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A computational tool to assist energy management of electrical appliances for the residential consumer

Uma ferramenta computacional para auxiliar o gerenciamento energético de equipamentos eletroeletrônicos do consumidor residencial

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Dyego de Campos
Mestrando em Sistemas de Energia Elétrica
Instituição: Instituto Federal de Santa Catarina (IFSC)
Endereço: Av. Mauro Ramos, 950-centro, Florianópolis-SC, 88020-300
E-mail: dyego.campos@ifsc.edu.br

Fabrício Yutaka Kuwabata Takigawa
Doutor em Engenharia Elétrica
Instituição: Instituto Federal de Santa Catarina (IFSC)
Endereço: Av. Mauro Ramos, 950-centro, Florianópolis-SC, 88020-300
E-mail: takigawa@ifsc.edu.br

Ricardo Luiz Alves
Doutor em Engenharia Elétrica
Instituição: Instituto Federal de Santa Catarina (IFSC)
Endereço: Av. Mauro Ramos, 950-centro, Florianópolis-SC, 88020-300
E-mail: ricardoalves@ifsc.edu.br

Daniel Tenfen
Doutor em Engenharia Elétrica
Instituição: Instituto Federal de Santa Catarina (IFSC)
Endereço: Av. Mauro Ramos, 950-centro, Florianópolis-SC, 88020-300
E-mail: daniel.tenfen@ifsc.edu.br

Rubipiara Cavalcante Fernandes
Doutor em Engenharia Elétrica
Instituição: Instituto Federal de Santa Catarina (IFSC)
Endereço: Av. Mauro Ramos, 950-centro, Florianópolis-SC, 88020-300
E-mail: piara@ifsc.edu.br

RESUMO
Nos últimos anos, diversos pesquisadores focaram suas pesquisas nos consumidores residenciais e nos seus hábitos de consumo de energia. Aliado a isso, incentivos governamentais e avanços tecnológicos, procuram melhorar a eficiência energética dos equipamentos residenciais e sua utilização. Neste sentido, surgem as casas inteligentes que integram a comunicação entre os equipamentos da residência e, com base em informações de padrão de uso dos ambientes, buscam

tornar mais eficiente e automatizado o consumo de energia pelos diversos dispositivos eletroeletrônicos no ambiente residencial. No entanto, os estudos relacionados ao gerenciamento energético do consumidor, na maioria das vezes, são efetuados por meio do deslocamento ou do controle de suas principais cargas instaladas, que dependem de cada país, clima e tarifas. Neste sentido, o consumidor tem que alterar seu hábito de consumo, o que pode gerar desconforto, minimizando o potencial e até tornando inócuos os efeitos da redução das flutuações de demanda. Por outro lado, uma parte do consumo de energia de uma residência pode ser evitada, eliminando o consumo de equipamentos eletroeletrônicos (de standby e de consumo pleno quando os mesmos não estão sendo utilizados). Desta forma, neste artigo é apresentado uma modelagem matemática para auxiliar o gerenciamento energético do consumidor em que o principal objetivo é aplicar inteligência no uso de equipamentos eletroeletrônicos (como a televisão e os diversos aparelhos conectados a mesma). O problema matemático resultante possui característica linear e inteira. Diversas análises foram efetuadas no programa computacional desenvolvido, considerando perfis de uso distintos, a possibilidade de realocação de carga e as tarifas horárias do Brasil.

Palavras Chave: Gerenciamento pelo lado da demanda, Smart home, Programação linear e inteira, Equipamentos eletrônicos, Standby

ABSTRACT
In recent years, several researchers have focused their attention on residential consumers and their energy consumption habits. In addition to this, government incentives and technological advances have sought to improve energy efficiency of household appliances and their usage. As a result, smart homes have emerged which integrate communication between household appliances and, based on usage patterns of the different rooms, aim to improve efficiency and automation of energy consumed by the different electrical appliances in residential settings. However, the majority of studies on consumer energy management are conducted through shifting or controlling the main installed loads. The consumer is then required to alter your consumption habits, which can cause discomfort and even render the effects of a reduction in demand fluctuations innocuous. Conversely, part of the energy consumed in residences can be avoided, eliminating appliance energy consumption. For this purpose, a mathematical model to assist with the consumer's energy management is presented in this paper. Its main aim is to apply intelligence to the use of electrical. The resulting mathematical problem has linear and integer characteristics. Several analyses on the developed computer program were conducted and took into consideration different usage profiles, load shifting possibilities and hourly rate in Brazil.

Keywords: Demand management, Smart home, Mixed integer and linear programing, Electronic appliances, Standby

1 INTRODUCTION

Growth in the global economy and population, the improvement in the standard of living and the rural exodus have all contributed to an increase in energy consumption around the world. This consumption is expected to rise by approximately 28 % between 2015 and 2040 [1]. During this period, a growth of 2 % per year in electrical energy consumption worldwide is projected for the commercial and residential sectors.

According to [2], a solution for this increase in energy consumption is a move away from the traditional power grids towards smart grids in order to increase efficiency and reduce the need for the installation of new energy sources. Smart grids [3] can store, communicate and make decisions and a bi-directional communication is created between the consumer and energy supplier and this can be used to optimize consumption [4].

Demand response is the cheapest option available for operating the power system. However, incentives for consumers to respond and change their consumption habits are normally based on price variation over time and at critical moments in the system [5]-[6]. However, to determine the value of the offered incentive is a challenge for the system operator, as can be observed in [7].

In contrast, intelligent houses, or smart homes, employ the concept of integration of different services within one home through a common communication network. In tandem with technological and communication grid advances, this has become the focus of much research in recent years [8]-[9].

In this context, our main aim is to reduce energy consumption through intelligent management of appliances within a residence where the appliances are all connected to the grid and can communicate with each other. This communication enables monitoring, control and management of said appliances. According to the consumer's choice, consumption and electricity bills can be reduced [8], as well as, demand during peak times [10]-[11]. Figure [12] shows an automatic management proposal whose purpose is energy saving in the home.

However, studies related to consumer energy consumption mainly occur through shifting or controlling the main installed loads [13]-[14], which depend on each country, climate and tariffs. In this way, the consumer must alter their consumption habits which can result in discomfort and minimize potential. The effects of the reduction in demand fluctuations may also be rendered innocuous.

On the other hand, a part of the energy consumed in a residence can be avoided through the application of intelligent usage of electrical appliances. This intelligence can be based on monitoring the different rooms [15] or simply habitual use of common appliances, such as the television and other equipment connected to it.

Domestic electrical appliances when energized have two operational modes: turned on (ON) and turned off (OFF). When the device is ON, it is working normally and consumes its nominal power. On the other hand, on OFF mode, known as standby, the equipment is not performing its main function but continues to consume energy because some internal circuits (clock, LED signaling and remote control detection) continue working [16]. Studies show that standby contributes significantly to overall consumption [14]-[17].

Standby energy consumption is considered a waste of energy and it has been increasing due to the increase in the number of electrical appliances in households [18]-[19]. Another important point is that, currently, many different devices are connected to one main appliance and these are not in use at different moments but remain turned on.

In this paper, we present a mathematical modeling which assists consumer energy consumption. The main objective is to apply intelligence to the use of electrical appliances (such as the television and other devices connected to it). The resulting mathematical problem contains both linear and integer characteristics and various analyses were performed on the computational program we developed taking into consideration alterations to consumer use profile, load shifting possibility, consumption reduction, elimination of standby consumption and hourly rates/tariffs in Brazil.

The paper is organized as follows: in section II characteristics of the Brazilian scenario are presented; in section III, the problem to be addressed is explained; in section IV, the developed mathematical modeling is presented. In section V, the case study is outlined together with the results and analysis of the computational tool. Section VI illustrates the main conclusions reached.

2 NOMENCLATURE

The following notation is used throughout the paper:

Abbreviations:

CELESC	Electricity distributor of Santa Catarina

Constants:

A	Number of loads used
H	Number of intervals throughout the day
Pot_a	Nominal power of load a in one hour [kWh]
X_{ah}	Binary variable associated with use of load a at interval

Variables:

A	Load used
H	Interval
P_h	Tariff fee at interval h [R$/kWh]
N_a	Total sum of number of times load a should be turned on throughout the day
Status	The value equal to 0 indicates that load X_{ah} is necessarily turned off and, equal to 1, that the load must be turned on

3 THE BRAZILIAN CONTEXT

According to [20], Brazil consumed 2.6 % of all electrical energy generated worldwide in 2014, figuring on the list of the 10 highest consumers. This figure represents a 3.2 % growth compared to energy consumption the previous year. Brazilian residential and commercial consumers were responsible for 47.9 % of the energy consumed in the country in 2016. In Brazil, there are approximately 80 thousand electrical energy consumers and 86 % of these are residential consumers, responsible for consuming 28.8 % of the energy generated in the country.

In Brazil, residential consumers can opt for two kinds of tariffs: conventional and white tariff. The conventional tariff applies to energy consumption regardless of the time and has a fixed cost. For the white tariff category, consumption is billed using three different rates for Off-peak, Intermediary and Peak times [21]. On working days, Peak hours run from 6 pm to 8 pm, Intermediary hours from 5 pm to 9 pm and the remaining hours in the day (and weekends) are considered Off-Peak. Table 1 presents the tariffs implemented by the electricity distributor of Santa Catarina (CELESC) [22].

Table 1 - CELESC Tariff Rates

Tariff	Energy R$/kWh
White Tariff - Peak	0.79710
White Tariff - Intermediary	0.52223
White Tariff – Off Peak	0.39249
Conventional Tariff	0.45985

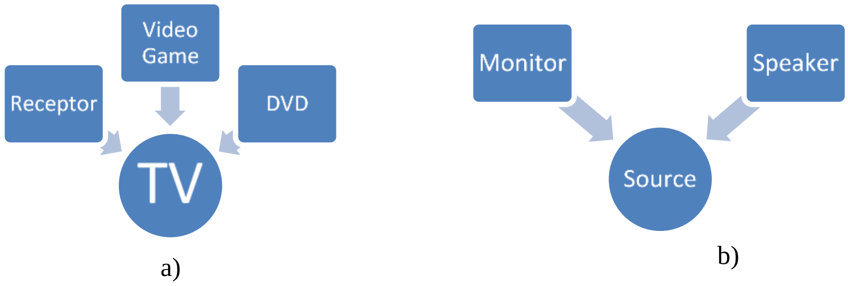
It is important to mention that the time-of-use tariff option for residential consumers is being implemented gradually, beginning with the those with the highest consumption. Every residential consumer in Brazil will have the time to-use option from 2020.

4 DESCRIPTION OF THE PROBLEM

The electrical appliances considered in this research are not responsible for the largest amount of consumption in a household however they are used worldwide and, in general, each residence has more than one of each of these appliances.

The appliances will be classified as primary load and secondary load. The primary load is that which needs to be working for other loads (secondary) to be used. Fig. 1 shows examples using the television set (TV) and the computer power supply as primary loads and the satellite TV receiver, video game and DVD player as secondary loads of the TV. The computer monitor and the speakers are secondary loads of the computer power supply.

Figure 1 - Classification of loads: primary and secondary



In this way, when a primary load is off, the secondary loads could also be turned off which would save energy. In this work, the loads to be studied are TV (primary load), satellite TV receiver, DVD player and video game (secondary loads).

In order to provide comfort to the consumer, the following requirements should be met:

- The user can determine the number of times a determined load will be used;
- The use of loads can be moved (if the user permits) throughout the day but said loads cannot be removed;
- The secondary loads cannot be turned on if the primary loads are turned off (automatically disconnected);
- Only one secondary load can be turned on at the same time as a primary load;
- The primary load will be turned off when it is not being used, saving standby energy.

5 MATHEMATICAL MODELING

The mathematical modeling, Equation (1), aims to provide intelligence to the use of electrical equipment in a home, such as the TV and its peripheral equipment. The intelligence enables the consumer to smartly manage these devices while meeting the consumer's demands and reducing electricity billing costs.

$$min \sum_{a=1}^{A} \sum_{h=1}^{H} P_h Pot_a X_{ah} \qquad (1)$$

a	Load used, where a=1 represents the primary load. The others are secondary loads;
A	number of loads used;
h	Interval, where h=1 represents 1 a.m;
H	number of intervals throughout the day;
P_h	Tariff fee at interval h [R$/kWh];
Pot_a	Nominal power of load a in one hour [kWh];
X_{ah}	Binary variable associated with use of load a at interval h. In the case of load in normal use with nominal

demand consumption, the binary variable takes on a value of 1. If not, assume value as 0.

Where:

Restriction (2) is inserted to ensure all loads are selected according to the load profile defined by the consumer.

$$\sum_{h=1}^{H} X_{ah} = N_a \qquad (2)$$

Where:

N_a Total sum of number of times load *a* should be turned on throughout the day.

Restriction (3) aims to ensure that the dependence between loads is maintained, i.e. the secondary loads are only turned on when the primary load is on (limits the number of loads turned on simultaneously). It also ensures that no load is the only one turned on, except for the TV as its use does not necessarily depend on the other loads (the TV can be used to access apps or the internet and can be connected to an external antenna, analogical or digital signal).

$$-X_{1h} + \sum_{a=2}^{A} X_{ah} \leq 0 \qquad (3)$$

Additionally, restriction (4) enables the user to define if load *a* at interval *h* is used (or not).

$$X_{ah} = Status \qquad (4)$$

Where:

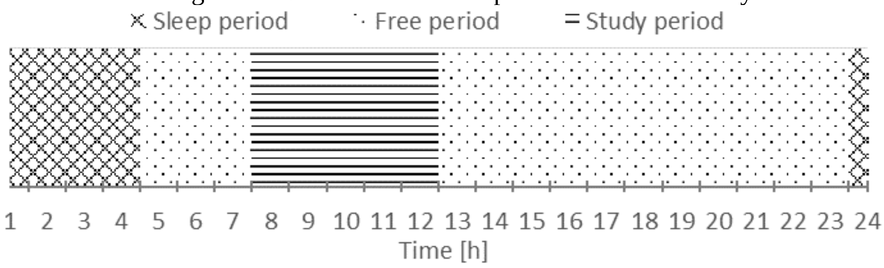
Status The value equal to 0 indicates that load X_{ah} is necessarily turned off and, equal to 1, that the load must be turned on.

The optimization problem (1)-(4) results in a mixed integer and linear programming and permits the inclusion of intelligence in the use of electrical appliances.

6 RESULTS

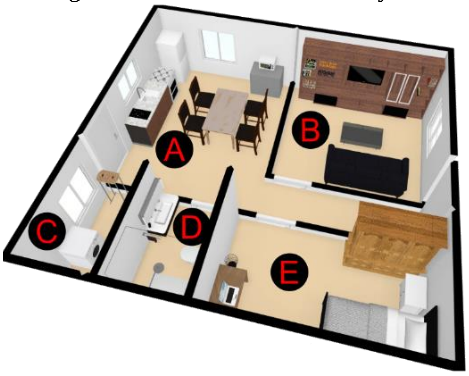
The case in our study is a residence with one occupant who lives alone and is a university student. His routine is divided up as follows: on working days, he sleeps between 12 am and 5 am, studies between 8 am and 12 am and the rest of the day is considered free time, as illustrated in Fig. 2. On weekends, holidays and vacation, the student returns to his parents' home in another city.

Figure 2 - Customers' consumption habits on weekdays



The residence has five rooms and the layout is as follows: kitchen (A), living room (B), laundry room (C), bathroom (D) and bedroom (single) (E). The floor plan is shown in Fig. 3.

Figure 3 - Residence to be analyzed



The electrical appliances to be included in the study are in the living room and can be seen in Fig. 4.

Figure 4 - Residence to be analyzed

The TV set was selected as the primary load and the TV receiver (2), video game (3) and DVD Player (4) are the secondary loads. All loads have a relationship of use between them, as described in the outline of the problem, and also have the standby function with energy consumption.

In Table 2, we can see the appliances and their respective average power in normal and standby use [23], as well as the time of use of the appliances defined by the student.

Table 2 - Equipment power and time used by the student

Equipment	**Power [W]**		**Time of use [h]**
	Normal	**Standby**	
TV	78.10	10.96	13
DVD	30	16.99	2
Game	15	3.98	4
Receptor	32	21.10	7

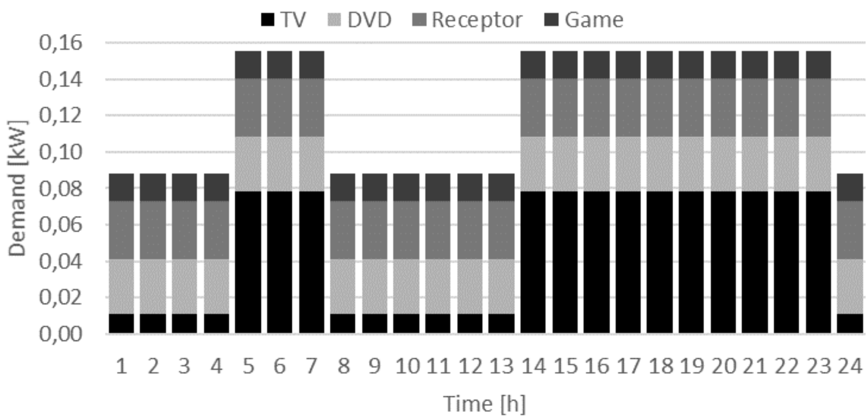
6.1 SCENARIO 1

Scenario 1 is the baseline scenario and considers the student's consumption habit when he:

- Sleeps from 12 am to 5 am;
- Wakes up at 5 am, watches TV via satellite receiver until he leaves for class;
- Studies from 8 am to 12 am;
- Arrives home at 1 pm and at 2 pm he uses the DVD for two hours continuously;
- Then, he plays video games for two hours; and,
- Turns on the receiver to watch his favorite programs on TV;
- Before bed, he plays another two hours of videogames from 10 pm to 11 pm.

However, he keeps all the appliances turned on, all day every day during the week, except for the TV, which remains on standby when not in use. The student's consumption is illustrated in Fig. 5.

Figure 5 - Student's normal habits on working days – Scenario 1



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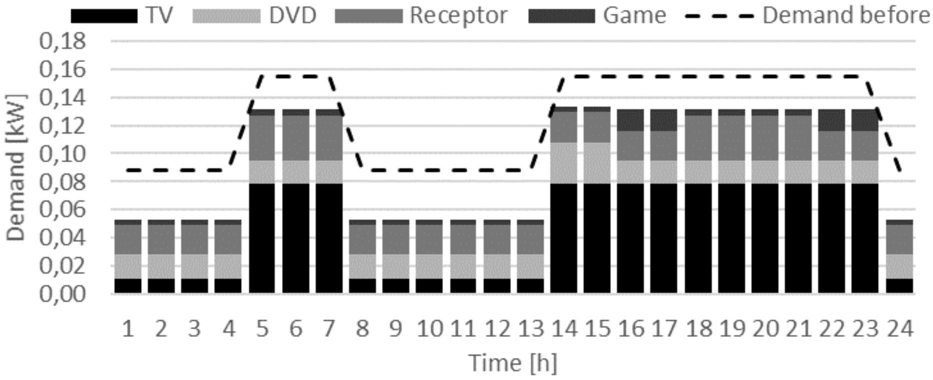
In Table 3, we can see the consumer's values for demand and cost for working days and non-working days (weekend or holiday). On non-working days , all the appliances remain turned on and the TV stays on standby during the whole day.

Table 3 - Tariff costs and demand in scenarios studied for one day - Scenario 1

Period	Working day		Non-working day	
	Demand [kW]	Cost [R$]	Demand [kW]	Cost [R$]
Off-Peak	2.2084	0.8668	1.6712	0.6559
Intermediary	0.3102	0.1620	0.1759	0.0690
Peak	0.4653	0.3709	0.2639	0.1036
Total	2.9839	1.3996	2.1110	0.8286

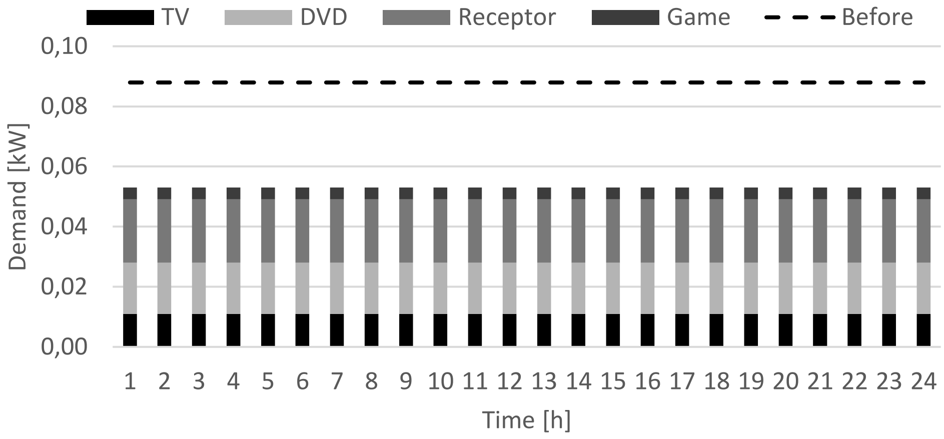
Additionally, scenario 1a considers that the student may slightly alter his consumption habit and turn off all the appliances when they are not in use (leaving them on standby mode). This small modification to the student's behavior, illustrated in Fig. 6 for working days and in Fig. 7 for non-working days, reduces the demand for electrical energy by 22 % and 40 % respectively. These reductions can be observed in the Figures by the difference between the dotted line (scenario 1) and the bars (scenario 1a).

Figure 6 - Appliances and times of use on working days – Scenario 1a



It can be observed in Fig. 6 that the equipment still consumes energy on standby mode when they are turned off. For example, between 5 am and 7 am, the consumer uses the TV and receiver but it can be seen that the DVD and video game continue consuming energy on standby. The same occurs during the sleep period (12 am to 5 am).

Figure 7 - Equipment and times of use on non-working days – Scenario 1a

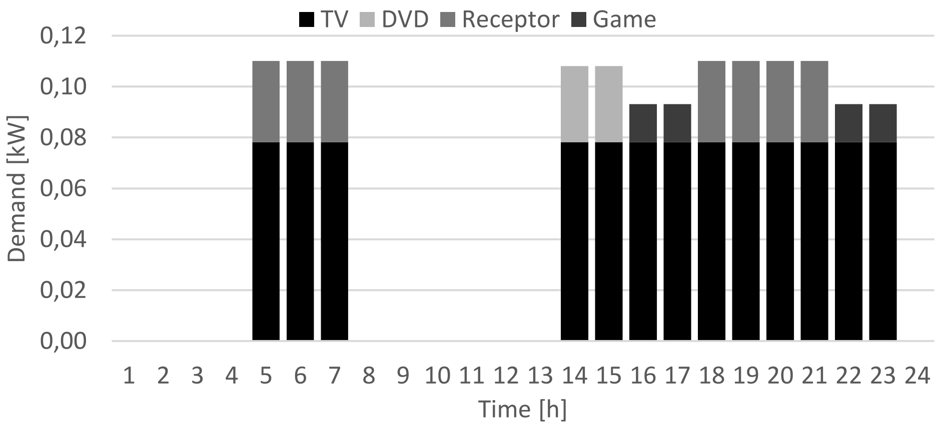


In Fig. 7, the student is not at home and by implementing scenario 1a (turning off all equipment), a significant reduction can be observed between the dashed line and the bars (which represent all the devices on standby mode).

6.2 SCENARIO 2

Scenario 2 uses the mathematical formulation (1)-(4), which simulates the student's consumption profile. For this, the loads and times of use were defined in (4). Fig. 8 presents the daily consumption of scenario 2. The influence of the computational tool can be observed in the elimination of consumption on standby mode while the appliances are turned off.

Figure 8 - Equipment and times of use on working days – Scenario 2



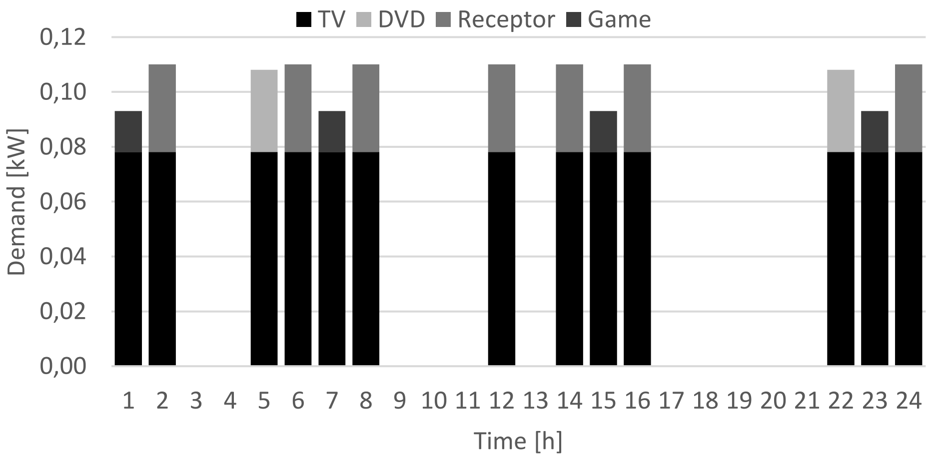
In addition, Fig. 8 shows that only one secondary load is simultaneously turned on with the TV and there aren't any two loads turned on at the same time. Furthermore, we can observe that between 12 am and 5 am, no energy is consumed (all devices were turned off), as this is the period when the student is sleeping or studying. At 1 pm, the student is already at home but is not in the habit of using the appliances under study in this paper.

On non-working days, using the computational tool, consumption fell to zero, signifying a reduction of 100 %. Therefore, only reductions on working days will be considered for the remaining scenarios.

4.3 SCENARIO 3

In this scenario, allocation of any load at any time is possible, only respecting the number of times each load is used. Fig. 9 presents allocation of loads for Scenario 3. It can be seen that at peak and intermediary times (5-9pm), no loads were allocated as these times have a higher tariff than at peak times. Therefore, the loads were allocated randomly during the off-peak period as the tariff was the same.

Figure 9 - Equipment and times of use – Scenario 3



It is important to highlight that the number of times the devices were used is the same as in Scenario 1. However, the result is unfeasible as the load was allocated during the sleep period and several alterations were made by the student to his use of the equipment.

Consequently, the value of the overall demand was reduced by 54 %, as illustrated in Table 4. A load shift of 100 % from the intermediary and peak periods to the off-peak period occurred as well as a reduction in demand for the off-peak period. This change is related to the elimination of standby. In this scenario, the consumer saves 62 % on the amount he is billed.

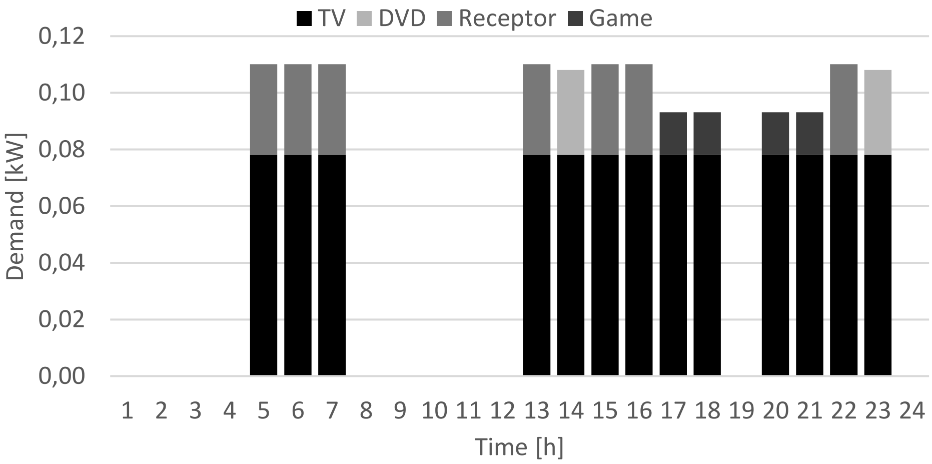
Table 4 - Tariff costs and demand after optimization – Scenario 3

Period	Working day		Reduction	
	Demand [kW]	Cost [R$]	Demand [%]	Cost [%]
Off-peak	1.3593	0.5335	38	38
Intermediary	0	0	100	100
Peak	0	0	100	100
Total	1.3593	0.5335	54	62

6.4 SCENARIO 4

In this scenario, using (4), it was defined that the loads cannot be turned on during the sleep period and the study period. Fig. 10 illustrates the results from Scenario 4.

Figure 10 - Equipment and times of use – Scenario 4



In Fig. 10, we can see that at 1 pm, a load has been added, whereas before, there was no load. During peak and intermediary times, after optimization, the loads with lower consumption and, consequently, those representing lower cost, were added in these periods.

Table 5 presents the result of Scenario 4, in which there was a fall in demand and cost during the off-peak period, resulting in a reduction of 55 % in the consumer's billing.

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Table 5 - Tariff cost and demand after optimization – Scenario 4

Period	Working day		Reduction	
	Demand [kW]	Cost [R$]	Demand [%]	Cost [%]
Off-peak	0.9869	0.3873	55	55
Intermediary	0.1862	0.0972	40	40
Peak	0.1862	0.1484	60	60
Total	1.3593	0.6330	54	55

6.5 SCENARIO 5

In Scenario 5, the student defines through (4) that, during peak time, the receiver should be turned on between 5 am and 7 am and between 6 pm and 7 pm. The result can be seen in Fig. 11 and Table 6.

Figure 11 - Equipment and times of use – Scenario 5

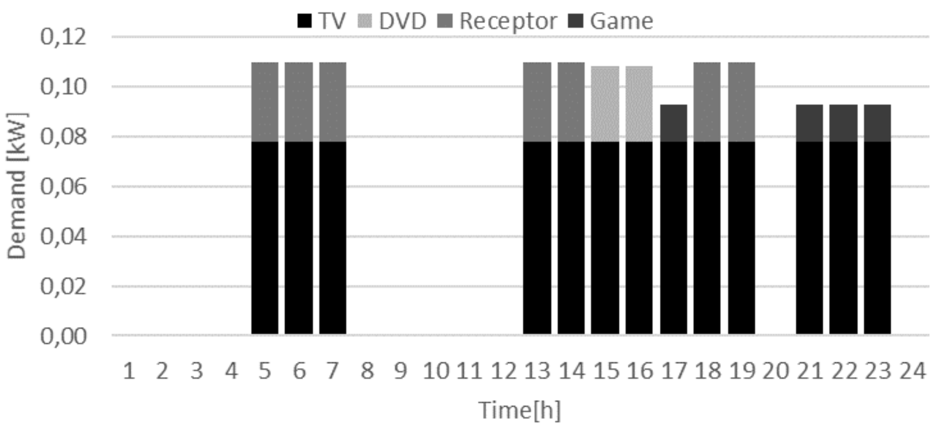
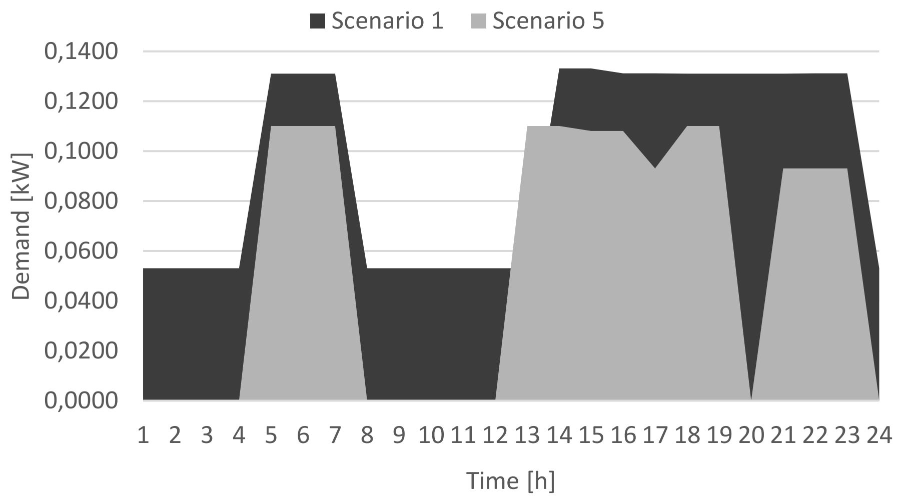


Table 6 - Tariff cost and demand after optimization – Scenario 5

Period	Working day		Reduction	
	Demand [kW]	Cost [R$]	Demand [%]	Cost [%]
Off-peak	0.9529	0.3740	57	57
Intermediary	0.1862	0.0972	40	40
Peak	0.2202	0.1755	53	53
Total	1.3593	0.6468	54	54

We can observe a reduction of 54 % in the billing cost compared to Scenario 1. In addition, Fig. 12 presents the curve of the consumer’s daily demand, on working days, compared to the demand in Scenario 1 and Scenario 5. It is possible to notice a considerable difference in the reduction of demand (54 %), and, most noticeably, in the elimination of consumption in standby mode and reallocation of the appliances.

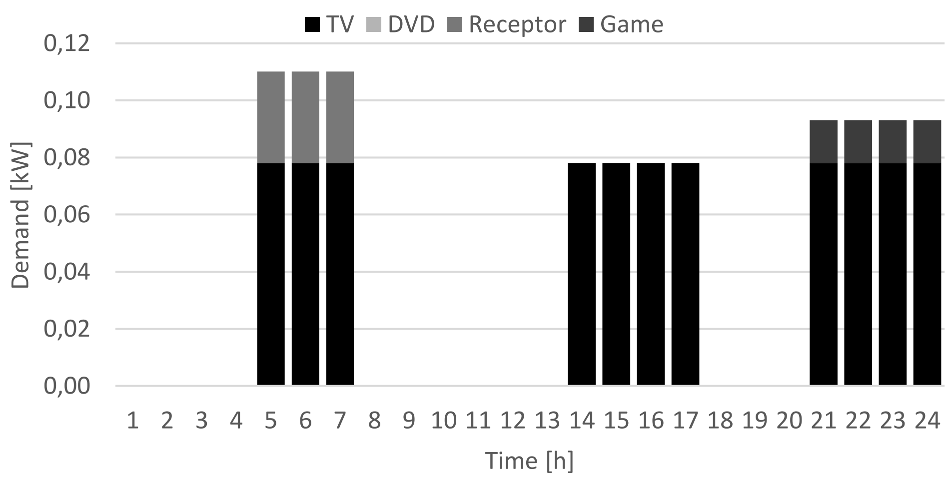
Figure 12 - Comparison of consumption between scenarios 1 (before) and 5 (after)jhjbnbnjbnjknbjkbn



6.6 SCENARIO 6

This scenario considers the possibility of a behavioral change in the student where he defines the use of the receiver (5 am -7 am), videogame (9 pm -12 am) and TV (2 pm-5 pm). In this case, the TV will be used as an external antenna and/or to access apps on the internet. Fig. 13 shows the result of this scenario, where only the defined loads were kept ON.

Figure 13 - Allocation of specific loads – Scenario 6



6.7 COMPARISON OF SCENARIOS

In Table 7 and Table 8, the cost of electrical energy for each considered Scenario is presented, respectively, for working and non-working days. The columns in the table refer to the number of the scenario and the costs and reductions for Peak times (P), Intermediary (I), Off-peak (OP) and Total (T).

Table 7 - Comparison between scenarios – Working days

Nº	**Working days**							
	Cost [R$/kW]				**Reduction [%]**			
	OP	**I**	**P**	**T**	**OP**	**I**	**P**	**T**
1	0.8668	0.1620	0.3709	1.3996	-	-	-	-
1a	0.6423	0.1370	0.3134	1.0927	26	15	15	22
2	0.3241	0.1061	0.2633	0.6935	63	34	29	50
3	0.5335	0	0	0.5335	38	100	100	62
4	0.3873	0.0972	0.1484	0.6330	55	40	60	55
5	0.3740	0.0972	0.1755	0.6468	57	40	53	54
6	0.3312	0.0894	0	0.4206	62	45	100	70

It is clear that the reductions are significant whether these are due to a slight improvement in the consumer's habits (Scenario 1a), or the use of the computational tool which eliminated standby consumption and/or reallocated the use of appliances which resulted in significant reductions of over 50 %.

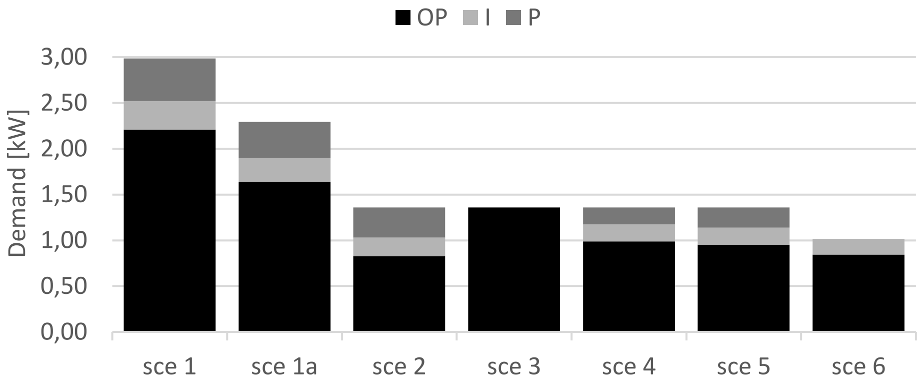
Table 8 - Comparison between the different scenarios – Non-working days

Nº	**Non-working day**							
	Cost [R$/kW]				**Reduction [%]**			
	OP	**I**	**P**	**T**	**OP**	**I**	**P**	**T**
1	0,6559	0,0690	0,1036	0,8286	-	-	-	-
1a	0,3955	0,0416	0,0624	0,4995	40	40	40	40
2-6	0	0	0	0	100	100	100	100

In Table 8, it can be seen that a simple change to the consumer's habits, shown in Scenario 1a, can reduce consumption by 40 % and, when the computational tool is used, consumption on non-working days can see a reduction of 100 %.

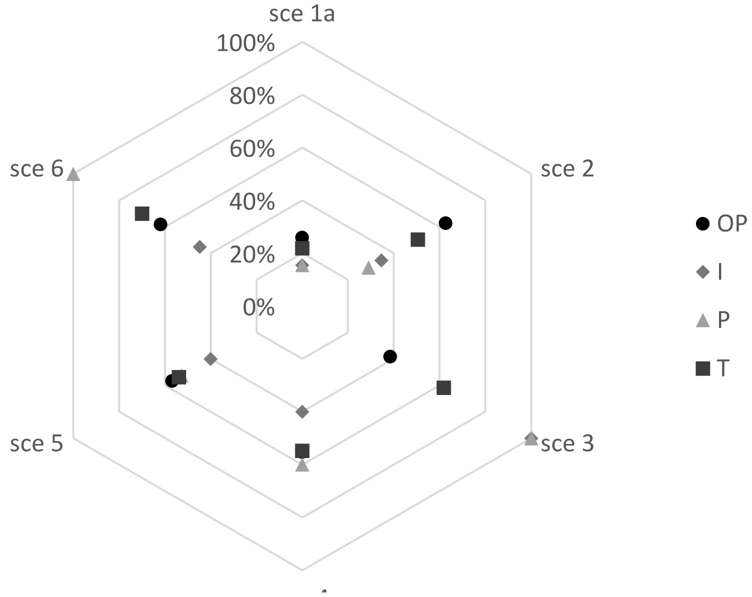
Fig. 14 presents a comparison between the allocation of demand in the different scenarios and different tariffs (OP, I and P). We can see a reduction in demand in all scenarios when compared to Scenario 1.

Figure 14 – Demand allocation comparison between the scenarios – working days



Conversely, Fig. 15 presents the comparison of the reductions in percentages between the different scenarios, for the OP, I, P and T periods. Thus, it is possible to observe that the total reduction, which indicates demand on a working day, is greater in Scenario 6, reaching 70 %. For the peak period, Scenarios 3 and 6 saw a reduction of 100 % and Scenario 3 reduced 100 % in the intermediate period.

Figure 15 - Comparison of reductions in demand in OP, I, P and T periods – working day



7 CONCLUSION

Normally, proposals and studies related to consumer energy management result in shifting or controlling the main installed loads. This forces the consumer to alter his consumption habits, causing discomfort, minimizing potential and even, sometimes, rendering innocuous effects. Making alterations to consumer behavior is a difficult task as it involves various indirect factors, such as education, acquisitive power, marketing, knowledge, number of occupants in a residence, among others.

However, the appliances used in this study, despite not representing the greatest part of consumption in a residence, are used worldwide and, generally, households have more than one of these devices per residence. Also, due to the various technological advances and development of new devices, consumers increasingly possess more secondary electrical appliances attached to the TVs and these, as is the case with TVs, consume energy on standby mode.

For all these reasons, the focus of this study was to devise and test the insertion of a computational tool for consumer energy management which possessed intelligence and minimized alterations to the consumer's habits, reducing the associated costs and maintaining the consumer's comfort. It is important to highlight that the proposed computational tool proved efficient and versatile. It also enabled different kinds of consumers to enjoy similar benefits regarding tariffs, taxes, main equipment and consumption, among others.

To conclude, the authors intend to develop a prototype (hardware and software) which can be internally and/or externally attached to the main appliance (TV), as well as conduct a real analysis of the computational tool and its use. Manufacturers of electrical appliances may be interested in this automated tool for the consumer in the future.

AUTHOR'S CONTRIBUTIONS

All authors contributed to this work.

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DATA AVAILABILITY

The data that supports the findings of this study are available within the article

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