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An Agent-Based Simulation Model for Understanding Diffusion Dynamics of Open-Source (OS) Software in the Presence of Upgrades

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Abstract

There is an increasing interest in the evolution of open-source software (OS). Researchers as well as practitioners are trying to better understand factors that impact the diffusion of OS. This paper presents an agent-based model of OS diffusion. Specifically, we investigate how software upgrade cycle affects firms' OS adoption. In addition, we also incorporate factors such as variability in OS support costs, interoperability issues and network structure that have not been systematically studied in prior OS research. Simulation results demonstrate the individual and interaction effects of these variables on the rate of OS diffusion. High variability in OS support costs and more frequent introduction of major upgrades encourage OS diffusion. The rate of diffusion is also influenced by the degree of cliquishness in the network structure. Interoperability issues hinder OS diffusion when proprietary software (PS) is currently the dominant standard. However, if other factors encourage OS diffusion and a critical mass of OS adopters is reached, then interoperability issues encourage OS diffusion. The impact of interactions between network structures and other factors on diffusion dynamics is also illustrated.

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1.0 Introduction

There is an increasing interest in open source systems. Researchers have tried to address the various dimensions of adoption and diffusion of open source software such as factors that motivate programmers to contribute to open source systems (Lerner and Tirole, 2001) and factors that influence organizations to develop and/or use such systems. (Lerner and Tirole, 2001; Mustonen, 2005).

Previous research reveals conditions under which a) open source software (OS) prevails over proprietary software (PS) (Masanell and Ghemawat, 2006), or b) both can co-exist but the vendor of the proprietary software must carefully assess the pricing strategy to compete with open source systems (Mustonen, 2005). While these results are valuable, they stem from studies that make assumptions regarding their models; for example, simplifying assumptions about the type of market condition (monopoly, duopoly etc.) and the factors influencing the adoption decision (demand, costs, benefits, risks etc.) (Chatterjee & Eliashberg (1990); Dalle and Jullien, 2001; Economides and Katsamakas, 2006; Kim et al, 2006; Masanell and Ghemawat, 2006). This paper focuses on adoption of OS by individual firms and the evolution of the open source market from an agent-based modeling perspective. It studies the effects of a more comprehensive and under-researched set of factors on the diffusion of OS.

Organizations considering OS adoption are attracted by low or negligible initial costs. However, they are often reluctant to adopt OS for various reasons, such as uncertainty regarding quality and consequent support costs due to product defects and in some cases, lack of experience with OS (Bowman, 2006; Kim et al., 2006). This paper models this variability in support costs and also allows individual organizations to be different in terms of support costs. In addition, it studies the effect of important but under

researched factors such as business relationships (network structure) between adopting organizations, interoperability issues and the introduction of upgrades. Thus, this paper focuses on the following research question:

How do variability in OS support costs, network structure, interoperability issues and introduction of upgrades impact OS diffusion?

The next section provides a brief review of the literature on adoption and diffusion of open source systems and agent-based modeling followed by a description of our simulation model (Section 3). Experimental design is discussed in Section 4, followed by simulation results (Section 5). A discussion of results and model extensions is presented in Section 6. Finally, conclusions and future research are summarized in Section 7.

2.0 Literature Review

This section reviews relevant literature. First, we summarize previous literature on adoption and diffusion of OS. Then, section 2.2 reviews related research on agent-based modeling.

2.1 Adoption and Diffusion of OS

Bonaccorsi and Rossi (2003) concluded, on the basis of reviewed literature that the adoption of OS 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 OS 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. They modeled the adoption decision based on the perceived intrinsic value of open source software, the network externality and coordination factors (based on other member-firms in the network). They concluded that OS diffusion depended on the initial distribution of intrinsic values assigned to the technology by agents.

Dalle and Jullien proposed that any firm would choose OS over PS (proprietary software) if its local and global benefits 'outweighed' its idiosyncratic preferences (Dalle and Jullien, 2001). 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 showed through mathematical modeling techniques that under certain market conditions both proprietary and open source software can co-exist (Mustonen, 2005). However, the firm selling the proprietary software must carefully evaluate pricing strategies.

Kim et al studied two types of consumer firms (high/low-type based on internal technical capability) and three different types of pricing schemes for OS software (commercial, dual licensing and support) under different market conditions (monopoly and duopoly) (Kim et al, 2006). Using mathematical modeling techniques, they were able to demonstrate that i) the dual-pricing strategy for the OS software was viable in a competitive market; ii) the support model in which OS 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 OS vendor iv) OS support model is viable in case of quality asymmetry regardless of whether OS software is higher or lower in quality than PS.

All of these studies provide valuable insights into the different economic and market conditions and effects surrounding the adoption and diffusion of open source software. However, there are some aspects which require further investigation:

i) Practitioner literature indicates that there is considerable variability in the magnitude of OS support costs (Leading Edge Forum, 2004). This variability could play a role in the rate and magnitude of diffusion of OS.

ii) Previous literature on standards clearly indicates that network structure affects the magnitude and rate of diffusion of standards (Weitzel et al, 2006). This paper uses the Watts and Strogatz algorithm (Watts and Strogatz, 1998) to study the adoption and diffusion of OS under different network structures which vary in the degree of cliquishness (Figure 1).

iii) It is known that when proprietary software vendors develop upgrades, and support for older versions is withdrawn over time. Evaluating the adoption of OS is different when organizations consider potential upgrades compared to switching to OS from PS in the absence of PS upgrades. This is because PS upgrades often involve additional setup costs (Leading Edge Forum, 2004) and comparing this with OS reduces the relative switching costs of moving to OS. It is at this point that firms can be expected to consider the adoption of a new standard as opposed to a forced upgrade.

iv) Finally, previous literature on standard adoption indicates that interoperability issues play a significant role as well (Chen, 2003). There are different ways in which interoperability costs can be operationalized. We theorize that in the present context, when two neighboring firms using a different standard interact with each other, they may employ some labor at an hourly rate to intervene and remove the interoperability issues. The overall extent of these costs would vary for the different firms based on their transaction volume[2].

This paper uses agent-based modeling which is a useful technique for studying social networks such as economic markets, modeling of organizations etc., in a simulated environment (Tesfatsion and Judd, 2006). The following section provides a brief introduction to agent based modeling and how it can be applied to explore our research question.

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[2] An alternative way of modeling interoperability costs would be to assume that the firm incurs a one-time cost on some middleware to deal with interoperability issues.

2.2 Agent-Based Modeling (ABM)

ABM is a simulated agent based modeling technique. In this research, each agent represents a firm. Each agent has a set of attributes (such as whether the firm uses OS, its support costs and others). Each agent can either act independently or be influenced by the behavior of other agents. Any meaningful behavior exhibited by the system arises from the cooperation and competition amongst the agents. This 'emergent behavior' is the product of countless interactions between the different agents and the environment (Waldrop, 1992).

This paper uses an agent-based modeling approach for the following reasons. First, in situations where significant amount of empirical research has not been done, simulations can illuminate or eliminate avenues for future research. Second, we find support of this practice in the literature on adoption and diffusion of open source systems (Bonaccorsi and Rossi, 2003; Dalle and Jullien, 2001; Delre et al, 2007; Mustonen, 2005; Westarp and Wendt, 2000). Third, agent based simulations, particularly, in business scenarios, facilitate the development of more sophisticated models that are not limited by considerations of mathematical tractability and allow combination of social as well as economic factors (Tesfatsion and Judd, 2006). *Hence, agent-based modeling facilitates crossing boundaries (economic vs. social modeling) in diffusion research.* Finally, increasing computing power has made these computationally expensive simulations feasible (Srbljinović and Skunca, 2003).

Table 1 summarizes the factors considered specifically for the adoption of a new standard in the previous literature. It also indicates whether OS systems were studied in a particular paper or not and whether agent based modeling was used to study these factors. The last column in the table shows which variables have been included in our existing model. The following section provides a brief description of that proposed model.

3.0 Simulation Model: Parameters and Process

The model simulates a multi-firm market using proprietary and 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. Firms using OS represent a very small percentage of the total population firms and are randomly distributed (Wheeler, 2005). Neighboring firms connected with each other incur interoperability costs which reflect interoperability issues between the different standards. At any given time major upgrades are available for the proprietary and open-source software at additional costs. These upgrades are visible to the entire market for a certain duration which we call the *upgrade cycle* (UC). Each firm considers whether to adopt a new standard or upgrade its existing standard during this period based on certain cost factors: i) *license costs:* annual license costs per machine for both OS and PS firms; ii) *setup costs*: one-time costs for setting up a machine with OS or PS; iii) *support costs*: annual support costs per machine charged by the OS or PS vendor; iv) *training costs*: annual costs for training users on an OS or PS machine; v) *interoperability costs*: costs incurred by a firm while conducting transactions with other firms using the same or different standard.

The rationale behind having upgrade costs and an upgrade cycle is that typically firms using PS will consider switching when the PS vendor announces a new version of its software. While some firms upgrade because of the functionality of the new version, others may upgrade because of the threat of withdrawal of support for the older version of the software (Bowman, 2006). Hence, some firms may feel that even though support may be uncertain for OS software, they could switch to a different, open standard, in order to avoid being locked in to a vendor who forces upgrades. Irrespective of whether a firm is using proprietary or open source software, it may decide to upgrade its software at some point. However, it could be expected to have greater control over the timing and cost of such an upgrade with OS software (Vaughan-Nicholas, 2006). The adoption or switching decision is as follows

$$\left(\frac{B-A}{B}\right) \geq [T \times (1-P)]$$

Here T is the threshold value which depicts the risk assessment of the firm with reference to the upgrade/new standard. High value of T would mean that the firm will only consider upgrading/switching to the new standard if the expected savings are really high. P is the proportion of neighboring firms using the proposed new standard. The use of such thresholds has a basis in diffusion modeling from both social and economic perspectives. This models the local network effects of using a particular standard. In the present case, P indicates that if none of the existing neighbors is using the proposed new standard (P=0), firms will not experience a positive externality if they adopt the new standard and will be less likely to switch. B represents aggregate costs for current standard and A represents aggregate costs if the firm were to upgrade or adopt the proposed new standard. The components of these costs will be different depending on whether the firm considers the adoption decision in the presence or absence of an upgrade (please refer to Figure 2 for details).

Once upgrades become available, adoption of upgrades over time is assumed to follow a standard S-shaped curve. At the end of the upgrade cycle new upgrades become available and this process is repeated. Table 2 summarizes the simulation parameters used in this paper. These parameter values were chosen based on relevant literature (wherever available) or to illustrate different scenarios.

4.0 Experimental Design

There are four primary variables of interests: *network structure, upgrade cycle (frequency of major upgrades), support costs for OS* and *interoperability costs*. Although some of the initial values obtained for these variables are based on published reports, it is important to do some sensitivity analysis for a range of possible parameter values. Therefore, different sets of parameter values were used (Table 3). The

following subsections provide insights into the choice of these variables for experimental design and their expected influence on the diffusion or rate of diffusion of a particular standard.

4.1 Network Structure

As mentioned in the literature review none of the studies on the adoption and diffusion of OS have taken the network structure into account. However, other related diffusion studies such as standard diffusion (Weitzel et. al 2006) and product diffusion (Delre et al, 2007) have studied the impact of network structure on diffusion. While these studies find that network structure has a significant impact on diffusion, these studies model network structure differently. Results regarding the type of network structure that best encourages diffusion are mixed and depend on multiple factors. Hence, we make the following proposition regarding the effect of the network structure on the rate of diffusion of OS and attempt to study network structure along with other factors:

Proposition 1: Network Structure will impact the diffusion rate of OS.

4.2 Upgrade Cycle

Practitioner literature has illustrated that PS vendors sometimes pressure existing customers to upgrade by withdrawing support for earlier versions (Bowman, 2006). Hence, we model the frequent introduction of upgrades as positively influencing OS adoption decisions. We also study the interaction between frequency of upgrades and network structures on the rate of diffusion. One of the major changes we can expect is that a greater proportion of firms will be exposed to the upgrade/adoption choice when upgrades are more frequent during each time period. When they consider switching earlier, they interoperability costs or network structure will not weigh in significantly enough on their decision. The emphasis will switch on license costs, training costs, setup costs etc. Hence, multiple nodes on a network could switch simultaneously. By contrast, when upgrades are less frequent only few nodes consider upgrades in each time period, the longer intervals between upgrades allows network structure and interoperability costs to

play their roles and their impact on OS adoption takes time to percolate throughout the network. Hence we expect that impact of network structure on OS diffusion will be influenced by frequency of upgrades.

Proposition 2: The effect of Network Structure on OS diffusion rate depends on the length of the upgrade cycle.

4.3 OS Support Costs

There are mixed reports about OS support costs in comparison with the PS support costs (Wheeler, 2005; Ideas International, 2005). Different OS support cost distributions are used to model this variability. However, given our input parameters we know that when the OS support costs follow the $N(60,15)$ distribution, there is a greater percentage of firms (on average) that will end up with an OS support cost higher than 50 (which is the fixed support cost for PS) compared to when the $N(60,60)$ distribution is used. This means that in case of $N(60,60)$ diffusion of OS will be faster because a greater proportion of firms will have support costs less than 50. Hence, we expect more firms to switch from PS to OS early in the simulation and this in turn would encourage more rapid diffusion of OS.

Proposition 3: Diffusion of OS will be faster in the presence of greater variability in support costs.

4.4 Interoperability Costs

Communication between firms involves transactions. If the firms are using different standards they will have to deal with interoperability issues. The magnitude of these interoperability costs for a firm depends on its connectivity (e.g. number of trading partners or neighbors) and standards used by these neighbors (Galli, 2007). These interoperability costs affect the magnitude of the network externality effect – lower interoperability costs, lower the influence of the neighbors. Hence,

Proposition 5: If the initial market is dominated by PS, high interoperability costs decrease the rate of OS diffusion.

4.5 Other Interaction Effects.

The aim of the preceding discussion was to introduce the primary variables of interest and highlight their possible independent effects and selected interaction effects on the magnitude and rate of diffusion of a particular standard. For example, it is expected that the network structure and interoperability costs will interact to affect the rate of diffusion. These interactions effects are expected to be complex. The following section contains our interpretation of these interactions.

5.0 Simulation Results

In order to study the impact of network structures we examined the rate of diffusion of OS (or conversely the rate of decrease of PS) under different network structures. Figure 3 illustrates the diffusion paths for one set of parameter values. Repeated measures ANOVA was used to check if the diffusion paths were significantly different for different network structures ($p<0.05$). Networks structures that had the fastest and slowest diffusion rates for each set of parameter values were identified. Tables 4 and 5 summarize our simulation results for long and short upgrade cycles.

Network structure was found to have a significant impact on diffusion rates (thus supporting proposition 1). Tables 4 and 5 illustrate differences between low and high upgrade cycles in terms of which network structure drove the fastest (or slowest) diffusion. This is indicative of the interaction effect between network structure and upgrade cycle on the rate of diffusion which supports proposition 2. Figure 4 illustrates the effect of varying support costs on the diffusion of OS. It can be seen that diffusion of OS is fastest in the presence of high variability – N(60,60) – which is consistent with propositions 3. Finally, Figure 5 shows the effect of varying interoperability costs on the rate of diffusion of OS. Notice that the rate of diffusion of OS increases as the interoperability costs are increased. Initially, the rate of diffusion is slowest in the presence of interoperability issues but later on it becomes the fastest. This is understandable because initially, in a PS dominated network, low OS support costs overcome the negative

effect of higher interoperability costs and encourage some switching towards OS. Later on however, as the number of OS firms in the network increases, the high interoperability costs coupled with the low OS support costs work in favor of OS and encourage faster diffusion. This significant effect of interoperability costs supports proposition 5.

Given the space limitations it is not possible to further discuss all the results from our experiment. However, a couple of interesting results demand attention. Previous literature seemed to indicate that under certain circumstances the random or fully rewired network exhibited the fastest rate of diffusion. Interestingly, in our research context we see that unless there is a high degree of heterogeneity in a key variable (like OS support costs) a random network generally results in the slowest rate of diffusion (Tables 4, 5 and Figure 6).

6.0 Discussion

In general, the results confirm the importance of interoperability issues in case of OS diffusion. Everything else being equal low interoperability issues can confer benefits on the existing users of the competing standards regardless of which standard they are using which in turn will mean more customers and possibly more revenue for the respective vendors. The caveat is that eliminating interoperability issues shifts emphasis on other factors such as cost or quality concerns.

It is interesting to note that the network structure has a significant impact on the rate of diffusion of OS for a range of parameter values when upgrade introductions are not extremely frequent. While clustered networks encourage rapid diffusion in the presence of high interoperability issues, other types of networks may encourage faster diffusion in the presence of low interoperability issues. This is an interesting result, because it illustrates that OS proponents do not always benefit by encouraging clusters of organizations to adopt OS. It is interesting to note that more frequent introduction of upgrades reduces the impact of the

network structure since the relatively large number of early adopters drive diffusion irrespective of network structure.

This paper studies the effect of upgrade cycles, a factor which has not been studied in the OS diffusion literature. It illustrates the importance of upgrade cycle in driving the rate of diffusion and affecting the impact of network structures on diffusion rate. We find that frequent upgrade cycle favors diffusion of OS and it diminishes the impact of network structures on diffusion rate.

In summary, our results illustrate interesting interaction effects between the parameters studied. Although, we tried to get access to real data and figures reported in market surveys and research studies, the results must be interpreted in light of the initial conditions and assumptions made in the model. Two limitations must be noted: a) we assume static pricing decisions in this model – a more realistic approach would be to allow dynamic pricing for both OS and PS; b) we assume that consumer firms do not try to anticipate the adoption decision of their neighbors – in reality, however, data is available which may allow consumer firms to estimate the decision of their neighboring firms (Weitzel et al., 2006).

7.0 Conclusion and Future Research

This study has contributed to the growing body of OS diffusion research by presenting an agent based model of OS diffusion dynamics. The proposed model integrates factors such as upgrade introductions and variability in OS support costs which have been mentioned in the practitioner literature but have not been included in prior OS diffusion models. The proposed model integrates these factors with other important factors such as interoperability issues which are currently being addressed by OS vendors (Galli, 2007) and have been studied in the context of standards adoption (Chen, 2003). The effect of different network structures (cliques) is also studied using the Watts and Stogartz (1998) algorithm. Simulation results illustrate the individual and interaction effects of these factors on the diffusion of OS.

More comprehensive model development and experimentation using additional parameter values is currently underway.

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Table 1 – Factors affecting the adoption of a new standard.

Factors considered in the adoption of a new standard	OS	ABM	Reference	Factors considered in the present model
• Perceived intrinsic value of the OS S/W • Negative externality effect as a result of the other more dominant standard • Positive externality effect as a result of association with OS communities • The competitive reaction from the proprietary S/W firms	✓	✓	Bonaccorsi & Rossi (2003)	
• Local benefits* • Global benefits* • Idiosyncratic preferences * based on the number of participants in a firm's network including those using a different standard	✓	✓	Dalle & Jullien (2001)	• Local benefits • Global benefits
• Network effects • Expected benefits • Adoption costs (including transactional risk and legal barriers)	✓		Zhu et al (2006)	• Network effects • Expected (cost) benefits • Adoption costs
• Switching costs • Legacy effect of using PS • Date of adoption of OS • Firm size • Perceived importance of direct and indirect externalities • Level of involvement in the OS community	✓		Bonaccorsi et al (2006)	• Switching costs • Firm size • Perceived importance of direct and indirect externalities
• Expectation of performance • Price • Risk		✓	Chatterjee & Eliashberg (1990); Kim et al, (2006)	• Expectation of performance • price
• Connectivity (# of links to other participants) • Heterogeneity of preferences • Price		✓	Westarp & Wendt (2000)	• Connectivity • Heterogeneity of preferences
• External marketing effort • Influence of each consumer on her personal network		✓	Delre et al (2007)	• Influence of each consumer on her personal network

16

Table 2 – Simulation variables

Variable	Initial Value	Explanation of the variable and, where required, theoretical justification for including it in the model
N	1000	Number of firms in the simulation
M_i	$U \sim [5, 20]$	Number of machines for each firm based on a uniformly random distribution. It reflects the different types of consumer firms which is similar to the high-tech and low-tech consumer firms introduced by Kim et al's (2006) modeling the varying degrees of technologically proficient firms
α_i	0.1	Proportion of OS-based firms at the start of the simulation. The idea of open-source systems is relatively new compared to proprietary software hence it is safe to assume that the former's level of prevalence in the market is smaller. 90% is the commonly reported share of Microsoft in the Desktop market
p_f	0, 0.09, 0.9	From Watts and Strogatz (1998): degree of disorderliness in a small-world network where 0 indicates orderly set of connections and 1 indicates completely random connections
b	4	Initial number of immediate neighbors (Watts and Strogatz, 1998)
PH	3, 6	This is the upgrade frequency or planning horizon. We know from previous literature that at the decision-making stage firms plan ahead and consider costs spread out over a certain period (Ideas International, 2005).
Vm_{a-b}	$N \sim [10, 2]$	Volume of transactions randomly generated for each pair of firms
TrC_k	(0,0) (10,10) (10,50)	Interoperability costs between neighboring firms using the same or different standards. If firms are using the same standard, they will incur lower costs or in other words no interoperability issues. We tried different pairs of interoperability costs to model a spectrum of interoperability concerns and their effect on the adoption decision.
CpL_d	299,50	License cost per PC per year for PS & OS respectively (Guth, 2007; Vaughan-Nicholas, 2006). Upgraded PS costs are 199.
TnC_d	20,30	Training costs (include learning costs)
StC_d	325,70	Setup costs for PS and OS respectively (Vaughan-Nicholas, 2006)
SpC_d	50,X	Sp stands for Support Costs. 50 for PS, and N(60,15), N(60,60) for OS. Different distributions of OS support costs in contrast to PS support costs were tried to model the effect of variability in support costs. N(60,60) is probably the most realistic one in which the OS support costs are slightly higher but there is high degree of variability in them.
T	$U \sim [0.2, 0.8]$	Threshold value modeling the risk assessment of each firm for the new standard or available upgrade. Threshold models have been used in previous literature. For example, look at Delre et al (2007) for a brief review of such models.
P	N/A	Proportion of firms in the immediate neighborhood using the proposed new standard. This models the local network effects.

Table 3 – Parameter values for simulation experiments

Variable	Values	Description
p_f	0, 0.09, 0.9	0: indicates a network in which each firm is connected to a fixed number of immediate neighbors ("no rewiring" or clustered); 0.9: indicates a network in which firms are randomly connected to each other ("full rewiring" or random); 0.09: indicates a network in which there are cliques of firms connected to each other
PH	3,6	Different upgrade frequencies. For each of these the percentage of firms that were given the option to consider an upgrade decision was different.
SpC_0	N(60,15); N(60,60);	Given a certain amount of ambiguity in the literature regarding the support costs for OS, we tried two different scenarios: slightly higher costs compared to PS but low variability and slightly higher costs compared to PS with very high variability. Of these two, N(60,60) seems to be closest to the reports in the published literature.
TrC_k	(0,0) (10,10) (10,50)	Interoperability costs were modeled to reflect interoperability issues between communicating firms: (0,0) reflects no interoperability issues; (10,10) reflects low but similar interoperability issues between firms using the same or different standard; (10,50) reflects more severe, but different interoperability issues between firms using different standards

Table 4 – Differences in rates of diffusion of OS across different network structures for long upgrade cycle (UC = 6)

Support Costs →	N(60,15)			N(60,60)		
	Interoperability Costs			Interoperability Costs		
Network Structure	Zero	Low	High	Zero	Low	High
Clustered	Fastest		Fastest	Fastest	Fastest	Fastest(5), Slowest(50)
Small World		Fastest				Middle(38), Fastest (50)
Random	Slowest	Slowest	Slowest	Slowest	Slowest	Slowest(5),Fastest(38),Middle(50)

Table 5 – Differences in rates of diffusion of OS across different network structures for short upgrade cycle (UC = 3)

Support Costs →	N(60,15)			N(60,60)		
	Interoperability Costs			Interoperability Costs		
Network Structure	Zero	Low	High	Zero	Low	High
Clustered	Fastest	Fastest	Fastest	Fastest	Fastest	Fastest
Small World						
Random	Slowest	Slowest	Slowest	Slowest	Slowest	Slowest

Figure 1 – Different network typologies based on the Watts and Strogatz algorithm

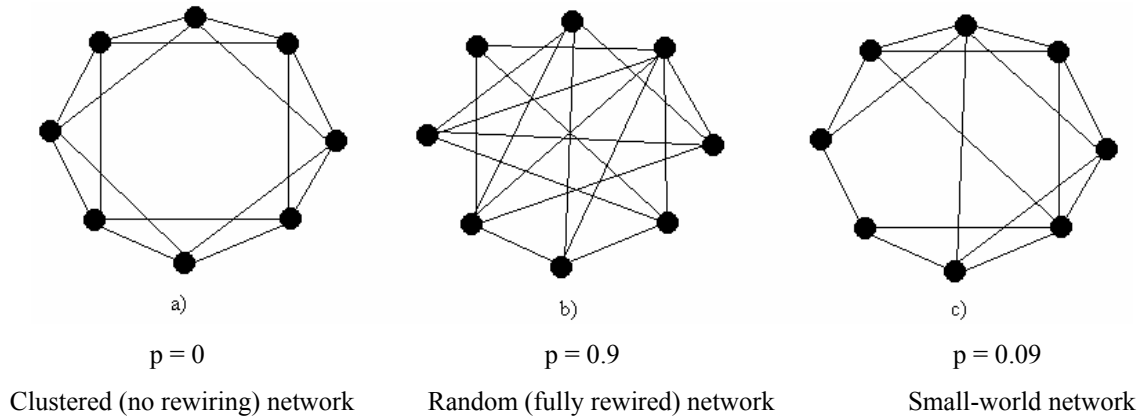| a)	b)	c)
p = 0	p = 0.9	p = 0.09
Clustered (no rewiring) network	Random (fully rewired) network	Small-world network

Figure 2 – Cost factors affecting adoption decision

Components of Adoption Decision With Upgrades

B – Costs before adoption

$$\left(\begin{array}{l} [\text{Upg Licence Costs (cs)} + \text{Upg Support Costs(cs)} + \text{Upg Transaction Costs(cs)}] * PH \\ + [(\text{Upg Setup Costs(cs)} + \text{Upg Training Costs(cs)}) \times \# \text{ of Upgs in } PH] \end{array} \right)$$

where cs = current standard

A – Costs after adoption

$$\left(\begin{array}{l} [(\text{Upg Licence Costs (ps)} + \text{Upg Support Costs(ps)} + \text{Upg Transaction Costs(ps)}) \times PH] \\ + [(\text{Upg Setup Costs(ps)} + \text{Upg Training Costs(ps)}) \times \# \text{ of Upgs in PH}] \end{array} \right)$$

where ps = proposed new standard

Components of Adoption Decision Without Upgrades

B – Costs before adoption

$$\left([\text{Licence Costs (cs)} + \text{Support Costs(cs)} + \text{Transaction Costs(cs)}] \times PH \right)$$

where cs = current standard

A – Costs after adoption

$$\left(\begin{array}{l} [(\text{Upg Licence Costs (ps)} + \text{Upg Support Costs(ps)} + \text{Upg Transaction Costs(ps)}) \times PH] \\ + [(\text{Upg Setup Costs(ps)} + \text{Upg Training Costs(ps)}) \times \# \text{ of Upgs in PH}] \end{array} \right)$$

where ps = proposed new standard

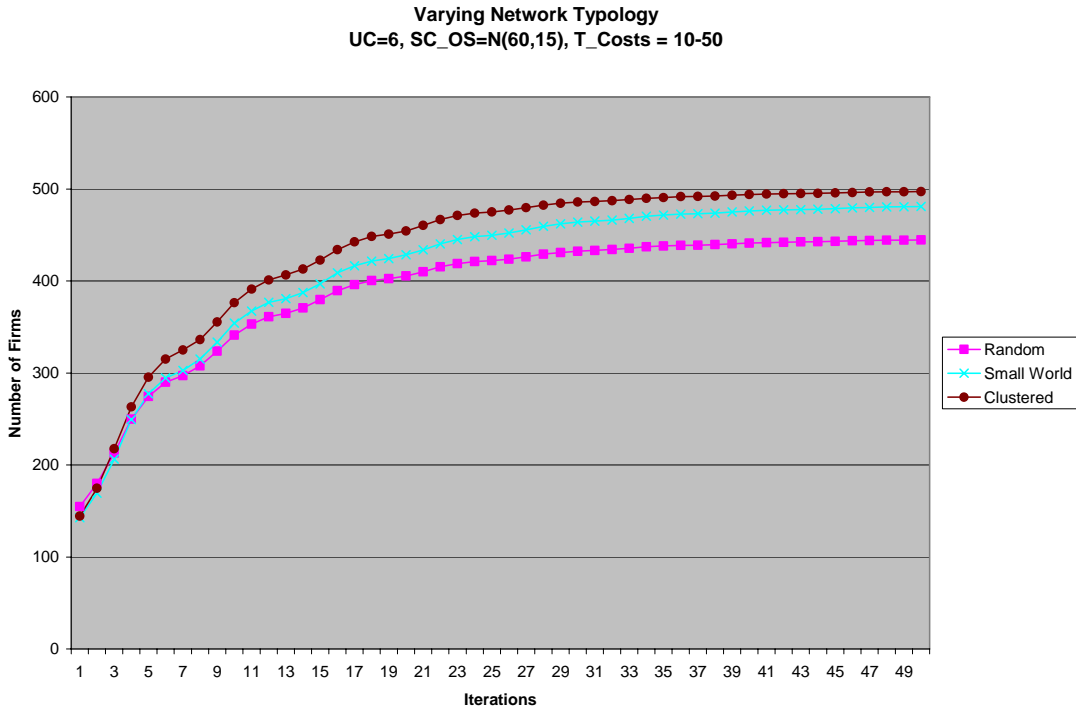**Figure 3 – Impact of Network Structure on OS Diffusion Rate**

Varying Network Typology
UC=6, SC_OS=N(60,15), T_Costs = 10-50

Figure 4 – Impact of OS Support Costs on OS Diffusion Rate

Varying OS Support Costs
Random, UC=6, T_Costs=10-50
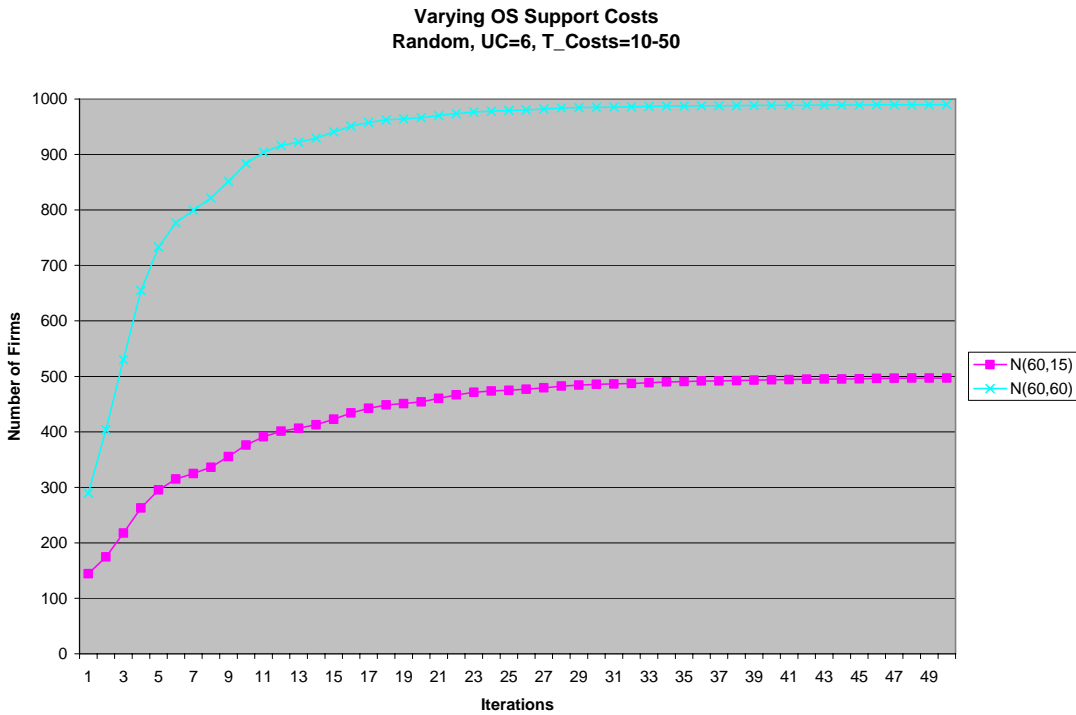
Figure 5 – Impact of Interoperability Costs on OS Diffusion Rate

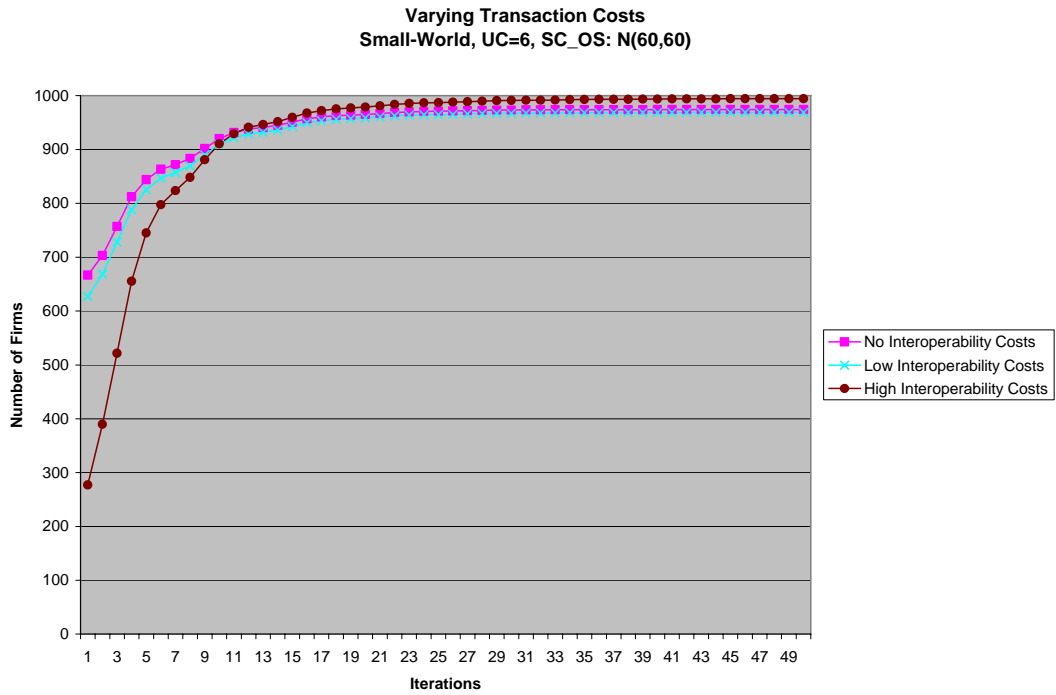Varying Transaction Costs
Small-World, UC=6, SC_OS: N(60,60)

Figure 6 – Impact of Network Structure on OS Diffusion Rate

Varying Network Typology
UC=6, SC_OS=N(60,60), T_Costs = 0-0