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Competitive dynamics in the operating systems market: Modeling and policy implications

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ABSTRACT

Based on concepts of population dynamics and organizational ecology, the study analyzes the evolutionary and competitive dynamics of the highly concentrated desktop/laptop operating systems market and draws conclusions on the impact of open source software on market competition. Market evolution is estimated and forecasted by applying the Lotka–Volterra model, which describes the competitive interaction of species for a common supply. Genetic algorithms are also deployed for the estimation of the model's parameters.
Findings suggest that Linux can survive competition, even in a highly concentrated market, while Mac OSX is mostly benefited by the existence of Linux. As one step further, the study performs a sensitivity analysis of the possible effects on market structure induced by a rise in Linux adoption and identifies the conditions under which market structure can dramatically change, even to a competitive one. Results can provide valuable inputs for managerial decisions and strategic planning to the players of software markets.

1. Introduction

Market structure and the degree of competition had long attracted the interest of researchers [1], as they play an important role in studying market power, business behavior and the performance of market players. In the case of software industry most market sectors are characterized by a tendency to high concentration. This is mainly due to the fact that software has some special attributes that create conditions favorable to a monopolistic behavior [2]. Network and lock-in effects on both demand and supply sides, together with the high switching costs, create favorable conditions for a potential monopolist. Firms may compete for prices, quality, innovation; they may even compete for the monopoly.

The emergence of Open Source Software (OSS) during the last decade, has been claimed to be able to offset this problem by changing the rules of competition in the market [3]. The innovative development model of OSS enabled the reduction of the high fixed development costs of proprietary software. As a result, many firms were able to overcome the high entry barriers and appear in the field of market competition, by adopting new or adapting their old business models towards OSS [4]. These new OSS business models have managed to gain substantial market shares from the established incumbents, indicating that OSS can be the solution for the software's tendency for monopolistic markets.

A very popular business model adopted by software firms is the creation of proprietary software, which has been derived by incorporating large or important parts of OSS code. Firms that adopt this strategy also maintain or support OSS communities that produce open source software, offered for free. This is the case for instance of IBM's WebSphere which has used the Apache web server as a key infrastructure component [5], MySQL with a dual licensing strategy, Apple's Mac OSX operating system and many others. The derived proprietary software can be placed in a third software category; the other two categories being the proprietary and open source software. For the purposes of this study this software category is defined as 'partly OSS.'

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As a result, the study of the evolution of the market structure, due to the existence of OSS, is considered of great interest for both research and practice. Although a number of studies have tried to model competition in software markets due to OSS (e.g. [6–14], etc.), most of them are mainly qualitative, based on theoretical models, which are not able to estimate actual evolution of the market structure. Moreover, they consider duopolistic markets with two kinds of software: OSS and proprietary. None of them examines the interactive competitive effects among the three kinds of software OSS, proprietary and partly OSS. Motivated by this gap in the literature, the purpose of the present work is to study the evolution of the market structure and concentration, as formulated due to the existence of OSS. The study considers a highly concentrated market, the desktop (DT) and laptop (LP) operating systems sector, in order to provide some insights of the potential of OSS even in the case of high market concentration. Using historical data, this paper aims to study the competition in the market and answer the following research questions:

How is the DT and LP operating systems market shaped? Is there an equilibrium? Will Linux survive competition at the equilibrium? Does the market concentration change? Are there any conditions under which market structure can dramatically change?

Based on concepts of population dynamics and organizational ecology, the study analyzes the evolutionary and competitive dynamics of the three leading players of the market, namely the OSS Linux, the partly-OSS Mac OSX and the proprietary Windows operating systems. Market evolution is estimated and forecasted by applying the Lotka–Volterra competition (LVC) model, which describes the competitive interaction of species for a common supply [15,16]. As one step further, the study performs a sensitivity analysis of the possible effects on market behavior, induced by a rise in Linux adoption. Such a rise could be attributed to an organizational change of policy towards Linux adoption, as for instance in the public sector, following a governmental initiative. In this case, the Lotka–Volterra model is reformed to accommodate different adoption levels of the Linux operating system. Results demonstrate the effects of such policy on market concentration, according to different levels of Linux adoption. Findings also reveal useful implications for practice, in terms of the role of OSS and its derivative partly-OSS products in markets with high concentration.

The main outcomes, which also define the importance of contribution of the proposed methodology, are the estimation of the modeled system dynamics, the provision of forecasts regarding market equilibrium and the estimation of the "churn effect," which reflects the level of users' switching among the operating systems. The model also provides information on the survival or extinction of each species, due to the competition effects and the market structure at the equilibrium.

Although a number of alternative modeling approaches for market evolution taking into account competitive effects in the diffusion process exist in literature, probably the most characteristic based on the Bass diffusion model [17–24], they are not able to model competition explicitly. Thus, they cannot be used for equilibrium analysis and estimation of the churn effect. Moreover, the Lotka–Volterra approach can also reveal interactions, or unexpected market behaviors, such as mutualism, that may guide strategic planning. Therefore, they have been widely applied in a number of studies regarding competition in the Information and Communication Technologies (ICT) sector and other technology markets [25–31]. Yet, the method has never been previously applied in the operating systems market considering a three species competition. Also, among the innovative elements of the methodology, is the deployment of genetic algorithms (GA) for the estimation of the LVC model's parameters. Genetic algorithms [32,33] are adaptive heuristic search algorithms, designed to simulate processes in natural systems necessary for evolution. They are increasingly used as a novel method for parameter estimation, because of their efficiency to produce better results, as compared to the often used classical methods of nonlinear least squares (NLS), maximum likelihood estimation (MLE), etc. [34].

The rest of the paper is structured as follows: Section 2 gives an overview of the operating systems market. Section 3 provides the necessary theoretical background of population dynamics and ecological modeling, as well as the mathematical equations that describe these concepts. Based on these theoretical concepts, the methodology developed for the case of the operating systems market is presented. The empirical analysis and results are illustrated in Section 4. Section 5 explores the effects on market structure induced by migration from Windows to Linux at an organizational level, while Section 6 discusses the managerial implications of the study. Conclusions together with directions for future research are provided in Section 7.

2. The operating systems market

Operating system (OS) is a vital component of a computer system, therefore its existence can be traced back to the 50's, with the appearance of the first computers. For a long time, OS was offered bundled with the computer, free of charge and with source code open. In the 1970's, however, software unbundling together with firms' policy to keep the source code hidden has created new market prospects for firms to make profits out of software. Operating systems competition started mainly for servers running on mainframes and supercomputers. With the introduction of the personal computers (PC) and more powerful workstations in the early 1980s, the OS market was widened to non-technical users that could have a PC even at home. Toward the end of the 1980s, simple PC-based client–server systems also came into existence. This has, in turn, induced greater competition among software firms for OS shares. Windows, proved to be a market winner when version 3.0 was released in May 1990. Windows was often criticized as lack-luster; however, since it was light-weight and compatible with existing MS-DOS applications, it became a success overtaking IBM's OS/2. Microsoft and Novell were dominating the PC desktop and server markets respectively, until Microsoft introduced the Windows server OS in 1993, which rapidly superseded Novell's Netware [35].

However, in March 1994, Linux version 1.0 was released, initiating the open source software era and changing the scene in the software market. During the next two or three years Linux gathered momentum. Hundreds of volunteer programmers worked on improving the system and a minor industry of Linux distributors emerged. Linux carried all the advantages of open source software, which made it popular among software industry players. Among the most commonly cited advantages for OSS and Linux are:

- Open source products typically not only have lower license costs, but also dramatically reduced hardware costs [36], as well as development and maintenance costs [37]. For large organizations this can be translated into savings of tens of millions of dollars.
- A huge community of users test OSS across a range of platforms before it is certified for production. Bugs are found and fixed quickly. Rapid iteration and extensive public review has helped OSS to acquire technical strengths such as reliability, flexibility and scalability [38,39].
- The community of developers also provide with greater innovative capability, offering new products, better or faster than competitors [40].
- Source code availability leads to higher quality, because it enables customizations and provides more choice and control [41,42]. As OSS is out in the open, it is typically more secure and suffers fewer vulnerability attacks than proprietary software. When a problem is uncovered, it is addressed quickly. This, in turn, raises system's *security* [43,44].

2.1. Freedom from vendor lock-in

Organizations frequently adopt OSS so as to become less dependent on their software vendors [41,45]. An organization locked-in to its current vendor depends on that vendor for its products and services and switching to another vendor would entail a significant cost. Also, users of proprietary software must rely on the original vendor for changes to the software and they are reluctant to make complementary investments in anticipation of a future hold-up. The latter may occur in the case that a future relationship with the software vendor is not feasible, or involves high uncertainty (e.g. about the type of modifications that will be necessary). As a result, proprietary software causes underinvestment in complementary products due to the fear of hold-up, especially if the user expects to need highly customized modifications. OSS can be considered an extension of the open systems movement, which mainly aims to ensure interoperability among systems and reduce vendor lock-in.

Due to these reasons, Linux has quickly grabbed large market shares from Windows and Unix in the organizational setting, especially in the markets of servers and embedded systems where there is greater demand for customized versions of software. For instance, most hosting companies like Google, Amazon and E-bay prefer to grow Linux server farms to host their services. In addition, the Netcraft's Secure Servers Survey reported that Linux has achieved a market share equal to Windows in Secure Servers, leaving Unix lagging behind [46]. According to IDC, migration from Unix servers is most probable to lead to Linux than to Windows [47]. Finally in the embedded systems sector, Linux has met wide acceptance [48,49]. Recently, Android, which is a Linux based OS, has become the new emerging trend in the mobile and tablets market [50].

However, the picture in the market of DT/LP is totally different. This sector mainly addresses to non-technical users, who have no need for customizing their OS but only perform simple tasks. Linux, on the other hand, had initially focused on technical characteristics and robustness, neglecting end-user requirements like documentation, ease of installation and friendly interface. The latter, together with the fact that most DT/LPs came with a pre-installed Windows OS, deterred non-technical users from switching to an unknown OS like Linux. During the last years, Linux distributions have entered a new phase of maturity, featuring more mature management tools, integrated virtualization, a larger application portfolio and better interoperability. However, the "Year of Desktop Linux", which is so much expected by the Linux' advocates, has not arrived. Recently, the accelerating market for cloud computing, the new trend in industry of a more centralized approach to desktop delivery via various virtualization and/or cloud computing options (such as virtualized desktop on a thin client) and the economic downturn, has brought back the question of desktop strategy, creating new hopes for Linux on the desktop [51,52].

The Windows OS is proprietary software, established in the market for almost two decades, enjoying the benefits of lock-in effects. Among its other characteristics, it keeps the leading place by offering its customers regular -but not often- versions. Windows has been frequently questioned of its quality (e.g. [53–55] in terms of reliability, [44] security, etc.), while the Vista release didn't meet the expected success. However, most of its customers are reluctant to bare the switching costs of adopting an alternative OS. Windows shares reach about the 90% of the total market [56–58], creating a highly concentrated market.

Windows shares are followed by the Apple Mac OSX operating system. Mac OSX is a partly OSS [59], with its kernel based on the open source Darwin OS. Darwin was built upon open source BSD Unix and was released under the Apple Public Source License (APSL), which is an Open Source Initiative (OSI) approved license. Mac OSX was released in 2001 and based its kernel and other important parts on Darwin. Because of the BSD license, Apple was able to re-license everything in Mac OSX kernel with its own terms. Apple says it uses FreeBSD as a reference operating system. Their approach was to keep the source code of the kernel open and achieve good relationship with the OSS community. For example, Apple has hired key developers, including Jordan Hubbard, who is one of the FreeBSD founders and was for a long time a core member of the development group [60]. At the moment, the user interface and many other system tools related to OSX technology are proprietary and they are licensed in a way similar to Microsoft Windows. However, Apple has provided access to the system for many GNU/Linux open source programmers, making its modifications publicly available for the community, even if there is no such license requirement. The operating system has gained popularity during the last years and managed to leave Linux behind in total DT/LP market shares, eating away at the edges of Windows estates [56–58].

3. Theoretical and methodological overview

Population dynamics can be described as the study of marginal and long-term changes in the numbers and characteristics of individuals, in one or several populations, combined with the biological and environmental processes that influence those changes [16]. Population modeling is the application of appropriate mathematical models for studying these changes in populations, as a consequence of interactions of organisms with the physical environment and with individuals, of either their own or different species (intraspecies and interspecies competition, respectively).

The definition for species competition can be summarized to the following: "*Competition occurs when two or more individuals or species experience depressed fitness (reduced growth rates or saturation levels) attributable to their mutual presence in an area*" [16,61]. Thus, if two or more species are present in a closed environment each of them will impinge on the available sources supply for the others. In effect, they will cause a reduction to the growth rates and saturation populations of each other. Modis [62], described the possible types of interaction among the species which are illustrated in Table 1.

Under specific conditions, in a closed established oligopolistic or competitive market each participant's shares are reduced, due to the coexistence and interaction with the other market players. The assumption holds true, provided that the principle of rationality also holds, i.e. market players seek to maximize their market shares and profit. In these cases, the most appropriate interaction type to describe the dynamics of the market is "Competition". Competition is expected to be the most appropriate type of interaction to describe the operating systems market analyzed in this work, since OSs are competing for the existing and potential users and each of their market share is reduced due to the existing of the others.

The LVC model, apart from its efficiency and accuracy of estimations, has a number of advantages, which make it superior than most of the known alternative modeling approaches. Probably the most characteristic alternative approach is the Bass diffusion model and its modifications, which include the competitive effects of the market over the diffusion process [17–24]. However, the Bass formulations cannot provide equilibrium analysis and switching levels among users. The LVC model, though quite simple, can nevertheless fully describe well- known economic principles, such as competitive effects and the law of increasing returns. It can also account for both the group effects and the individual behaviors emphasized by previous diffusion theories, by modeling both the internal and external effects on populations of different species. Finally, the Lotka–Volterra approach can also reveal interactions, or unexpected market behaviors, such as mutualism [62] that may guide strategic planning.

Several researchers have used the Lotka- Volterra equations to model competing technologies. Bhargava [63] has treated them as a technological substitution model, illustrating the variation in substitution curve shape as a function of the model parameters and indicating that in certain cases the model reverts to logistic substitution. Other works examined the equations in detail, focusing especially on the physical meaning of the model parameters and showing that many types of behavior (such as linear, exponential, logistic and Gompertz) can be expressed by Lotka-Volterra equations with different limiting model parameter values [64].

The methodology developed in the present work is built upon the same assumptions that describe the behavior of competing species, which are represented by the market shares percentages of each OS. Market shares reflect the level of concentration in a given market, constituting an accurate indicator for estimating the degree of competition, since they can be considered as the observed outcome of the underlying, usually non-cooperative game of the participating players. They also reflect the results of managerial and strategic decisions, such as advertising, pricing policy and quality of services. Species compete for a common source, which is reflected by the OS market potential. In this way, interspecies as well as intraspecies competition can be modeled, in order to estimate the market's equilibria, i.e. the possible outcomes in the market's structure.

3.1. Model description

The most common approach to capture the reduction of the growth rate of each species, as a result of the interaction with the others, is to incorporate suitable parameters into the formulations of the models that describe population growth. This is achieved by the well-known "Lotka–Volterra" model, based on the work of Alfred J. Lotka and Vito Volterra. Analytical description together with informative examples regarding interaction and competition between two species can be widely found in literature, such as in [15,16,65,66].

Table 1
Types of interaction among species.

Type	Interaction
"Prey–Predator"	One of the species serves as direct food to the other.
"Competition"	Both species suffer from each other's existence.
"Mutualism", or "Symbiosis"	Each population's growth rate is enhanced due to co-existence of the species.
"Commenalism"	Occurs in a parasitic type of relationship in which one benefits from the existence of the other, who remains unaffected
"Amenalism"	One suffers from the existence of the other, who remains unaffected
"Neutralism"	There is no interaction among the species

According to the model, the dynamics of a system comprising of m competing species can be represented by the following system of first-order nonlinear differential equations:

$$\frac{dN_i}{dt} = N_i\left(a_i - \sum_{j=1}^{m} a_{ij}N_j\right), i = 1, 2, .., m \tag{1}$$

In (1) dN_i/dt describe the rate of change for each species, i. The coefficients a_i provide a measure analogous to the carrying capacity of the species, which is related to the saturation value of N_i. When $i = j$, the coefficients a_{ij} are the parameters of the niche capacity and reflect the coupling strength of interaction with the same species. When $i \neq j$, the coefficients a_{ij} are called competition rates and measure the coupling strength of interaction of species i with species j. Each competition rate provides important insight for the interpretation of the "churn effect", that is the loss of the market shares of one operating system due to the competition it faces from another, expressed by the movement of users among them. The churn effect expresses the effects which each member of one species exerts on the carrying capacity of the second species. The higher the coefficient α_{ij} is compared to coefficient α_{ji}, the faster that the species j squeezes species i out of the shared niche. When $a_{ij} > a_{ii}$, then species i faces strong competition from species j. When $a_{ij} < a_{ii}$, competition is low and the species can evolve following their own dynamics and not being interfered by any other rival [30].

The study of the churn effect itself is of particular interest for high technology markets, as it is related with the products' diffusion rates and the probability of opting for a certain technology. Other approaches to churn prediction is to model individual customers' likelihood of churn by using a predictive model, such as Markov chains and discrete choice models. A Markov chain is a probabilistic technique used to represent correlations between successive observations of a random variable [67], while a discrete choice model specifies the probability of an individual to choose a certain alternative, expressed as a function of observed attributes of the individual and of the alternatives available to him, and these attributes are supposed to be causal variables affecting the choice [68].

The dynamics of the operating systems market can be described by the system of Eq. (1), where N_i, $i = 1,..,3$, refer to the market shares percentages of each software product, Linux, Mac and Windows, respectively. The a_{ij} $(i \neq j)$ parameters capture the influential interaction among the users of the different software categories (proprietary, OSS, partly OSS). More particularly, the model for this study, as derived from (1) is described by the following system of equations:

$$\begin{aligned} \frac{dN_1}{dt} &= N_1(a_1 - a_{11}N_1 - a_{12}N_2 - a_{13}N_3) = F(N_1,\ N_2,\ N_3) \\ \frac{dN_2}{dt} &= N_2(a_2 - a_{21}N_1 - a_{22}N_2 - a_{23}N_3) = G(N_1,\ N_2,\ N_3) \\ \frac{dN_3}{dt} &= N_3(a_3 - a_{31}N_1 - a_{32}N_2 - a_{33}N_3) = H(N_1,\ N_2,\ N_3) \end{aligned} \tag{2}$$

The derived system is assumed to be closed, in the sense that only these interacting species exist for the period under consideration. Additionally, there are no migration effects and all other external factors that may affect the dynamics of the system are assumed constant for the considered period of time. The influential behavior of other external factors is not explicitly studied, since the main target of the work is to suggest an alternative methodology for describing the generic behavior of the software market and model its balance when all competitors are present.

3.2. Equilibrium analysis and solution of the system

The equilibrium state among the m competing species occurs when none of the population levels is changing or, equivalently, when all equations of system (1) are equal to zero. In the case of the three competing operating systems, the system (2) is considered. Its solution provides with $2^m = 2^3$ critical, or equilibrium points. However, not all of the solutions correspond to stable critical points. The latter can be identified by performing an eigenvalue analysis.

The analysis is performed by substituting the calculated values of the critical points into (2) and study the behavior of the corresponding system in the neighborhood of each solution. Thus the feasibility of linearization of the system in the neighborhood of the corresponding solution is explored for each critical point. If the participating functions are twice differentiable (which is the case of the present model), the system is almost linear in the neighborhood of a critical point and can be therefore approximated by a corresponding linear system. In the case of three competitors such an approximation can be achieved by considering the following transformation:

$$U = N_1 - N_1^0 \quad V = N_2 - N_2^0 \quad W = N_3 - N_3^0 \tag{3}$$

where (N_1^0, N_2^0, N_3^0) is a critical point. Then, the linear system that approximates the nonlinear system of Eq. (2) near the critical point is derived by the Jacobian matrix of the partial derivatives:

$$\frac{\partial}{\partial t}\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} F_{N_1}\left(N_1^0, N_2^0, N_3^0\right) & F_{N_2}\left(N_1^0, N_2^0, N_3^0\right) & F_{N_3}\left(N_1^0, N_2^0, N_3^0\right) \\ G_{N_1}\left(N_1^0, N_2^0, N_3^0\right) & G_{N_2}\left(N_1^0, N_2^0, N_3^0\right) & G_{N_3}\left(N_1^0, N_2^0, N_3^0\right) \\ H_{N_1}\left(N_1^0, N_2^0, N_3^0\right) & H_{N_2}\left(N_1^0, N_2^0, N_3^0\right) & H_{N_3}\left(N_1^0, N_2^0, N_3^0\right) \end{pmatrix}\begin{pmatrix} U \\ V \\ W \end{pmatrix} \tag{4}$$

where

$$F_{N_i} = \frac{\partial F}{\partial N_i},\ G_{N_i} = \frac{\partial G}{\partial N_i},\ H_{N_i} = \frac{\partial H}{\partial N_i},\ i = 1, \ldots, 3 \tag{5}$$

The general solution for Eq. (4) is given by Eq. (6):

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = c_1 \begin{pmatrix} \xi_{11} \\ \xi_{12} \\ \xi_{13} \end{pmatrix} e^{\lambda_1 t} + c_2 \begin{pmatrix} \xi_{12} \\ \xi_{22} \\ \xi_{23} \end{pmatrix} e^{\lambda_2 t} + c_3 \begin{pmatrix} \xi_{13} \\ \xi_{23} \\ \xi_{33} \end{pmatrix} e^{\lambda_3 t} \tag{6}$$

where c_i are arbitrary constants and λ_i, ξ_{ij} are the eigenvalues and eigenvectors of the Jacobian. An equilibrium point can be stable, only if the real parts of all of the eigenvalues are negative [66]. The stability of a critical point can also be graphically illustrated with the aid of a phase portrait, a plot of the tangent vectors of the trajectories of the system's solutions, evaluated at a large number of points. In general, a critical point is considered unstable if the trajectories of solutions depart from the critical point as the time variable, t, increases, while it can be considered stable otherwise.

The final solution of Eq. (2) is derived by Eq. (6) after reversing the transformation of Eq. (3), for the stable critical point, if it exists. That is:

$$\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix} = \begin{pmatrix} U \\ V \\ W \end{pmatrix} + \begin{pmatrix} N_1^0 \\ N_2^0 \\ N_3^0 \end{pmatrix} \tag{7}$$

3.3. Methodological procedure

The methodology used in this paper is developed in four discrete steps, which are presented in the following paragraphs. The first step is the construction of the model used to evaluate the competition in the DT/LP OS market, according to the system of equations described by Eq. (1). The model was defined in Eq. (2).

As a second step, the model's parameters are estimated. The study of the parameters' values provides with important information regarding the process dynamics, intraspecies and interspecies competition. They reveal the dynamics of each competitor that influences the equilibrium of the market. The parameters are estimated with the employment of genetic algorithms. The concepts and methodology of the genetic algorithms approach are described in more detail in Subsection 3.4.

As described in 3.2, the estimated parameters allow for the calculation of the critical points. However, an unstable critical point cannot be considered valid to reflect the market equilibrium. Therefore and as a third step, the stability of the critical points is tested by performing an eigenvalue analysis. Finally, if a stable critical point exists, it is used for the calculation of the solution of the system Eq. (2), as given by Eq. (7). The solution enables the estimation and forecasting of the demand functions of the three competing technologies, as well as the market equilibrium.

3.4. Parameter estimation — genetic algorithms

Estimation of the model's parameters is necessary in order to reproduce the so far observed process and consequently estimate and forecast market behavior. This is known as the “training” of the model and it is based on the available historical data. Estimation of parameters can be achieved by utilizing managerial judgments, regarding the evolution of market and competition. However, this approach could include bias, since it may reflect personal or group opinions, based on corresponding knowledge, experience and perception. Alternative approaches for parameter estimation include the use of analytical methods, such as least squares, or heuristic methods, such as genetic algorithms. GAs are adaptive heuristic search algorithms based on the mechanisms of natural systems and natural genetics. They were initially introduced by Holland [32,33] and they are designed in a way appropriate to simulate processes in natural systems necessary for evolution. They derive by the principles first laid down by Charles Darwin, regarding the survival of the fittest and they represent an intelligent exploitation of a random search within a defined search space in order to solve a problem.

The key points to the process are reproduction, crossover and mutation and they are all performed according to given probabilities, in a way similar to what happens in the real world. Reproduction involves copying (reproducing) solution vectors, crossover involves swapping partial solution vectors and mutation is the process of randomly changing a cell in the string of the solution vector preventing the possibility of the algorithm being trapped. The process continues until it reaches the optimal solution of the fitness function, which is used to evaluate individuals. On the contrary to the estimation of the parameters based on managerial judgments, genetic algorithms can provide accurate estimates once a minimum number of data points become available.

The most commonly used alternative methods for the estimation of model parameters are Ordinary Least Squares (OLS), Non-linear Least Squares (NLS) and Maximum Likelihood Estimation (MLE). However, all of these techniques suffer from inefficiencies, such as multicollinearity, which in turn may lead to bias [69]. Theoretical arguments regarding the ability of the GAs to efficiently produce better parameter estimates are additionally provided in [34]. The arguments were based on evaluation of GAs performance against alternative estimating methods. The evaluation was based on a number of statistical measures, such as Mean Squared Error (MSE) and Mean Absolute Percentage Error (MAPE).

In general, genetic algorithms are capable of producing accurate estimates, especially in the cases that there are more than six parameters, or when there are not many data points available and the solution space becomes very rough. GAs have been used to estimate diffusion of high technology products and they constitute a rapidly growing area of artificial intelligence [70]. In the context of describing market dynamics, GAs were used to develop bargaining agents able to react to different market situations, evolve their best-response strategies accordingly for different market situations [71] and simulate agent behaviors in virtual negotiation environments [72]. In addition, they have been applied over a wide range of optimization problems, such as solving the flexible assembly line balancing problem [73], choosing the right set of plans for queries which minimizes the total execution time [74], or solving constrained optimization problems [75].

The general steps of a genetic algorithm are:

i. Define the fitness function for the particular optimization problem.
ii. Set crossover and mutation probabilities.
iii. Randomly generate an initial population, $N(0)$
iv. Generate the next generation population, $N(t+1)$, by probabilistically select individuals from $N(t)$ to produce offsprings via genetic operators of crossover and mutation.
v. Compute the fitness for each individual in the current population $N(t)$. Offsprings with values closer to the fitness function are more probable to contribute with one or more offsprings to the next generation. Discard Offsprings that diverge from the fitness function.
vi. Repeat Steps 4 and 5 until either a prefixed number of generations is created, or after some predefined time has elapsed.

The above algorithm is performed into the context of this study and for the system described by (2), with the following characteristics[1]:

Objective function: The objective (fitness) function was set as the minimization of the Mean Square Error (MSE), between observed and estimated values for each competitor's market share:

$$MSE = \frac{1}{T}\sum_{t=1}^{T}\left(N_i(t) - \hat{N}_i(t)\right) \quad (8)$$

where $N_i(t), \hat{N}_i(t)$ are the observed and the estimated values for competitor *i*, respectively.

Initial values of parameters: They were based on estimations of the rates of change of the market shares. Genetic algorithms require a set of initial values for the parameter in order to start performing. These values can be obtained either arbitrarily or by making some rational assumptions. In the present work, initial values are obtained following the assumption that each OS is alone in the market, facing no competitive effects. This approach is best described by a diffusion process and a corresponding aggregate diffusion model, such as the logistic, whose parameters can be estimated by NLS with a high level of accuracy. The produced parameter estimates are given as input to the Lotka–Volterra model in order for the GAs to start performing. This approach is also expected to lead to a faster convergence of the evolutionary algorithm, since the initial estimates would probably fall into the appropriate range of values. However, it could also impose some level of biasness, since a deterministically estimated set of initial values is used. In addition and for the same reason, the algorithm could be trapped to a local optimum instead of the global one. To avoid this, the genetic algorithm was additionally executed with sets of randomly generated initial values. Avoidance of trapping to a local optimum was also enhanced by creating a sufficiently large random population and by choosing different values of mutation probabilities, in order to maintain genetic diversity from one generation to the next and avoid local minima by preventing the population from becoming too similar to each other, thus slowing or even stopping evolution.

Stopping condition: The algorithm is terminated when the reduction value of the objective function becomes less than 0.01% in the last 10.000 iterations.

The *population size* was set to 500 individuals per generation, the crossover rate to 0.8 and the mutation rate to 0.01. The operations of crossover and mutation are not performed for every reproduction but the probability of a string to be selected for crossover is proportional to the string's fitness. Each operation is assigned a particular probability of occurrence or application. The probability of mutation is always very low, since the primary function of a mutation operator is to remove the solution from a local minimum. The probabilities are assigned based on the characteristics of the problem.

[1] Evaluation of the methodology was based on the Palisade Evolver software, a plug-in for Microsoft Excel that implements Genetic Algorithms (http://www.palisade.com).

4. Empirical analysis and results

4.1. Description of the data

The data used for evaluation are the market shares, expressed in percentages. They were extracted from W3Schools' log-files [57], over an eight year period and on a quarterly basis, spanning from 2003 to the second quarter of 2010. W3Schools is a website for people with an interest for web technologies, containing tutorials and references related to web development subjects, such as HTML, XML, CSS, and JavaScript. The site keeps monthly statistical information for web browsers and the corresponding operating systems from its log-files. Although this is only a part of the actual data for operating systems market shares, the high activity of the site [76] and the type of population visiting the site creates a credible statistical sample for the overall trends of the segment. Data, however, were cross validated with other operating systems statistics, that are provided by:

(i) *Market Share portal of Net Applications* [56]. The data are collected from the browsers of site visitors to an exclusive on-demand network of live stats customers. They are compiled from approximately 160 million visitors per month. The information published is an aggregate of the data from this network of hosted website statistics.
(ii) *Statcounter.com* [58]. Stats are based on aggregate data collected by StatCounter on a sample exceeding 15 billion pageviews per month collected from across the StatCounter network of more than 3 million websites.

All of the three data sources agreed that Microsoft Windows (all versions) is the dominant operating system with a market share of about 90%, leaving Apple's Mac OSX and Linux lagging behind, with the Mac OSX being second. It should be noted that W3Schools presented higher scores for Linux and lower for Windows with an inclination of about 4%. This can be justified by the fact that the W3Schools is accessed by more skilled and technology aware users, who are more probable to use Linux. The reason for opting for the W3Schools' statistics in this study was the availability of longer time interval datasets. This would, in turn, enable higher efficiency of the calculations and model's results. The descriptive statistics of the W3Schools data are presented in Table 2.

4.2. The operating systems market dynamics

Firstly, the genetic algorithms were applied on the dataset, producing the 12 parameters of (2). The estimation results for each operating system are illustrated in Fig. 1.

The accuracy of estimation is evaluated by the means of Mean Squared Error (MSE), Mean Absolute Percentage Error (MAPE) and the coefficient of determination (R^2), presented in Table 3. It can be observed that the statistic results validate the GAs estimation.

Substitution of the estimated values to the system of Eq. (2) yields the system of Eq. (9) that describes the dynamics of the examined operating systems:

$$\begin{aligned}\frac{dN_1}{dt} &= N_1(0.21-0.01N_1-0.39N_2-0.2N_3)\\ \frac{dN_2}{dt} &= N_2(4.95-1.06N_1-6.7N_2-5N_3)\\ \frac{dN_3}{dt} &= N_3(3.14-5.28N_1-3.26N_2-3.09N_3)\end{aligned} \tag{9}$$

In Eq. (9) the estimated parameters provide useful insight on the type of interaction and the churn effect (as described in Section 3.1) among the three operating systems. The negative signs of all of the a_{ij} parameters indicate that the type of interaction that describes the operating systems market is competition. That was an expected result, since OSs are competing for the existing and potential users and each OS's share is reduced due to the existence of the others.

Mac OSX exposes the highest intra competition growth rate (6.7) of all operating systems. It is also higher than the reduction rates it faces as a result of the competition with the other two systems (1.06 for Linux and 5 for Windows). It can be deduced that, Mac OSX is less affected by competition with the other two species and more affected by its own growth dynamics. This can be explained by the fact that Mac OSX mainly runs on its own Apple Mac PC and laptops, creating its “own” market. It is very

Table 2
Descriptive statistics for the three OS.

	Linux	Mac OSX	Windows
Observations	30	30	30
Mean	0.035	0.04	0.92
StDev	0.006	0.015	0.02
Variance	0.00003	0.00024	0.00045
Skewness	−0.26	0.56	−0.27
Kurtosis	0.1	−0.55	−0.62
Minimum	0.022	0.018	0.88
Median	0.035	0.038	0.92
Maximum	0.048	0.07	0.95

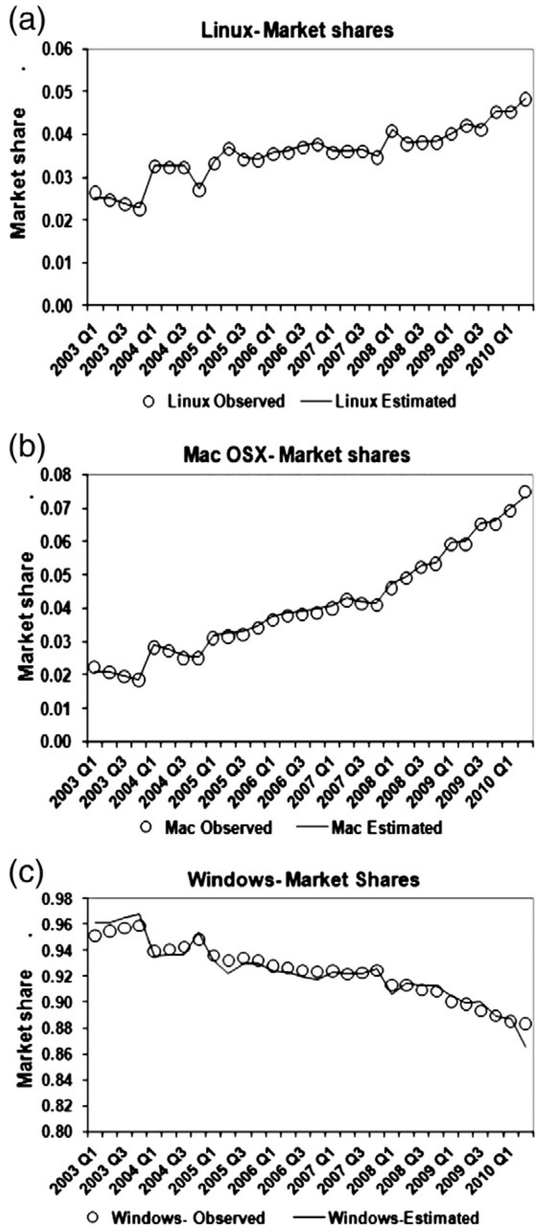

Fig. 1. Estimation results for (a) Linux, (b) Mac OSX, and (c) Windows.

improbable that a user of a Mac PC would opt for another OS than Mac OSX. Thus, its growth is mainly affected by its own positive or negative characteristics that would lead to adoption. As shown in Eq. (9), Mac OSX has the largest carrying capacity (4.95), showing that it grows faster than any of its competitors and that it has great prospects for growth. One interesting result here is a “hidden” mutualism of Mac OSX and Linux. Mac OSX is benefited by the existence of Linux, because Linux exerts low competition pressures on Mac OSX (1.06) and high competition pressures on Windows (5.28), which is the main competitor for Mac OSX (competition rate = 5).

Table 3
Statistical measures of parameter estimation results.

Observed vs estimated	Linux	Mac OSX	Windows	Average
R^2	0.995	0.997	0.919	*0.970*
MSE	1.84E-07	7.59E-07	3.5E − 04	*1.20E-05*
MAPE	0.011	0.021	0.005	*0.013*

Mac OSX is a partly OSS, that has gained approval by the open source community with its strategy to reveal large parts of the code to the OSS developers. Thus, a user who prefers the OSS technology for advantages like security and stability, while on the same time, is less technically skilled and feels more comfortable with a proprietary software, would opt for the Mac OSX rather than Linux. The main competitor for Mac OSX is the incumbent Windows system, which had the first mover's advantage and its users are more reluctant to change. As a result, the growth of Mac OSX is limited by the existence of Windows. Yet, although Mac OSX is a late follower, it has achieved a considerable market share, leaving Linux behind. This justifies many firms' strategies towards new OSS business models.

Windows also exhibit growth with a carrying capacity of 3.14; yet it is much lower compared to Mac OSX. Non skilled users, with functioning requirements limited to a document, spreadsheet, or e-mail, are reluctant to switch to another OS with different interface. Despite the fact that it is the incumbent operating system, it faces an intense competition by both Linux and Mac OSX. This can be deduced by the corresponding parameters values (5.28 with Linux and 3.26 with Mac OSX) and shows that Windows is most vulnerable to competition pressures it faces by both OSs. In addition, Windows suffer a greater loss by Linux (5.28), while Linux is negligibly threatened by Windows (0.2). This implies that Linux shares are raised due to Windows users that churn to Linux, while Linux users are less probable to churn to Windows.

On the contrary, the low, but steady growth rate of Linux (0.21) is acquired by the Windows shares. This implies that a fraction of Windows users who, for some reasons, are not satisfied by the Windows OS (e.g. the Vista distribution was a market failure) are more probable to try Linux, rather than Mac OSX. For example, some users may follow a dual boot operating system with both Linux and Windows, or even different Linux distributions through virtualization. They are mainly the kind of users who are technology aware and seek for cost efficiency and performance, rather than a brand name.

Finally, Linux has a low carrying capacity (0.21) and its diffusion is highly affected by the competition with the other two OSs. Its growth rate is rather small and is not expected to experience higher growth rates, at least under the current market conditions. It is threatened more by Mac (0.39) than by Windows (0.2). Thus, Linux users are more probable to churn to a 'partly OSS' Mac solution, which offers both the quality characteristics of OSS and the friendlier interface that is usually expected by a proprietary software. However, the churn effect is low, meaning a small but steady increase in Linux market shares.

Overall, following the interpretation of the estimated parameters it can be deduced that a firm like Apple, which based its product on an open source software and still maintains an open source community, has many opportunities in the competition race. Although a late follower, Apple has achieved to attract both Linux and Windows users and be established in the market, leaving Linux behind.

4.3. Equilibrium analysis

In order to calculate the equilibrium state of the system of equations in (9), they are simultaneously set equal to zero, that is:

$$F(N_1, N_2, N_3) = 0, \quad G(N_1, N_2, N_3) = 0, \quad H(N_1, N_2, N_3) = 0 \tag{10}$$

The solution of (10) provides with 8 critical (equilibrium) points, as shown in Table 4. The seven of them lead to the extinction of one, two or three operating systems; only the eighth one indicates the coexistence of all species.

However, not all of them are stable critical points. After dropping the non-valid triads of critical points (not belonging to the positive octet) and in order to examine the stability of the rest of the points, an eigenvalue analysis is performed. The eigenvalues and eigenvectors for each valid triad N_1^0, N_2^0, N_3^0 of Table 4 is derived by calculating the corresponding Jacobian matrices of Eq. (4), as described in Section 3.2. The analysis resulted in only one stable critical point, i.e. the eighth critical point of Table 4, which indicates that none of the competing species becomes extinct at the equilibrium. The rest of them are unstable, since the eigenvalues of the Jacobian matrices are of different sign and thus in the derived general solutions, one of the variables dominates and causes the system to be unbounded and unstable [66].

Table 4
Critical points of the system.

	Critical points		
	Linux	Mac OSX	Windows
	N_1	N_2	N_3
1	0	0	0
2	0	0	1.01
3	0	0.74	0
4	1.37	0	0
5	0	−0.09	1.11
6	−0.03	0	1.06
7	1.60	0.49	0
8	0.07	0.12	0.81

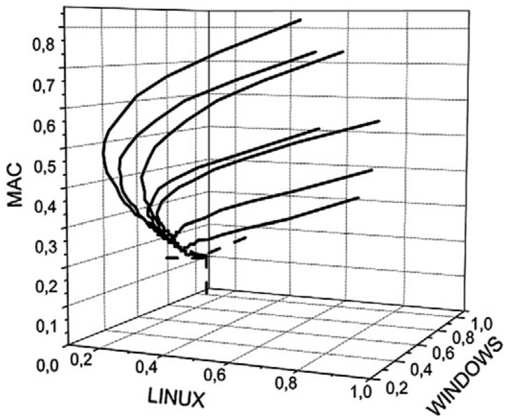

Fig. 2. Phase portrait of dynamic system based on random initial market shares: all trajectories tend to the stable critical point.

The stability of system (9) at the specific critical point is also graphically illustrated by a phase diagram, as shown in Fig. 2, based on different initial values for market shares. As observed, whatever the initial conditions are, all trajectories converge to the estimated critical point, validating its stability.

The stable critical point provides information regarding market equilibrium among the three competing operating systems. At the equilibrium, Windows will remain the leader in the market with an 81% market share; yet its shares are reduced, due to the other two operating systems. Mac OSX is expected to reach a 12% market share and be established in the market with an

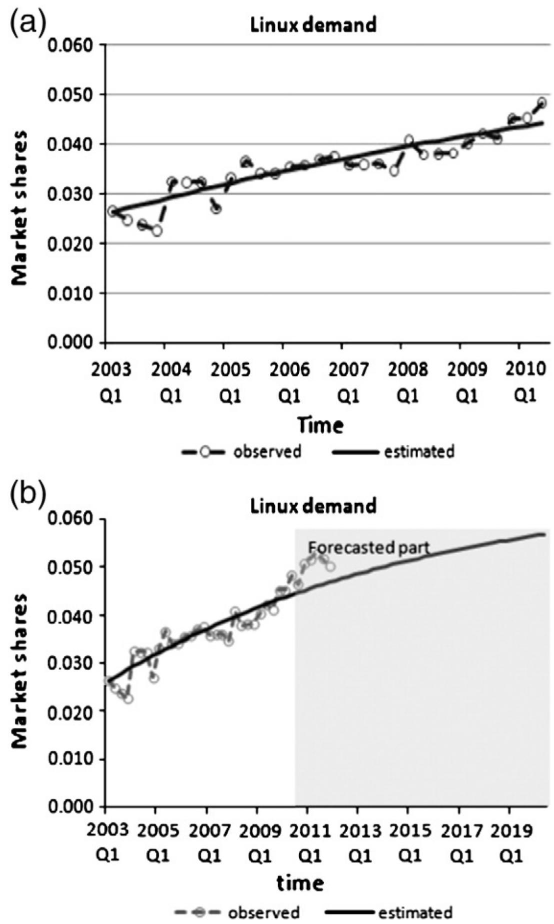

Fig. 3. Estimated (a) and forecasted (b) demand for Linux.

important fraction of users. Linux has a low growth rate, yet it is not pushed out of the market. Despite the fact that competition is hard for Linux, its market share increases reaching a 7% and co-exists with the two prevailing systems.

4.4. System solution and demand functions

By substituting the eigenvalues and eigenvectors of the Jacobian for the stable critical point (0.07, 0.12, 0.81) into Eq. (6), the general solution of the system in Eq. (9) is derived and illustrated in Eq. (11).

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = c_1 \begin{pmatrix} 0.006 \\ 0.272 \\ 0.962 \end{pmatrix} e^{-3.04t} + c_1 \begin{pmatrix} -0.038 \\ -0.735 \\ 0.677 \end{pmatrix} e^{-0.26t} + c_1 \begin{pmatrix} 0.215 \\ 0.571 \\ -0.792 \end{pmatrix} e^{-0.02t} \quad (11)$$

In Eq. (11) c_1, c_2, c_3 are arbitrary constants. However, since it is an initial value problem, substitution of the initial values (the initially recorded market share values) into the general solution allows for their calculation. Thus, the final solution is given by:

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} 0.0002 \\ -0.0099 \\ -0.0351 \end{pmatrix} e^{-3.04t} + \begin{pmatrix} 0.0005 \\ 0.0087 \\ -0.008 \end{pmatrix} e^{-0.26t} + \begin{pmatrix} -0.041 \\ -0.111 \\ 0.153 \end{pmatrix} e^{-0.02t} \quad (12)$$

The evolution of the market for each operating system, as reproduced by the above Eq. (12), is illustrated in the figures Figs. 3 to 5.

The statistical measures of accuracy, MSE, MAPE and R^2 of the observed versus the estimated values, for each operating system are shown in Table 5.

The figures present the estimated demand functions, as well as their forecasts projected for a ten years period. In order to depict the accuracy of forecasting, the observed values spanning from 2010 (Q3) until 2011 (Q4) were obtained from the

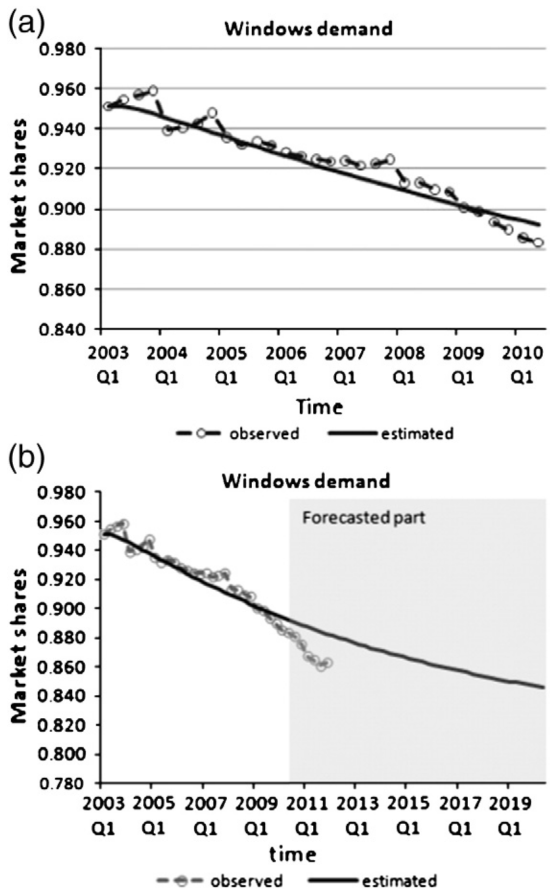

Fig. 4. Estimated (a) and forecasted (b) demand for Windows.

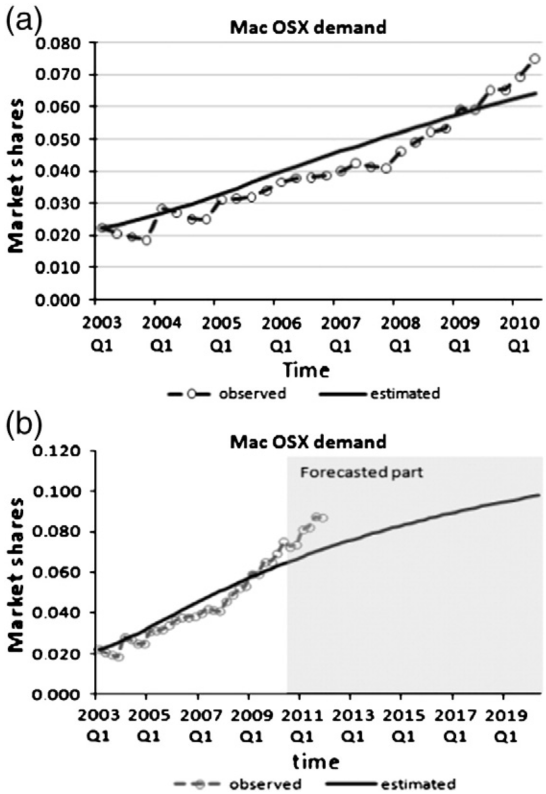

Fig. 5. Estimated (a) and forecasted (b) demand for Mac OSX.

W3schools site. The observed versus the forecasted values are illustrated in Figs. 3–5. Moreover, the MAPE of the forecasted part is illustrated in Table 5, verifying the forecasting efficiency of the model.

However, it should be noted that long time interval forecasts cannot be realistic in the rapidly evolving software market and is beyond the scope of this work. The values beyond a five year forecast are added mainly to exhibit the future trends of the market, rather than the actual values. Market conditions, such as new entrances, or government interventions may alter the demand curves, as shown in Section 5.

Figs. 3–5 show that, although the demand for Windows is ultimately decreased due to the competition stressed by its opponents, in the long run Windows will retain high market shares. Linux, on the other hand, achieves a small increase in its shares, yet it will still co-exist with the two proprietary firms and will not be pushed out of the market. Finally, Mac OSX, although a late follower, it exhibits observable growth and is expected to be established in the market, achieving to alter a monopolistic market to an oligopolistic one.

5. Sensitivity analysis of Linux adoption

Public and private sector have a number of good reasons for Linux and OSS adoption, as already described in previous sections. Despite the fact that Linux has matured to a point that even less technically advanced users could adopt it, the rise of desktop Linux adoption has not dramatically changed during the last years. However, there are new conditions set in the market, which have created new prospects for Linux adoption in organizations.

Table 5
Evaluation of the estimation.

Observed vs estimated	Linux	Mac OSX	Windows	Average
R^2	0.891	0.852	0.918	0.88
MSE	6.59E−06	2.6E−05	3.55E−05	2.27E−05
MAPE	0.064	0.121	0.005	0.063
Forecasting				
MAPE	0.094	0.151	0.021	0.089

Firstly, the new market trends for a more centralized approach to desktop delivery via various virtualization and/or cloud computing options (such as virtualized desktop on a thin client) and the economic downturn has brought back the question of desktop strategy in organizations' managers and decision makers [51,52]. This, together with the fact that a large number of organizations have already installed Linux servers in their central systems, could yield a large increase in Linux adoption at the organizational setting. If non-technical users become acquainted with Linux at work (private or public sector) they would also opt for it at home.

Moreover, inspired by the OSS values, a number of other forms of open initiatives have been gaining momentum. Open source systems extend even beyond software to include open access, open documents, open science, open government and more. In the context of eGovernment (eGov) the notion of governmental openness has met wide acceptance among nations and became closely related to one of its goals [77]. For instance, the US government has introduced the open government initiative declaration [78] and in Europe the EU Ministerial Declaration [79] pays particular attention to the benefits resulting from the use of open specifications, promoting the open source model in eGov projects. Both declarations, contain principles (like accessibility, transparency and openness) and methodologies (like collaboration and sharing), that are obvious references to open source.

This trend by governments towards OSS has resulted to a number of actions and policies that promote OSS in the public sector worldwide [80,81]. Motivations for such actions, apart from technological (quality) and economical (OSS is cost effective) [47] could also be ideological, as OSS technologies transfer the ideas, believes and notions of freedom and openness, as for example in the case of Venezuela [82]. Lewis [83] reported three hundred and sixty-four open source policy initiatives worldwide, many of which are aiming at Linux adoption in the public sector.

Motivated by these trends in both the private and public sector, this section creates a model for a possible rise of Linux adoption in expense of Windows and examines the outcomes and market structure at different adoption levels. Such a case would be for instance, if governments decided to migrate to the desktop Linux, in different parts of the public sector, such us public authorities, schools, universities, hospitals, etc.

More particularly, different levels of adoption, *g*, are assumed, in order to examine the consequences of such actions in the OS market structure and competition. To achieve this, the model of Eq. (9) is redefined so that to capture the "churn-effect" of the Windows potential that migrates to Linux. The model assumes that a fraction (percentage) of *g* Windows users that belong in some organizations will migrate to the Linux system, thus adding potential to Linux users. In mathematical notation, the interspecies competition rate indicating the number of Windows users that migrate to Linux, i.e. $5.28\ N_1$, will be increased by a number of gN_1 users. As a result, the intraspecies coefficient, or growth rate of Linux users will be increased by the same number of gN_1 users. No further changes are assumed regarding the Mac OSX system. The new model is defined in (13).

$$\begin{aligned}\frac{dN_1}{dt} &= N_1(0.21-(0.01-g)N_1-0.39N_2-0.2N_3)\\ \frac{dN_2}{dt} &= N_2(4.95-1.06N_1-6.7N_2-5N_3)\\ \frac{dN_3}{dt} &= N_3(3.14-(5.28+g)N_1-3.26N_2-3.09N_3)\end{aligned} \tag{13}$$

The methodological procedure described in Section 3 is also followed for the system in Eq. (13). The analysis is performed for different values of *g*, which correspond to different levels of adoption and is measured in percentage rate. The stable equilibrium points corresponding to each value of *g* are presented in Table 6. The equilibrium points illustrate how the market structure is formed at the equilibrium state, for different levels of adoption promotion (*g*).

Table 6 also provides information about competition intensity, expressed in terms of the Herfindahl –Hirshman Index (HHI). The HHI index is calculated at the equilibrium, for the different values of *g*. The trivial case where $g = 0$ corresponds to the absence of an adoption policy, that is system (9). The diffusion function of each of the competing species has been calculated for each promotion level, *g*, following the same methodology as in the previous sections. The demands are graphically illustrated in Fig. 6. The estimated demand functions are projected to a five years period.

It can be deduced that the overall market competition rate is increasing analogously to the Linux adoption rate, *g*. At a 3% level of promotion the market structure is turning to competitive, in contrast to the case of no promotion, which corresponds to a rather oligopolistic market. Moreover, the time where market equilibrium is reached, is lessened proportionally to the adoption rate *g*.

Table 6
Equilibrium points and market concentration for different levels of Linux promotion.

Values of portion *g*	Equilibrium points (Linux, Mac, Windows)	HHI
0.00	(0.07, 0.12, 0.81)	0.67
0.01	(0.09, 0.19, 0.72)	0.56
0.03	(0.13, 0.28, 0.59)	0.44
0.05	(0.15, 0.34, 0.50)	0.39
0.07	(0.17, 0.39, 0.43)	0.37
0.08	(0.18, 0.41, 0.40)	0.36

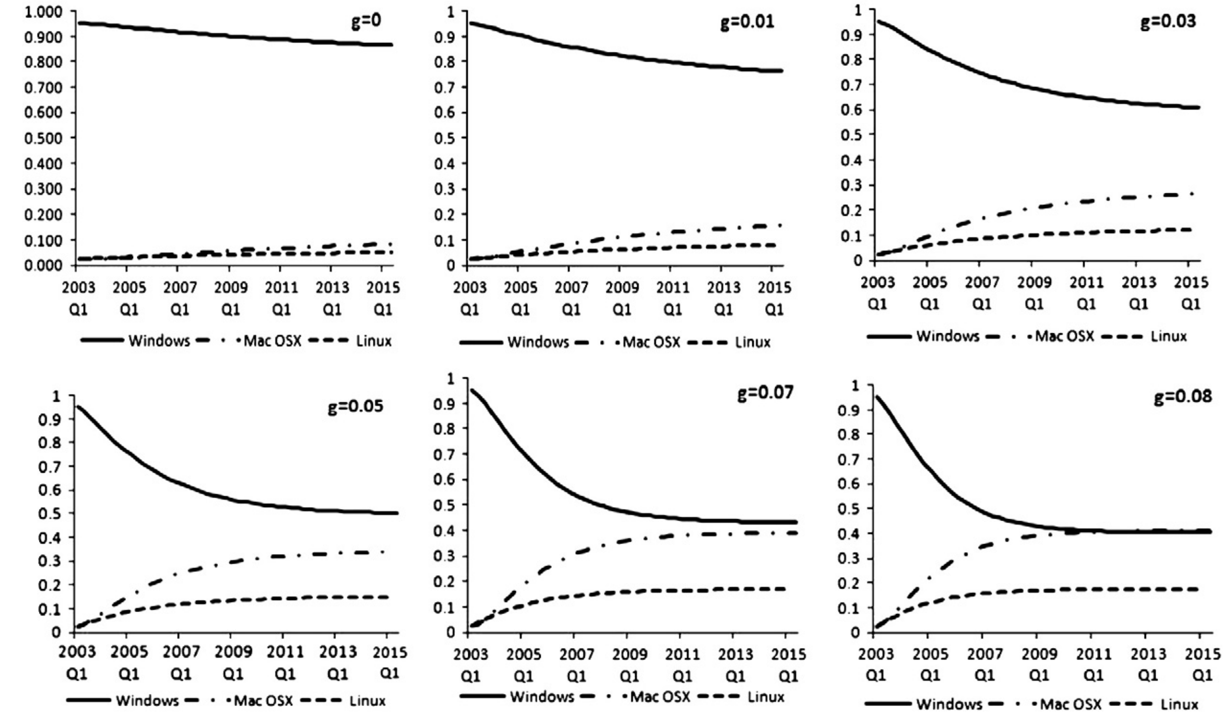

Fig. 6. Demand functions and equilibrium for different levels of Linux adoption at a five year forecast.

As expected, the market shares of Linux increase, while the shares of Windows decrease. In model (9) Linux had a very low growth rate and market share, which could not allow for radical changes in its shares; yet, as *g* increases, Linux achieves a considerable market share and manages to be established in the market of DT/LPs. The intriguing element, however, is the rise of Mac OSX shares at a level capable of a direct threat against the incumbent Windows. At an 8% level of Linux adoption, Mac OSX overtakes Windows.

This can be explained by the fact that in Eq. (13) Linux is growing at the expense of Windows, which is the main competitor of Mac OSX. The competition rate between Mac OSX and Linux is very low (1.06), indicating that Linux cannot influence Mac OSX. On the other hand, competition rate of Mac OSX with Windows is much stronger (competition rate 5). The fact that Linux adoption decreases Windows shares forces Windows to exert less competition pressure on Mac OSX. This, in turn, results to an increase in Mac OSX shares. The effect can be compared with the strategy of alliance between two smaller firms in order to confront a monopolist [30]. Although there is no alliance between Mac OSX and Linux, the mutualism indicated in model (9) has a stronger effect now, as Linux becomes stronger and Windows shares decrease.

As a result, the churn of Windows users can overturn market dynamics in favor of Mac OSX and turn the DT/LPs market to a competitive one. The increase in the market competition would consequently enable more potential entrances in the market.

6. Managerial implications

Results of Sections 4 and 5 show that OSS can play an important role even in highly concentrated markets, like the DT/LP market. Though Windows continues to dominate at the equilibrium, the market will become less concentrated due to competition it faces with Linux and Mac OSX. It can be deduced that the role of OSS here is twofold. Firstly, Linux as an open source software has exerted pressure on the Windows shares. Although “Linux desktop year” has not come, Linux is not pushed out of the market. On the contrary, it is growing at a small pace, impinging Windows' shares. This is mainly due to the fact that Linux has built a reputation for quality and security characteristics through years of testing and validation.

Secondly, Linux has created the conditions for new entrances, especially for those with an open source business model. That is the case of the commercial, yet partly-OSS, Mac OSX. As it is deduced from the model (9) there is an indication of mutualism. Mac OSX is less affected by the competition, enjoying the benefits of its open source nature. This nature makes Mac OSX favorable to less skilled users who seek for both OSS quality characteristics and a commercial alternative. Though a late follower, it has achieved to be established in the market, leaving Linux behind. As it was shown, Mac OSX has the largest growth prospects.

This justifies many firms' strategies towards new OSS business models, setting OSS an important part of an IT strategy. Today, a company is one that stands behind its software and offers a development roadmap, technical support from the developers and other services. These companies deliver open source software with certified binaries, complete documentation and easy installation software. This gives customers the best of both worlds, that is enterprise-grade software without the risk of platform lock-in. Successful examples for Linux distributions are RedHat (Fedora), Canonical (Ubuntu), the emerging Clement Lefebvre with Linux Mint, etc.

Moreover, as the modified model (13) indicated, there are conditions under which the DT/LP market structure can dramatically change and even become purely competitive. This could be enabled by a rise of Linux adoption at the expense of Windows, in public and/or private organizations. As deduced by model (13), a strategy towards Linux adoption would lead to more competitive structures.

Model (13) also shows that if Apple and Linux act cooperatively, Apple's shares would substantially increase. As Linux doesn't grow on the expense of Mac OSX, an Apple's strategy towards Linux would directly benefit Apple. Thus, Linux could be promoted directly by Apple itself. Apple's paradigm could be followed by other prospective entrants in the DT/LP market.

The consequences of the OSS impact in the OS market have been reflected in the new and rapidly evolving market sector, which emerged due to the software requirements of devices like mobile phones and tablets. In this sector, Apple with iOS dominates the market; however the market is not concentrated. iOS is derived from Mac OSX, with which it shares the open source Darwin kernel. Consequently, iOS carries the success reputation of OSS and Mac OSX. In this case, Windows didn't have the first mover's advantage, thus the partly-OSS, iOS, has been immediately widely accepted. On the contrary, Windows Phone and Windows Mobile of the Windows Embedded Compact (CE) family products have been almost pushed out of the market with a less of 0.5% market share each [56]. The new market entrance is now Google with Android, which is OSS licensed under the Apache License and is widely based on the Linux kernel. Android has achieved a 19% [56] and is continuously increasing its shares. Contrary to iOS, Android is purely OSS and thus enjoys a wider acceptance and support by the OSS community, with the purely commercial OSs in the mobile/tablets market, having a share of less than 3%. It can be deduced that OSS entrances have been substantially benefited in this new market.

7. Conclusion

The work presented in this paper proposed a methodology for the modeling of DT/LP operating systems market concentration and competition intensity, due to the emergence of Open Source Software (OSS). The construction of the methodology was based on concepts of population dynamics, ecological modeling and the Lotka–Volterra model. The model's parameters were estimated by applying genetic algorithms, which are adaptive heuristic search algorithms based on the mechanisms of natural systems and genetics. The main assumption of the methodology was to consider the three software products as interacting species competing for a common source, the market itself, expressed in terms of market shares. The study of the constructed system's dynamics was performed over the three most popular DT/LP operating systems, Linux, Mac OSX and Microsoft Windows.

The empirical analysis showed that, at the equilibrium, all operating systems will coexist, while the highly concentrated market will have a tendency to become oligopolistic. Regarding the dynamics of the market, it was shown that Mac OSX has the highest growth rate and is less affected by the competition with the other systems, while is more affected by its own growth dynamics. An indirect mutualism effect, where the partly OSS Mac OSX is ultimately benefited by the existence of Linux, could also be deduced.

Windows, on the other hand, experiences a decrease in its share, as it faces intense competitive pressures by both Linux and Mac OSX, with Linux being its main opponent. Results show that Linux shares are raised, mainly due to Windows users that churn to Linux, while Linux users are less probable to churn to Windows. However, the low growth rate of Linux is not expected to increase substantially, at least under the current market conditions and Windows will retain its leading position.

The above results add to the issue of the impact of OSS on competition. Firstly, OSS has a direct impact by the emergence of quality OSS such as Linux, which can offset the monopolistic behavior of the software market. Even in the highly concentrated DT/LP OS market, Linux not only survives but also raises its shares. Secondly, OSS allows for the creation of new business models, like the partly OSS that enable successful entrance in the market. The partly OSS Mac OSX paradigm shows that Mac OSX, though a late follower, has successfully entered a highly concentrated market.

The consequences of the OSS impact in the OS market have been reflected in the new and rapidly evolving market sector, which emerged due to the software requirements of devices like mobile phones and tablets. In this case, the descendant of Mac OSX for mobiles and tablets iOS has become the dominating OS, while the corresponding Windows descendants, windows phone and windows mobile, exhibit negligible shares. On the contrary, the new entrant, open source Google Android is rapidly evolving. These outcomes justify many firm's strategies towards new OSS business models, setting OSS an expected part of an IT strategy.

Finally, the study performs a sensitivity analysis to test the possible effects on market structure, induced by migration from Windows to Linux at an organizational level. Results demonstrate that there are conditions under which the DT/LP market structure can dramatically change and even become purely competitive. Moreover, there is a clear indication of mutualism between Linux and Mac OSX, where the rise of Linux adoption directly benefits Mac OSX. It can be deduced that if Apple and Linux act cooperatively, Apple's shares would substantially increase. The effect can be compared with the strategic alliance between two smaller firms in order to confront a monopolist [30]. Thus, Linux could be promoted directly by Apple itself. Apple's paradigm could be followed by other prospective entrants in the DT/LP market.

Overall, the proposed methodology and results can provide valuable inputs for managerial decisions and strategic planning to the players of software market. Although the model does not consider any random effects, which could be desirable for a more real description, it is the most appropriate for the present case, where the main target is to point out that the main interest resides in the competitive dynamics of the model. Furthermore, it is a good starting point to gain a better understanding of the OSS competition dynamics. Future work directions include the development of suitable methodologies based on the other approaches of the Lotka–Volterra models, such as seasonality, stochastic extensions, or influential behavior of other external factors, in order to comprehensively study the different aspects of the market, such as complementary and substitute software products.

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