ICEV Recycling in Environments with Limited Conventional Energy: Insights from a Queuing Model

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ABSTRACT

Nowadays Sustainability is a huge issue. Sustainability deals with the need for the protection of the natural environment and ecosystems health and requires innovation and commitment with the future. This manuscript presents an economic supported decision process modelled through a $M|G|\infty$ queue system (*M* means that arrivals follow a Poisson process, *G* (general) that the service time can follow any probability distribution, and ∞ that there are infinite servers) to help to choose if either *ICEV*-Internal Combustion Engine Vehicles, normally cars but not only, turn idle when conventional energy becomes scarce, or a new *status quo* is required. In such a case, they are recycled, becoming either *EV*-Electric Vehicles or *HEV*-Hybrid Electric Vehicles or *FCEV*-Fuel Cell Electric Vehicles, or are dismantled (*DV*-Dismantled Vehicles). Our model shows that when the rhythm *ICEV* become *EV*, *HEV*, *FCEV* and *DV* is greater than the rate at which they get idle the system tends to balance. In a cost-benefit analysis perspective, there are minimum benefits above which, both dismantling and recycling, are interesting. Additionally, the most interesting is the one for which the minimum benefit is the least.

Keywords: ICEV; EV; HEV; FCEV; DV; M|G|∞; hazard rate function; sustainability; innovation; modelling; environment; dismantling; recycling.

1. INTRODUCTION

Sustainability is nowadays recognized as imperative, involving a vast and complex number of factors, and having a relevant economic, environmental, and

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social impact. Many causes for the deterioration of the environment make the situation unsustainable for numerous resources and ambiences. The environmental quality, for example - determinant for healthy communities - implies the need for clean air, healthy and balanced living resources, sustainable natural resources, and a nontoxic environment. For instance, many health problems relate directly to air and water quality, to which Internal Combustion Engine Vehicles (*ICEV*) contribute.

The recent public health crisis that emerged from the spread of the Covid-19 disease made the collective conscience recognize suddenly that the environmental map of the world got radically different, after pollution almost disappear from many regions of the world where previously was very serious. In fact, the world almost paralyzed and the traffic was radically reduced. The effect may seem like the one resulting from the replacement of *ICEV* for non-polluter vehicles.

In the present days, the collective urban consciousness, that is a product of the pandemic's effects, invokes the need of reducing increasingly the levels of pollution up to the present levels, what remarkably will allow a very different quality in air, water, and environment in general.

Car manufacturers are modifying the production lines to work new non-polluter and less-polluter vehicles, changing the previous *status quo*. However, there are millions of cars already produced and an innovative solution may increase the speed at which the environmental quality improves.

Nowadays, this search for a sustainable performance is considered a core idea in business and society [1]. As the search for a balance between sustainability and economic development becomes indispensable, the problem of materials involved in cars composition, the problem of fuels in cars, or the alternative sources of energy are issues that need a strong discussion to allow fast decisions on the improvement processes, for getting the best options on cars production and on the viable reconversions.

Changes in the climatic conditions prompted by increased in pollution level indicate the sensitivity of natural and human systems [2], showing the urgency for new mentalities and needs.

As there are many over-exploited non-renewable resources and a new paradigm is coming, innovation is required to overcome challenges posed by a coming new energy order. In the current days, conventional sources of energy such as oil, gas and coal continue to be broadly used, and in a near future, if the consumption remains at the present levels, they will end. Maybe firstly oil, then gas and lastly coal. Meanwhile it is interesting to notice that the consumption reduced drastically after the Covid-19 crisis, what made oil price to decrease for very low levels that were not seen since several years ago. It is evident that changes will drastically happen in the world and in collective conscience, and after this public health crisis ends, its effects will be much visible in social, economic, and financial dimensions.

The relationship between sustainability and business turned into one of the principal debates at the national and international levels in both industrialized and emerging countries [3]. Many investments around the world allow getting new technologies for alternatives to the currently most used sources of energy. New prospects for business are becoming evident and began to be experienced all over the world associated to the new sources of energy.

Considering the viability of recovering the existing vehicles, which are moved by fossil fuels (based on oil, gas), we construct different scenarios to analyze the best options to give a new life to these vehicles.

In this study, we apply a model to choose the most efficient technique, by starting from the technology and the process selected to make the conversion from a situation to another one.

The goal of this paper is to show that *ICEV*, based on oil, in a collapsing scenario of the conventional energy or by considering a different energy paradigm can be converted; or can be simply dismantled. In this model, infinite servers' queues are used - see for instance [4] and [5] – allowing to state that too many *ICEV* will become idle if either conventional energy misses or conventional energy becomes replaced by a renewable one. *ICEV* dismantling or recycling will become very usual once there will not be a way to get them functional with conventional oil, from the instant it is depleted or their use, in the existing conditions, is not allowed anymore.

The cadence at which we perform the recycling and dismantling actions is relevant, being central in this analysis the *hazard rate function* of the service time:

$$h(t) = \frac{g(t)}{1-G(t)} \tag{1.1}$$

In (1.1), $G(t)$ is the distribution function and $g(t)$ is the probability density function, see [6].

The hazard rate function of the service time depends basically on the technology and protocols used in *ICEV* recycling and dismantling. Accordingly, the choice among the available ones is now of importance[1].

The problem associated to the future of this kind of cars, in this case, comes in a very short time. The major producers reported that they are considering a decision on this in a very short time. They will stop making diesel cars very soon,

[1] *If the random variable represents the lifetime of a device, the hazard rate function is the rate of failures of that device, that is, of occurrences in which its lifetime ends. In this case, a variable that represents the duration of a service, the hazard rate function is the rate of occurrences in which the service time ends.*

for ethical and environmental reasons, still considering manufacturing gasoline cars in a middle term, and electric, hybrid and fuel cell cars.

Considering that the car industry assumes this awareness, ending the manufacture of diesel cars worldwide and implementing the manufacture of electric and hybrid cars, so a new era will come soon. Depending on how long rests the conventional energy, the question about the urgency of dismantling or recycling *ICEV* is posed. Also, a preliminary replacement of diesel cars by either electric or hybrid or fuel cell cars is considered. On this, from the economic point of view, it is difficult to predict what will happen because there are several variables to consider, for example:

- This "decreed" obsolescence of diesel cars makes them loosing value. A question may be also posed: alternatively, will there be a moment on which their value increases due to their increasing rarity?
- How costly will be manufacturing plants for dismantling or converting the existing diesel cars?
- What will occur with the diesel cars in the meantime by means of getting idle: dismantling, recycling? And, at what cost?
- Reducing the number of diesel cars possibly leads to a decrease in oil consumption, delaying the arrival of the traditional energy shortage situation.

This study aims mainly to contribute to the sustainability of the humankind standard of living, and a suitably preserved natural environment. On this primary principle see also [7-17,5,18-21]. In [22] some reflections were when considering the need of reconversion in a situation of scarce oil environment.

The remaining part of the paper is organized as follows. Follows the literature review. In section 3, materials and methods are proposed. The section 4 deals with the results and in the section 5 these results are discussed. The conclusions are presented in section 6.

2. LITERATURE REVIEW

Queues theory studies mathematically the queues, or the waiting lines. A model is created to predict queue length and the waiting time. Generally considered as a branch of operations research, queues theory contributes for the decision-making in business and a set of other very different areas.

Some key moments will be presented here on Queues theory history.

Queuing theory began in the first decade of the 20th Century, having been a work of Erlang [23] the first publication on this area, applying a model to telecommunications. In this paper, Erlang modeled the number of telephone calls arriving at an exchange by a Poisson process; in 1917 he would solve the $M|D|1$ queue; and later, in 1920, solved the $M|D|k$ queueing model.

In [24] Pollaczek solved the $M|G|1$ queue. A solution in probabilistic terms would be presented in [25], that is now known as the Pollaczek–Khinchine formula.

In [26] Kendall solved a $GI|M|k$ queue, introducing the modern notation for queues (the so-called Kendall's notation[2]). By his turn, in [27] was used an integral equation for studying the $GI|G|1$. The paper [25] is now known for having provided a formula (Kingman's formula) for the mean waiting time in a $G|G|1$ queue. Kleinrock, having first applied the queue theory to the message switching (1960's), worked later the queueing theory application to the packet switching (1970s) – his work is produced for example in Kleinrock [28-30].

The matrix geometric method and matrix analytic methods have allowed queues with phase-type distributed inter-arrival and service time distributions to be considered (see [31]).

Problems such as performance metrics for the $M|G|k$ queue remain an open problem (see [32 and 33]).

These are some of the important works that have marked the evolution of Queueing theory. Although many works have been developed along more than a century, the presented above are usually considered within the group of the ones that have been considered fundamental for the development of the theory.

The queue model here used is the $M|G|\infty$ queue. The symbol ∞ means that it is a queue with infinite servers, see [4]. This quality makes the model suitable to deal with great populations, as it is the case of the car's population considered in this study. Note that when talking about infinite servers, it is not considered the physical presence of an infinite number of servers. The physical realization of this infinity can translate into ensuring that whenever a client arrives at the system it always finds an available server. This is what happens in the case under study. Whenever an owner decides to transform his/her vehicle, he/she immediately finds someone available to provide the service. In case of having to wait, the waiting time is incorporated into the service time.

As we will see later, using this model we will obtain stability conditions of the system, in terms of the *hazard rate function* of the service time and the *rate of arrivals* to the system. Note that this function is widely used in reliability theory, see again [6], and in this study it will depend on the technological characteristics of the process used in the transformation of vehicles.

From the many others that have been developed for this area, we select a set of the $M|G|\infty$ queue applications, some of which have been developed in areas as the unemployment, diseases, finance, management, and logistics, see for example [10,4,12,15,17,5]. As for this article subject, see for instance [11,22].

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[2] *In its simplest version $M|N||k|l$, M describes the random variable that governs the arrivals process, N that governs the service time, k is the number of servers, and l the number of customers that can be waiting (if not indicated it assumes it is infinite).*

As for the literature on technology related to the environment, see [13,14] on the natural environment; and [16,18,19,20] on the human environment, and based on game theory.

3. MATERIALS AND METHODS

In the $M|G|\infty$ queue, customers arrive according to a Poisson process at rate λ and each one receives a service which time is a positive random variable with distribution function G (·) and mean value α. There are infinite servers, that is: when a customer arrives, it always finds an available server, see for instance [4]. The service of a customer is independent from the other customers' services and from the arrivals process. An important parameter is the *traffic intensity*, defined as ρ=$\lambda\alpha$. The $M|G|\infty$ queue has neither losses nor waiting.

In what concerns to the present study, the costumers are the *ICEV* that become idle. The *arrivals rate* is the rate at which the ICEV become idle. The service time for each one is the time that goes from the instant they get idle until the instant they are either recycled or dismantled.

The *hazard rate function* of the service time is the rate at which the services end. For the situation under study in this paper, is the rate at which the motorcars are either recycled, turning either *EV* or *HEV*, or *FCEV,* or dismantled, turning *DV*.

Denoting $p_{1'0}(t) = G(t)e^{-\lambda\int_0^t[1-G(v)]dv}$, the probability the $M|G|\infty$ queue has no costumers at instant t, being the time origin an instant at which a costumer arrives at the system finding it empty (symbolized by the $1'$), see, for instance, [34]:

Proposition 3.1:

If $G(t) < 1, t > 0$ continuous and differentiable and

$h(t) \geq \lambda, t > 0$ (3.1)

$p_{1'0}(t)$ is non-decreasing.

Dem.: It is enough to note that $\frac{d}{dt}\ p_{1'0}(t) = e^{-\lambda\int_0^t[1-G(v)]dv}\big(1-G(t)\big)\big(h(t)-\lambda G(t)\big)$. □

Obs.:

- If the rate at which the services end is greater or equal than the costumers 'arrivals rate $p_{1'0}(t)$ is non-decreasing.
- For the $M|M|\infty$ system, exponential service times, $h(t) = {}^1/_\alpha$ and (3.1) is equivalent to

$\rho \leq 1$ (3.2).

Either Equation (3.1) evidence that if the recycling or the dismantling rate is greater or equal than the rate at which the motorcars become idle, the probability that the system is empty at instant t, meaning it that there is no idle *ICEV*, does not decrease with t. Therefore, the system tends to balance as far as time goes on.

Denoting now $\mu(1', t) = 1 - G(t) + \lambda \int_0^t [1 - G(v)]\, dv$ the mean number of customers in the $M|G|\infty$ queue at instant t, being the time origin an instant at which a costumer arrives at the system finding it empty (symbolized by the $1'$), see, for instance, [4]:

Proposition 3.2:

If $G(t) < 1, t > 0$ continuous and differentiable and

$$h(t) \geq \lambda, t > 0 \tag{3.3}$$

$\mu(1', t)$ is non-increasing.

Dem.: It is enough to note that $\frac{d}{dt}\mu(1', t) = (1 - G(t))(\lambda - h(t))$. □

Obs.:

- If the rate at which the services end is greater or equal than the customer's arrivals rate, $\mu(1', t)$ is non-increasing.
- For the M|M|∞ system $h(t) = {}^{1}\!/_{\alpha}$ and (2.3) is equivalent to

$$\rho \leq 1 \qquad (3.4).$$

Either equation (3.3) evidence that if the recycling or the dismantling rate is greater or equal than the rate at which the *ICEV* become idle, the mean number of *ICEV* in the system does not increase with time. This means that the system has a propensity to balance as far as time goes on.

4. RESULTS

In the former section, we saw how important the roles of *h(t)* and λ were, in monitoring the *ICEV* recycling and dismantling management.

To perform an economic analysis, based on the model presented behind, consider additionally:

- *p* as the probability, or percentage, of the *ICEV* arrivals designed to the recycling,
- Being consequently 1-*p* the same to the dismantling.

In addition,

- Be q the percentage or probability of ICEV designed for recycling that turn EV,
- r will be the same for ICEV designed for recycling that turn HEV,
- And 1-*q*-*r* will be the same for *ICEV* designed for recycling that turn *FCEV*.

Call $h_i(t), c_i(t)$ and $b_i(t), i = EV, HEV, FCEV, DV$ the *hazard rate function*, the mean cost, and the mean benefit, respectively for an *ICEV* turn either *EV* or *HEV* or *FCEV* or *DV*. Therefore, the *total cost* per unit of time for motor cars recycling and dismantling is:

$$C(t) = \lambda[pqc_{EV}(t) + prc_{HEV}(t) + p(1-q-r)c_{FCEV}(t) + (1-p)c_{DV}(t)] \quad (4.1)$$

and the *benefi*t per unit of time resulting from recycling and dismantling:

$$B(t) = b_{EV}(t)h_{EV}(t) + b_{HEV}(t)h_{HEV}(t) + b_{FCEV}(t)h_{FCEV}(t) + b_{DV}(t)h_{DV}(t) \quad (4.2).$$

So, consider a period *T*. It must be $\int_0^T B(t)dt > \int_0^T C(t)dt$. It is not a simple matter to deal analytically with this expression. But, considering $b_{EV}(t), b_{HEV}(t)$, $b_{FCEV}(t)$ and $b_{DV}(t)$ are all constant in $[0, T]$ with values $b_{EV}, b_{HEV}, b_{FCEV}$ and b_{DV}, respectively, are admissible the following criteria:

4.1 Recycling, Turning *ICEV* in *EV*, is Interesting, if

$$b_{EV} > max\left\{\frac{\lambda[pqC_{EV}^T + prC_{HEV}^T + p(1-q-r)C_{FCEV}^T + (1-p)C_{DV}^T]}{\ln\frac{1-G_{EV}(0)}{1-G_{EV}(T)}} - \frac{b_{HEV}\, ln\frac{1-G_{HEV}(0)}{1-G_{HEV}(T)} + b_{FCEV}\ln\frac{1-G_{FCEV}(0)}{1-G_{FCEV}(T)} + b_{DV}\, ln\frac{1-G_{DV}(0)}{1-G_{DV}(T)}}{ln\frac{1-G_{EV}(0)}{1-G_{EV}(T)}}, 0\ )\right\} \quad (4.3)$$

4.2 Recycling, Turning *ICEV* in *HEV*, is Interesting if

$$b_{HEV} > max\left\{\frac{\lambda[pqC_{EV}^T + prC_{HEV}^T + p(1-q-r)C_{FCEV}^T + (1-p)C_{DV}^T]}{\ln\frac{1-G_{HEV}(0)}{1-G_{HEV}(T)}} - \frac{b_{EV}\, ln\frac{1-G_{EV}(0)}{1-G_{EV}(T)} + b_{FCEV}\, ln\frac{1-G_{FCEV}(0)}{1-G_{FCEV}(T)} + b_{DV}\, ln\frac{1-G_{DV}(0)}{1-G_{DV}(T)}}{ln\frac{1-G_{HEV}(0)}{1-G_{HEV}(T)}}, 0\ )\right\} \quad (4.4)$$

4.3 Recycling, Turning *ICEV* in *FCEV*, is Interesting, if

$$b_{FCEV} > max\left\{\frac{\lambda[pqC_{EV}^T+prC_{HEV}^T+p(1-q-r)C_{FCEV}^T+(1-p)C_{DV}^T]}{\ln\frac{1-G_{FCEV}(0)}{1-G_{FCEV}(T)}} - \frac{b_{EV}\, ln\frac{1-G_{EV}(0)}{1-G_{EV}(T)}+b_{HEV}\ln\frac{1-G_{HEV}(0)}{1-G_{HEV}(T)}+b_{DV}\, ln\frac{1-G_{DV}(0)}{1-G_{DV}(T)}}{ln\frac{1-G_{FCEV}(0)}{1-G_{FCEV}(T)}}, 0\ )\right\} \tag{4.5}$$

4.4 Dismantling is Interesting if

$$b_{DV} > max\left\{\frac{\lambda[pqC_{EV}^T+prC_{HEV}^T+p(1-q-r)C_{FCEV}^T+(1-p)C_{DV}^T]}{\ln\frac{1-G_{DV}(0)}{1-G_{DV}(T)}} - \frac{b_{EV}\, ln\frac{1-G_{EV}(0)}{1-G_{EV}(T)}+b_{HEV}\, ln\frac{1-G_{HEV}(0)}{1-G_{HEV}(T)}+b_{FCEV}\, ln\frac{1-G_{FCEV}(0)}{1-G_{FCEV}(T)}}{ln\frac{1-G_{DV}(0)}{1-G_{DV}(T)}}, 0\ )\right\} \tag{4.6}$$

where $C_i^T = \int_0^T c_i(t)dt, i = EV, HEV, FCEV, DV$.

But if moreover $G_{EV}(t), G_{HEV}(t), G_{FCEV}(t)$ and $G_{DV}(t)$ are all exponential, with means α_{EV} , α_{HEV}, α_{FCEV} and α_{DV} , respectively, (4.3), (4.4), (4.5) and (4.6) become:

4.5 Recycling, Turning *ICEV* in *EV*, is Interesting, if

$$b_{EV} > max\left\{\frac{\rho_{EV}[pqC_{EV}^T+prC_{HEV}^T+p(1-q-r)C_{FCEV}^T+(1-p)C_{DV}^T]}{T} - b_{HEV}\frac{\alpha_{EV}}{\alpha_{HEV}} - b_{FCEV}\frac{\alpha_{EV}}{\alpha_{FCEV}} - b_{DV}\frac{\alpha_{EV}}{\alpha_{DV}}, 0\ )\right\} \tag{4.7}$$

with $\rho_{EV} = \lambda\alpha_{EV}$

4.6 Recycling, Turning *ICEV* in *HEV*, is Interesting if

$$b_{HEV} > max\left\{\frac{\rho_{HEV}[pqC_{EV}^T+prC_{HEV}^T+p(1-q-r)C_{FCEV}^T+(1-p)C_{DV}^T]}{T} - b_{EV}\frac{\alpha_{HEV}}{\alpha_{EV}} - b_{FCEV}\frac{\alpha_{HEV}}{\alpha_{FCEV}} - b_{DV}\frac{\alpha_{HEV}}{\alpha_{DV}}, 0\ )\right\} \tag{4.8}$$

with $\rho_{HEV} = \lambda\alpha_{HEV}$

4.7 Recycling, Turning *ICEV* in *FCEV*, is Interesting, if

$$b_{FCEV} > max\left\{\frac{\rho_{FCEV}\left[pqC_{EV}^{T}+prC_{HEV}^{T}+p(1-q-r)C_{FCEV}^{T}+(1-p)C_{DV}^{T}\right]}{T} - b_{EV}\frac{\alpha_{FCEV}}{\alpha_{EV}} - b_{HEV}\frac{\alpha_{FCEV}}{\alpha_{HEV}} - b_{DV}\frac{\alpha_{FCEV}}{\alpha_{DV}}, 0\right\} \quad (4.9)$$

with $\rho_{FCEV} = \lambda\alpha_{FCEV}$

4.8 Dismantling is Interesting if

$$b_{DV} > max\left\{\frac{\rho_{DV}\left[pqC_{EV}^{T}+p(1-q)C_{HEV}^{T}+p(1-q-r)C_{FCEV}^{T}+(1-p)C_{DV}^{T}\right]}{T} - b_{EV}\frac{\alpha_{DV}}{\alpha_{EV}} - b_{HEV}\frac{\alpha_{DV}}{\alpha_{HEV}} - b_{FCEV}\frac{\alpha_{DV}}{\alpha_{FCEV}}, 0\right\} \quad (4.10)$$

with $\rho_{DV} = \lambda\alpha_{DV}$.

Let´s illustrate formulae (4.7), (4.8), (4.9) and (4.10) application in a practical situation. Consider, for instance, a period of 30 days ($T = 30$) and $\lambda = {}^{30}/_{day}$. Also, $p = 0{,}6, q = 0{,}2$ and $r = 0{,}1$. In the following table we give a set of possible values for the parameters defined above:

Table 1. Parameters values in the example

$\boldsymbol{i}$	$\boldsymbol{\alpha_i}$	$\boldsymbol{b_i}$	$\boldsymbol{C_i^{30}}$
EV	*1 day*	*50 m.u.*	*150 m.u.*
HEV	*2 days*	*30 m.u.*	*200 m.u.*
FCEV	*2 days*	*30 m.u.*	*175 m.u.*
DV	*1,5 days*	*20 m.u.*	*100 m.u.*

Entering with these values in formulae (4.7), (4.8), (4.9) and (4.10) we obtain respectively:

- *50 m.u. > 48,75 m.u.*;
- *30 m.u. > 27,50 m.u.*;
- *30 m.u. > 27,50 m.u.*;
- *20 m.u. > 43,13 m.u*. (false).

So, in this context, dismantling is the only option that is not economically interesting. Otherwise, the most efficient options are to recycle, transforming *ICEV* into *HEV* or *FCEV*, because they are the most economically interesting, from lower levels. Thus, this model can function as a decision support system.

This model can also be applicable to the dismantling and recycling situation resulting from the universal abandonment of the construction of diesel cars described in section 1. Now the option of recycling should consider a fourth option, the conversion of diesel cars to gasoline cars.

5. DISCUSSION

In our world, resources get scarcer each day and the collective *status quo* define new principles for life. The need of finding the best option for resources is posed. Considering the importance of developing strategies to preserve resources and to improve efficiency, this methodology allows the economic and financial monitoring of the studied situations, the technological choice of the process for each option and allows to note that the paces of recycling and dismantling must be adapted to the pace of energy extinguishing that is intended to be replaced (or simply the arrival of a new life collective option). Accordingly, this model allows to promote good practices and get efficient decisions, by defining innovative proposals in the context of the discussed problem in this paper.

In this situation, although this is not a problem, in general, given the high demand for these services, it is relevant to check if customers' arrivals are made according to a Poisson process. It is anyway important to estimate λ and *h(t)* for results concerning the system given the available data. A right estimate of λ depends on the arrivals process to be Poisson. The approach is to decide for a mean λ estimate for a given period since it is easy to admit that the arrivals rate will depend on time. For very large populations, such as the studied ones, the estimation of *h(t)* is in general technically not easy. Considering that, it is convenient to directly estimate *h(t)* instead of estimating initially the service time distribution and then the consequent computation of *h(t*). All this is particularly easy for exponential service times once in this case, $h(t)$ does not depend on time.

6. CONCLUSIONS

This is a study that uses a model that shows the tendency to the balance of a system when the rhythm *ICEV* becomes *EV*, *HEV*, *FCEV*, and *DV* is bigger than the rate at which they become idle.

In terms of a cost-benefit analysis, there are minimum benefits above which, from both dismantling and recycling, are interesting. And the most interesting is the one for which this minimum benefit is the least.

The model developed in this paper contributes for an improved analysis of this kind of problems. With possible modifications, for some other social problems (as unemployment, health, pensions' funds, investment projects or repair systems) this model is also appropriate.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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