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Delays in electricity market models

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ABSTRACT

From several types of material delays that can be found in literature, most System Dynamics (SD) modelers select, apparently for simplicity, first-order delays (FODs) to represent the construction and decommissioning of power plants in electricity market models, even though pipeline delays, or transport delays (PLDs) model better the entry and exit of power plants. Although both types of delays can be used for representing material delays, each one offers different results with pros and cons that need to be well considered. Therefore, this paper seeks to implement FODs and PLDs in a generic electricity market model in order to assess their effectiveness and adequacy in the closest representation of the reality. As a result, SD modelers shall see through this investigation the importance and implications of material delays in their models, but also they will be able to choose the appropriate material delays for their applications. In fact, the simulation results comparing both models markedly show that PLDs are a better approximation to model the delays of construction of new plants as well as the retirement of old plants. Accordingly, if FODs are solely used, the electricity market models not only always provide less electricity in one or various years, they also produce inaccurate values that can lead to a dangerous energy planning, mainly because they modify the dynamics of the entire system.

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1. Introduction

SD has become a powerful modeling technique since its foundation in the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology [1]. This approach can be a useful mathematical modeling technique for understanding and discussing complex issues and problems in several areas [2].

SD modeling has been extensively used to study electricity markets and has also been considered one of the most appropriate modeling techniques when it is desired to analyze complex systems [2–5]. Therefore, analysis in security of supply [6–8], energy efficiency [9–12], market reforms [13–15], greenhouse gases [16–18] among others [4,19,20], are contributions that not only reflect the importance of modeling electricity markets, but also the necessity of developing models with an increasingly higher degree of realism. For this reason, the purpose of the present study is to assess an important characteristic of the electricity markets: the delays. An adequate model of delays guarantees that the dynamic of the systems reflect better the reality.

In this context, when talking about electricity markets it is clear that there will be plants to construct when a producer of energy decides to invest, or there will be retirement of old plants, which are turned off, when their lifetime ends; however, the construction of new plants or the retirement of old ones always takes time. Depending on different conditions, the construction of new plants might take between 5 and 7 years while the retirement of old ones might take between 20 and 35 years, if the generation source is a hydro-base system. In other words, there is a delay between the investment decisions and the finished plants, and there is a delay between the finished plants and their decommissioning. The present facts suggest that these delays are *material delays* with constant delay time (as the example of mailing letters mentioned by J. Sterman in Ref. [1]). The output distribution of these kind of material delays is depicted in Fig. 1. As can be seen, after the decision of constructing a plant is made, put it into operation takes some years, but also, after a long period of time it becomes useless and must be decommissioned, i.e., retired from the installed capacity.

Modeling and using delays have become a determining in the electricity market behavior, especially when their output distributions are very different. According to Ref. [1], PLDs and FODs (which

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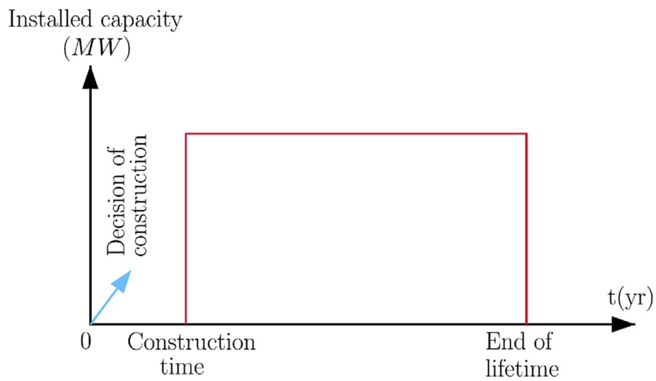

Fig. 1. The plant construction and its respective retirement always involve a delay.

are considered the first approximation of PLDs) have a stock and flow structure and an output distribution as shown in Fig. 2.

Mathematical differences can also be observed from the stock and flow diagram of Fig. 2(a), which are defined as follows:

1.1. PLD

$$o(t) = i(t - \tau) \tag{1}$$

1.2. FOD

$$o(t) = S_2/\tau \tag{2}$$

where $o(t)$ is the outflow, $i(t)$ is the inflow (defined as a unit pulse [1]), τ is the constant delay time and S_2 is a stock.

Notice that mathematically and graphically speaking the models of PLDs and FODs are completely different; nevertheless, though both are material delays, it constantly becomes confusing about what should be used in the variety of existing electricity markets. On one hand, some authors use FODs for simplicity or because they are considered a good and valid approximation to PLDs, see for example [14,21,22]. On the other hand, both types are usually applied, PLDs for modeling the construction of new plants, but also FODs for the case of retiring old plants [23–25]. Unfortunately, in other cases the authors do not even mention what type of material delays were implemented [7,26–28], which might raise doubts about the overall results or conclusions of their research.

In this manner, the pressing open problem not only remains on choosing the appropriate material delay for achieving more accurate models, it is also necessary to raise SD community awareness about the importance and implications of using determined delays. Therefore, the aim of this paper is to assess the electricity market behavior when two different types of material delays (PLDs and FODs) are used, so that SD modelers recognize their differences and understand the importance of mentioning the type of delay they are using in their models. For doing so, in this work PLDs and FODs are applied in a generic electricity market model as an example. In particular, a simplified scenario based on the Colombian electricity sector is considered in order to avoid unreal examples. However, this study only focuses on comparing the implications of using these material delays, we are not evaluating the Colombian electricity market or policy/decision issues.

The paper is organized as follows: Section 2 explains in detail the models to be analyzed. Specifically, Section 2.1 formulates the dynamic hypothesis of the generic electricity market model, followed by Sections 2.2 and 2.3, where is proposed and described stocks and flows diagrams with PLDs and FODs giving a detailed specification of each variable involved. Then, Section 3 exposes the differences of the models with PLDs and FODs by using simulations. After all, Section 4 explains the final discussion and conclusions of this paper.

2. Detailed SD model

After a brief introduction of the main problem to be address in this paper, here we start defining the dynamic hypothesis of a generic electricity market model, which will be used to implement both types of delays.

2.1. Dynamic hypothesis

Similarly to Ref. [29], Fig. 3 shows the hypothesis of a generic

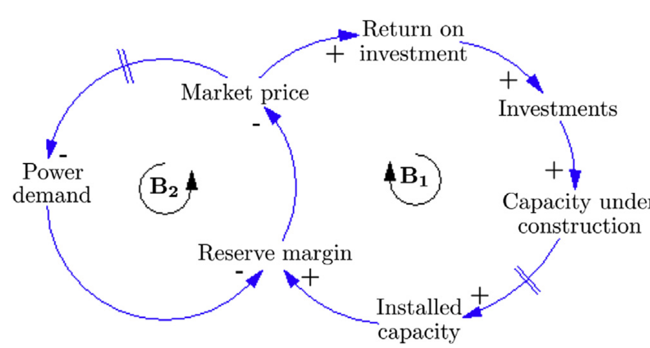

Fig. 3. Causal loop diagram of a generic electricity market model.

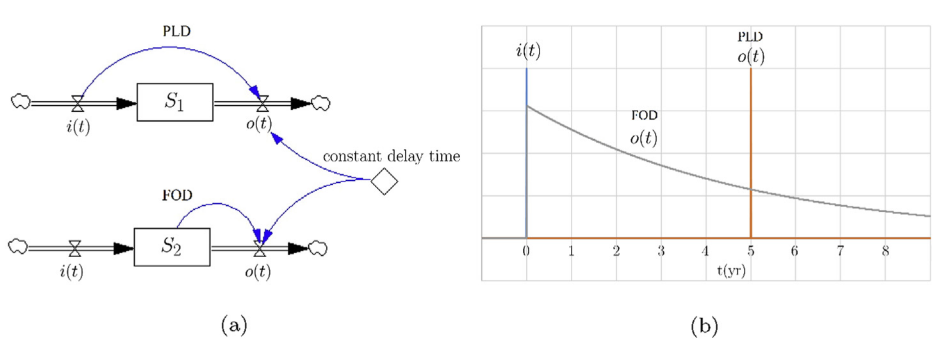

Fig. 2. PLD and FOD comparison. (a) Stock and flow structure of a PLD and a FOD and (b) their output distributions. The constant delay time is 5 years.

electricity market model that exhibits two balance loops. Notice that B_1 indicates how a high market price produces a desired return on investment, which in turn incentivise the system expansion. After a certain time delay, the installed capacity increases, which at the same time causes an increase in the reserve margin; then it is balanced with a reduction in the market price. On the other hand, B_2 indicates that as power demand increases, the reserve margin decreases, inducing a negative effect on the market price; which in turn affects negatively the power demand.

Once the dynamic hypothesis has been defined, the core of the SD model in terms of stocks and flows is obtained in order to perform a more detailed quantitative analysis. Here we want to highlight that a different stock and flow diagram is shown for each type of material delay in order to better appreciate their differences.

2.2. Model structure using FODs

Fig. 4 shows that the proposed model exhibits three stock variables, the capacity under construction, installed capacity and power demand. Besides, in the model structure can be distinguished two components: the supply and demand side (which will be explained in detailed below), but also, and more importantly, two FODs in the supply side. Here the FODs are considered to approximate the finished plants and the retirement of old plants.

2.2.1. The supply component

The supply side (see inside the dashed line in Fig. 4) includes the capacity under construction and the installed capacity. The capacity under construction is influenced by its input and output flows: investment decision in capacity to build (input) and finished plants (output). Similarly, the installed capacity is influenced by its input and output flows: finished plants (input) and retirement of old plants (output).

The capacity under construction strongly depends on the investment decision in capacity to build, which is considered the producer's desired of investment. This basically means that producers decide to invest once they receive a positive return on investment. For this model the return on investment $roi(t)$ is computed as follows:

$$roi(t) = \frac{mp(t) - VC + I}{VFC} 100\% \tag{3}$$

where $mp(t)$ is the market price, and the constant values VC, I and VFC represent the variable costs, the incentives and the variability fixed cost, respectively.

Eq. (3) shows that $roi(t)$ is mainly influenced by the market price. Moreover, if we assume that the producers make the decision to invest or not, every year, the investment decision in capacity to build $inv(t)$ is defined as:

$$inv(t) = \begin{cases} 0 \left[\frac{\text{MW}}{\text{yr}}\right]; & roi(t) \le 0\% \\ k_1 \delta(t-n) \left[\frac{\text{MW}}{\text{yr}}\right]; & 0\% < roi(t) \le 10\% \\ k_2 \delta(t-n) \left[\frac{\text{MW}}{\text{yr}}\right]; & roi(t) > 10\% \end{cases} \tag{4}$$

where $n = 0,1,2,3 \ldots$, and $\delta(t-n)$ guarantee one decision of investment per year.

In other words, Eq. (4) ensures that producers only give one impulse of investment per year when $roi(t)$ is positive: k_1 MW/yr only when $roi(t)$ is less or equal than 10% and k_2 MW/yr when $roi(t)$ is greater than that 10%. Also note that k_1 and k_2 are constant values that determine the amplitude of the investment. Taking into account the size of the plants that are usually built in Colombia, here we consider $k_1 = 500$ MW and $k_2 = 2500$ MW. Then, the capacity under construction is accumulated as follows:

$$x(t) = x(0) + \int (inv(t) - fp(t)) \cdot dt \text{ [MW]} \tag{5}$$

where $x(0)$ is the initial condition of $x(t)$, and $fp(t)$ represents the finished plants, which are also modeled using the FOD definition (see Eq. (2)):

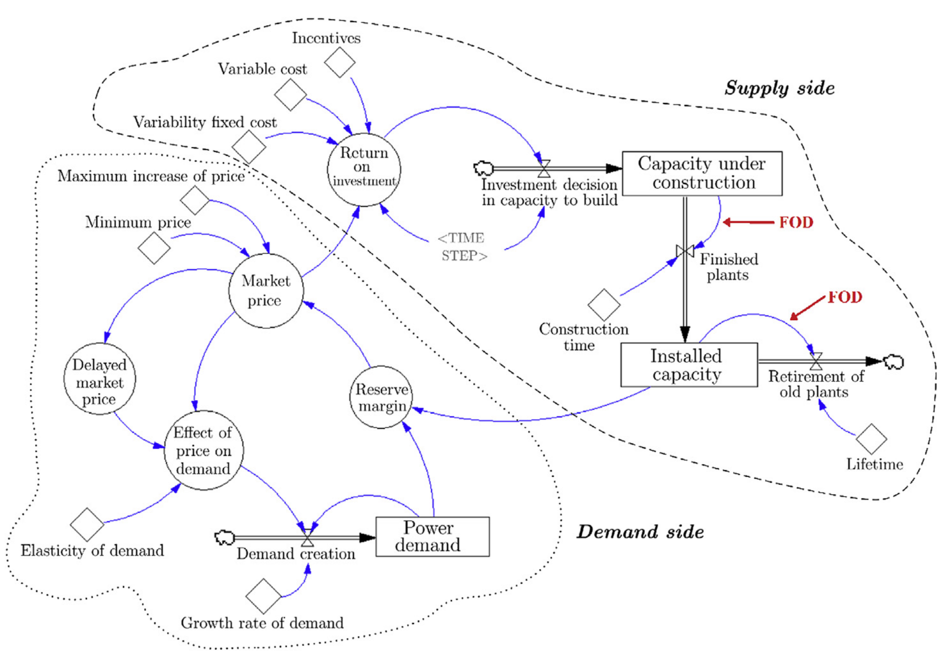

Fig. 4. Stock and flow structure of the generic electricity market model using FODs.

$$fp(t) = \frac{x(t)}{CT}\left[\frac{\mathrm{MW}}{\mathrm{yr}}\right] \tag{6}$$

where CT is a constant value that represents the time needed to build a plant.

Similarly, the installed capacity is accumulated as follows:

$$y(t) = y(0) + \int (fp(t) - rop(t)) \cdot dt \ [\mathrm{MW}] \tag{7}$$

where $y(0)$ is the initial condition of $y(t)$, and $rop(t)$ represents the retirement of old plants that are also modeled according to the FOD definition (see Eq. (2)):

$$rop(t) = \frac{y(t)}{LT}\left[\frac{\mathrm{MW}}{\mathrm{yr}}\right] \tag{8}$$

where the constant value LT is the lifetime of the power plants previously built.

Now, according to Eqs. (6) and (8) the capacity under construction and the installed capacity available at any time can be rewritten respectively as:

$$x(t) = x(0) + \int \left(inv(t) - \frac{x(t)}{CT}\right) \cdot dt \ [\mathrm{MW}] \tag{9}$$

$$y(t) = y(0) + \int \left(\frac{x(t)}{CT} - \frac{y(t)}{LT}\right) \cdot dt \ [\mathrm{MW}] \tag{10}$$

2.2.2. The demand component

As can be seen inside the dotted line in Fig. 4, the power demand is affected by an inflow called demand creation. Additionally, the demand creation is directly influenced by the growth rate of demand (parameter externally obtained according to population and economic growth) and the effect of price on demand. Accordingly, the power demand $z(t)$ is defined as:

$$z(t) = z(0) + \int dc(t) \cdot dt \ [\mathrm{MW}] \tag{11}$$

where $z(0)$ is the initial condition of $z(t)$, and $dc(t)$ represents the demand creation, defined as:

$$dc(t) = GRD \cdot epd(t) \cdot z(t) \tag{12}$$

where the constant value GRD is the growth rate of demand and $epd(t)$ is the effect of price on demand.

On the other hand, the effect of price on demand $epd(t)$ is a variable defined to directly affect the power demand according to the market price behavior. To understand the effect of price on demand first it is necessary to determine the market price, whose value depends on the reserve margin of the system. Here is important to highlight that the reserve margin measures the amount of generation capacity available to meet expected demand, and it is calculated as shown in Eq. (13).

$$rm(t) = \frac{(RAF \times y(t)) - z(t)}{z(t)} \tag{13}$$

where RAF is the resource availability factor used to model the derated capacity, which basically represents the fact that power plants cannot operate at their 100% capacity. According to Ref. [30], under normal and average conditions thermal and hydro plants exhibit an historical resource availability factor of 0.925 and 0.72, respectively, up to 2015. Then, considering that this model incorporates the 30% thermal and 70% hydro capacity in a general installed capacity $y(t)$, the RAF value needs to be computed as a combination of the thermal and hydro resource availability factor:

$$RAF = \frac{(30\% \times 0.925) + (70\% \times 0.72)}{100} = 0.7815 \tag{14}$$

Once the reserve margin has been defined, the market price is modeled taking into account Fig. 5, where can be seen that the market price achieves its maximum increase of price when the reserve margin is closed to zero, and drops to its minimum price when the reserve margin reaches its highest value. This is expressed in Eq. (15).

$$mp(t) = \frac{(MIP + MP \cdot e^{rm(t)} - MP)}{e^{rm(t)}} \tag{15}$$

where the constant values MIP and MP represent the maximum increase of price and minimum price, respectively. Here the market price is measured in COP/kWh since MIP and MP are also given in COP/kWh (COP is the currency abbreviation for the Colombian peso).

Now, the effect of price on demand is affected by the market price and the delayed market price (see Fig. 4), which is the market price delayed by 3 months (0.25 years), i.e., the consumer perceives the current value of the market price 3 months later for the Colombian case. Therefore, the delayed market price $dmp(t)$ is obtained as:

$$dmp(t) = mp(t - 0.25)\left[\frac{\mathrm{COP}}{\mathrm{kWh}}\right] \tag{16}$$

Finally, the effect of price on demand $epd(t)$ is measured according to the market price and the delayed market price as follows:

$$epd(t) = \left(\frac{dmp(t)}{mp(t)}\right)^{\varepsilon} \tag{17}$$

where ε is the elasticity of demand (also known as price elasticity of demand) normally taking values between -0.2 and -0.5. Note that once $dmp(t) \geq mp(t)$, the effect of price on demand or $epd(t)$ takes values between 0 and 1 (reducing effect). On the contrary, when $dmp(t) \leq mp(t)$, the effect of price on demand takes values between 1 and 2 (raising effect).

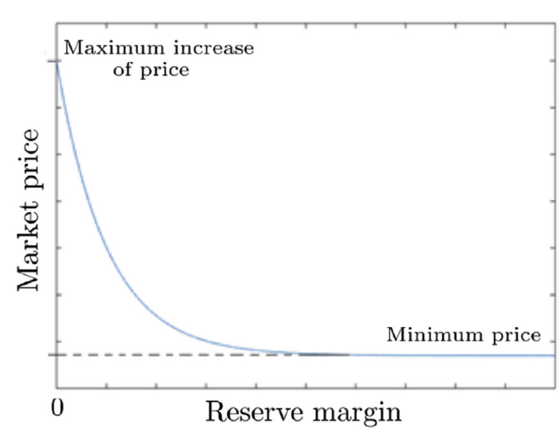

Fig. 5. Market price versus reserve margin.

2.3. Model structure using PLDs

Here it is proposed the same model structure of Fig. 4 but with a different supply side, i.e., PLDs are considered instead of FODs in order to approximate the finished plants and the retirement of old plants. We want to recall that a PLD is an infinite order delay defined as Eq. (1), while a FOD is a first approximation of a PLD defined as Eq. (2), where the stock represents one of the system state variables (accumulation of megawatts built or to build). The proposed model with PLDs in the supply side can be seen in Fig. 6.

2.3.1. The supply component

The supply side remains almost the same as in Section 2.2.1, only the finished and the retirement of old plants are modeled differently taking into account the definition of a PLD. The stock and flow structure of the supply side can be seen inside the dashed line in Fig. 6.

The supply side shows that the causalities of the flows investment decision in capacity to build, finished plants and retirement of old plants are now different from the respective causalities of the supply side in Fig. 4, since PLDs are used instead of FODs. In fact, as described in Ref. [5], assuming that the electricity market is in the long-run equilibrium, the installed capacity can be described through an accumulation resulting from the rate at which new capacity enters, and the rate at which old capacity abandons the system. It means that the retirement of old plants will depend on the investment rate at period $t = t - CT$ and $t = t - (CT + LT)$, while the finished plants will depend on the current investment rate and on the investment rate at period $t = t - CT$, both represented by PLDs. Then, the capacity under construction is accumulated as Eq. (18). Notice that Eq. (18) has the same expression of Eq. (5).

$$x(t) = x(0) + \int (inv(t) - fp(t)) \cdot dt \ [\text{MW}] \tag{18}$$

Nevertheless, the finished plants $fp(t)$ are now modeled through a PLD (see Eq. (19)) according to the PLD definition (see Eq. (1)), and the investment decision in capacity to build $inv(t)$ was already defined in Section 2.2.1.

$$fp(t) = inv(t - CT) \ \left[\frac{\text{MW}}{\text{yr}}\right] \tag{19}$$

Similarly to the FODs model, the installed capacity in this case also has one inflow and one outflow (see the supply side in Fig. 6), which results in the same definition given in Eq. (7):

$$y(t) = y(0) + \int (fp(t) - rop(t)) \cdot dt \ [\text{MW}] \tag{20}$$

However, the retirement of old plants $rop(t)$ is modeled as a PLD (see Eq. (1)):

$$rop(t) = fp(t - LT) \ \left[\frac{\text{MW}}{\text{yr}}\right] \tag{21}$$

Now, according to Eqs. (19) and (21) the capacity under construction $x(t)$ and the installed capacity $y(t)$ can be rewritten as:

$$x(t) = x(0) + \int (inv(t) - inv(t - CT)) \cdot dt \ [\text{MW}] \tag{22}$$

$$y(t) = y(0) + \int (inv(t - CT) - inv(t - CT - LT)) \cdot dt \ [\text{MW}] \tag{23}$$

2.3.2. The demand component

As can be seen inside the dotted line in Fig. 6, the demand side is the same than the demand side of Fig. 4, which was described in Section 2.2.2.

3. Simulation results

In Section 2 two different types of models were described to examine a generic electricity market model with only one remarkable difference; one of them uses FODs and the other one uses PLDs (infinite order delays). Consequently, the capacity under construction and the installed capacity are directly affected by

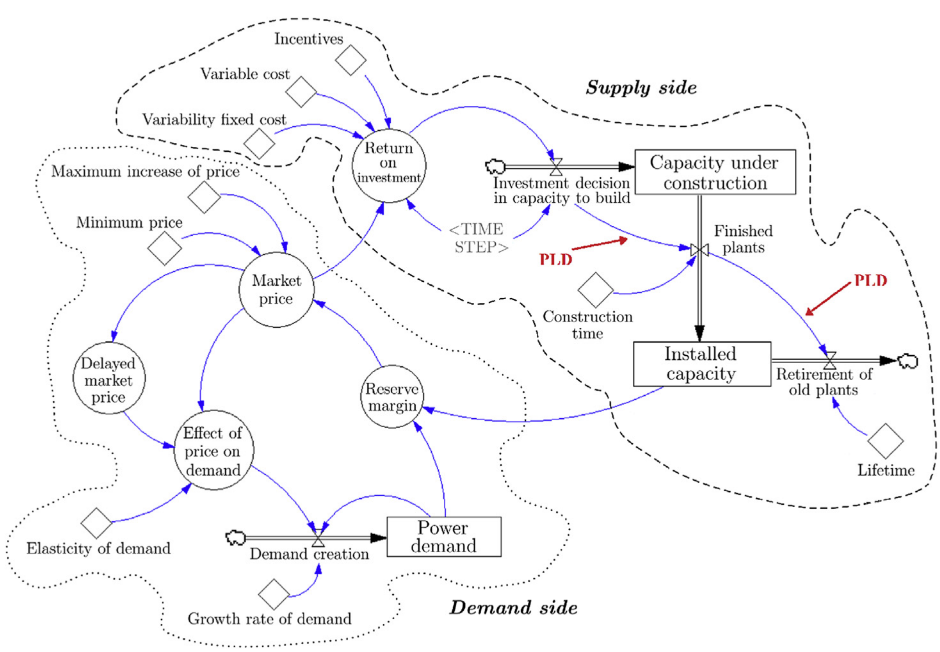

Fig. 6. Stock and flow structure of the generic electricity market using PLDs.

these different delays as is summarized in Table 1.

Mathematically speaking, from Table 1 one can see that the equations of the model using FODs can be easily solved, by basically integrating their stocks. In other words, ordinary differential equations are obtained; as a result, the system response will be smooth and continue since the solution of the equations is exponential. On the contrary, to solve the equations of the model using PLDs one has to integrate the investment functions in different delayed periods of time. Notice that in this case delayed differential equations are obtained; as a result, the system response is non-smooth since the solution to periodic impulses are steps of different amplitudes. Here we want to highlight that both types of equations produce a huge difference in the systems behavior that is graphically analyzed in detail below.

To simulate both models it was considered a similar scenario to the Colombian electricity sector, a thermal and a hydro-base generation system under average and normal conditions. Accordingly, neither water contributions, reservoirs, climate variability nor fuel availability problems were taken into consideration. Since our model is a simplified version of the Colombian market we also combine both main technologies of generation; therefore, the 2015 net installed capacity of the Colombian market, which accounts for 15521 MW (10778 MW and 4743 MW of hydro and thermal plants, respectively) [30], is used as initial condition in our model. Similarly, the parameter values of Table 2 were averaged and combined.

The time horizon of the simulation goes from 2015 to 2050. The simulation results show that the capacity under construction $x(t)$ is one of the most affected variables when two different types of delays are used (see Fig. 7). The capacity under construction with PLDs shows a stepped behavior (as expected), whereas the capacity under construction with FODs shows an oscillatory behavior similar to a ripple. Although both are clearly different, their tendency resembles in the long term. However, in electricity markets the transient behavior is extremely important since investment decisions depend on it. For instance, from 2033 to 2041 the capacity under construction with PLDs starts to decrease to eventually reach zero (see Fig. 7). This occurs due to the capacity under construction becomes the new installed capacity simultaneously when the return on investment becomes negative (see Fig. 11); as a consequence, the investment decision in capacity to build is zero. By contrast, the capacity under construction with FODs subtly drops due to the return on investment is decreasing; however, it never becomes negative. Unlike the capacity under construction with PLDs, the capacity under construction with FODs never decreases significantly because its investment inflow is always present.

The installed capacity $y(t)$ exhibits less differences than the capacity under construction previously analyzed (see Fig. 8). The installed capacity with FODs behaves like a line tendency of the installed capacity with PLDs. Nevertheless, and being more precise, most of the time the installed capacity with FODs exhibits an average difference of 19% with respect to the installed capacity with PLDs. In other words, if the model using PLDs reaches an installed capacity $y(t)$ of 44000 MW during a fixed year, the model using FODs would reach an installed capacity $y(t)$ of 35853 MW, 8147 MW less, equivalent to several plants that would supply an entire city. It is worth to highlight that in this case both models are able to meet the demand (see Figs. 8 and 9). However, if it is considered a model only using FODs to analyze the energy supply of an electricity market of any country, the SD modeler might draw the conclusion that, in case demand exceeds supply, there will be insufficient electricity to meet the demand of a determined year or years.

On the other hand, Fig. 9 shows that the power demand $z(t)$ is almost the same either the model uses PLDs or FODs. This is the result of a power demand that does not depend on delays but is mainly influenced by the growth rate of demand.

Moreover, Figs. 10 and 11 show that both the market price $mp(t)$ and the return on investment $roi(t)$ with PLDs achieve values considerably different from those exhibited by the market price and the return on investment with FODs. Once more, both the market price and the return on investment with FODs behave like a line tendency of the market price and the return on investment with PLDs; however, most of the time their average differences encircle a 55%. In fact, Fig. 11 shows that unlike the return on investment with FODs, the return on investment with PLDs becomes negative for a while.

As a result of all these discrepancies, the dynamic and values of both the capacity under construction $x(t)$ and the installed capacity $y(t)$ evolve differently in an electricity market with PLDs and FODs.

4. Discussion and conclusions

In the field of electricity markets, the SD simulation methodology has been broadly used and developed; however, delays are often not properly modeled or treated causing some confusion between SD modelers and inaccurate results from their models. Therefore, this research is aimed at determining the appropriate delay that must be used when it is necessary to model the construction of new plants and their decommissioning. To analyze the two main options of delays, a generic electricity market was considered taking into account a similar scenario to the Colombian electricity sector.

A brief description of PLDs and FODs reveals the problem under study. Mathematically and numerically speaking both delays show different characteristics. Hence, both were explained in detailed and simulated to observe their differences.

Table 2
Parameters of the Colombian electricity sector.

Parameter	Value
construction time (CT)	5 yr
lifetime (LT)	30 yr
growth rate of demand (GRD)	0.03
variable cost (VC)	150 COP/kWh
incentives (I)	0 COP/kWh
variability fixed cost (VFC)	60 COP/kWh
$y(0)$	15521 MW
$z(0)$	9320 MW
$x(0)$	0 MW
minimum price (MP)	35 COP/kWh
maximum increase of price (MIP)	350 COP/kWh
elasticity of demand (ε)	−0.3

Table 1
Mathematical differences between FODs and PLDs.

Stock variables	Model structure using FODs (see Fig. 4)	Model structure using PLDs (see Fig. 6)
$x(t)$	$x(0)+\int\left(inv(t)-\frac{x(t)}{CT}\right)\cdot dt$	$x(0)+\int(inv(t)-inv(t-CT))\cdot dt$
$y(t)$	$y(0)+\int\left(\frac{x(t)}{CT}-\frac{y(t)}{LT}\right)\cdot dt$	$y(0)+\int(inv(t-CT)-inv(t-CT-LT))\cdot dt$

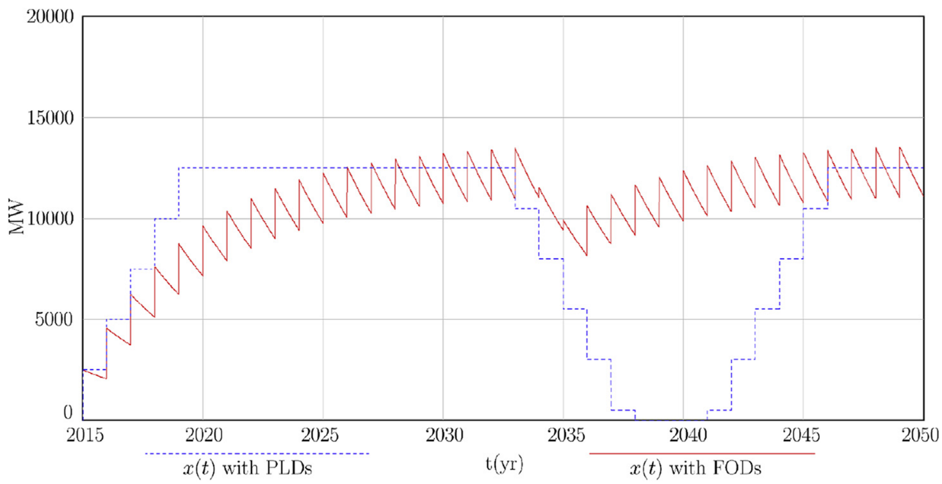

Fig. 7. Simulation of the capacity under construction $x(t)$ under PLDs and FODs.

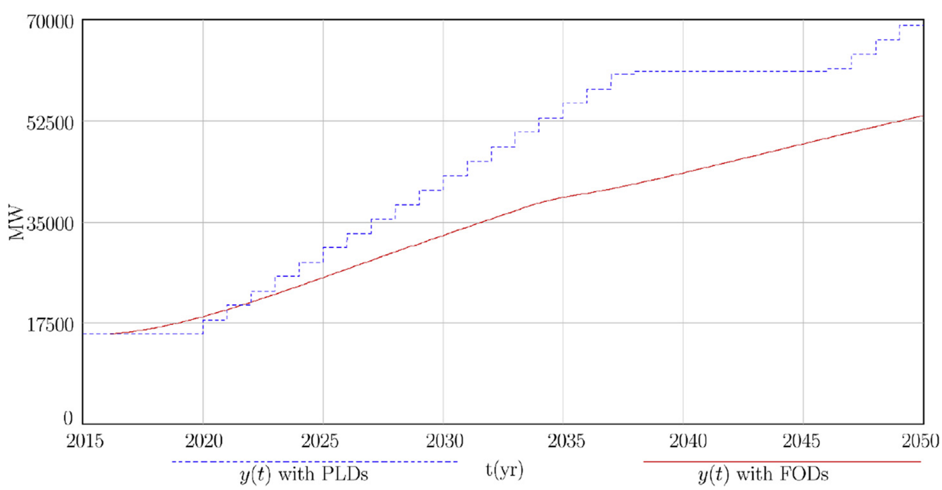

Fig. 8. Simulation of the installed capacity $y(t)$ under PLDs and FODs.

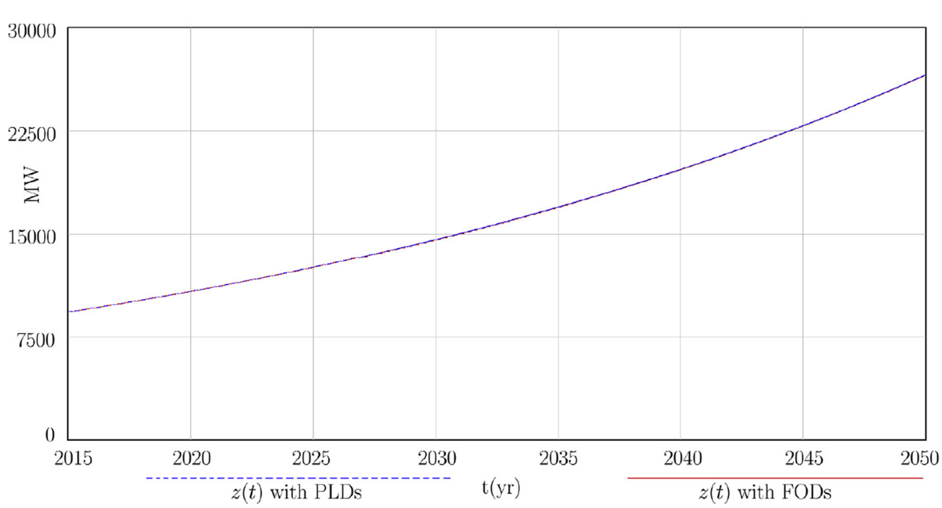

Fig. 9. Simulation of the power demand $z(t)$ under PLDs and FODs.

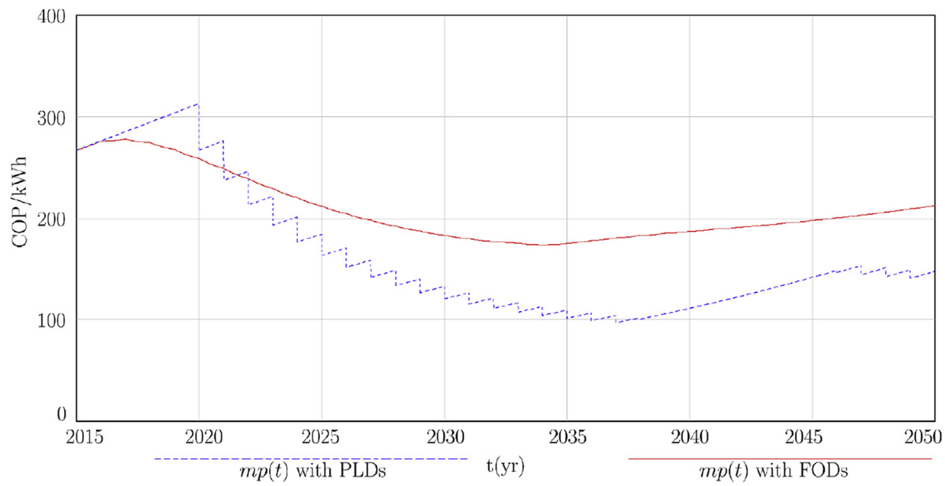

Fig. 10. Simulation of the market price $mp(t)$ under PLDs and FODs.

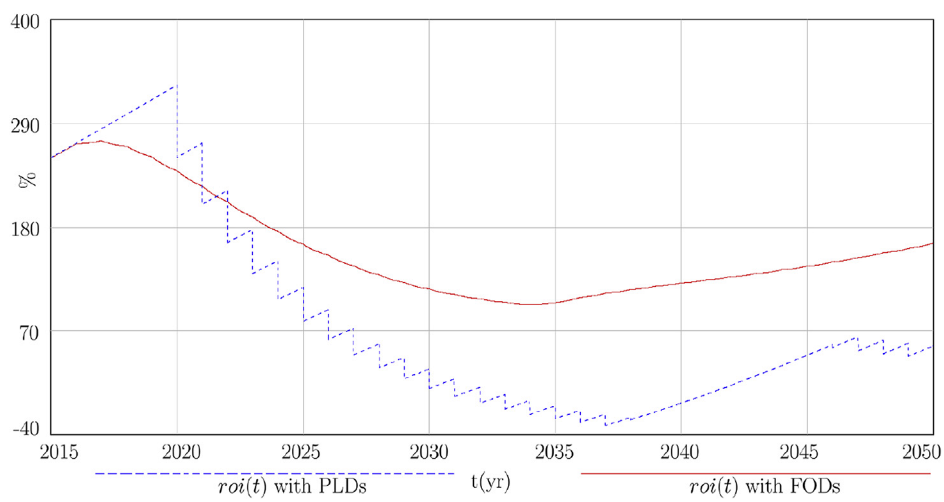

Fig. 11. Simulation of the return on investment $roi(t)$ under PLDs and FODs.

The results show that the capacity under construction $x(t)$ was one of the stocks most affected since the transient behavior of the model with FODs differs significantly from the model with PLDs. More importantly, the latter exhibits zero capacity under construction from 2038 to 2041, whereas the former always exhibits far and positive values of capacity under construction.

Moreover, the installed capacity $y(t)$ with PLDs grows faster than the installed capacity with FODs showing its characteristic stepwise growth. Although the installed capacity with FODs follows the tendency of the installed capacity with PLDs, their difference in values is considerably large, usually reaching more than 20%. In the worst case 16000 MW of disagreement (close to 2038), equivalent to an electricity system that would supply a big city. This means that if a SD modeler considers FODs to represent either the construction or the decommission of power plants in an electricity market model of any country, there will always be less electricity produced, and in case demand exceeds supply, insufficient electricity to meet the demand in one or various years.

Additionally, Figs. 10 and 11 show that both the market price $mp(t)$ and the return on investment $roi(t)$ exhibit differences that cannot be neglected. Regarding to the market price, one can appreciate that the market price with PLDs reaches the highest and lowest values comparing to the market price with FODs, which also affects their return on investment directly. In other words, when the market price with PLDs reaches the lowest values, its respective return on investment becomes negative for a while. This makes a huge difference with the model that uses FODs since its return on investment never goes to negative values.

On the other hand, from the mathematical and numerical point of view, using FODs as material delays provides easier equations to solve and smoother behaviors; however, they are not a suitable approximation, especially when the model deals with the construction of new plants and the retirement of old plants, as it was demonstrated by this paper. Consequently, we can affirm that any electricity market model using FODs shall lose valuable information, causing inaccurate conclusions from its results.

This paper succeeds showing that the delays associated to the construction of new plants and the retirement of old ones are more properly modeled by PLDs, providing to the models a higher grade of realism.

To this end, in this paper we demonstrate that SD modelers must use PLDs in electricity market models, and encourage them to always mention the type of delay they are using in their models so that the readers can rely on their research results.

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References

[1] J. Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw-Hill Higher Education, Irwin/McGraw-Hill, 2000. https://books.google.de/books?id=CCKCQgAACAAJ.

[2] Reducing carbon emissions in China: industrial structural upgrade based on system dynamics, Energy Strategy Rev. 2 (2) (2013) 199–204 east Asian Energy System Management Challenges.

[3] F. Teufel, M. Miller, M. Genoese, W. Fichtner, Review of system dynamics models for electricity market simulations, Work. Pap. Ser. Prod. energy 2 (2013) 1–34.

[4] S. Ahmad, R.M. Tahar, F. Muhammad-Sukki, A.B. Munir, R.A. Rahim, Application of system dynamics approach in electricity sector modelling: a review, Renew. and, Sustain. Energy Rev. 56 (2016) 29–37.

[5] F. Olsina, F. Garcs, H.-J. Haubrich, Modeling long-term dynamics of electricity markets, Energy Policy 34 (12) (2006) 1411–1433. http://dx.doi.org/10.1016/j.enpol.2004.11.003.

[6] S. Osorio, A. Ackere, Security of supply in the swiss electricity market: a system dynamics approach, in: Proc. Of 32st Int. Conf. of the Syst. Dynamics Society, 2014.

[7] A. Aslani, P. Helo, M. Naaranoja, Role of renewable energy policies in energy dependency in Finland: system dynamics approach, Appl. Energy 113 (2014) 758–765.

[8] Y. Prambudia, M. Nakano, Integrated simulation model for energy security evaluation, Energies 5 (12) (2012) 5086–5110, http://dx.doi.org/10.3390/en5125086.

[9] I. Dyner, R.A. Smith, G.E. Peña, System dynamics modelling for residential energy efficiency analysis and management, J. Operational Res. Soc. 46 (10) (1995) 1163–1173. http://www.jstor.org/stable/2584613.

[10] A. Blumberga, G. Zogla, P. Davidsen, E. Moxnes, Residential energy efficiency policy in Latvia: a system dynamics approach, in: Proc. Of Int. Conf. of the Syst. Dynamics Society, 2011, in: http://www.systemdynamics.org/conferences/2011/proceed/papers/P1106.pdf.

[11] G. Patill, G. Yarnal, V. Puranik, System dynamics modelling approach for energy management in a sugar industry, J. Contemp. Res. Manag. 3 (4) (2008) 21–40.

[12] B. Glumac, M. Oosterbaan, W. Schaefer, Energy Saving Potential for Corporate Property: System Dynamic Approach, Tech. rep., European Real Estate Society (ERES), 2014 http://eres.scix.net/data/works/att/eres2014_66.content.pdf.

[13] C.J. Franco, M. Castaneda, I. Dyner, Simulating the new british electricity-market reform, Eur. J. Operational Res. 245 (1) (2015) 273–285. http://dx.doi.org/10.1016/j.ejor.2015.02.040.

[14] M. Pourhossein, N. Nahavandi, M. Sheikh-El-Eslami, Transition in Iran's electricity market considering the policies on elimination of electricity subsidies: system dynamics application, Int. J. Industrial Eng. 25 (4) (2014) 263–270. http://ijiepr.iust.ac.ir/files/site1/user_files_2hops2/n_nahavandi2-A-10-147-5-72def0f.pdf.

[15] T. Jamasb, M. Pollitt, Electricity market reform in the european union: review of progress toward liberalization & integration, Energy J (2005) 11–41. http://www.jstor.org/stable/23297005.

[16] L.M. Cardenas, C.J. Franco, I. Dyner, Assessing emissions-mitigation energy policy under integrated supply and demand analysis: the colombian case, J. Clean. Prod. 112 (Part 5) (2016) 3759–3773. http://dx.doi.org/10.1016/j.jclepro.2015.08.089.

[17] J. Fiksel, Sustainability and resilience: toward a systems approach, Sustainability: Science, Pract. Policy 2 (2) (2006) 14–21. http://www.resilience.osu.edu/CFR-site/pdf/0608-028.fiksel.pdf.

[18] T.S. Fiddaman, Exploring policy options with a behavioral climate–economy model, Syst. Dyn. Rev. 18 (2) (2002) 243–267, http://dx.doi.org/10.1002/sdr.241.

[19] M. Cepeda, M. Saguan, Assessing long-term effects of demand response policies in wholesale electricity markets, Int. J. Electr. Power & Energy Syst. 74 (2016) 142–152. http://dx.doi.org/10.1016/j.ijepes.2015.07.023.

[20] S. Arango, Simulation of alternative regulations in the colombian electricity market, Socio-Economic Plan. Sci. 41 (4) (2007) 305–319. http://dx.doi.org/10.1016/j.seps.2006.06.004.

[21] K. Vogstad, A. Botterud, K.M. Maribu, S. Grenaa, The transition from fossil fuelled to a renewable power supply in a deregulated electricity market, in: Proc. Of the Int. Conf. of the Syst. Dynamics Society, 2002. https://www.researchgate.net/profile/Klaus_Vogstad/publication/235003769_The_transition_from_fossil_fuelled_to_a_renewable_power_supply_in_a_deregulated_electricity_market/links/0912f5103a73593c05000000.pdf.

[22] K. Vogstad, I.S. Kristensen, O. Wolfgang, Tradable green certificates: the dynamics of coupled electricity markets, in: Proc. Of the Int. Conf. of the Syst. Dynamics Society, 2003, in: http://www.systemdynamics.org/conferences/2003/proceed/PAPERS/347.pdf.

[23] A. Dimitrovski, M. Gebremicael, K. Tomsovic, A. Ford, K. Vogstad, Comprehensive long term modeling of the dynamics of investment and growth in electric power systems, in: Proc. 2004 EPNES Workshop, 2004. http://web.eecs.utk.edu/~ktomsovi/Vitae/Publications/DIMI04b.pdf.

[24] K. Vogstad, A System Dynamics Analysis of the Nordic Electricity Market: the Transition from Fossil Fuelled towards a Renewable Supply within a Liberalised Electricity Market, Doctoral thesis at NTNU, 2005, NTNU, Trondheim, 2005, p. 15.

[25] H. Flynn, D. Breger, A. Belden, A. Bier, C. Laurent, N. Andrews, W. Rickerson, System dynamics modeling of the Massachusetts srec market, Sustainability 2 (9) (2010) 2746–2761, http://dx.doi.org/10.3390/su2092746.

[26] R. Rasjidin, A. Kumar, F. Alam, S. Abosuliman, A system dynamics conceptual model on retail electricity supply and demand system to minimize retailer's cost in eastern Australia, Procedia Eng. 49 (2012) 330–337. http://dx.doi.org/10.1016/j.proeng.2012.10.145.

[27] M. Assili, M.H.J. D.B, R. Ghazi, An improved mechanism for capacity payment based on system dynamics modeling for investment planning in competitive electricity environment, Energy Policy 36 (10) (2008) 3703–3713. http://dx.doi.org/10.1016/j.enpol.2008.06.034.

[28] I. Dyner, S. Arango, C. Franco, Can a reliability charge secure electricity supply? an sd-based assessment of the colombian power market, in: Proc. Of the Int. Conf. of the Syst. Dynamics Society, 2007, in: http://www.systemdynamics.org/conferences/2007/proceed/papers/ARANG353.pdf.

[29] I. Dyner, Energy modelling platforms for policy and strategy support, J. Operational Res. Soc. 51 (2) (2000) 136–144, http://dx.doi.org/10.1057/palgrave.jors.2600813.

[30] XM, Información Inteligente, 2017. http://informacioninteligente10.xm.com.co/pages/default.aspx (accessed 10.01.17).