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Energy planning for aquaponics production considering intraday markets

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Abstract: The smart household connected to the energy dispatch arises to overcome the environmental crisis, encourages the penetration of renewable energies and promotes consumer respond to intraday market prices. Aquaponic production results from the combination of fish farming and hydroponics (cultivating plants using fish waste as nutrients). The prototype was built based on the rule of the 3 Rs: reduce, reuse and recycle. The crop reduces the consumption of water and energy, reuses water in a recirculation process, which is filtered by: 1) gravity, 2) biofilters and 3) porosity. Recycling is expanded to plastic containers and food containers of polystyrene. The aquaponic production system is decorative, completely organic (without chemicals), promotes the growth of green areas for comfortable homes and allows the consumption of healthy food, as well as energy planning to save energy. The system is done with a digital level control connected to a water pump and an oxygen pump. A novel method allows the aggregator to optimize the recirculation programming of the aquaponic system for periods of 24 hours. The method maximizes the economic benefits with the help of an energy balance between hours.

Key words: aquaponic system, energy programming, intraday markets, smart household

1. Introduction

Global environmental problems include an increase in population, public health, climate change, water scarcity, effluents, soil degradation, increasing demand for food and energy [1]. Smart grids face many of these issues when connected to smart homes [2]. Smart homes allow

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residents to respond to market signals (response to demand) by programming their energy consumption. Traditional strategies consist of taking groups of clients and managing their intraday consumption (refers to a forecast horizon that does not exceed 24 hours a day) [3, 4]. Clients have limited knowledge, thus their change of habits cannot be guaranteed. Smart homes integrate energy consumption controllers, which serve the clients to reflect on their costs of energy [2].

In Colombia, the purchase and sale of energy is done in the scheduled dispatch. This allows the generators to send their price offers for the whole day and the availability of units per hour the day before. The price of the offer cannot be modified, however, the declared availability can be updated before the operation without implying a commercial penalty for the deviation. In these cases redispatches are performed (reprogrammed dispatches), which causes two non-optimal situations: 1) the difficulty in verifying the cause of the redispatch and 2) the National Dispatch Center (CND by its initials in Spanish) knows only offers and availabilities of the previous day, thus it is limited to taking advantage of resources. In this area, the CREG 004B proposes that the scheduled dispatch changes from being indicative to binding [5].

Considering the implementation of intraday markets, the construction of an aquaponic system for the production of fish and vegetables in smart homes is proposed. Smart homes with aquaponics production have two common goals: comfort and saving energy [1, 4]. The aquaponic systems bring together two technologies: recirculation systems in fish farming and hydroponic systems (production of plants in water without soil) [6]. Households with the aquaponics production arise from the need to improve the production and consumption of healthy food. The cultivation of food and the production of fish with sustainability require innovations that exceed traditional paradigms [6].

The prototype was built based on the rule of the 3 Rs; reduce, reuse and recycle. The crop reduces the consumption of water and energy. The water consumption is reduced because it is not replaced, as the recirculation process fulfills the function of clarifying by using a filter system and the energy consumption is minimized using a digital control for periods (this consideration aims to overcome the problem that many aquaponic systems are not cost effective) [1]. The toxic ammonium produced by the fish is converted into nitrate, through the filter system by: 1) gravity, 2) biofilters and 3) porosity. The gravity system allows excess nutrients to be removed from the fish. Biofilter bacteria provide nitrogen for plants. The porous filter clarifies the water supplied to the fish according to Darcy's law [7].

The paper has the following structure. Section 2 studies the advances in energy management systems for aquaponic systems. Section 3 presents the physical structure of the aquaponics production prototype. Section 4 presents the contribution of this article regarding the formulation of energy planning. Section 5 presents the solution method implemented. Section 6 shows the results. Section 7 presents the discussion around the results obtained and other technologies. Finally, section 8 presents the conclusions.

2. State of art

This proposed work contributes to: 1) sustainability in homes (SH), 2) filter system (FS) and 3) energy planning (EP). Table 1 shows the analysis of constructed prototypes of aquaponic systems. The aquaponic system 1 produces lettuce and goldfish for horticulturists in Bogotá and is proposed to control the pH in the future [8]. Aquaponic system 2 produces oregano *Origanum*

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vulgare and fish. Variables such as plant growth and water nitrate indicators are measured and are slightly decorative [9].

Table 1. Prototypes of aquaponic systems

No.	SH	FS	EP	Comments
1	No	Yes	No	Includes a biofilter and a clarifier [8]
2	No	Yes	No	Includes a biofilter [9]
3	No	Yes	No	Includes a biofilter [10]
4	No	Yes	Yes	Includes a biofilter and a clarifier [11]
5	No	Yes	No	Includes a biofilter and a clarifier [12]
6	Yes	Yes	Yes	Includes a biofilter, a clarifier, energy costs and a gravity filter

Aquaponic system 3 cultivates peppermint *basilicum, Menta x piperita* and *M. spicata* and Nile tilapia. They measure water indicators such as nitrogen and phosphorus [10]. Aquaponic system 4 produces vegetables (lettuce, basil and cherry tomato) and tilapia at small, medium and large scale. They perform the quantification of the economic costs of energy, but they lack strategies to reduce energy consumption [11]. Model 5 proposes a revision on the importance of the use of the waste generated by the fish and used by the plants in the implementation of aquaponic crops [12].

The aquaponics prototype 6 is the one proposed in this article, which was adapted to operate in the homes of Ocaña for the production of tilapia *Oreochromis sp.* and chili pepper *Capsicum*. The prototype has a system for monitoring the main variables such as: growth of the plants, PH of the fish tank, relative humidity and air temperature. It has a filtration system for cleaning the hydraulic network and capturing the nutrients required by the plant. The filtration system consists of a gravity filter, which allows excess nutrients to be removed. The biofilter promotes root development and nutrient capture, and the porous filter is a water clarifier, which has the level control of a necessary amount of water, so that the plants have a continuous supply of organic fertilizer. In addition, the implementation of intraday markets was considered to reduce energy costs. The prototype of aquaponics production is able to respond to demand, that is, its energy consumption changes depending on the price offer.

3. Acuaponic production

The prototype is designed to monitor the variables of flow, pH, growth, temperature and relative humidity. The aquaponic system operates in Ocaña, where the average room temperature is 25°C, relative humidity is 91% and altitude is 1 202 m above sea level. The cultivated plant is the chili pepper *Capsicum Annuum*, which is typical of this region (Fig. 1(a)). The type of fish used was red tilapia *Oreochromis sp.* ideal for pond production (Fig. 1(b)).

The rule of the 3 Rs, reduction, reuse and recycling, serves as criteria to build the prototype. A styrofoam tray and recycled plastic containers house the biofilter with the plants to be cultivated (Fig. 2(a) and (b)). The filter system reduces water consumption up to 90% [6]. The water circulates through the gravity filter, which captures the heavy particles. The biofilters nourish the plants

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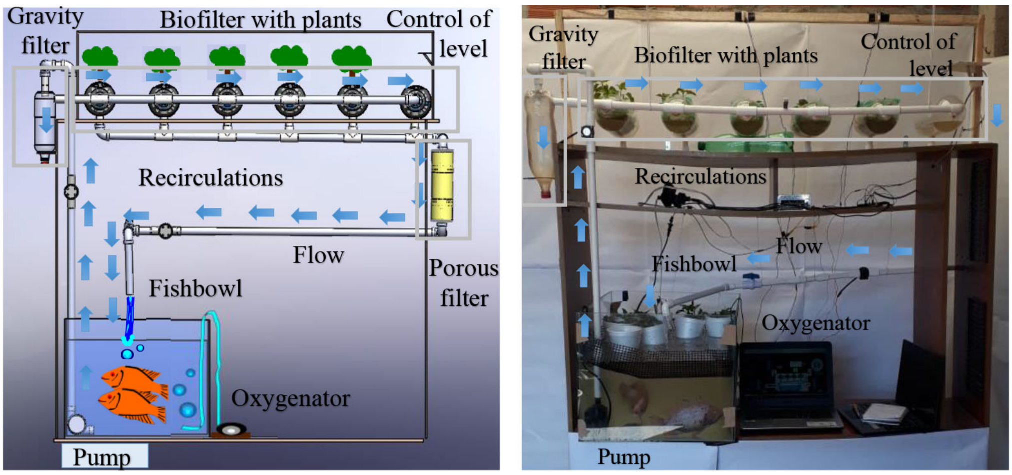
(a) (b)

Fig. 1. Agronomy supplies: cultivation of chili pepper (a); production of red tilapia (b)

and transform the toxic residues of the fish into nitrate. The porous filter clarifies the water, with a determined pressure drop [9]. The level control ensures that there are no spills. The latter is linked to an intraday electric market, which has a price curve for electric power per hour. The contribution of this article consists in the implementation of heuristic optimization algorithms, to perform recirculations when energy is cheaper. The implementation is done once the prototype has been built (Fig. 2(b)).



(a) (b)

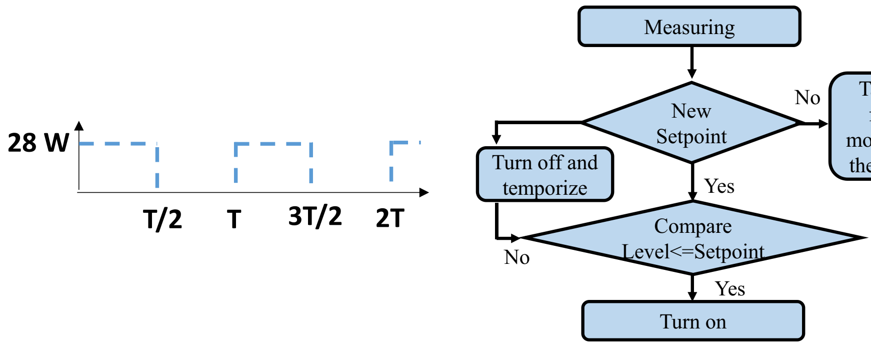
Fig. 2. Aquaponics production: design (a); prototype (b)

4. Energy planning

The control system and oxygen pump consume a power of 28 W and 0.5 W, respectively.

4.1. Timed control system

A timed control device with relay output (an electromagnetic device on and off) decreases energy consumption to 50% in the periods of circulation, as shown in Fig. 3(a). The power consumption is 14 W because in the periods of ignition, the oxygen pump goes off. The fish receives the oxygen when the water jet falls into the fish tank, which is maintained without interruption due to the level control.



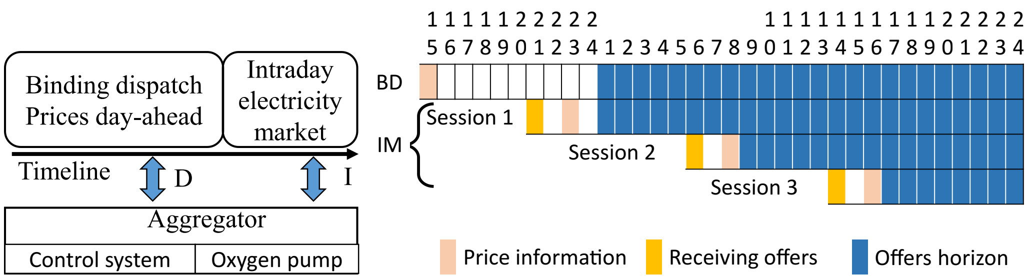
(a) (b)

Fig. 3. Timed control: energy consumption (a); flow diagram output to relay (b)

The water level control has an HC SR04 sensor that takes the readings in millimeters, an Arduino Uno card, where the data is stored in the WPROM, and a Bluetooth terminal mobile app HC-05 that allows changing the setpoint with the cell phone to avoid spills and the data can be sent in real time using the WhatsApp application. Fig. 3(b) shows the flow diagram of the control system.

4.2. Load control with intraday markets

The objective of the aggregator is to solve energy needs from the binding dispatch (BD) and intraday electricity markets (IMs). The aggregator decides when recirculations should be carried out and operates after the close of the binding dispatch. Thus, it has a one-day forecast horizon, chooses the 4 hours in which it must perform the recirculations and in which market to make the purchase as shown in Fig. 4(a) [13].



(a) (b)

Fig. 4. Intraday markets and binding dispatch: description of the problem (a); scheduling (b)

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4.3. Intraday markets and binding dispatch

In Colombia, the authors of [5] propose a timetable with three intraday auctions that are symmetric. Symmetry favors the participation of agents. The implementation of three symmetric intraday markets is presented in Fig. 4(b).

4.4. Uncertainty of electrical markets

The Monte Carlo Simulation (SMC) technique generates 5 000 scenarios and uses a probability function. The scenarios are created according to (1) [14].

$$Xs(t) = x^{\text{forecast}}(t) + x^{\text{error},\, s}(t), \tag{1}$$

where $x^{\text{error},\, s}$ is the normal probability distribution with zero mean and the standard deviation σ, and x^{forecast} is the forecast value over time [14]. In the second case, a technique called the Bender decomposition is used to exclude scenarios with low probability and combinations with statistical metrics [15].

4.5. Scenario reduction

The scenarios are reduced to 500 using the expected value of the perfect information (EVPI), Equation (2) is a metric of the most likely scenario. The EVPI represents the number of decisions that the policyholder has to pay to obtain perfect information about the future. The term z^{S*} is the stochastic solution and z^{P*} represents the wait-and-see solution, all the variables are defined as dependent on the scenario [15].

$$\text{EVPI} = z^{S*} - z^{P*}. \tag{2}$$

The value of the stochastic solution (VSS) measures the advantage of applying the stochastic programming approach to a deterministic problem (3) [15]. z^{D*} is the optimal value of the modified stochastic problem [15].

$$\text{VSS} = z^{D*} - z^{S*}. \tag{3}$$

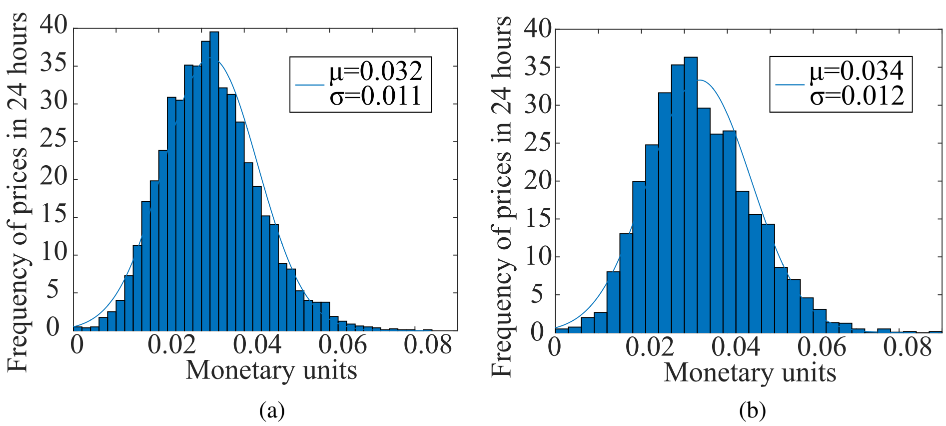
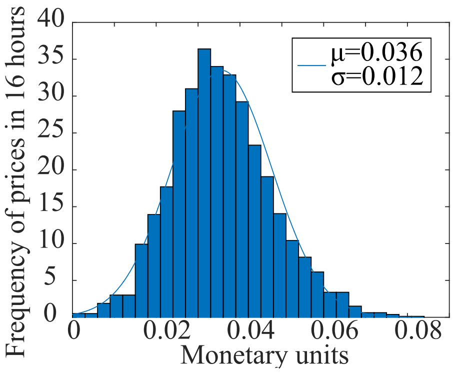
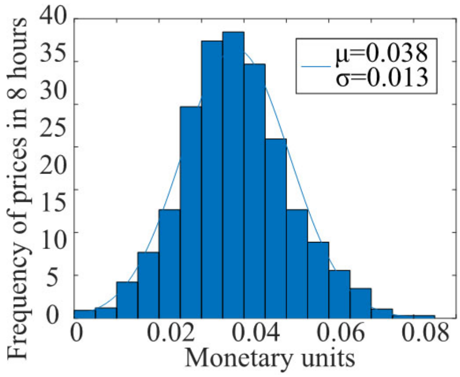


Fig. 5. Scenarios: binding dispatch (a); intraday market 1 (b)

The 500 scenarios are permuted by choosing groups of maximum 166 scenarios with a normal probability function. The user can choose the form of evaluation using 1 to 166 scenarios. The scenarios are taken from [14] and the histogram, the mean μ, the standard deviation σ for 166 binding dispatch scenarios and intraday markets 1, 2 and 3 are shown, respectively in Fig. 5(a) and (b), and in Fig. 6(a) and (b).



(a)



(b)

Fig. 6. Scenarios: intraday market 2 (a); intraday market 3 (b)

4.6. Objective function

The implementation of three intraday markets proposes a function divided into 3 parts. The energy costs to be minimized are presented in (4), while the first and second terms within the parentheses represent the purchase transactions in the binding dispatch and the intraday market 1, both with a horizon of one day. The third term within the second and third parentheses represents the intraday market 2 with a horizon of 16 hours and the fourth term of the third parenthesis represents the intraday market 3 with a horizon of 8 hours. The variables x are binary and state that if "1" indicates that there was a transaction and if it is "0", there was no transaction. P indicates the power consumed in W by the aquaponic prototype. The probability of occurrence of scenarios is denoted by $\pi(s)$. PM indicates the price market, N_S indicates the number of scenarios and T indicates the time.

$$\begin{aligned}
\text{Minimize Co} = &\sum_{s'=1}^{N_S}\sum_{t=1}^{T=8}\left(P_{\text{buy}(t,s)}\cdot\left(x_{\text{Day+1}(t,s)}PM_{(t,s)}^{\text{Day+1}} + x_{\text{Iday 1}(t,s)}PM_{(t,s)}^{\text{Intraday 1}}\right)\right)\cdot\pi(s)+ \\
&+\sum_{s'=1}^{N_S}\sum_{t=9}^{T=16}\left(P_{\text{buy}(t,s)}\cdot\left(x_{\text{Day+1}(t,s)}PM_{(t,s)}^{\text{Day+1}} + x_{\text{Iday 1}(t,s)}PM_{(t,s)}^{\text{Intraday 1}}\right.\right. \\
&\qquad\left.\left.+x_{\text{Iday 2}(t,s)}PM_{(t,s)}^{\text{Intraday 2}}\right)\right)\cdot\pi(s)+ \\
&+\sum_{s'=1}^{N_S}\sum_{t=17}^{T=24}\left(P_{\text{buy}(t,s)}\cdot\left(x_{\text{Day+1}(t,s)}PM_{(t,s)}^{\text{Day+1}} + x_{\text{Iday 1}(t,s)}PM_{(t,s)}^{\text{Intraday 1}}+\right.\right. \\
&\qquad\left.\left.+x_{\text{Iday 2}(t,s)}PM_{(t,s)}^{\text{Intraday 2}} + x_{\text{Iday 3}(t,s)}PM_{(t,s)}^{\text{Intraday 3}}\right)\right)\cdot\pi(s)
\end{aligned}, \quad (4)$$

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which are subject to the restrictions of (5). This indicates that a transaction is made every hour as well as Equation (6) indicates that the oxygen pump remains on for 20 hours and recirculations are carried out for 4 hours (7). This restriction also takes into account that the oxygen pump cannot operate at the same time as the control system of the aquaponics prototype (8).

$$x_{\text{Day+1}(t,\,s)} + x_{\text{Iday 1}(t,\,s)} + x_{\text{Iday 2}(t,\,s)} + x_{\text{Iday 3}(t,\,s)}, \tag{5}$$

$$\sum_{t=1}^{T=20} P_{\text{oxygen pump}(t,\,s)} + 10\,\text{W} \quad \text{for a day}, \tag{6}$$

$$\sum_{t=1}^{T=4} P_{\text{control system}(t,\,s)} + 56\,\text{W} \quad \text{for a day}, \tag{7}$$

$$\sum_{t=1}^{T=24} P_{(t,\,s)} = \sum_{t=1}^{T=20} P_{\text{oxygen pump}(t,\,s)} + \sum_{t=1}^{T=4} P_{\text{control system}(t,\,s)} = 66\,\text{W} \quad \text{for a day}, \tag{8}$$

$$\text{for } t = 1, \ldots, \cdot T \cdot y \cdot s = 1, \ldots, N_S, \quad x_{\text{Day+1}(t,\,s)} \in \{0,\ 1\}, \quad x_{\text{Iday 1}(t,\,s)} \in \{0,\ 1\}, \quad x_{\text{Iday 2}(t,\,s)} \in \{0,\ 1\}, \quad x_{\text{Iday 3}(t,\,s)} \in \{0,\ 1\},$$

5. Solution strategy

This problem proposed by the objective function is called a knapsack problem [16]. The authors in [16] propose an objective function with 3 decision variables called lighting, refrigerator, TV and decoder. The calculation of response options is greater than 5 184, thus it can obtain a direct solution. The problem proposed in this article is superior to 402 billion feasible solutions and contemplates the price uncertainty of the binding dispatch and intraday markets.

The calculation is obtained by the multiplication of 2^8*3^8*4^8*3654 = 402 billion. The 2^8 represents the operation of the binding dispatch and the intraday market 1 for 8 hours. The 3^8 represents the operation of the two previous markets plus the intraday market 2 for 8 hours. The 4^8 represents the operation of the binding dispatch and all intraday markets for 8 hours, and 3 654 are the options due to the knapsack problem, which consist in turning on the aquaponic control system for 4 of the 24 hours a day. According to the problem, the objective function and the solution method are evaluated.

5.1. Objective function

The authors in [14] propose, for uncertainty cases, to use a ranking index (RI) as the sum of the average operating costs plus the standard deviation (4.6).

$$\text{RI} = \text{Average}\,(\text{Co}) + \sigma\,(\text{Co}). \tag{9}$$

5.2. Selection of the algorithm

Metaheuristics include a variety of strategies; in this study, the two techniques that produced the best results in the formulated problem were chosen. The VNS-DEEPSO algorithm was introduced in 2018 for the dispatch of energy in intelligent distributed networks, as a hybrid technique for environments with uncertainty [17]. The VNS-DEEPSO algorithm means variable neighborhood search – differential optimization of evolutionary particle swarms.

5.2.1. DEEPSO algorithm

DEEPSO is a high level hybrid technique constructed from different metaheuristics: Evolutionary Algorithms (EAs), Optimization of Particle Swarm (PSO) and Evolutionary Differential (DE). The advantage of these methods is that they oriented the optimum in a globally correct direction. The combination of these techniques aims to generate a more robust algorithm [18].

DE is an attempt, at many variations, looking for successful self-adaptive schemes. This search is also the motivation of the EPSO algorithm [18], which includes the positive effect of a probability of communication between particles, implementing the stochastic scheme [18].

5.2.2. VNS algorithm

The VNS strategy consists in extending the local search to make systematic changes in the neighborhoods, solving complex problems. The algorithm explores distant neighborhoods and updates the best solution [19]. The operational structure of the algorithm has two main phases: initialization and repetition. In the start phase, the number of neighborhoods is defined, an initial solution is found and the moment in which it is stopped is chosen. In the repetition phase, a local search method is applied using the initial solution, and the new point is called local optimum. If the local optimum is better than the solution found in the process, the overall solution will be changed, otherwise the search continues. This is repeated successively up to the stop criterion [19].

6. Results

Table 2 presents the summary of the results obtained by the VNS-DEEPSO algorithm, considering 10 scenarios and 1 500 000 iterations, for 20 simulations. RI represents the ranking index, which is obtained as the sum of the average operating costs (Co) and the standard deviation (σ).

Table 2. Prototype ranking index

Simulations	RI	Average (Co)	σ (Co)
20	1.63 (100%)	1.52 (93.25%)	0.11 (6.75%)

Results are presented for the three auctions. Fig. 7(a) presents the participation of markets for the first auction. In the solutions found, the binding dispatch has a higher probability of appearance. In auction 2, the binding dispatch has a greater possibility of providing an optimal solution (Fig. 7(b)). Intraday markets 1 and 2 share the possibility of providing feasible solutions.

In auction 3 (Fig. 8(a)), the binding dispatch has an important share in the optimal solutions, with the exclusion of the 21st hour, in which intraday market 1 may become the best solution. Fig. 8(b) presents the probability of incidence of optimal circulations, in which it can make circulations of the aquaponic prototype.

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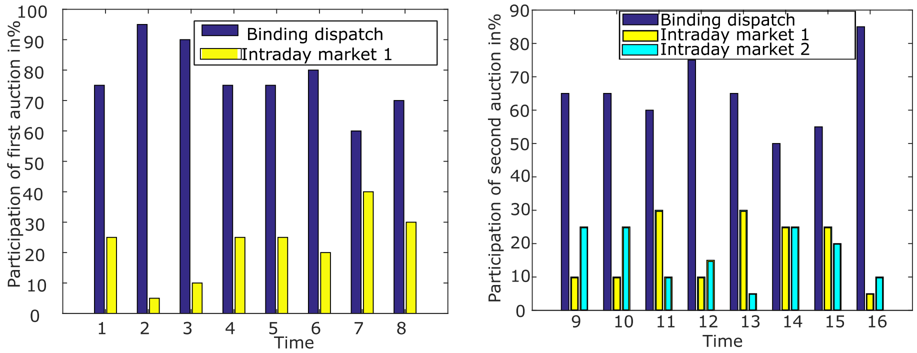
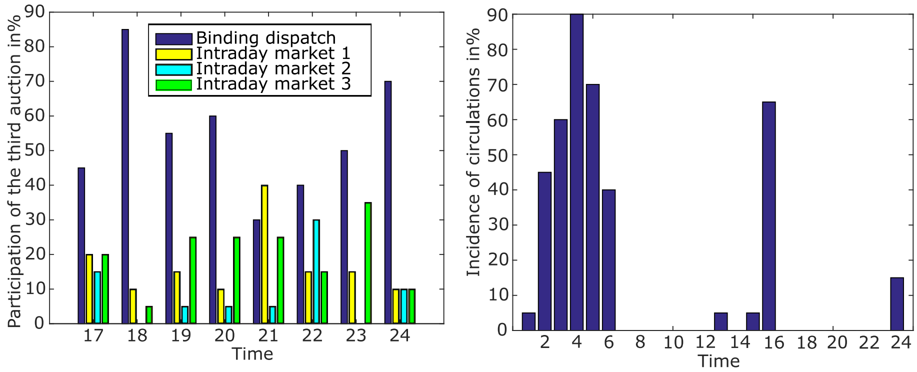


(a) (b)

Fig. 7. Markets participation: auction 1 (a) and auction 2 (b)



(a) (b)

Fig. 8. Schedule: market participation in auction 3 (a); circulation of the aquaponics prototype (b)

Fig. 9 presents the most feasible solution, which was selected by the VNS-DEEPSO algorithm. The circulation are made from 3 to 5 am and at 4 o'clock in the afternoon.

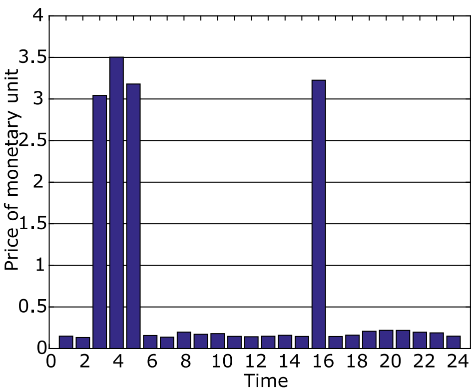


Fig. 9. Price per unit of solution with higher incidence

7. Discussion

The timed water level control proved to be efficient in controlling the recirculation of the aquaponics prototype and in turn clarifying the water. This allows savings in terms of energy and water consumption. A bad decision of the operator must be assumed by the client [2]. In order to avoid bad decisions of the aggregator, the average of 20 operations of the water control system with normal probability distribution are calculated, which yield a value of 2.45, compared with the RI of 1.63 in Table 2. The saving is equivalent to 33%.

The water control system for aquaponics production is compared with other technologies to obtain fresh food such as the use of a refrigerator. In terms of energy consumption, aquaponics production is less expensive, as shown in Table 3. Volume of the fishbowl is 100 L, with allows for the accommodation of 5 red tilapia adults *Oreochromis sp.* and aquaponics production has a capacity of 1 000 g of chili pepper *Capsicum Annuum*, the aquaponic system cannot replace the functions of the refrigerator with this amount but it reduces its capacity of 250 L, saves energy and allows food preservation without refrigeration.

Table 3. Energy consumption per day

Element	Temperature [°C]	Efficiency [kWh/day]
Refrigerator with volume of 250 L	2 4 6	860 [16] 1 220 [16] 1 613 [16]
Aquaponic prototype	25	66

8. Conclusions

A new energy planning technique for aquaponics production is proposed for a real prototype. The implementation of intraday markets and a binding dispatch allows for the determination of the hours in which the prototype must operate. Binding dispatch has more influence than intraday markets in terms of operation. The three intraday market auctions proposed per day increase the complexity in terms of operation, which is why the use of the VNS-DEEPSO algorithm is proposed. Savings of 33% are obtained with this algorithm. It also shows that circulations must be carried out between hours 3 to 5 am and 4 o'clock in the afternoon. The aquaponics production is competitive in terms of energy saving with other food preservation systems, such as the refrigerator. For future work, the influence of intraday markets and binding dispatch in distribution networks can be analyzed.

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