C7 - A mathematical model for decision-making of a non-potable water system in residential buildings: decentralized in clusters or individual decentralized?

Dias, C. M., (1), Oliveira L.H (2), Kurokawa, F.A. (3)
1. christinemdias@gmail.com
2. lucia.helena@usp.br
3. fernando.kurokawa@usp.br
(1) Master's degree in Civil Engineering, University of São Paulo, *Escola Politécnica*, Department of Construction Engineering, Brazil
(2) Associate Professor, University of São Paulo, *Escola Politécnica*, Department of Construction Engineering, Brazil
(3) Assistant Professor, University of São Paulo, *Escola Politécnica*, Department of Construction Engineering, Brazil

Abstract

Among the options to restore the balance between supply and demand of water is the use of reclaimed water by deploying non-potable water systems, this being one of most used strategies today. Non-potable water systems can be of the centralized type, when the effluents from buildings are collected and transported to a single treatment site and redistributed to a set of dwelling buildings; or decentralized, when the collecting, transport and treatment of wastewater occurs near the production site. However, there is no consensus in the literature about what the most appropriate method is, since both centralized and decentralized systems have particularities that either do or do not make them attractive in social, economical and environmental terms. In this context, the aim of this article is to formulate a mathematical model for decision making to help find the optimum solution for a condominium with ten buildings. For this study, a bibliographic review was carried out with the purpose of collecting data about the main variables that interfere in the choice of each type of system. From the principles of Integer Programming, a mathematical model is formulated to reveal which type of system has the lowest total cumulative cost, how much the cost is over time, and how many systems need to be installed to meet a specific demand. Thus, based on the information in the literature consulted for this purpose, the decentralized-in-cluster system proved to be more advantageous than the individual decentralized system in terms of installation, maintenance and energy costs, considering a 20-year service life. However, the choice of the most viable system should not only focus on the costs involved, but should also take into account qualitative variables, such as the quality of the non-potable water produced.

Keywords

Non-potable water system; decision-making; decentralized-in-cluster system; decentralized system; integer programming

1 Introduction

The research work related to the use of non-potable water in individual decentralized systems focuses specifically on verifying the quality of the water offered and on the economic feasibility only in the first year of operation. However, other variables must be taken into account at the decision-making moment as to which non-potable-water building system will be employed in dwelling buildings.

The decision-making in the use of non-potable water in building systems must include all the risks involved in its adoption. Not only is it important to take into account the costs of acquiring and implementing the system, but also, and equally important, is the analysis of operating and maintenance expenses.

Oliveira *et al*. (2013) [1] set forth a model, based on the nearest-neighborhood algorithm, the results of which indicated that the centralized non-potable water system is more feasible economically than the decentralized one, but without considering how much the total cost is at the end of a given period of time.

Therefore, the aim of this paper is to formulate a mathematical model for decision making to afford the choice for the optimum solution for a condominium with ten buildings, but from the principles of Integer Programming.

2 Non-potable water systems

A building's water system has two water subsystems: potable and non-potable. Types of non-potable water in residential buildings after treatment include rainwater, wastewater and underground water.

In Germany and the United Kingdom, where scarcity of water is less critical, but environmental conservation is a real concern, institutions aim at researching new technologies to be implemented in buildings that use non-potable water, verifying the implications for health and the environment resulting from their use, and increasing the awareness and acceptance of users of reuse systems in dwelling buildings [2].

Brazil has the greatest undertaking in South America to produce non-potable water for industrial purposes – Aquapolo – which is apt to treat 1,000 liters/second of sewage, thereby saving approximately 2.58 billion liters/ month of drinking water [3]. However, reclaimed water is as yet little utilized in buildings.

2.1 Centralized and decentralized systems

Based on the concept of waste treatment systems, it is possible to establish a parallel with non-potable water systems of different scales. In centralized systems, wastewater from several buildings is collected and conveyed to a single place, and then is treated and distributed to the same or to another building for use. However, in decentralized systems, wastewater from a house or building is collected, treated and reused or disposed in locus or near the generation point [4], [5], [6].

The alternatives for a decentralized treatment are on-site or in clusters. The on-site system (in locus), the entire process of collection, transport, treatment, and reuse of non-potable water occurs in a single dwelling or building. In the scope of this study, the on-site systems are called individual decentralized systems. On the other hand, in-cluster systems, the collection of wastewater takes place in more than one building or community and is directed to an adequate treatment site, to then return to the population as non-potable water [5].

Based on the literature [4], [6], [7], [8], [9], [10], [11], no consensus exists as to which system, whether centralized or decentralized, is more attractive. Each one has particular advantages that must be evaluated considering both direct consequences, such as infrastructure and expenses involved, and indirect consequences in the systems, such as regional characteristics and environmental impacts.

2.2 Variables for decision-making regarding the type of system to be used

Low implementation, operating and maintenance costs are cited by most authors as important attributes when it comes to choosing the best alternative among centralized and decentralized systems. Nevertheless, the study conducted by [4], in Australia, showed that the belief that a non-potable water system represents a low-cost option of supply is a common mistake made today.

Owing to lack of knowledge, the development of building non-potable water systems usually bases feasibility on expenses arising from the construction of the system and treatment of effluents. In this case, it disregards indirect costs, such as acquisition of the plot of land, labor, machinery, infrastructure, operation, maintenance, and paralyzation of the system, which means that the actual cost of non-potable water production is much higher than that forecasted initially [12]. In addition, the investments carried out are entirely related to the standard of water quality, depending on the activities at which they are aimed in buildings [13].

There are four factors that influence the decision-making process concerning decentralization, especially in the case of small communities: costs, flexibility in the use of the territory owing to smaller physical occupation as compared to centralized systems, maintenance, and environmental protection [14]. Thus, the main variables that interfere in the decision-making as to which system to utilize are presented as follows.

2.2.1 Demand and supply

On analyzing the daily capacity of the production of a non-potable water system, one notices a decrease in the cost of a liter of water with an increase of scale of the system, which may lead to increases in the installation and operating costs for individual decentralized systems [4].

2.2.2 Types of treatment

Regardless of whether the system is centralized or decentralized, the protection of public health must be the main focus of the project developed. Therefore, the costs involved in the generation of non-potable water are directly proportional to its final quality.

2.2.3 Implementation, operating and maintenance cost of the system

While the majority of treatment types favor the choice for centralized systems since they involve better-known technologies and offer more control of the inputs received, the cost of carrying out distribution and collection systems favors decentralization, due to the proximity of effluent generation points to the site of treatment and consumption of non-potable water [15]. However, in individual decentralized or decentralized-in-cluster systems, the overall implementation costs of various treatment stations may be higher than the investment in a single centralized unit, which produces higher volume of non-potable water.

As to the operating and maintenance costs regarding chemical products, electric energy, employees, and equipment, [12] divides them into fixed and variable costs. According to the authors, the fixed costs do not depend on the volume of water treated and reused, whereas variable costs are proportional to the amount of effluent generated. For example, the more the demand for non-potable water, the greater the use of energy for the treatment and pumping of the input. It is important to estimate the values spent with operational and preservation services, for they will never be nonexistent throughout the system's lifecycle.

Considering the total resources spent in auxiliary activities of centralized treatment stations, maintenance represents approximately 36% of the total cost of such expenditure [16]. This means that while planning a non-potable water treatment station, it is essential to consider the costs involved in its maintenance, since the cumulative effect of such in few years can surpass the value spent on its construction. Moreover, in the study developed by [17] in 338 wastewater treatment stations in Spain, the authors verified that the maintenance and management costs are the most important factors, which show the differences between stations in terms of efficiency.

2.2.4 System monitoring

The management of non-potable water quality helps reduce the risk of contamination of the users. With this in mind, [12] show that the number of professionals required depends on the type and size of treatment, and on the system's automation, with the costs with labor decreasing as the production of non-potable water increases. Thus, albeit more judicious, the management of a centralized system can be more economical, since the cost of hiring a qualified and permanent team is lower than the overall cost of various outsourced teams for all the individual systems implemented.

2.2.5 Electric energy consumption

A balance carried out in the United Kingdom showed that, in fact, reuse systems afford a reduction in the consumption of drinking water, but lead to somewhat increased energy consumption owing to the utilization of equipment to collect, treat, and distribute water throughout the building system [18]. In centralized systems, some 41 to 44% of expenses correspond to pumping effluents [7], [16].

In Brazil, the majority of buildings have indirect water supply systems, that is, they have lower and upper water storage tanks. Thus, when a non-potable water system is installed, the demand for repression energy is needed both for drinking water and for non-potable water. Consequently, greater volumes of treated and reused water imply greater energy expenditure. However, the consumption of a smaller amount of reclaimed water implies a smaller reduction in the consumption of drinking water, thus rendering reuse little appealing.

This situation was observed in California, in the U.S., where an energy consumption of 10.3 kWh/m^3 was observed in a decentralized system as opposed to a consumption of 1.9 kWh/m^3 in a centralized system for the same volume of treated water. The authors concluded that decentralized systems require seven times more energy to operate than a centralized system [6].

Therefore, regarding the decision for decentralized or centralized systems based on the energy consumption, one verifies advantages and disadvantages in each one of the systems. The overall energy consumption for the treatment of effluents from various decentralized systems can be much higher than that of a centralized system that caters to the same set of buildings.

3 Methodology

In this study, a bibliographical research was conducted with the purpose of collecting data that may characterize and compare individual decentralized systems with decentralized-in-cluster systems. Moreover, based on the information obtained and with the assistance of Integer Programming, it was possible to formulate a mathematical decision-making model, wherein the solution is determined using the LINDO™ software. The general formulation of the model is set forth as follows.

3.1 General formulation of the decision-making model

This model has the purpose of answering which type of system – individual decentralized or decentralized-in-cluster – offers the lowest overall cost and what the value of the total cumulative cost is in the period of analysis, taking as a basis the data in the references consulted.

Considering X_{ij} the decision-making variable that represents the possibility or impossibility of installing a given available system, where i represents the type of system ($i = 1,2,\dots,n$) e j

is the type of cost relative to that type of system ($j = 1, 2, \dots, m$), a general formulation for a decision-taking model can be given by:

$$(\text{MIN}) \quad Z = \sum_{i=1}^{n} \sum_{j=1}^{m} A_{ij} X_{ij}$$

$$s.a. \quad \begin{cases} \sum_{i=1}^{n} X_{ij} = 1, & j = 1,2, \dots m \\ X_{ij+1} - X_{ij} \leq 0, & i = 1,2, \dots, n \text{ and } j = 1,2, \dots m-1 \\ X_{ij} \in \{0, 1\} & \forall\, i, j \end{cases} \tag{1}$$

where the coefficients A_{ij} of the objective function (Z) represent the costs (implementation, maintenance, operation, etc.) relative to each type of system.

It is important to point out that the values of i and j change according to the number of system types available to the designer and to the costs needed to make the comparison.

In Equation (1), the objective function (Z) is minimized since the aim is to find the lowest total cost, and it is subject to restrictions (s.a.), represented by inequalities.

The m first equations represent mutually exclusive groups of alternatives, i.e., in each equation, only one variable can be equals one, because the model must return as a final result the possibility of there being only one cost, such as an implementation cost, a maintenance cost, an operating cost, and so forth. Thus, the variables that represent other costs must be equals zero.

The $n + m$ inequalities within the brace refer to contingent decisions, i.e., that may or may not occur, but that depend on the results of previous decisions. In this case, whatever the answer to variable X_{11}, consequently variables $X_{12}, X_{13}, \dots, X_{1m}$ will have the same results. The same is true for the other variables of the model.

This model was formulated based on the principles of Integer Programming with variables 0 and 1. Thus, a variable $X_{ij} = 1$ means the possibility of installing one of the n options available, taking into account the necessary costs, whereas a variable $X_{ij} = 0$ represents the impossibility of installation due to the fact that another option has a lower total cumulative cost.

4 Case study

In this section, results for the decision-taking model and considerations made for the solutions found concerning the type of system to be installed in a hypothetical residential condominium with approximately 1,700 dwellers are presented. It must be pointed out that the model was formulated in order to compare the total costs of individual decentralized systems with decentralized-in-cluster systems involving different types of treatment, which may be implemented in this residential condominium. For this case study, the implementation, maintenance and operating costs were taken into account.

4.1 Characteristics of the systems used in the study

The data used for the formulation of the model are based on the characteristics of the systems detailed in [19] and [20]. Moreover, the absent information was adapted from [21]. In Table 1, the costs referring to the populations indicated in each literature source are shown in detail. The values were rounded off to simplify the model setting.

Table 1 Population, costs and energy consumption in each system indicated in the literature in the year of the systems' operation

System	Type of Treatment	Maximum Population Served	Implementation Cost (US$)	Maintenance Cost (US$/year)	Operating Cost (US$/year)
1	Rotating Biological Contactor (RBC) [1]	170 [1]	43,486 [1]	16,780 [1]	0 [1]
2	Physical-Chemical [2]	360 [2]	60,642 [2]	23,824 [2]	656 [2]
3	UASB Reactor with Aerated Submerged Biological Filter [3]	1,719 [3]	305,229 [3]	7,640 [4]	5,809 [4]

Source: elaborated from [19], [20], [21], [22].

It is emphasized that in this study the implementation cost includes expenses with the acquisition of the system and the civil works needed for its installation. The maintenance cost includes the chemical-physical analysis of the non-potable water produced, the replacement of chemical products, the removal of sludge, and the cleaning of equipment, components and tanks. On the other hand, the operating cost comprises the consumption of electrical energy for the treatment of wastewater, as obtained in the data of the literature. Consumptions related to the operation of pumps for the repression of the non-potable water produced were not accounted for.

Moreover, we point out that the expenses related to lubrications, adjustments and replacements of components and accessories, and to the corrective maintenance for the replacement of equipment were not accounted for in the calculation of the maintenance costs. In addition, since no data were found in the literature regarding the actual rate of adjustment of the maintenance costs of different types of treatment of non-potable water, it was considered that the maintenance costs of the three systems of analysis have a symbolic increase of 1% per year.

4.2 Characteristics of the hypothetical residential condominium

Aiming at comparing the decentralized-in-cluster systems and the individual decentralized systems, it was considered that these systems would be implemented in a hypothetical condominium, comprised of ten 14–storey residential buildings with four apartments per floor, and with a capacity to roof an average population of 170 persons, thus totaling at least 1,700 dwellers.

The designer finds the three systems shown in Table 1 available in the market. Thus, according to maximum populations served, the options to distribute the systems in order to cater to the demand of the condominium are the following:

- Option 1: ten units of individual decentralized systems, composed by system 1, and able to supply the demand of 1,700 dwellers;
- Option 2: five units of decentralized-in-cluster systems, consisting of system 2, and able to supply the demand of 1,800 dwellers;
- Option 3: one unit of decentralized-in-cluster system, represented by system 3, and able to supply a demand of 1,719 dwellers.

4.3 Decision-making model

The model formulated for this case aims to answer what the lowest total cumulative cost is among the three options of system distribution available to the designer, with the data obtained in the consulted references serving as a basis.

Thus, taking into account the implementation, maintenance and operating costs, from Equation (1), the following decision-making model is attained for each operation quinquennium of the systems:

$$\text{(MIN)} \quad Z = A_{11}X_{11} + A_{12}X_{12} + A_{13}X_{13} + A_{21}X_{21} + A_{22}X_{22} + A_{23}X_{23} + A_{31}X_{31} + A_{32}X_{32} + A_{33}X_{33}$$

$$s.a. \begin{cases} X_{11} + X_{21} + X_{31} = 1 \\ X_{12} + X_{22} + X_{32} = 1 \\ X_{13} + X_{23} + X_{33} = 1 \\ X_{12} - X_{11} \leq 0 \\ X_{13} - X_{12} \leq 0 \\ X_{22} - X_{21} \leq 0 \\ X_{23} - X_{22} \leq 0 \\ X_{32} - X_{31} \leq 0 \\ X_{33} - X_{32} \leq 0 \\ X_{ij} \in \{0, 1\} \end{cases} \qquad (2)$$

where the coefficients of the objective function correspond to:

- A_{i1} – implementation cost of option i;
- A_{i2} – maintenance cost of option i, cumulative over time;
- A_{i3} – operating cost of option i, cumulative over time.

The coefficients A_{i2}, referring to the maintenance costs cumulative over the time of analysis, are calculated as follows:

$$A_{i2} = C_{i2} + C_{i2} \times (1+t) + \cdots + C_{i2} \times (1+t)^{n-1} \qquad (3)$$

where:

- C_{i2} is the maintenance cost of option i in the frst year of operation, which corresponds to the sum of the maintenance cost of each type of system included in option i;
- t corresponds to the rate of yearly increase in the maintenance cost defined for each option i;
- n is the service life, in years, determined to conduct the analysis.

And the coefficients A_{i3}, which represent the operating costs cumulative over the time of analysis, are calculated according to Equation (4):

$$A_{i3} = C_{i3} + C_{i3} \times (1+s) + \cdots + C_{i3} \times (1+s)^{n-1} \qquad (4)$$

in which:

- A_{i3} is the operating cost of option i in the first year of operation, equals to the sum of the operating cost of each type of system included in option i;
- s corresponds to the rate of annual adjustment in the charge of electric energy. In this research, a rate of 10.35% per year was used for this purpose.
- n is the service life, in years, determined to carry out the analysis.

For this model, total costs were calculated referring to the implementation of each option to meet the demand of the condominium. Regarding options 1 and 2, which have more than one system, the total cost was calculated by multiplying the costs of one system by the amount to be implemented in the condominium.

Table 2 shows the costs of each option for the first year of operation, considering the characteristics of the systems detailed in [19], [20], [21], [22].

Table 2 Costs of each option in the first year of operation

Option	Type of System	Number of Systems	Implementation Cost (US$)	Maintenance Cost (US$/year)	Operating Cost (US$/year)
1	**Individual Decentralized**	**10**	**434,860**	**167,800**	**0**
2	**Decentralized-in-Cluster**	**5**	**303,210**	**119,120**	**3,280**
3	**Decentralized-in-Cluster**	**1**	**305,229**	**7,640**	**5,809**

Source: elaborated from [19], [20], [21], [22].

Considering that the maintenance costs of the systems have an adjustment rate of 1% per year, Table 3 shows the cumulative maintenance costs of each option in each quinquennium of analysis.

Table 3 Cumulative maintenance costs of the options for the quinquenniums of analysis

Option	Cumulative Maintenance Cost (US$)				
	1st year	5th year	10th year	15th year	20th year
1	**167,800**	**855,780**	**1,753,510**	**2,693,190**	**3,674,820**
2	**119,120**	**607,512**	**1,244,804**	**1,911,876**	**2,608,728**
3	**7,640**	**38,964**	**79,838**	**122,622**	**167,316**

Source: elaborated from [19], [20], [21], [22].

As indicated in Item 3.1, the rate of adjustment of the operating cost was regarded as 10.35% a year. Thus, Table 4 shows the summary of the cumulative operating costs of the options at every five years of operation.

Table 4 Cumulative operating costs of the options for the quinquenniums of analysis

Option	Cumulative Operating Cost (US$)				
	1st year	5th year	10th year	15th year	20th year
1	**0**	**0**	**0**	**0**	**0**
2	**3,280**	**20,165**	**53,160**	**107,150**	**195,494**
3	**5,809**	**35,712**	**94,149**	**189,767**	**346,228**

Source: elaborated from [19], [20], [21], [22].

Therefore, based on the data of Tables 2, 3 and 4, the objective function of equation (2) in the twentieth year is given by:

$$\text{(MIN)}\ Z = 434{,}860X_{11} + 3{,}674{,}820X_{12} + 0X_{13} + 303{,}210X_{21} + 2{,}608{,}728X_{22} + 195{,}494X_{23} + 305{,}229X_{31} + 167{,}316X_{32} + 346{,}228X_{33} \quad (5)$$

4.4 Results and discussion

With the model formulated, the data were inserted into the software LINDO™, so as to find the solution for each year of operation. Figure 1 displays the solution obtained for the decision-making model considering the twentieth year of operation of the systems:

```
OBJECTIVE FUNCTION VALUE

     1)      818773.0

 VARIABLE        VALUE
      X11          0.000000
      X12          0.000000
      X13          0.000000
      X21          0.000000
      X22          0.000000
      X23          0.000000
      X31          1.000000
      X32          1.000000
      X33          1.000000
```

Figure 1 – Results provided by the software LINDO™ for the model formulated

Table 5 displays the synthesis of the results obtained for each quinquennium.

Table 5 Synthesis of the results obtained

Service Life (year)	Objective Function Result (US$)	Option	Type of System	Type of Treatment
01	**318,678**	**3**	**Decentralized-in-cluster (one system)**	**UASB Reactor with Aerated Submerged Biological Filter**
05	**379,905**	**3**	**Decentralized-in-cluster (one system)**	**UASB Reactor with Aerated Submerged Biological Filter**
10	**479,216**	**3**	**Decentralized-in-cluster (one system)**	**UASB Reactor with Aerated Submerged Biological Filter**
15	**617,618**	**3**	**Decentralized-in-cluster (one system)**	**UASB Reactor with Aerated Submerged Biological Filter**
20	**818,773**	**3**	**Decentralized-in-cluster (one system)**	**UASB Reactor with Aerated Submerged Biological Filter**

Source: obtained from [19], [20], [21], [22].

As shown in Figure 1 and Table 5, option 3, which consists in the implementation of a decentralized-in-cluster system unit, the principle of treatment of which is the combination of a UASB Reactor with an Aerated Submerged Biological Filter, offered the lowest overall cost during the service life period of the compared options, based on the first information provided in [19], [20], [21], [22].

Figure 2 represents the total cumulative cost of each option throughout the service life considered. It can be seen from this figure, the difference between the total cumulative costs of the three options available. It is clear that even without consuming electric energy, option 1, with 10 individual decentralized systems, has the highest total cost. Moreover, it can be seen that the advantage of option 3, the implementation of a decentralized-in-cluster system unit, is mainly attributed to the fact that its annual maintenance cost is much lower than that of options 1 and 2, as shown in Table 1.

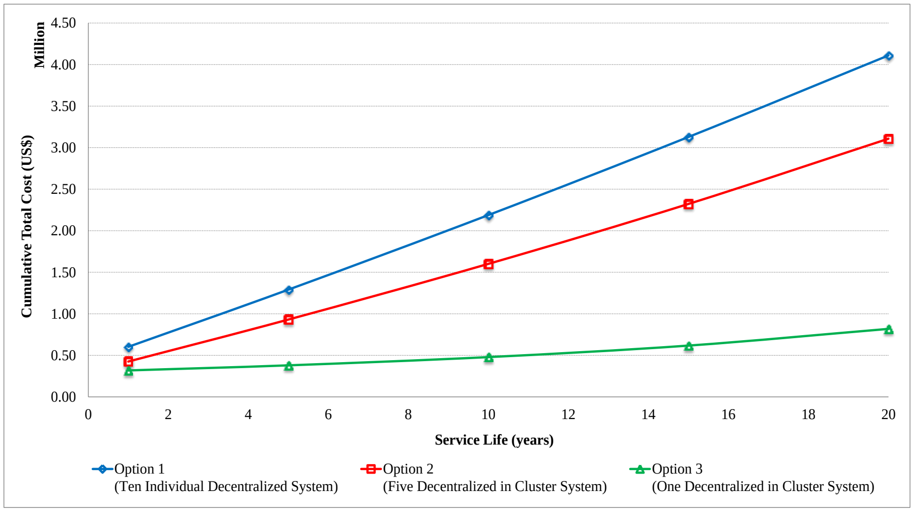

Figure 2 – Total cumulative cost during the service life of the options available for a condominium with 1,700 dwellers

5 Final considerations

The principles of Integer Programming afforded a decision-making mathematical model, which made it possible to indicate which type of system offers the lowest total cumulative cost and what the value of this cost is at the end of a given period of time to cater to a specific demand.

Through the sources consulted, the results obtained pointed out the importance of analyzing cost performance throughout the service life of the systems, as well as the relevance that all the variables inserted into the model have, because the type of treatment or system that seems competitive at first may prove to have a higher total cumulative cost as compared to other options available.

Moreover, we would like to point out that the formulated model can be improved should it consider different maintenance frequencies for each type of treatment, and, also, the influence of a scale effect on maintenance costs, resulting from the increase of population and from the number of systems implemented for each option.

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7 Presentation of Authors

Christine Miranda Dias holds a Master’s of Civil Engineering from *Escola Politécnica* of the University of São Paulo, Department of Construction Engineering. Her thesis is the issue of models for decision-making of non-potable water in buildings.

Lúcia Helena de Oliveira is an associate professor at the Department of Construction Engineering of *Escola Politécnica* of the University of São Paulo, where she teaches and conducts research work on building services.

Fernando Akira Kurokawa is an assistant professor at Department of Construction Engineering of *Escola Politécnica* of University of São Paulo, where he teaches and conducts researches on CFD simulations and graphical geometry for engineering.