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Diffusion Dynamics of Open-Source Software in the Presence of Upgrades: An Agent-Based Computational Economics (ACE) Approach

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DIFFUSION DYNAMICS OF OPEN-SOURCE SOFTWARE IN THE PRESENCE OF UPGRADES: AN AGENT-BASED COMPUTATIONAL ECONOMICS (ACE) APPROACH

Dynamique de diffusion des logiciels libres comportant des montées en version: une approche par l'économie computationnelle fondée sur les comportements d'agents

Completed Research Paper

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Abstract

Researchers have identified numerous factors that impact the diffusion of open source software (OSS). This paper proposes an integrated model that studies how key factors affect the diffusion dynamics of OSS. Specifically, we investigate the role of software upgrade cycle in the diffusion of OSS. We also incorporate factors such as variability in OSS support costs, interoperability issues and network structure that have not been systematically studied in prior OSS research. Our results demonstrate interesting effects of these factors on diffusion dynamics of OSS. Variability of OSS support costs, length of upgrade cycle and interoperability costs are identified as major determinants of OSS diffusion. The results illustrate that a proprietary software (PS) vendor should consider several other strategic variables besides price such as interoperability costs and upgrade cycle that affect OSS diffusion. The proposed model can be used as a building block to model competitive dynamics in software markets.

Keywords: open-source software, upgrades, diffusion dynamics, agent-based modeling, ACE

Résumé

Cette communication propose une modèle intégré de simulation basé sur les comportements d'agents qui étudie comment la dynamique de diffusion des logiciels libres est influencée par les facteurs clés suivants : topologie du réseau, taille du voisinage local, variabilité du coût d'assistance pour les logiciels libres, coûts d'interopérabilité, durée du cycle de montée en version et nombre initial d'adopteurs du logiciel libre. Le modèle proposé peut être utilisé comme une première pierre afin de modéliser la dynamique concurrentielle sur le marché des logiciels.

Introduction

There is increased interest in the evolution of open-source software (OSS). Reports indicate that a growing number of servers and databases being run online are using OSS and an increasing number of organizations are either looking to move completely to open-source systems or they are making their existing systems compatible with OSS (Wheeler, 2005). OSS has been studied from various perspectives such as diffusion (Bonacorsi and Ross 2003), pricing (Kim et al, 2006), licensing (Tirole and Lerner, 2005), contribution (Lerner and Tirole, 2001), quality and release management (Michlmayr, 2005). Previous research on these issues has shown that under some circumstances, OSS prevails over PS (Masanell and Ghemawat, 2006), or that both can co-exist but the PS vendor must carefully assess the pricing strategy to compete with OSS (Mustonen, 2003). There is some understanding of the factors that cause firms to adopt OSS (Bonaccorsi et al, 2006; Kim et al, 2006; Masanell and Ghemawat, 2006; Zhu et al., 2006). However, the manner in which these factors determine the dynamics of OSS diffusion has not received adequate attention. This study focuses on the diffusion dynamics of OSS. It recognizes that OSS diffusion is a complex phenomenon and emphasizes the need to study it using multiple theoretical perspectives. OSS is an innovation and hence can be studied from the diffusion of innovation perspective (Rogers, 1995). OSS can also be viewed as a type of standard and hence can be examined using the growing body of research on standards (Zhu et al, 2006). Since OSS is a software product, characteristics of software products such as upgrades (Ngwenyama et al, 2007) and support are also important.

Based on these theoretical perspectives, we propose an agent-based model of OSS diffusion that illustrates the effect of the following key variables on the diffusion of OSS: i) network topology; ii) size of the local neighborhood of a firm, iii) variability in the support cost for OSS; iv) interoperability costs between different software; v) frequency of upgrades for competing PS; and vi) initial proportion of OSS adopters. Specifically, we address the following research question: How do key variables individually and collectively affect the diffusion dynamics of OSS? Our study is the first one that examines how upgrades affect the diffusion of two competing software. We also incorporate several under studied factors, such as network structure and variability in support cost, into a unified framework. The agent-based computational economics approach (Tesfatsion and Judd, 2006) used in our model allows for significant agent (OSS or PS adopter) heterogeneity in terms of size, planning of upgrades, technical competence with OSS, and support costs of OSS and allows integration of economic and social concepts. The proposed model uses social networking concepts of small-world networks and centrality in modeling the effect of network structure on diffusion (Watts and Strogatz, 1998). The desktop operating system (OS) market is used as an exemplar in this study since some empirical data regarding its cost components are available.

Our results demonstrate interesting main and interaction effects of the above parameters on diffusion dynamics of OSS. In particular, variability of OSS support costs is a major determinant of OSS diffusion. The results illustrate that a PS vendor should consider several other strategic variables besides price such as interoperability costs, upgrade cycle, and network structure that affect OSS diffusion. Interaction effects between these variables are studied.

This paper is organized as follows: the next section provides a brief review of the relevant literature on OSS diffusion and agent-based modeling. This is followed by the details of the proposed model and description and discussion of results. Finally, some conclusions and ideas for future research are discussed.

Literature Review

Open Source Software

Open source software (OSS) is any piece of software whose source code is made publicly available under terms that follow the 'Open Source Definition' (Perens, 1999: pp 171-188). Generally, such software is freely available online. However, companies such as Red Hat and Ubuntu charge a fee for providing support.

OSS has been studied from various perspectives such as diffusion (Bonaccorsi and Ross 2003), pricing (Kim et al, 2006), licensing (Tirole and Lerner, 2005), contribution (Lerner and Tirole, 2001) and quality and release management (Michlmayr, 2005). There are certain aspects of this software that are distinctly different from proprietary software: zero or very low license costs, demand-driven upgrades, absence of pressure to upgrade from the vendor, uncertainty of support/quality, greater flexibility in terms of customization, uncertainty over the timing of new releases etc. These unique aspects affect the development as well as adoption dynamics of OSS. Given the context of our investigation i.e. diffusion dynamics, and given the space limitations, it is not possible to provide a detailed review of the literature on open source software. However, the following subsections provide a brief review of key findings in the literature on diffusion and agent-based modeling in the context of OSS.

Diffusion Studies

There have been various studies of the factors that affect adoption and diffusion of OSS. Some have used empirical methods whereas others have used mathematical modeling. Bonaccorsi and Rossi (2003) concluded, on the basis of reviewed literature that the adoption of OSS and its diffusion are influenced by i) the perceived intrinsic value of the open source software; ii) the negative externality effect as a result of the other more dominant standard; iii) the positive externality effect as a result of association with OSS communities; and iv) the competitive reaction from the proprietary software firms. They developed a simulation model with N firms (agents), all of them using proprietary software. The adoption decision was based on the perceived intrinsic value of open source software, the network externality and coordination factors (based on other member-firms in the network). The study concluded that OSS diffusion depended on the initial distribution of intrinsic values assigned to the technology by agents.

Dalle and Jullien proposed that any firm would choose OSS over PS if its local and global benefits 'outweighed' its idiosyncratic preferences (Dalle and Jullien, 2001). The concept of these 'idiosyncratic preferences' was in some ways similar to the one that was later used by Bonaccorsi and Rossi as 'intrinsic value'. Both the local and global benefits were considered as a function of the number of participants in a firm's network (including firms using the same or different standards). Mustonen (2005) showed through mathematical modeling techniques that under certain market conditions both proprietary and open source software can co-exist. However, the firm selling the proprietary software must carefully evaluate pricing strategies.

Kim et al (2006) studied two types of consumer firms (high/low-type based on internal technical capability) and three different types of pricing schemes for OSS (commercial, dual licensing and support) under different market conditions (monopoly and duopoly). Using mathematical modeling techniques, they were able to demonstrate that: i) the dual-pricing strategy for the OSS was viable in a competitive market; ii) the support model in which OSS vendors provided the software for free but charged for support services was not viable for them in a duopoly setting, iii) in a two-period model switching costs did not make much difference since the PS vendor chose a pricing scheme that eliminated the profit margin for the OSS vendor iv) OSS support model was viable in case of quality asymmetry regardless of whether OSS was higher or lower in quality than PS.

Agent-Based Computational Economics

Agent-based computational economics (ACE) is a relatively new, growing area of economics (Tesfatsion and Judd, 2006). It provides a useful modeling approach to analyze various phenomena. This section introduces ACE and how it can be applied to explore diffusion dynamics of OSS.

ACE is a simulated agent based modeling technique. It can be applied to a problem by defining a set of agents with related attributes, behaviors and fitness function; the simulation environment and the overall performance-measuring objectives of the environment. The term agent is originally from the field of Artificial Intelligence. It can be thought

of as some computational system which has certain attributes, rules/actions and goals. Depending on the nature of the system being modeled, there can be many types of agents (cells, species, individuals, firms, nations etc) and such heterogeneity can be modeled within each type of agent as well. Sometimes these agents act independently of each other and on other occasions they interact with each other while competing or collaborating towards their individual goals. As a result of countless interactions new behavior 'emerges' which had not been programmed into the behavior of the individual agents (Waldrop, 1992).

The open source market depicts similar characteristics: consumer firms, proprietary software vendors, open source support-providing firms (all acting as agents), working towards their individual goals (profit maximization and/or sustainability in the market) while taking different actions (adopting different standards, pricing strategies etc.). In this research, each agent represents a firm. All agents have a set of attributes (such as whether the firm uses OSS, its support costs and others). An agent can either act independently or be influenced by the behavior of other agents. The agents have to choose between two competing software based on their objective or fitness function. In this case the objective or fitness function measures the net annual cost savings. Any meaningful behavior exhibited by the system arises from the cooperation and competition amongst the agents.

Abbreviated Assessment of Previous Literature

Previous studies have not taken a more holistic view of important factors associated with the adoption of PS or OSS. First, there is considerable uncertainty regarding the magnitude of OSS support costs (Leading Edge Forum, 2004) which has not been adequately investigated. Second, availability and timing of technology upgrades in the context of adoption and diffusion of OSS have not been studied. When a software upgrade[1] becomes available firms have to incur one-time costs such as setup and training costs. It is at this point that firms choose whether to upgrade or 'jump ship' (McAllister, 2006). If firms neither upgrade nor switch to a different software, they anticipate that soon the support for the existing version will be withdrawn and they will have to make a different decision (Bowman, 2006). Availability of hardware upgrades also influences the decision of firms (McMillan, 2004). Furthermore, there has been extensive research on the release cycles of open source software which points to the coordination issues in release management (Michlmayr, 2005). Although release management is beyond the scope of this model, it is known that in the absence of vendors, OSS upgrades tend to be demand-driven whereas PS upgrades are vendor-driven. This is understandable since with open source software, consumers have the option to initiate and or get involved in the development of an upgrade they need. On the other hand, with proprietary software, consumers have to either wait for the vendor to come up with the upgrade, have the upgrade custom-made by the vendor, or purchase the required change through a third party. Therefore, it seems that the impact of varying upgrade cycles on rate of diffusion has not received adequate attention. Third, it is important that long-term costs are taken into account during upgrade decisions since choice of an operating system is more like a platform decision that affects hardware, existing application portfolio, staffing/training issues etc. (Gray, 2005). The duration of this "long-term" may vary for firms depending on their size and industry. Hence firms will value the same upgrade costs differently and that must be factored into the decision-making process. Fourth, as much as support costs affect the adoption decision, previous literature on standard adoption (Chen and Forman, 2006) indicates that interoperability issues play a significant role as well. Microsoft has a clear dominance in the desktop operating system market. As mentioned earlier, switching platforms can have several implications on a firm's existing portfolio of applications. Even supporters of Linux concede that the pool of compatible applications for Linux is smaller compared to the pool of compatible applications for Windows. This difference may diminish over time. However, right now firms can expect to incur some interoperability costs to communicate with partners using a different platform. None of the previous studies on diffusion of OSS have specifically addressed this issue. Finally, there has been a call in previous research (Masanell and Ghemawat, 2006) to explore "strategic variables other than price" to "better understand the drivers of adoption" particularly in the context of Windows and Linux. This paper addresses all of these points. Table 1 summarizes our contribution in comparison with the reviewed papers. Due to lack of space, some of the column headers had to be abbreviated. Here they are in order from left to right: perceived value/benefit, network effects (local and global), local connectivity (size of neighborhood), price (license cost), switching cost, support cost, other costs, risk (of adopting another software), consumer heterogeneity, network topology, length of PS upgrade cycle, firm size and technical capability (with respect to OSS). Thus, in our opinion, this paper builds on prior research by considering a more comprehensive, relevant range of factors that affect diffusion dynamics of OSS.

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[1] For the purpose of this study we do not consider minor upgrades or patches and focus on major upgrades

Simulation Model and Parameters

In our diffusion model, agents are firms that make software adoption decisions. They are connected in a network, in which each link represents a business relationship. According to prior diffusion studies on standards and other phenomena (Weitzel et al., 2006; Delre et al. 2007), network topologies have a significant impact on innovation diffusion. Thus, we examine OSS diffusion in three different types of networks: network with low cliquishness, network with high cliquishness, and small-world network. We used Watts and Strogatz algorithm (WSA) (Watts and Strogatz, 1998) to simulate these three networks in NetLogo 4.0.2[2]. WSA is an elegant algorithm that facilitates the creation of different network structures by varying one parameter and has been used to study diffusion of fashions (Delre et al., 2007) and effect of network structures on contribution to OSS projects (Singh, 2007).

Each firm will adopt either proprietary software or open-source software (for example, Microsoft XP and Red Hat Linux). As is the case in the market for desktop operating systems, we assume that the proprietary software dominates the network at the beginning of the simulation. Initially, firms using OSS represent a small percentage of the total population and are randomly distributed. However, each firm will periodically evaluate their technology (hardware and/or software). Mukherji et al (2006) state that "in the case of frequent upgrades, it is important for firms to decide the frequency at which its technology must be replaced" (pp. 1685). Furthermore they state that firms generally adopt a "long term 'plan' for investment in IT upgrades". Our use of a planning horizon is in line with this understanding. At the beginning of each planning horizon, firms will decide whether to upgrade the existing software or switch to the other software. The length of firms' planning horizon (PH) is greater than or equal to the upgrade cycle (UC) of their respective vendors. The longer the PH, the more reluctant a firm is to consider software changes due to reasons such as organizational inertia or lower innovativeness. To simulate that behavior we chose a range of values of PH for the firms and these values were distributed across the entire population in proportions similar to that exhibited by an S-shaped curve (i.e., 20% firms have a PH=UC, 30% have a PH=UC+1, 30% have a PH=UC+2, and 20% have a PH=UC+3). Each firm considers whether to adopt the other software or upgrade its existing software based on the following decision function.

$$\frac{C_{t+1}^U - C_{t+1}^S}{C_{t+1}^U} - \left((1-\alpha)\times(1-n)\right) \quad \begin{cases} > 0 \ \text{Switch to a different software} \\ < 0 \ \text{Upgrade the existing software} \end{cases}$$

where

C_{t+1}^U represents costs if the firm decides to upgrade its software

C_{t+1}^S represents costs if the firm decides to switch to the other software

α represents the centrality of a firm

n represents the proportion of a firms' neighbors who use the proposed new software

The first part in the decision function is the intrinsic value that the firm obtains through cost-saving benefits from switching to the other software. The following cost factors were taken into account: i) license costs: annual license costs per computer for both OSS and PS firms; ii) setup costs: one-time costs for setting up a computer with OSS or PS averaged over the planning horizon for each firm; iii) support costs: annual support costs per machine charged by the OSS or PS vendor; iv) training costs: one-time costs for training users on an OSS or PS machine averaged over the planning horizon for each firm; v) interoperability costs: costs incurred by a firm while conducting transactions with neighboring firms using a different software. OSS support costs incurred by a firm were discounted by a factor that was dependent on the firm's technical capability with respect to OSS. Firms that have higher technical capability with respect to OSS need not rely entirely on support provided by the vendor. Hence they may incur less *effective* support costs compared to less technically capable firms (Kim et al, 2006). The anticipated benefit from a switch is computed by looking at expected annual cost savings over the planning horizon.

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[2] Wilensky's basic implementation of a small-world network comes with NetLogo

Table 1: Determinants of diffusion studied in the literature

	Perceived Value	Network Effects	Local Connectivity	Price	Switch. Costs	Supp. Costs	Other Costs	Risk	Cons. Hetero.	Network Topology	PS Upg. Cycle	Firm Size	OSS Tech. Cap
Delre et al, 2007	✓	✓	✓						✓	✓			
Westarp and Wendt, 2000	✓	✓	✓	✓					✓				
Bonaccorsi et al, 2006	✓	✓		✓	✓		✓					✓	✓
Dalle and Jullien, 2001	✓	✓		✓					✓				
Kim et al, 2006	✓			✓	✓	✓							✓
Weitzel et al, 2006	✓	✓	✓	✓	✓	✓	✓			✓		✓	
Chatterjee and Eliashberg, 1990	✓	✓		✓				✓	✓				
Bonaccorsi and Rossi 2003	✓	✓											
Sundararajan, 2005	✓	✓	✓						✓	✓			
Zhu et al, 2006	✓	✓			✓	✓						✓	✓
Masanell and Ghemawat, 2006	✓	✓		✓									
Economides and Katsamakas, 2006	✓	✓		✓	✓								
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The second part in the decision function represents the threshold value that a firm needs to take into consideration. Interoperability issues exist for firms using different standards. Therefore, the more of its neighbors are using the proposed new software, the more likely a firm wants to switch. n describes the local network benefits from adopting the new software (Sundararajan, 2005). However, a powerful firm (such as Wal-Mart, for instance) is in a better position to dictate to its neighbors what standard they should use rather than be forced into an uneconomical choice. To model this social influence of a firm we measure its degree centrality (Ahuja and Carley, 1998) i.e. number of neighbors of a firm. A firm, with a high degree centrality, will place less weight on its neighbors' software adoption decisions. Since the understanding is that firms upgrade to keep up with the latest technology/features and/or to maximize the utility they can derive from the existing software (Ngwenyama et al, 2007), we assume that if they do not switch, they will necessarily upgrade to the latest available version of their existing software. Finally, to model the concept of withdrawal of support from the PS vendor, support costs are increased for those PS adopters whose existing version of the software is two generations older than the latest version.

It is important to reiterate that firms will either decide to switch to a different standard or upgrade their existing standard. Firms are 'forced' to upgrade under the assumption that upgrades offer quality advantages and that if firms do not find the other standard viable, they will want to avail the quality improvements offered by the upgrades. This eagerness to avail quality improvements may not be equally shared by all firms. Hence we use different planning horizons for each firm which models the firm's desire to keep abreast with the latest improvements available through the upgrade.

A 3x3x3x6x2x2 study was designed in order to study six main variables. This study uses three different parameters each for the following: network typology (network with low cliquishness, network with high cliquishness, small-world network), size of local neighborhood (small, medium, large) and OSS support costs (support costs slightly higher than PS on average with low variability; support costs slightly higher than PS on average with very high variability; support costs much higher than PS with very low variability); six different values for interoperability costs (between very low and very high). Two different parameters are used for the length of the PS vendor's upgrade cycle (short and long) and the initial proportion of OSS firms (low and high). For each of the random variables 50 samples were drawn from their distributions and the results were averaged. For each of the 648 combinations the simulation was run for 100 time cycles where each cycle in the simulation represented a year. We believe that since Microsoft has released six upgrades of its Operating System in approximately 20 years, it would be reasonable to investigate an extended time period with varying length of time between upgrades. Figure 1 illustrates the flow diagram for our agent-based OSS diffusion model. The key parameter values used in the simulation are summarized in Table 2. Wherever possible, we used numbers obtained from the practitioner literature. Simulations were extremely computationally intensive and were run on a Linux-based cluster which had 108 CPU cluster blade servers, Intel Xeon CPUs and gigabit Ethernet interconnections with 2TBs of dedicated network attached storage

Simulation Results and Analysis

Due to the large number of experimental combinations and the page limit of the paper, we have selected some representative graphs, where diffusion did occur, to demonstrate our main results. Overall analysis uncovered the following interesting results: Significant diffusion of OSS (double the initial number of OSS adopters) occurred only in the presence of high variability in support costs (N(60,60) in Table 2). This was because with this distribution some firms incur very low OSS support costs, thus their intrinsic value of OSS is large enough to motivate them to switch. When a sufficient number of OSS early adopters is reached (a critical mass), this drives further OSS diffusion. It is worthwhile to note at this point that if the proportion of OSS adopters were high (30%) to start with, then ceteris paribus, the critical mass will be attained much faster – so fast, in fact, that it might suppress the effect of other variables.

Coming back to the support cost distributions, the low variability or very high magnitude of support costs (N(60,15), N(250,50)) was not able to make OSS seem more attractive than PS. This result conforms with what is happening in reality: despite having an established base of locked-in customers in the desktop market, Microsoft is slowly but surely losing market share to Linux. Our explanation is that in addition to the low upfront costs, there are some firms which are facing very low OSS support costs (due to their technical capability or involvement in the open source online communities, or the way they are implementing these systems, flexibility in customizing and independent bug fixing and lock-in avoidance) and are finding it more attractive to adopt OSS than PS.

| Table 2: Key Simulation Parameters	
Attribute	**Description**
Network size	Number of firms in the network – 1000
Firm size	The number of computers each firm has is used as a proxy measure for firm size ~ U[100,500]
Initial number of OSS firms	Two different values were chosen : 10% (Wheeler, 2005) and 30% (Dalle and Jullien, 2001)
Rewiring probability	This probability allowed to create different network topologies. Three values were chosen to be 0, 0.09 and 0.9, for clustered/high cliquishness, small-world and random/low cliquishness networks. These values have been used in the previous literature (Watts and Strogatz, 1998)
Size of local neighborhood	This represents the immediate number of neighbors of a firm. Three values were picked: 5%, 15%, 25% representing small, medium and large neighborhoods. 5% means that the local neighborhood of each firm will have 5% of the total firms in the network. This implies that larger neighborhood size will mean denser networks. With 3 network topologies and 3 sizes of neighborhoods, 9 different networks were created. The values for the neighborhood sizes were chosen to ensure that structurally (in terms of centrality and cliquishness) the 9 networks were different.
Upgrade cycle	This represents the duration between successive major upgrades offered by the PS or OSS vendors. We chose an upgrade cycle of 4 (long) and 2 (short) years for proprietary software (Keizer, 2007) and fixed the upgrade cycle for OSS to 2 years. Keeping in view the demand-driven aspect of OSS upgrades, we kept shorter upgrade cycles for OSS than for PS.
Planning horizon	PH indicates how often a firm conducts a major software upgrade. PH depends on the upgrade cycle of the software the firm is adopting. A range of planning horizons were assigned such that some firms had very short or very long planning horizons, majority had planning horizons in between these two extremes. The range of values were UC, UC+1, UC+2, UC+3 where UC represents the upgrade cycle of the firm's existing software (OSS or PS).
Volume of transactions	This represents the total number of transactions on each link in the network generated using a uniform random distribution U[100,500]. It was used to compute interoperability costs
Level of interoperability costs	If neighboring firms were using a different standard, we assumed that they incurred interoperability costs. The level of these interoperability costs was varied from 0 to 5 per transaction for very low and very high interoperability costs, relative to license costs, on the average. For sensitivity analysis, a number of values were explored within this range (0.2, 0.4, 0.75, 1, 3, 5).
Current license Costs	This was chosen to be $199, $0 per machine for PS and OSS respectively (Guth, 2007; Vaughan-Nicholas, 2006)
Training Costs	This was chosen to be $20, $30 per machine for PS and OSS respectively. A lower value for PS was chosen under the assumption that since PS already has a large installed base, new hires would be expected to be more familiar, hence easier to train, using PS than OSS.
Setup Costs	This was chosen to be $325, $70 per machine for PS and OSS respectively (Vaughan-Nicholas, 2006)
Support Costs	Firms incur heterogeneous OSS support cost due to differences in degree of integration, customization, variability of OSS quality, lack of systematic version management and other factors (Kamphorst, 2002). Effective OSS support cost is determined by three normal distributions: N(60,15), N(60,60), N(250,50) depending on its mean value and variability. PS Support costs are kept fixed at $50 (Vaughan-Nicholas, 2006)
OSS technical capability	Firms' technical capability with respect to OSS are different (Kim, et al., 2006) and are determined by a random variable drawn from N(0.3, 0.1)
Degree centrality	The more neighbors a firm has, the more powerful it is in influencing its partner's standard adoption decision and the more strongly it can be influenced by the decision of its neighbors.
Withdrawal of support	We model the threat of withdrawal of support by the PS vendor by doubling the support costs if the firm is 2 or more versions behind its vendor's current version.
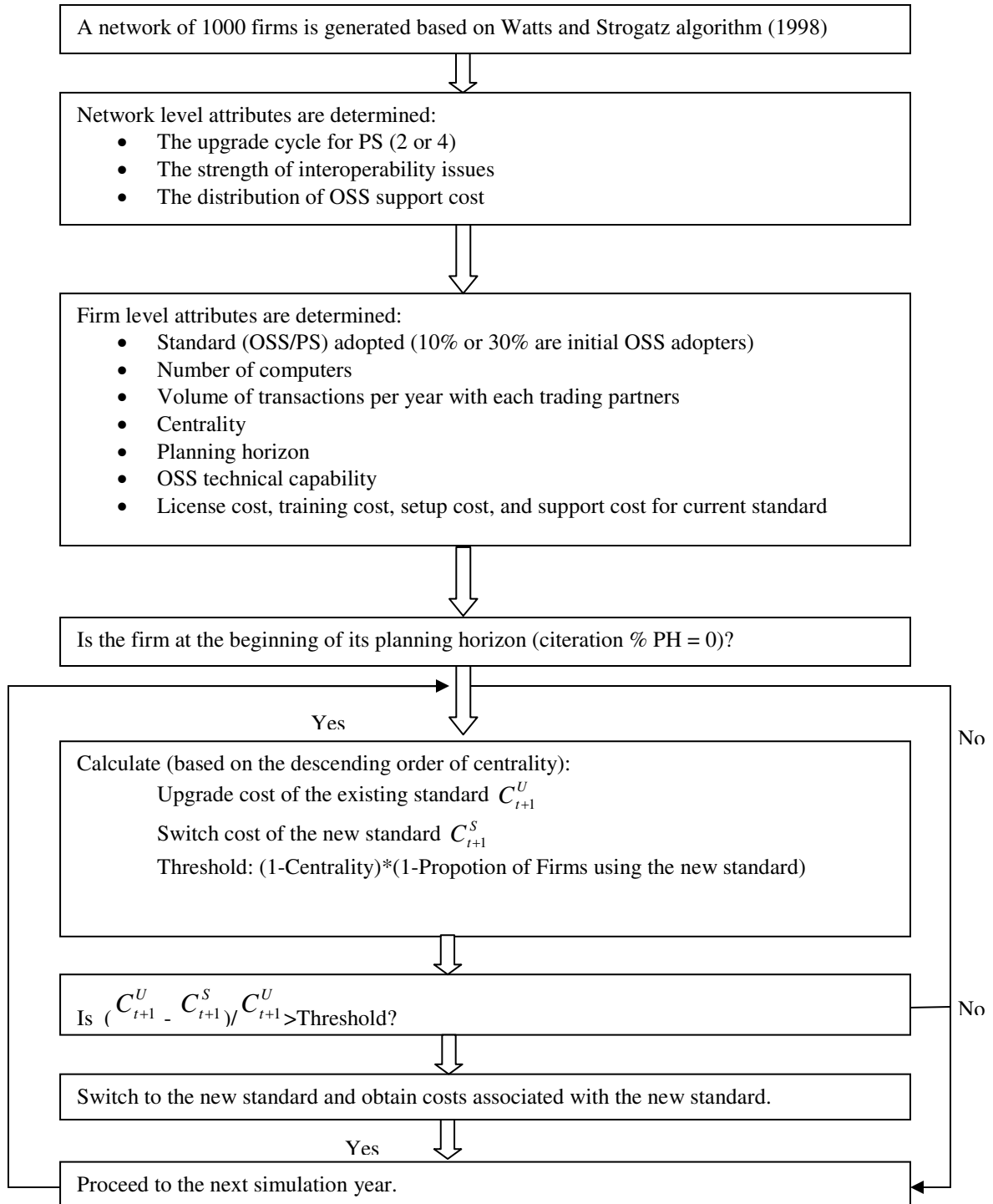
Figure 1: Flow diagram for the model

On the other hand, there are firms (at the high end of this distribution) which feel that (either due to their lack of technical capability or lack of available compatible pool of applications) the support costs for OSS are too high (Figure 2). Hence we state our first proposition:

Proposition 1: High variability in support costs favors the diffusion of OSS.

Figure 2. High variability in support costs favors the diffusion of OSS
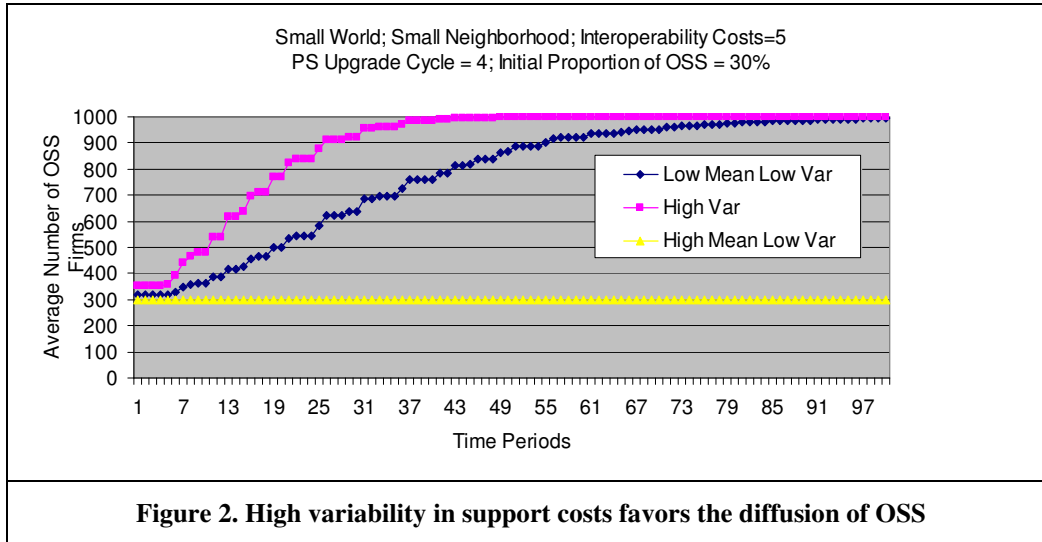
In the following sections, we focus on those experimental conditions that involve high variability in support costs while elaborating the main effects of other variables.

Main Effects

Analysis revealed that shorter duration of the PS upgrade cycle tended to favor the diffusion of OSS (Figure 3). This was because shorter PS upgrade cycle has two effects a) it encourages PS firms to consider upgrades more frequently; b) firms upgrading PS face the possibility of incurring higher one-time costs (such as setup and training costs), averaged per year, than OSS and this makes it attractive for some firms to switch to OSS:

Proposition 2: Shorter PS upgrade cycles favor the diffusion of OSS

Figure 3. Rate of diffusion of OSS is faster when the PS upgrade cycle is reduced
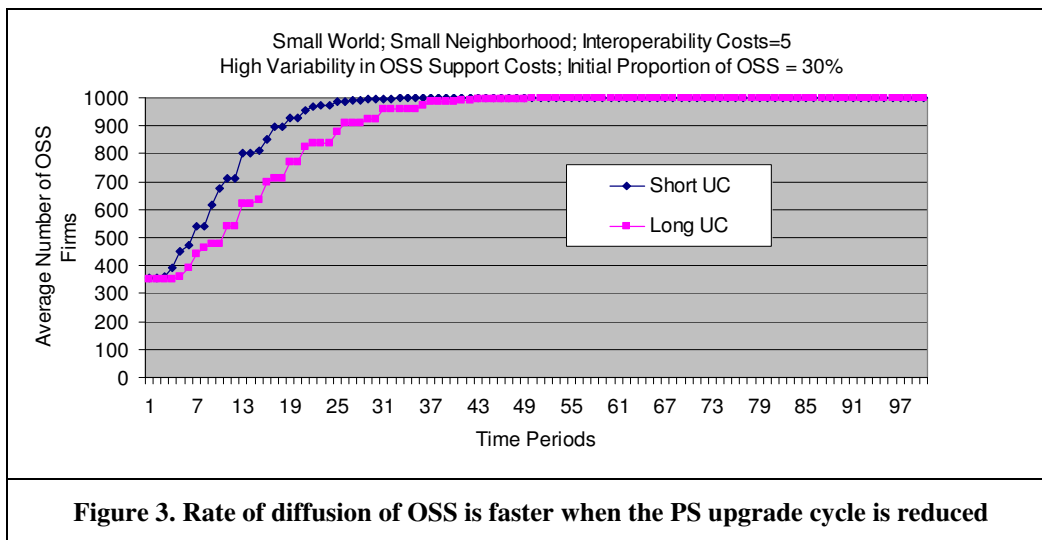
The results also revealed that high interoperability costs favored the dominant standard by locking-in its users whereas low interoperability costs shifted the emphasis on other factors such as costs, network structure etc. and reduced the possibility of lock-in (Figure 4). This meant that at the start of the simulation, high interoperability costs always prevented firms from switching to OSS. However, if due to other cost factors and network effects, OSS did manage to gain critical mass, the same interoperability costs hastened the diffusion of OSS throughout the network. This leads to the following hypothesis:

Proposition 3: Increasing interoperability costs reduces the diffusion of OSS

Furthermore the simulations demonstrated that the effect of size of neighborhood varies with the level of interaction with other variables. In general with a larger neighborhood, the news of a firm's decision gets 'communicated' through interoperability costs to a greater number of firms compared to when there is a small neighborhood. It is intuitive then to grasp that varying the size of the neighborhood may encourage or discourage the diffusion of OSS depending on other factors. Similarly, the effect of network topology varies with the level of interaction with other variables. Rate of diffusion may be faster in a network with low cliquishness because the number of new firms that are influenced by a firm's decision in each time period is likely to be more compared to the network with high cliquishness. In the latter case, the number of new firms that are affected in each time period will reduce over time due to high cliquishness. Small world networks have an element of both low and high cliquishness. They can be imagined as a connection of hub-and-spokes structures that, in some cases, may be able to take advantage of their highly cliquish and/or low cliquish nature. Propositions involving the interaction effect of size of local neighborhood and network topology will be discussed in the following section on interaction effects.

Figure 4. Decreasing interoperability costs favor diffusion of OSS
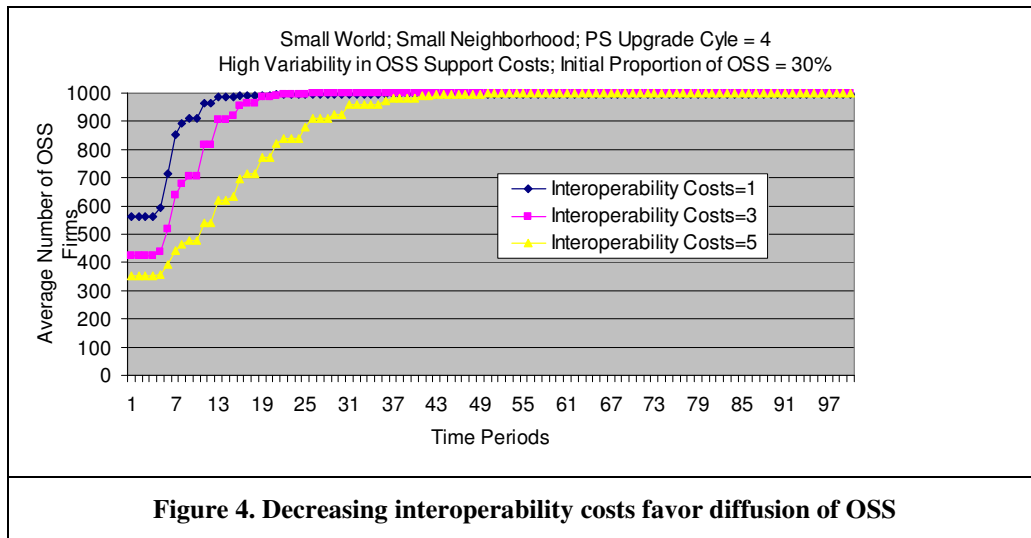
Interaction Effects

The interaction between the different variables uncovered some very interesting results. We have chosen to present some selected results in the following subsections.

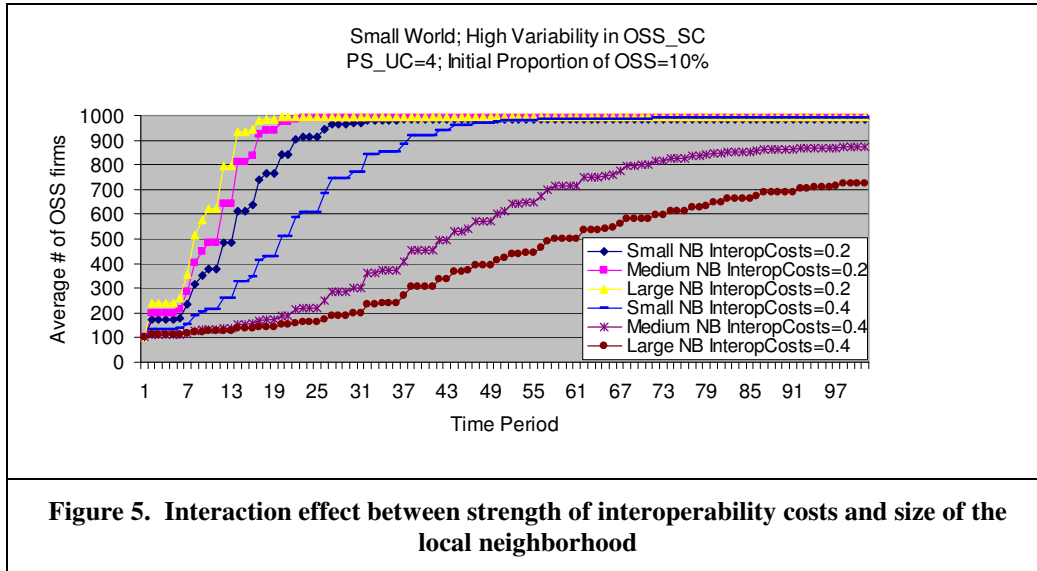### Size of Local Neighborhood and Interoperability Costs

Interestingly, simulation revealed two effects of varying the size of the local neighborhood. First, how a firm affects its neighbors (i.e., when the firm switches, how many other firms in the network immediately find out about it). Second, how the firm's neighbors affect the firm (i.e., if more people in the firm's local neighborhood are using a particular software, how does that influence the firm's choice?).

Simulations indicate that the effect of varying the size of the local neighborhood is strongly linked to the strength of interoperability costs. When interoperability costs are high, small neighborhoods encourage the diffusion of OSS the most, followed by medium and large sized neighborhood. This is because the initial proportion of OSS adopters is very low and large neighborhoods are able to exert greater pressure through interoperability costs: i) on the OSS adopters to switch over to PS, ii) and on existing PS adopters to stick with PS. However, when interoperability costs

are low, large neighborhoods encourage the diffusion of OSS the most, followed by medium and small sized neighborhood. This is due to the effect of interoperability costs. Low interoperability costs shift the emphasis on other costs factors. Low interoperability costs favor OSS in large neighborhoods since the influence of adoption of each firm spreads faster to a bigger audience than in small neighborhoods (Figure 5).

Proposition 4a: With increasing interoperability costs, diffusion of OSS is fastest in small neighborhoods and slowest in large neighborhoods.

Proposition 4b: With decreasing interoperability costs, diffusion of OSS is fastest in large neighborhoods and slowest in small neighborhoods.

Figure 5. Interaction effect between strength of interoperability costs and size of the local neighborhood

Interoperability Costs, Size of Local Neighborhood and Network Topology

It can be seen from proposition 4a that with large neighborhoods (dense networks), the impact of interoperability costs tends to be higher than with smaller neighborhoods. Also, in dense networks, the difference between network topologies would be more clearly visible than in less dense networks. Therefore,

Proposition 5a: With increasing interoperability costs, reducing the size of neighborhoods, reduces the effect of network topology on the diffusion of OSS

On the other hand, proposition 4b indicates that in the presence of low interoperability costs, larger neighborhoods will facilitate faster diffusion of OSS than will smaller neighborhoods. In this case, when all other factors are conducive to the diffusion of OSS, reducing the size of neighborhood will dampen the rate of diffusion of OSS and enhance the effect of network *topology* (See Figure 6).

Proposition 5b: With decreasing interoperability costs, reducing the size of neighborhoods, increases the effect of network topology on the diffusion of OSS

If due to other factors conducive to the diffusion of OSS, the rate of diffusion of OSS is very fast, it is hard to separate out the effect of the different variables. For example, in Figure 6, the top three curves compare rate of diffusion across the three network topologies with small neighborhood. The rate of diffusion is so fast that the effect of network topology is barely visible. However, the bottom three curves, in which the neighborhood size is large, the effect of network topology is somewhat visible given that the curves are not exactly overlapping. Conversely, if there are one or more factors which strongly prohibit the diffusion of OSS, it will be hard to capture the effect of other variables on the diffusion of OSS.

Discussion

The objective of the paper was to explore the effect of networks *topology*, size of local neighborhood, variability in OSS support costs, interoperability issues and the length of the PS upgrade cycle on the diffusion dynamics of OSS. The model is, to the best of our knowledge, a first attempt to bring all these factors together and present a holistic picture of the direct and interaction effects of these factors on the diffusion of OSS.

Figure 6. Interaction effect between size of neighborhood, network topology and interoperability costs
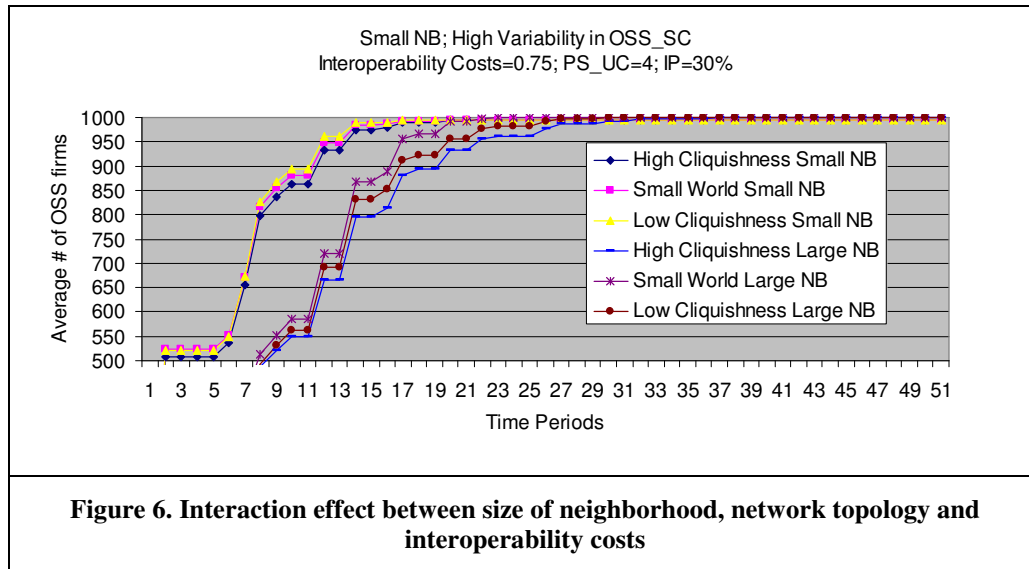
Contribution to Research

This paper has made the following contributions to the growing body of research on OSS. First, it has provided a framework that can be used to study the diffusion processes of competing software. The framework was applied to specifically study the diffusion processes of open source and proprietary software where the former is characterized by low license costs, high variability in support costs, OSS technical capability and no threat of withdrawal of support. We chose operating systems as the example because some empirical data was readily available to model the dynamics of this software. However, we believe that our framework is general enough to be applied to the investigation of other software as well. Second, it has studied the effect of length of PS upgrade cycle on the diffusion of OSS and demonstrated that shorter upgrade cycles result in comparatively higher setup/training costs which do not favor PS vendors against the diffusion of OSS. Third, it has demonstrated that the effect of network topology on diffusion of software is dependent on other factors such as interoperability costs, variability in support costs and size of neighborhood. It has also incorporated significant heterogeneity among adopters and included factors such as the threat of withdrawal of support by the PS vendor and the influence of centrality of neighbors on adoption decisions. Fourth, it has illustrated that variability in OSS support costs hastens the diffusion of OSS, given other factors. Fifth, it has proposed the use of social networking concepts such as degree centrality to study diffusion of OSS and standards. Compared to earlier papers our model provides a richer depiction of the critical variables and their interactions with each other.

Contribution to Practice

The simulation results revealed that the PS vendor is only threatened by OSS if there is high variability in OSS support costs i.e. if the OSS vendor is able to offer very low support costs and build a critical mass. In order to illustrate the effects of other variables we deliberately chose a PS vendor that did not react to the changes in the market. As a consequence we were able to uncover some interesting results. For example, we demonstrated that under some circumstances, despite charging a higher license cost or having significant interoperability issues, the PS vendor will not lose share to OSS in the long-run.

Conclusions, Limitations and Future Research

This paper proposes a model to facilitate the understanding of how diffusion dynamics of OSS is affected by six key factors some of which are under studied in prior literature. We believe that our model builds on prior research and helps to build a richer theoretical foundation for studying OSS diffusion. Such modeling helps to structure the debate and open up the field for additional research (Liberatore et al, 2000). The model presented in this paper could serve as a foundation on which different competitive actions by PS vendors can be superimposed. For example, different pricing policies and strategies for withdrawal of support can be examined. The results also indicated that apart from license costs, there are other key variables which the PS vendor can manipulate to prevent the diffusion of OSS. For example, the PS vendor could influence interoperability and upgrade costs, change the timing of withdrawal of support to influence the decision of existing and potential adopters.

Hence, our model can be considered to be similar in purpose to the agent-based models that have been used in other domains such as supply chain management to create building blocks for studying dynamics (Swaminathan et al, 1998). Future research will focus on integrating competitive dynamics with the model presented in this paper to build a CAS.

There are some aspects of this research study that limit its scope and applicability to some extent. First, some of the probabilistic variables in the simulation were modeled using uniform and normal distributions. While these are reasonable choices in the absence of other information, one approach would be to use multiple distributions to condition the results. Second, the decision function of the individual firms is based on net cost savings. These cost savings are treated as a proxy for measuring 'benefits'. We believe this is a reasonable approach since benefits are typically difficult to quantify. However, some domain-specific benefit modeling may be possible. Again, we view this as an extension that can be superimposed on the basic model proposed in this paper.

Though this paper has focused on OSS diffusion, we believe that the model is fairly general and is applicable to studying the dynamics of software diffusion in a variety of contexts. Examining the generalizability of this model is an area of future research.

References

Ahuja M. K. and Carley F. M. "Network Structure in Virtual Organizations", *Journal of Computer-Mediated Communication*, (3:4), June 1998

Bonaccorsi, A., S. Giannangeli, and Rossi C. "Entry Strategies Under Competing Standards: Hybrid Business Models in the Open Source Software Industry." *Management Science* (52:7), July 2006, pp. 1085-1098

Bonaccorsi, A. and C. Rossi "Why Open Source Software Can Succeed." *Research Policy* (32:7), July 2003, pp. 1243-1258.

Bowman, J. "The end of Windows 98", In Depth Technology: CBS News, July 15, 2006, http://www.cbc.ca/news/background/tech/windows98.html

Chen P. Y. and Forman C. "Can Vendors Influence Switching Costs and Compatibility in an Environment with Open Standards?", *MIS Quarterly*, 30, August 2006, pp. 541-562

Dalle, J. M. and N. Jullien "Open-Source vs. Proprietary Software", http://opensource.mit.edu/papers/dalle2.pdf, 2001

Delre S. A., Jager W. and Janssen M. A. "Diffusion dynamics in small-world networks with heterogeneous consumers", *Computational Math and Organization Theory*, (13:2), June 2007, pp. 185-202

Economides N. and Katsamakas E. "Two-sided competition of proprietary vs. open source technology platforms and implications for the software industry", *Management Science*, (52:7), July 2006, pp. 1057-1071

Gray J. R. "An Executive Decision: Windows OS vs. Linux OS vs. Hybrid", Graduate Research Report, Bowie State University, Maryland in Europe, April 2005

Guth R. "Linux starts to find home on Desktops", *The Wall Street Journal Online*, March 13, 2007, pg B3

Huang J. S. and Kapur M. "Diffusion of Pedagogical Innovations as a Complex Adaptive Process – Agent-based Modeling as Research Method", in *Supporting Learning Flow through Integrative Technologies*, T. Hirashima et al. (Eds.) IOS Press, 2007

Kamhorst E. M. "Open vs. closed. Some consequences of the open source movement for software markets", CPB Discussion Paper No. 13, CPB Netherlands Bureau for Economic Policy Analysis, Netherlands, September 2002

Keizer G. "Microsoft COO: Big client OS not dead yet", *Computerworld UK*, July 14, 2007

Kim B. C., Chen P. and Mukhopadhyay T. "Pricing Open Source Software", in the *Twenty-Seventh International Conference on Information Systems*, Milwaukee, Canada, December 2006, pp. 341-366

Leading Edge Forum: CSC "Open Source: Open for Business", *Leading Edge Forum Report*, September 2004, http://www.csc.com/features/2004/247.shtml

Lerner, J. and Tirole, J. "The open source movement: Key research questions", *European Economic Review* (45:4), May 2001, pp. 819-826

Liberatore, M., Hatchuel, A., Weil, B., and Stylianou, A. "An organizational change perspective on modeling". *European Journal of Operational Research*, (125:1), August 2000, pp.184-194.

Masanell R. C. and Ghemawat P. "Dynamic Mixed Duopoly: A Model Motivated by Linux vs. Windows", *Management Science* (52:7), July 2006, pp. 1072-1084

McAllister, N. "Open Enterprise: Desktop Linux Remains Hard Sell", Computer World:The Voice of Management March 21, 2006, http://www.computerworld.com.au/index.php/id;608238263

McMillan R. "The business case for Linux", *InfoWorld.com*, July 30, 2004

Michlmayr M. "Quality improvement in volunteer free software projects: Exploring the impact of release management", in the *Proceedings of the First International Conference on Open Source Systems*, Marco Scotto and Giancarlo Succi (Eds.), Genova, 11th-15th July 2005, pp. 309-310

Mukherji N., Rajagopalan B. and Tanniru M. "A decision support model for optimal timing of investments in information technology upgrades", *Decision Support Systems* (42:3), December 2006, pp. 1684-1696.

Mustonen M. "Copyleft - the economics of Linux and other open source software", *Information Economics and Policy* (15:1), March 2003, 99-121

Ngwenyama O., Guergachi A. and McLaren T. "Using the learning curve to maximize IT productivity: A decision analysis model for timing software upgrades", *International Journal of Production Economics* (105:2), February 2007, pp. 524-535.

Perens B. "The Open Source Definition", in *Open Source Voices from the Open Source Revolution*, DiBona C., Ockman S. and Stone Mark (Eds.), , O'Reilly & Associates Inc., Sebastopol, CA , 1999, pp. 171-188.

Rogers E. M. *Diffusion of Innovations*, Fourth Edition, The Free Press, New York, 1995.

Singh P. V. "Open Source Software Development and the Small World Phenomenon: An Empirical Investigation of Macro Level Collaboration Network Properties on Project Success", in the *Twenty Eighth International Conference on Information Systems*, Montreal, Canada, December 2007, pp. 1-17.

Srbljinović, A., & Skunca, O. "An introduction to agent based modeling and simulation of social processes", *Interdisciplinary Description of Complex Systems*, (1:1-2), 2003, pp. 1-8.

Sundararajan A. "Local Network Effects and Network Structure", Working Paper CeDER-05-02, Center for Digital Economy Research, Stern School of Business, New York University, May 2005.

Swaminathan J. M., Smith S. F. and Sadeh N. M. "Modeling Supply Chain Dynamics: A Multi-agent Approach", *Decision Sciences*, (29:3), Summer 1998, pp. 607-632

Tesfatsion L. and Judd K. L. "Handbook of Computational Economics: Agent-based Computational Economics Volume 2", *Handbook of Computational Economics Series*, North-Holland, Oxford, UK, 2006

Tirole J. and Lerner J. "The Scope of Open Source Licensing", *Journal of Law, Economics and Organization*, (21:1), April 2005, pp. 20-56.

Vaughan-Nicholas, S. J. "Upgrade price wars: Vista vs. Linux", *DesktopLinux.com*, September 06, 2006.

Waldrop, M. M. *Complexity: The Emerging Science at the Edge of Order and Chaos*, Touchstone, New York, NY, 1992

Watts DJ and Strogatz SH "Collective dynamics of "small-world" networks", *Nature*, 393, 1998, pp. 440–442

Weitzel, T., Beimborn, D., and Konig, W., "A Unified Economic Model of Standard Diffusion: The Impact of Standardization, Cost, Network Effects, and Network Topology", *MIS Quarterly*, Special Issue 30, August 2006, pp. 489-514.

Westarp F. V. and Wendt O. "Diffusion Follows Structure - A Network Model of the Software Market", in the *Proceedings of the 33rd Hawaii International Conference on System Sciences*, January 2000, 10 pp.

Wheeler, D. A. "Why Open Source Software/ Free Software (OSS/FS, FLOSS or FOSS)? Look at the Numbers!", 2005, http://www.dwheeler.com/oss_fs_why.html

Wilensky, U. "NetLogo Small Worlds model", Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL, http://ccl.northwestern.edu/netlogo/models/SmallWorlds