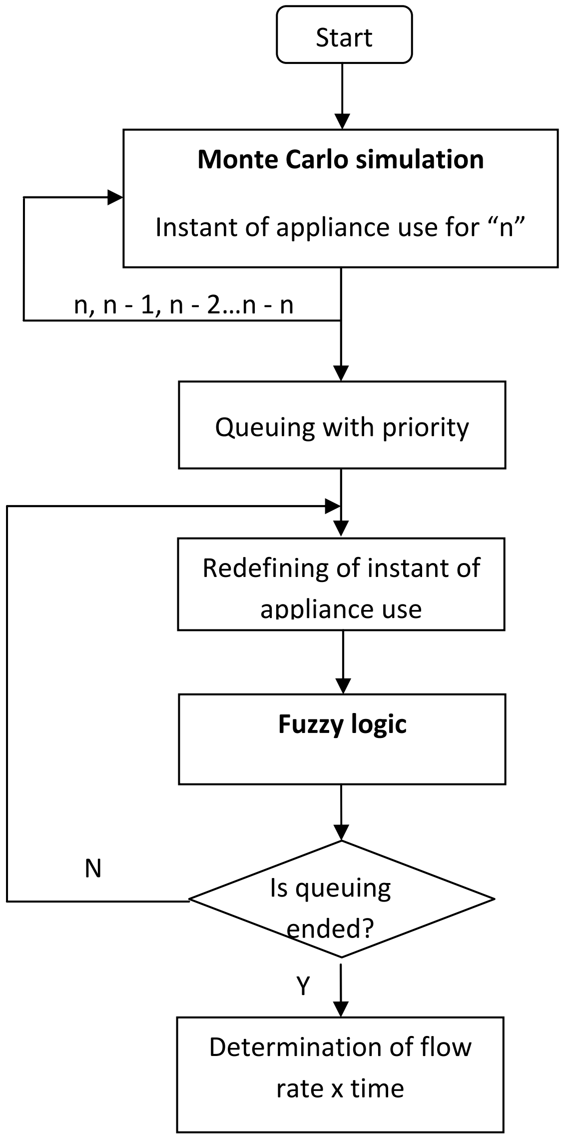

Figure 2: Step of the model to determine the design flow rate using Fuzzy Logic and Monte Carlo simulation

3.2 Measured duration of shower

At first the duration of shower times of each user have been measured in a period of 20 days, and with the use of a real time water measurement system, constituted of a volumetric water meter class C, nominal flow rate of 1.5 m^3/h, connected to a Cyble pulse and a data acquisition system (MGCplus – HBM).

The local where the measurements have been carried out was an apartment in the city of São Paulo-Brazil. Three male students live there. One is a under graduating student, one is master degree student and another one of PhD degree student. These students are from two regions of Brazil: North and Northeast, which present different climatic conditions, and both hotter than São Paulo. This might influence the habits of the users and the duration of showers. The apartment has three dormitories, one bathroom with one electric shower, one close-coupled toilet with nominal volume of discharge of 12 liters (WC) and one wash basin. The climatic conditions during the period of data collect was very hot, with maximum and minimum air temperature of a day ranging from 16 ^oC to 34 ^oC, and the temperature in the morning varied from 20 ^oC to 22 ^oC.

3.3 Determination of the duration of shower by fuzzy logic

Figure 3 shows an overview of the fuzzy reasoning system for the assessment of the duration of the morning shower.

All students leave the apartment in the morning and come back only at the end of the day. The peak period for the use of the shower in students' apartment is from 7:30 to 10:00 a.m.

For the sake of simplicity, amount the variables that affect the duration of shower in the peak period in the morning, two main variables "instant of shower" and "air temperature" are considered herein. Based on these two variables, the set of linguistic variables for "instant of shower", "air temperature" and "duration of shower" are defined by interviews applied to the users.

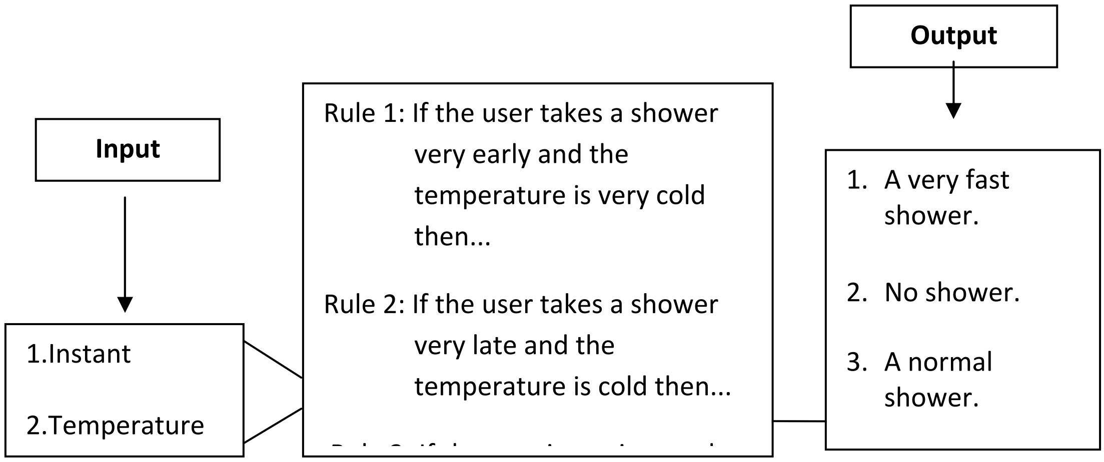

Figure 3: Fuzzy reasoning system to assess the duration of the morning shower as function of instant and air temperature

The questions carried through in the interview have been:

- Which the air temperatures you consider very cold, cold, pleasant, hot, very hot?
- During the peak period, what are the time intervals associated with the following expressions: very early, early, in time, delayed and very delayed.
- Associate the duration of your shower, in minutes, with the following expressions: very fast, fast, normal and long.

3.3.1 Linguistic variables

The interviews generates data that present some scattering, typical of personal subjectivity of the users. Thus, mean value obtained from the three users have been used to establish the sets of fuzzy linguistic values corresponding to “instant of shower”, “air temperature” and “duration of shower”, which are shown in Figure 4, 5 and 6 respectively.

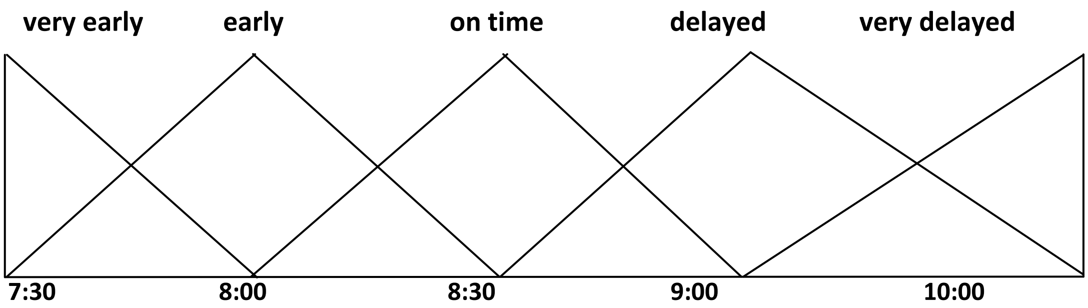

Figure 4: Linguistic values of the variable "instant of shower" of the students

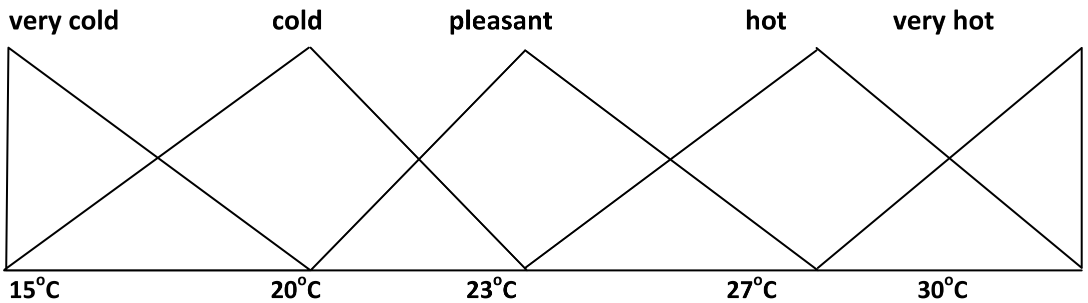

Figure 5: Linguistic values of the variable "air temperature" of the students

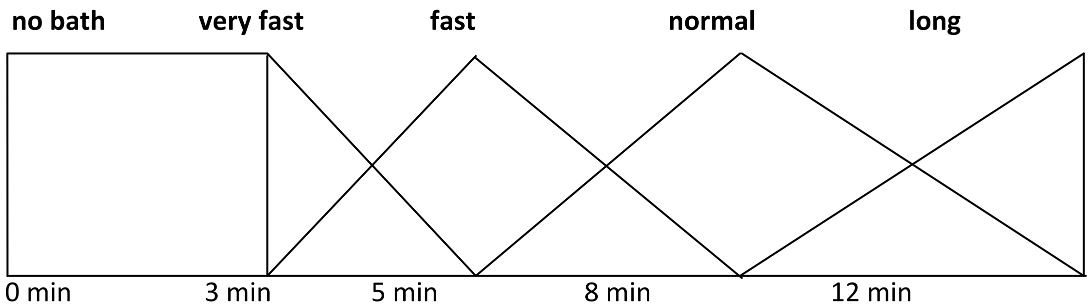

Figure 6: Linguistc values of the variable "duration of shower" of the students

3.3.2 Rules of the fuzzy reasoning

Also, from the interviews, a matrix of fuzzy reasoning rules is obtained for each user. As the matrices present different pattern due to different habits of the users, they are shown separately in Tables 1, 2 and 3.

Table 1 - Fuzzy matrix for the establishment of the shower time of the user A

Time / Temperature	very early	early	on time	delayed	very delayed
very cold	normal	normal	normal	fast	very fast
cold	normal	normal	normal	fast	very fast
pleasant	long	long	long	fast	very fast
hot	long	long	long	fast	very fast
very hot	long	long	long	fast	very fast

Table 2 - Fuzzy matrix for the establishment of the shower time of the user B.

Time / Temperature	very early	early	on time	delayed	very delayed
very cold	fast	fast	fast	very fast	no shower
cold	fast	fast	normal	very fast	no shower
pleasant	normal	normal	normal	fast	very fast
hot	long	normal	normal	fast	very fast
very hot	long	long	normal	fast	very fast

Table 3 - Fuzzy matrix for the establishment of the shower time of the user C

Temperature \ Time	very early	early	on time	delayed	very delayed
very cold	long	long	normal	fast	very fast
cold	long	normal	normal	fast	very fast
pleasant	normal	normal	normal	fast	very fast
hot	fast	fast	fast	fast	very fast
very hot	fast	fast	fast	fast	very fast

4. Results and discussions

Results obtained by measurements of the flow rate and duration of the use of the water closet (Figure 7) and the use of wash basin (Figure 8) with their respective distribution of use of these sanitary appliances by the three students.

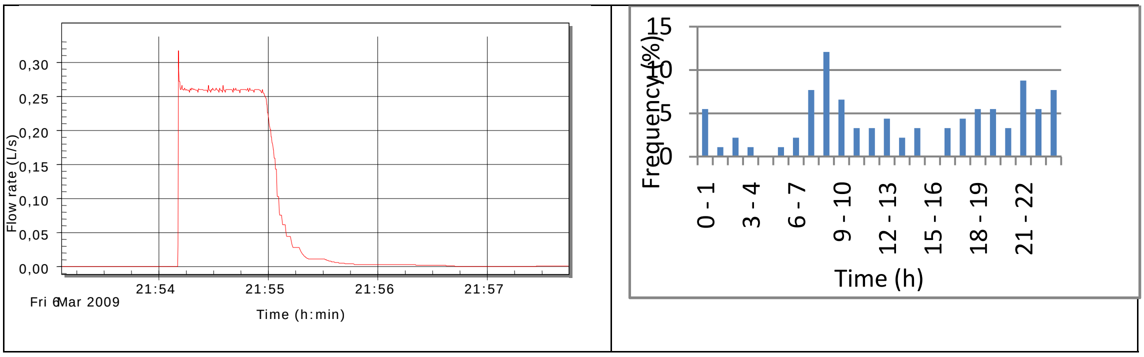

Figure 7: Water closet flow rate profile and respective distribution of water closet use

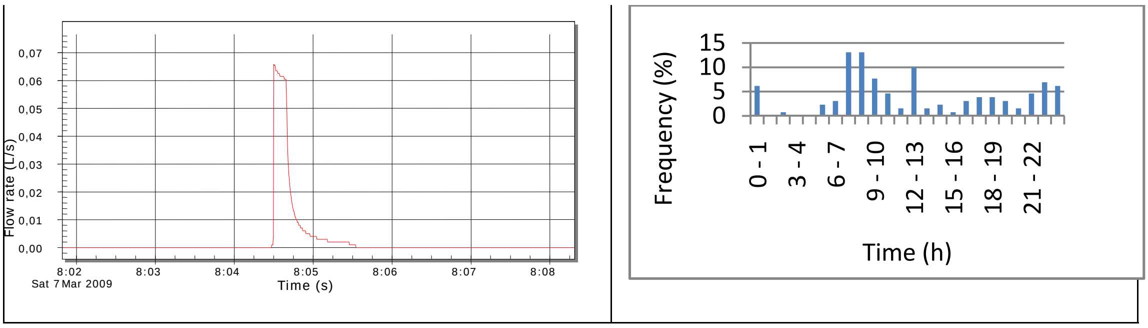

Figure 8: Wash basin flow rate profile and respective distribution of wash basin use

One of the results obtained by measurements of the duration of the bath of the student A is presented in Figure 9. It gives a measured time series of the flow rate due to the shower usage of the student A. The data show the duration of the shower. Since only the student A has the habit of taking shower in the morning, the validation of the duration of shower determined by fuzzy logic has been carried out using his data.

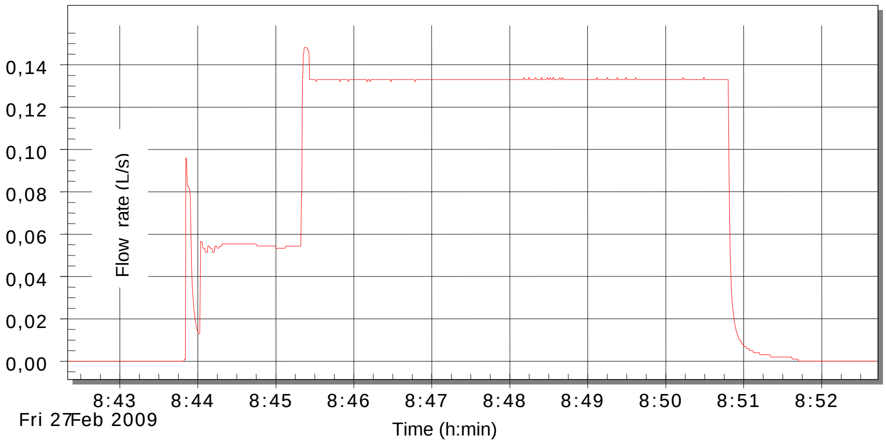

Figure 9: Shower profile of the student A collected in field

For the calculation of the duration of shower, by using Mamdani relation, a software in Java language has been developed. The results are giving in Figure 10 for the student A.

As mentioned before, the student A had the greater number of shower during the morning, therefore measured data that corresponds his showers have been used for the validation of the fuzzy approach.

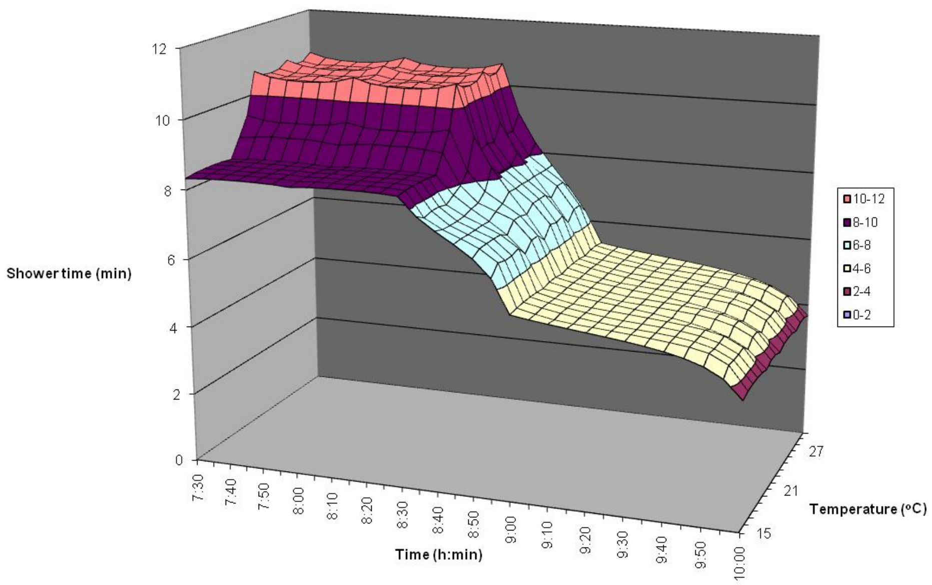

Figure 10: The duration of morning shower of the student A obtained by the fuzzy approach

Table 4 presents the time instant and the air temperature of the events recorded by the measuring system regarding to student A.

Table 4 - Instant of the shower of the student A and the corresponding air temperature obtained by measurement

Shower event	Time (h:min)	Temperature (°C)
A	7:33	22
B	8:44	22
C	8:49	22
D	8:57	22
E	9:10	22
F	9:27	22

Figure 11 shows the duration of the shower obtained from *in loco* measurements and that obtained by means of the fuzzy logic for the cases shown in Table 4. Since the measurement has been realized in a period whose patterns of daily temperature variation are almost the same, all the temperatures recorded in the peak periodo are very close to 22 °C.

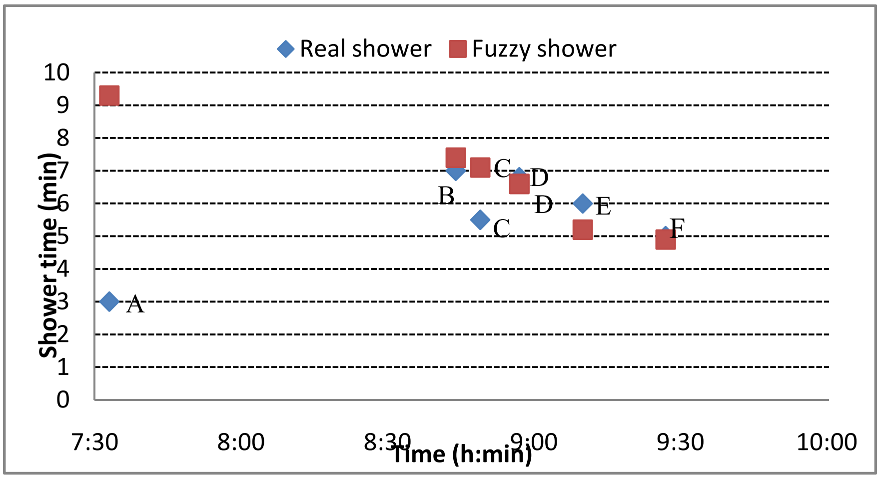

Figure 11: Shower times of the sudent A obtained by measurement in field and in real time by fuzzy logic

In Figure 11, it is observed that the measured and the calculated durations of the shower for the event A are quite different. There are two reasons for the discrepancy: the first one is that this shower was much more early than usual time of the student A and the second is that this shower have occurred in the weekend while the others had been in normal days of activities.

Thus, without considering this atypical event, which is expected because of some random events, the calculated duration of the shower of all other cases agrees well with the measured ones. This result gives some insight about the effectiveness of the approach based on Fuzzy Logic to estimate the duration of the usage of the sanitary appliances.

5. Final considerations

This paper presented the first stage of a research for the determination of design flow rate in a water supply system of multifamily buildings. This model considers Monte Carlo simulation for random variables and Fuzzy Logic to assess the duration of the shower in a residential apartment, due to it better represent the behaviour of the users. This first stage is focused on the assessment of the duration of shower by using fuzzy logic.

The fuzzy approach was validated by available measured data, and the results show good agreements between the measured and calculated ones. Thus, one of the great advantages of the approach is the ability of taking into account the influence of the subjectivity of the user on the usage of the sanitary appliances, mainly the showers.

In the second stage of the research, the simulation of the random events of the usage of all sanitary appliances will be carry out by using Monte Carlo simulation. The model will be validated by data of another apartments but the approach is very effective and serves as a basis for the development of a more accurate method to assess the design flow rate for the water supply system of the residential buildings.

Acknowledgements

The authors thank the Fundação de Apoio à Pesquisa do Estado de São Paulo - Fapesp for the financial support the research and the students of the monitored apartment.

6. References

[1] Gonçalves, O.M. Contribuições para a Economia e Qualidade dos Sistemas Prediais, Memorial circustanciado (Livre-docência junto ao Departamento de Engenharia de Construção Civil) - Escola Politécnica da Universidade de São Paulo, Brasil, 1997.

[2] Associação Brasileira de Normas Técnicas, NBR 5626: Instalação predial de água fria. Rio de Janeiro, Brasil, 1998.

[3] Gonçalves, O.M. Formulação de modelo para o estabelecimento de vazões de projeto em sistemas prediais de distribuição de água fria, Tese (Doutorado em Engenharia Civil) – Escola Politécnica, Universidade de São Paulo, São Paulo, Brasil, 1986.

[4] Kiatake, M.; Cheng, L.Y.; Petreche, J.R.D. Knowledge Representation of Architectural Design: A Case Study by Using IBIS-FRS System. Journal of Advanced Computer Intelligence and Intelligent Informatics, Fuji Technology Press, Japan, 9(6), 677-683, Nov. 2005.

[5] Shamblin, J.E.; Stevens Jr, G.T. Operation research – a fundamental approach. McGraw-Hill Book Company. New York, 1974.

[6] Von Altrock, C. Fuzzy-logic and neurofuzzy applications in business and finance, Prentice Hall PTR, New Jersey, United States, 1997.

[7] Cox, E. Fuzzy logic for business and industry, Charles River Media Inc, Massachusetts, 1995.

7. Presentation of Authors

Lúcia Helena is a professor at Department of Construction Engineering of Escola Politécnica of University of São Paulo where she teaches and conducts researches on building services.

Liang Cheng is a professor at Department of Construction Engineering of Escola Politécnica of University of São Paulo where he teaches and conducts researches on fuzzy analysis applied to designs, CFD simulations and graphical geometry for Engneering.

Orestes Gonçalves is a professor at Department of Construction Engineering of Escola Politécnica of University of São Paulo where he is the Head of the Building Services Research Group.

Pedro Massolino is a graduate student at engineering, Escola Politécnica of University of São Paulo.