Vulnerabilities and Risk Management of Open Source Software: An Empirical Study

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Abstract

Software selection is an important consideration in risk management for information security. Additionally, the underlying robustness and security of a technology under consideration has become increasingly important in total cost of ownership and other calculations of business value. Open source software is often touted as being robust to many of the problems that seem to plague proprietary software. This study seeks to empirically investigate, from an information security perspective specific security characteristics of open source software compared to those of proprietary software. Software vulnerability data spanning several years are collected and analyzed to determine if significant differences exist in terms of inter-arrival times of published vulnerabilities, median time to release 'fixes' (commonly referred to as patches), type of vulnerability reported and the respective severity of the vulnerabilities. It appears that both open source and proprietary software are each likely to report similar vulnerabilities and that open source software is only marginally quicker in releasing patches for problems identified in their software. The arguments favoring the inherent security of open source software do not appear to hold up to scrutiny. These findings provide evidence to security managers to focus more on holistic software security management, irrespective of the proprietary-nature of the underlying software.

Keywords: open source software, information security, risk management

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1. Introduction

Software selection is an important risk management consideration for information security. Utilizing software packages with strong security features can reduce the information security risk exposure of an organization. Additionally, the underlying quality and security of a technology under consideration has become increasingly important in total cost of ownership (TCO) and other calculations of business value (Pescatore, 2004). Open source software (OSS) has been cited as a possible solution to the information security problems and vulnerabilities often reported in propriety software. Open source software is software that by license provides unlimited access to the source code, so that the source code can be examined and modified according to the user's wishes. There are also prescriptions for the distribution of the software and subsequent modifications (Open Source Initiative, 2005). According to a recent Wall Street Journal article, supporters of open source software, particularly Linux, a pc-based operating system, viewed such software as less vulnerable to viruses and worms, making OSS a favorable choice over other operating systems, such as Windows XP (Bulkeley, 2004). Open source software is often developed and maintained by large numbers of volunteers. One of the oft promoted features of open source software is that the wide availability of source code, and hence the large number of critical eyes examining the source code, results in more robust and therefore more secure software and applications (Open Source Initiative, 2005). Many critics also suggest the push to market pressures among proprietary software vendors result in more problematic end products, including an increased number of software bugs and vulnerabilities. In light of these commonly-held beliefs, there is a growing perception that open source software, for example the various instantiations of the Linux operating system and various software applications, is inherently more secure, due to the freely available source code and greater levels of critical scrutiny.

Information security activities, in theory, are driven by risk management principles. Anti-virus software, firewalls, access control, and intrusion detection systems are certainly important in managing the risk exposure of the organization. Increasingly, organizations are looking to the information technology infrastructure itself, to ensure that components are utilized that provide the most functional and secure platform possible while minimizing the total cost of ownership (Silver and Pescatore, 2004). Given the general low acquisition costs and perceived higher levels of security, OSS such as Linux, Apache, and MySQL has received significant attention from the popular press. However, it remains unclear whether or not the deployment of OSS results in greater levels of security and therefore lower levels of risk to the organization. The question of reduced TCO remains for future research.

The objective of this research is to empirically determine if there is any validity to the claim of OSS proponents that OSS is more secure, using vulnerability and patch data available for both open source and proprietary software. While well-designed and secure software is much more than the collection of vulnerability and patch release data, these metrics provide at least a preliminary look into potential problems with specific technologies. In this research we focus on operating systems software, such as Linux, Microsoft XP and Apple OS. Data have been collected for a number of years, including the most recent available. We investigate and address the counter-criticism that the reason open source software appears to be less vulnerable is that it simply is less of a target, both in terms of market share and length of time in the market.

The rest of the paper is organized as follows: Section 2 examines the background of the open source versus proprietary software debate. We look at the context used to examine the data, including the software reliability literature. We also examine previous work in this area and differentiate the current research from this work. The research questions and framework are presented in Section 3. The methodology and information about the data is discussed in Section 4. Section 5 provides the results and discussion while Section 6 concludes the study and presents ideas for future research.

2. Related Background

Open source software is defined as software whose source code is publicly available for free or a nominal charge. Depending on the specific license agreement, the source code may be modified and redistributed. Software whose source code is not openly published, usually are commercial software, which we refer to as proprietary software. As the executable code may be free or of nominal charge for either propriety or open source software, we limit the distinction to the source code. The software development and maintenance work carried out for open source software, is often voluntary and performed by any number of hobbyists and/or other interested parties. The incentives and motivation for volunteering time and effort to open source projects has been studied by Lerner and Tirole (2002) and Hann, Roberts, and Slaughter (2004). In general, career concerns and peer recognition are motivating factors for those involved in open source projects. Open source software was modeled using the theory of public goods by Johnson (2001) who reported inefficiencies in open source development and distribution as compared to proprietary software.

Any bug or error in a user-application or a network application that can be exploited to compromise a system, or cause a security breach, is termed a vulnerability. Vulnerabilities can be classified according to the types of problems or breaches it can cause, or the potential damage it may inflict. The problems or threats created by vulnerabilities are qualified based on the nature of possible security attacks and the level of severity of the attacks. Typically, developers working on software take preventive measures to counter these threats due to known vulnerabilities by releasing what is known as a fix or a patch to eliminate the vulnerability.

There are numerous issues with patching vulnerabilities. First of all, the vulnerability must be discovered and reported. There are different mechanisms by which vulnerabilities can be reported. For example, CERT (http://www.cert.org) is a partnership between the federal government and public and private companies, and acts as an infomediary between those who identify vulnerabilities and software users. The ICAT Metabase is a database maintained by the National Institute of Standards and Technology (NIST) (http://icat.nist.gov/icat.cfm) that stores and maintains vulnerability and patch information, collected from various other security advisories maintained by the Center for Education and Research in Information Assurance and Security (CERIAS), Security Focus, Bugtraq, etc. There also exist market-based infomediaries such as iDefense (http://www.iDefense.com), providing incentives like monetary rewards for vulnerability identifiers**.** Arora, Telang and Xu (2004) examine a number of scenarios to study optimal vulnerability disclosure policy and find that the social welfare is maximized by the use of a neutral intermediary. However, there is a contingent of users who believe in immediate and full disclosure (http://lists.netsys.com/mailman/listinfo/full-disclosure). The chief concern is that if a particular vulnerability is known, an attack can be executed before affected systems are somehow patched or secured.

Next, a patch must be created, delivered or made accessible to all relevant users of the affected systems. The current system of patch delivery depends on the particular source or vendor of the technology. Some might be automatically located and applied via the Internet, whereas others might require far more work and expertise to locate. Third, the patch must be applied once it is obtained. While some patches and updates are simple to download and install, others have been known to cause further problems and system instability, for example Microsoft's Service Pack 2 (SP2) (Sliwa, 2004). It has been conjectured that such patches might introduce further vulnerabilities as they are sometimes quickly put together without sufficient development and testing procedures.

The proliferation of patches in itself has resulted in a new area of practice and research, namely patch management. Certainly, keeping up with the volume of patches for various systems is no easy task for organizations. Intuitively, well-developed software that was engineered for both functionality and security should result in fewer bugs, and therefore, fewer vulnerabilities and subsequent patches. From a TCO perspective, patching is quite expensive. Much effort is required to determine which patches should be downloaded and applied at what times, to which systems and follow-up must be performed to ensure adequate systems operations and stability (Silver and Pescatore, 2004). From a risk management perspective, the application of large numbers of patches implies that further problems, complexities and instability could be introduced to a system, therefore increasing the likelihood of more problems or failure. Both TCO and risk management dictate that fewer patches as a result of fewer vulnerabilities in software is desirous.

Open source software advocates claim that OSS is much less prone to attacks from viruses and other information security problems as there are fewer vulnerabilities to exploit. Others have proposed that the issue is more of simply being an interesting target to attack. For example, as Microsoft is the dominant player in the personal computer operating system market, (Hamm, 2005) they are the most interesting target for attackers and others with malevolent agendas. As Linux makes further inroads into the PC operating system market space, will the various instantiations of Linux become popular targets for virus writers and other attackers as well? The next section sets forth several research questions, along with the research framework in which we attempt to address the research questions. The vulnerabilities and patching behaviors are then examined using these questions, in Section 4.

3. Research Questions

The premise for this research has evolved from the concept of software reliability. Prior research examined software reliability from a technical viewpoint, and was often formulated as analytical models (Sumita and Shanthikumar, 1986). Software reliability studies have focused on such issues as mean time to failure and release times. For example, Jelinski and Moranda (1972) and Shooman (1973) presented a well-known reliability model that has its roots in hardware reliability. *R(t)* is the probability that no errors will occur from time 0 to time t; this is the reliability function. *F(t)* is the failure function; the probability that an error will occur in the time interval 0 to t.

$$F(t) = 1 - R(t) \tag{1}$$

The probability density function of *F(t)* is

$$f(t) = \frac{dF(t)}{dt} = \frac{-dR(t)}{dt} \tag{2}$$

A hazard function *z(t)* can be defined as the conditional probability that an error occurs in the interval *t* to *t* + Δ*t*, assuming that the error did not occur before time *t*. If *T* is the time that the error does occur,

$$z(t)\Delta t = P\{t < T < t + \Delta t \mid T > t\} \tag{3}$$

This expression is equivalent to

$$z(t)\Delta t = \frac{P\{t < T < t + \Delta t\}}{P\{T > t\}} = \frac{F(t + \Delta t) - F(t)}{R(t)} \tag{4}$$

Dividing both sides by Δt and taking the limit as Δt approaches zero,

$$z(t) = f(t) / R(t) = [-dR(t) / dt] / R(t) \tag{5}$$

Solving for R(t) by setting *R(0)* = 1,

$$R(t) = \exp\left(-\int_0^t z(x)dx\right) \tag{6}$$

and mean-time-to-failure (MTTF) is

$$MTTF = \int_0^\infty R(t)dt \tag{7}$$

Numerous extensions exist to this original model. Additionally, other models have been developed using different assumptions, such as error seeding models and complexity models (Myers, 1976). Banker, Datar, Kemerer, and Zweig (2002) point out that a major limitation of these models is that they offer little explanatory power. They proposed a conceptual model which attempts to better understand why errors occur or are introduced and determined that factors such as programmer experience, system volatility and complexity and frequency of minor modifications to the system impacted the error rates.

We are interested in software reliability from an information security viewpoint. Therefore, we consider the errors found in software to represent a superset of vulnerabilities that could lead to exploits and other security threats. We don't know the exact size of the vulnerability set relative to the set of all errors, however given the advances in software engineering practices and automation, we assume that security vulnerabilities represent the large majority of errors discovered in software post-release. Therefore, the discovery of software errors or bugs and vulnerabilities and the subsequent release of patches appear as ideal starting points for examining the security and reliability of various types of software. Arora, Nandkumar, Krishnan, and Telang (2004) looked at vulnerabilities and frequency of attacks, focusing on vulnerability disclosure policies. From a decision-making perspective, two papers (Cavusoglu and Raghunathan, 2004; Beattie, Arnold, Cowan, Wagle, Wright and Shostack, 2002) examined the optimal time to apply a software patch. In this research, we take an additional look at vulnerabilities and their fixes, in an attempt to compare open source and proprietary software, along the lines of software quality and reliability and gain insights into the development process of open source software. How well operating system vendors deal with security problems is bigger than just quick patch release and how easily the vendor enables administrators to apply those patches.

"…the key questions in judging operating systems are: how quickly does an operating system vendor fix public security vulnerabilities; how severe are those problems, compared with other vendors….." (MIZI Research, 2004, p. 1)

Given that OSS source code is much more widely available, it is commonly believed that more critical eyes are examining open source software in its development and debugging (Diffie, 2003). If more individuals are involved in the development and maintenance of open source software, repairs or patches for problem in the software should be issued in less time than for proprietary software products. Based on this belief, we expect open source to be faster in its response to fixing bugs. Formally, we state Hypothesis 1 as follows:

Hypothesis 1*: Open source software developers issue patches faster than proprietary software vendors.*

If patches are issued in closer time units to the discovery of the vulnerability, we can state that open source software is more secure from a patching perspective.

From a reliability/queuing perspective, the discovery of a vulnerability can be viewed as an arrival event. So, the inter-arrival times of vulnerabilities indicate the frequency of vulnerabilities that are discovered in unit time. Building on our initial belief about the inherent security of open source, we posit that the mean inter-arrival time of vulnerabilities will be greater for open source software. In other words, we expect to see fewer bugs being discovered in open-source systems, in unit time, reflecting their robustness. This leads to our second hypothesis,

Hypothesis 2*: In unit time, there are fewer vulnerabilities in open source software compared to proprietary software.*

The motivational profiles of open source and proprietary software developers have been widely studied based on theories of volunteerism and labor economics (Hann, Roberts and Slaughter, 2004; Lerner and Tirole, 2000). Open source software developers have been found to be more motivated to contribute and respond to the development process of open source software due to the apparent visibility of their contribution. This visibility provides an incentive to participate and consequentially brings in the desired recognition. Thus, we believe that high-severity vulnerabilities will be responded to faster by the open source community than the proprietary software developers. Hypothesis 3 follows:

Hypothesis 3: *Open source software patches high-severity vulnerability faster than proprietary software.*

Borrowing from the motivational profiles of open source software developers, we hypothesize that open source developers will respond faster to confidentiality, integrity, availability and security-protection type of vulnerabilities. This research question was then split into the following four sub-hypotheses.

Hypothesis 4a: *Open source software developers patch confidentiality-type vulnerabilities faster than proprietary software developers.*

Hypothesis 4b: *Open source software developers patch integrity-type vulnerabilities faster than proprietary software developers.*

Hypothesis 4c: *Open source software developers patch availability-type vulnerabilities faster than proprietary software developers.*

Hypothesis 4d: *Open source software developers patch security protection-type vulnerabilities faster than proprietary software developers.*

Hypothesis 5 is based on the exploit range of the vulnerabilities. High-severity vulnerabilities are usually remote-exploits by nature. So, following on hypothesis 3, we have,

Hypothesis 5: *Remote exploit-vulnerabilities are patched faster by open source developers than their proprietary counterparts.*

4. Data & Methodology

Data for our analysis has been obtained from the ICAT database (ICAT, 2004) maintained by the security division of National Institute of Standards and Technology (NIST) and the Common Vulnerabilities and Exposures (CVE) list maintained by the Mitre Corporation (MITRE, 2004). The data set contains vulnerabilities/bugs discovered and patched/fixed between the period of January 2001 and May 2004. The data is classified according to vulnerability type, severity of potential damage, and their exploited range. These classifications are made by the originators of the data sources, rather than by the researchers of this study.

As mentioned earlier, the focus of our study is on operating system software. Hence the dataset is classified as open source and proprietary, based on the underlying operating system software where the vulnerability has been discovered. The dates of discovery of the vulnerabilities and the dates when these bugs were fixed are recorded to obtain the response times of vendors to release a patch.

Depending on the perceived consequence of a security breach due to a prevailing vulnerability, borrowing from the well-known Confidentiality, Integrity and Availability (CIA) framework (CERT 2004), the data is classified into confidentiality, integrity or availability bugs. A fourth classification, namely security protection (S) is also used to qualify a more general consequence of a security breach. Thus, a vulnerability that has been discovered could be classified into multiple types (C, I, A, and/or S) depending upon the possible consequences of the same. The potential damage caused by the vulnerability is categorized into three types depending on their severity: High, Medium, and Low (H, M, and L). These classifications are contained within the database. Additionally, the exploit range of these bugs is defined to be either remote or local.

Approximately 700 vulnerabilities were identified and listed in the CVE during the 2001-2004 time period. For several of the vulnerabilities, we were unable to get information on the exact date of discovery of the vulnerability. Additionally, some of the vulnerabilities affected both open source as well as proprietary software, in which case, it was difficult to determine the date of discovery or the date when the vulnerability was fixed, for both. Also, there were some vulnerabilities that did not have information on the nature of the vulnerability, their type and/or their exploit range. We removed such data points and ended up with a list of 454 vulnerabilities. A bootstrap procedure was performed, explained in the following section, to impute those missing values where we only needed to estimate the date of discovery of the vulnerability. There were 170 such data points. The resulting data set contains 624 vulnerabilities. Sources for the information on dates of vulnerability discovery and patch application typically included the CERIAS website (http://www.cerias.purdue.edu), ISS X-Force, Security Focus, CERT, Microsoft Security Bulletins, Bugtraq, KDE, Neohapsis, etc. The dates of discovery of the vulnerabilities are as reported by these sources when the vendor is notified. For information on the dates of vendor response, we have taken them to be the dates when the security advisories were made public by the vendor, unless when the actual dates of vendor response were available.

Given the difficulty in obtaining such confidential details related to information security, and the resources available to us, getting exact dates of occurrence of these events was not an easy task. However, we have been consistent in this regard, during our entire data collection process and hence still believe that our preliminary findings would be validated. Next, we describe the procedure that was used to impute the missing data points.

Estimating Missing values

As mentioned earlier, a large number of vulnerabilities had missing values related to the date of discovery of the vulnerability. If these data points were deleted, our analysis would be possibly biased. In order to eliminate this bias, we estimated the missing values using a simple bootstrap procedure (Greene and Greene, 2002).

For simplicity, we initially built our full data set by drawing discovery dates randomly from our existing data set, with replacement. This inherently assumes that our full data set of patch times and inter-arrival times had a similar distribution to our existing data set. Then this random drawing was performed for 1000 iterations to obtain mean estimates. The overall patch times and inter-arrival times of vulnerabilities did not show much deviation from our original result. Our data sources contained information on the vulnerability type, the date it was patched and also when the CVE was assigned to these vulnerabilities. Now, to impute the patch times and inter-arrival times, we incorporated the following constraints:

1) We drew the values randomly from an exponential distribution where the mean was equal to the mean values obtained from our existing data set.

2) An upper limit and lower limit for each value randomly drawn was determined as an additional constraint, from the information contained in our data sources.

We, therefore present the results from our preliminary analysis for our final data set.

5. Results and Discussion

Year	Open Source Software			Proprietary Software			T-stat/p-value for difference of Means
	N	Mean (days)	Std. Dev.	N	Mean (days)	Std. Dev.	
2000	37	57.76	57.52	17	35.19	23.00	2.06(0.03)
2001	94	30.64	41.77	83	37.59	47.96	-1.02(0.16)
2002	81	34.12	37.78	105	42.56	47.49	**-1.35(0.09)**
2003	77	29.68	48.26	84	41.12	54.99	**-1.41(0.08)**
2004	16	24.73	14.75	27	24.41	18.50	0.06(0.48)
All	305	34.30	43.81	317	38.90	47.08	**-1.26(0.10)**

Table 1. Mean time to patch for open-source and proprietary operating system software.

Table 1 shows the mean time to patch for open-source and proprietary software, across different time periods. Goodness-of-fit tests were performed for the Normal, Lognormal, and Weibull distributions. Different parameter values of the Gamma distribution were tested and the exponential distribution was found to have the best fit. Note that we do not have adequate data points for years 2000 and 2004. Hence we can only make limited inferences here. However, if we look at years 2001-2003, we clearly see a smaller mean time to patch in the case of open-source systems. We compute the t-statistic to determine the statistical significance of the difference between the means in open-source and proprietary software (Greene and Greene, 2002). The last column in Table 1 shows the t-values for comparing the means. The results that are significant at 10% level for one-tailed p-values are indicated in bold. We see that Hypothesis 1 is supported only in some cases. We provide market share data (CNET, 2004) for both open source and proprietary operating system software in client applications, in Table 2, for comparison purposes. The data shown does not reflect any major trend reversals. Contrary to popular belief, proprietary operating system software market share only seems to grow larger. Do note that our dataset is restricted only to vulnerabilities in client applications (and not server applications).

Year	Market Share for OSS (in percentage)	Market Share for PS (in percentage)
2000	<1	94
2001	1	95
2002	2.4	95
2003	2.8	97
2004 (Estimates)	1	98

Table 2. Market share data for open source and proprietary operating system software (CNET, 2004).

Figure 1 illustrates the exponential distribution of the counts of the patch-times for the two software-types. The overall mean time to patch for open-source software was 34.30 days, clearly about 14% less than the mean times in proprietary software (38.90 days).

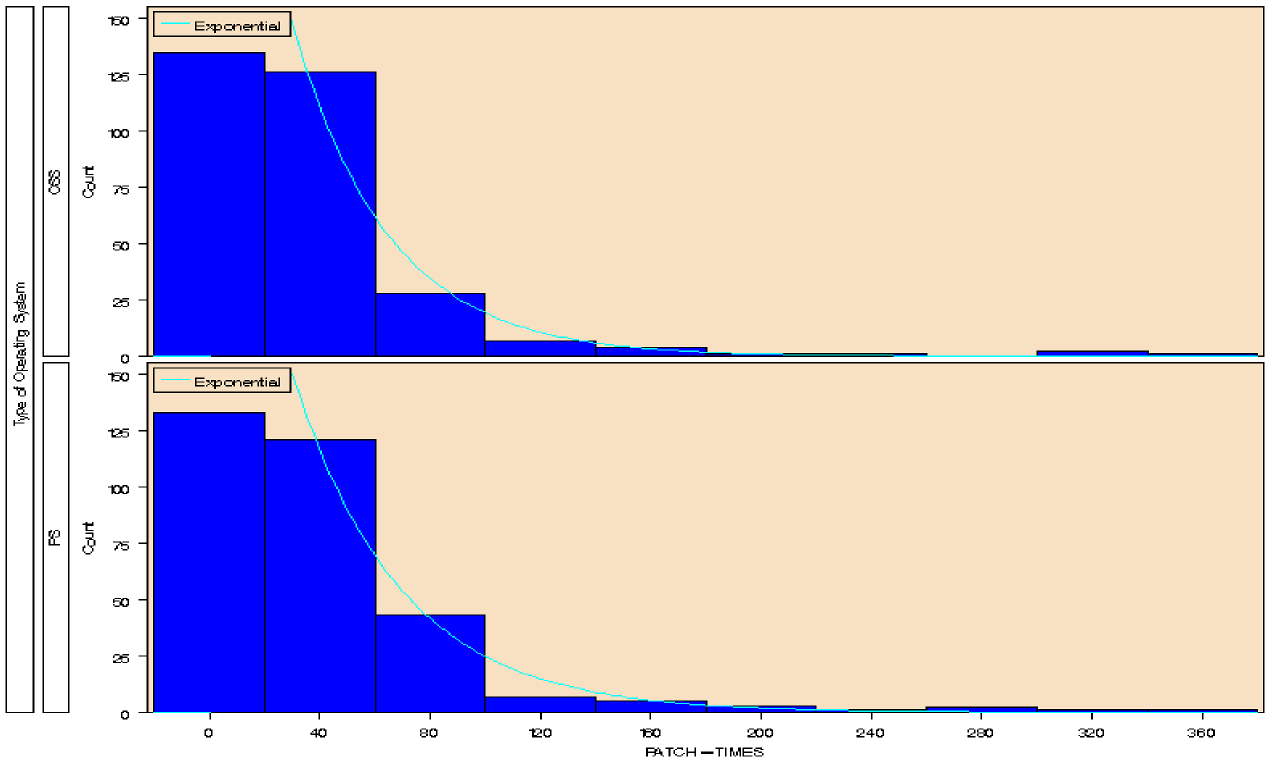


Fig. 1. Overall mean time to patch for open-source and proprietary operating system software.

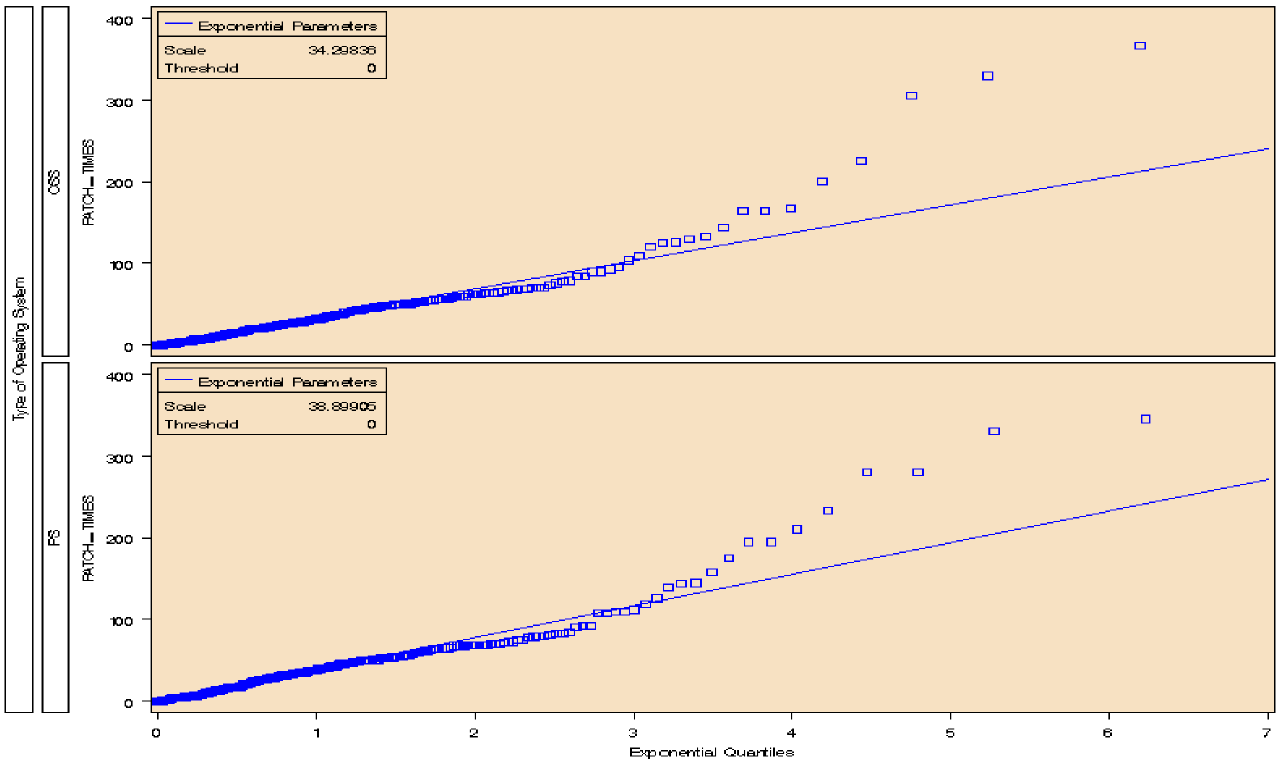


Fig. 2. Fit of the exponential distribution for vulnerability patch-times.

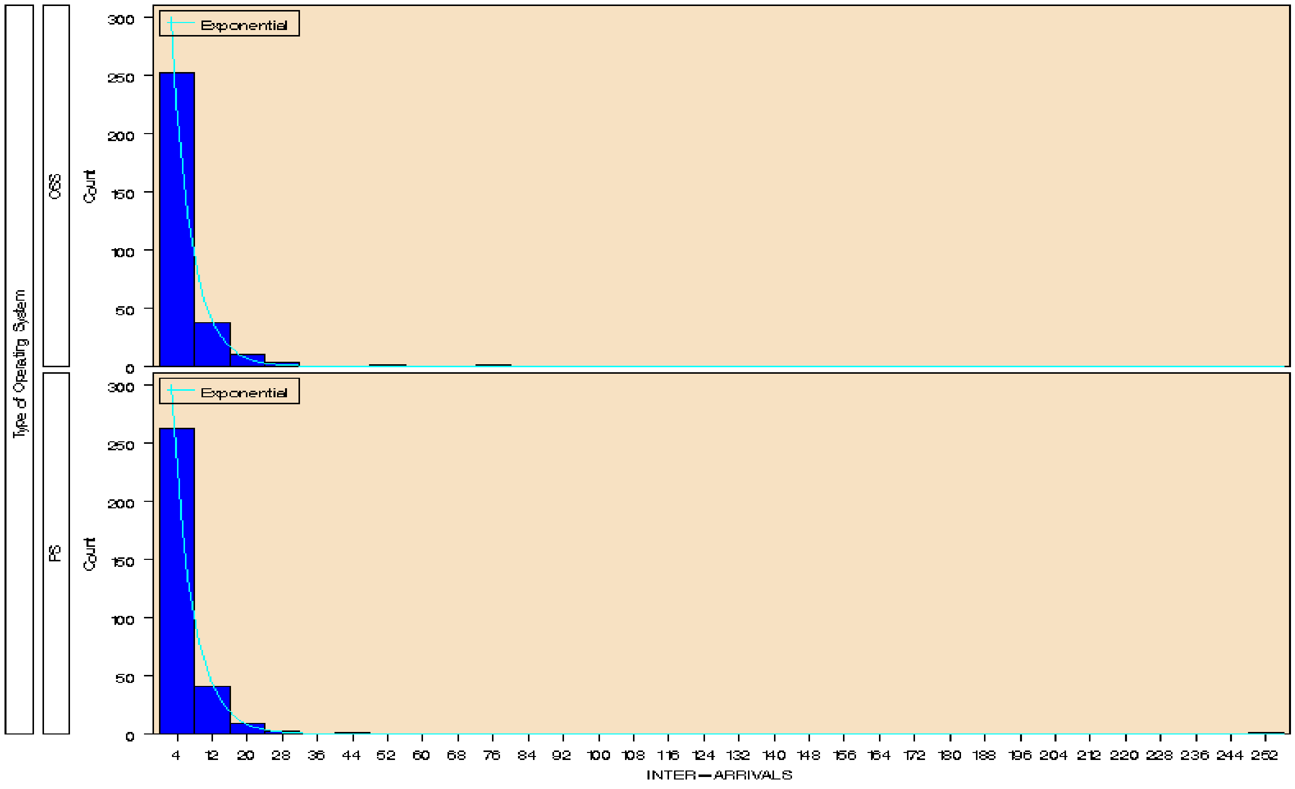


Fig. 3. Inter-arrival times of vulnerabilities for open-source and proprietary operating system software.

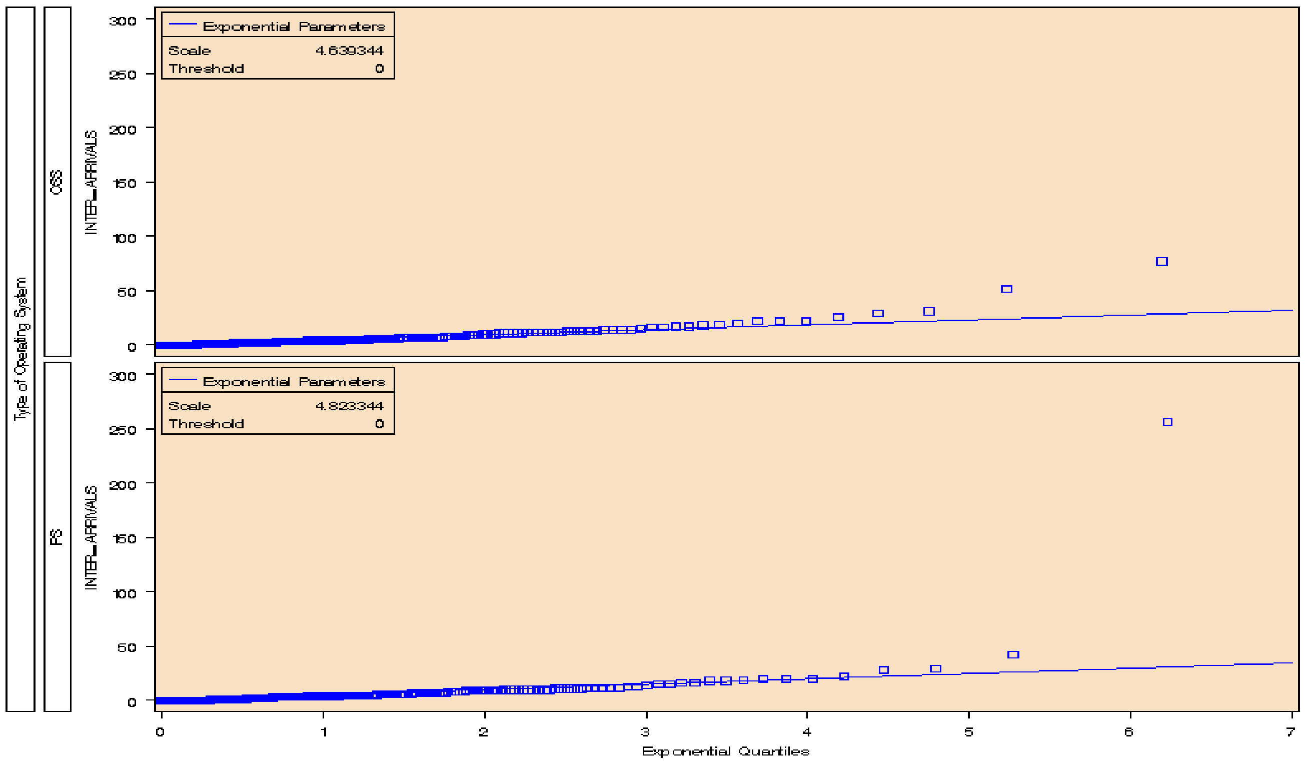


Fig. 4. Fit of the exponential distribution for inter-arrival times of vulnerabilities.

Type of OS affected	Inter-arrival times of vulnerabilities (T-stat of Difference of means = -0.20)		
	N	Mean (days)	Std. Deviation
O	305	4.64	7.14
P	317	4.82	15.08

Table 3. Mean inter-arrival times of vulnerabilities for open-source and proprietary operating system software.

The numbers in Table 3 show the difference in the mean inter-arrival times of vulnerabilities for the two software-types. There is not much difference in the mean inter-arrival times and though proprietary software exhibits a lot more variation, the difference in the means is not statistically significant (t-value = 1.10) at the 10% level. Hence, at this point, we cannot conclude that open-source software exhibit greater robustness. We, therefore, reject Hypothesis 2.

Type of Severity	Open Source Software			Proprietary Software			T-stat/p-value for difference of means
	N	Mean (Days)	Std. Deviation	N	Mean (Days)	Std. Deviation	
High	148	34.30	51.30	171	41.99	51.98	**-1.33(0.09)**
Medium	146	33.64	39.53	131	36.11	41.90	-0.50(0.31)
Low	11	42.91	27.64	15	28.07	31.51	1.27(0.12)

Table 4. Severity of the vulnerability. The 1-tailed p-values at the 10% significance are shown in bold.

Table 4 shows the relative performance of the two software systems based on the type of severity. As we had hypothesized earlier, we find a significant difference in the performance for high-severity vulnerabilities. Hypothesis 3 is supported. The medium and low-severity vulnerability meanwhile do not show differences that are statistically significant.

The classification based on the type of the vulnerability (C, I, A or S) is shown below in Table 5. We do see a significant difference in the patch times of confidentiality-type vulnerabilities, but the difference is in favor of proprietary software systems. Integrity and Availability-type vulnerabilities do not show any significant difference. Thus, hypotheses 4a, 4b and 4c are not supported. A more general type of vulnerability, namely the Security protection, meanwhile, also does not show a significant difference in the patch times. Hypothesis 4d is not supported. Also, looking at the means, it is difficult to ascertain if one type of software is better than the other.

Type of Vulnerability	Open Source Software			Proprietary Software			T-stat/p-value for difference of means
	N	Mean (Days)	Std. Deviation	N	Mean (Days)	Std. Deviation	
Confidentiality	41	46.80	38.79	36	35.99	25.44	1.46(0.07)
Integrity	58	32.83	22.24	42	30.46	27.26	0.46(0.32)
Availability	85	45.23	37.06	87	45.43	38.04	-0.04(0.49)
Security Protection	18 2	47.72	28.75	21 1	50.38	39.80	0.77(0.22)

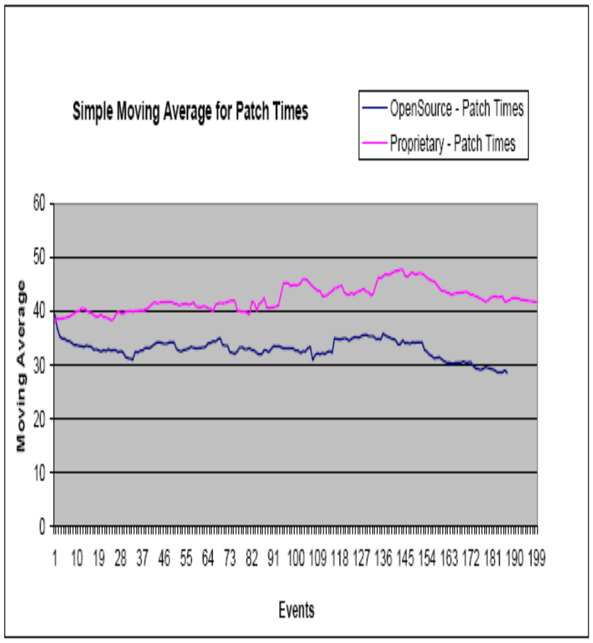
Table 5. Type of vulnerability. The 1-tailed p-values at the 10% significance are shown in bold.

Consistent with hypothesis 5, we find that open source software developers patch faster than the proprietary software developers in the case of Remote-exploit vulnerabilities, but the difference is not statistically significant. Hypothesis 5 is not supported. The corresponding results are presented in Table 6.

Exploit Range	Open Source Software			Proprietary Software			T-stat/p-value for difference of means
	N	Mean (Days)	Std. Deviation	N	Mean (Days)	Std. Deviation	
Remote	125	35.50	39.80	168	39.94	43.64	-0.91(0.18)
Local	192	34.02	48.16	155	36.41	48.74	-0.46(0.32)

Table 6. Exploit range. The 1-tailed p-values at the 10% significance are shown in bold. compares the exploit range for open source and proprietary software systems.

Fig. 5 shows the moving averages for the patch times and the vulnerability-interarrival times. Adequate smoothening has been done, considering 120 event-intervals to show the trajectory of the two curves. Since the two parameters were found to be exponentially distributed, an exponential moving average was also computed and Fig. 6 shows the relative convergence of the two curves for the patch times and inter-arrival times. As expected, the exponential moving averages yield a smoother convergence.



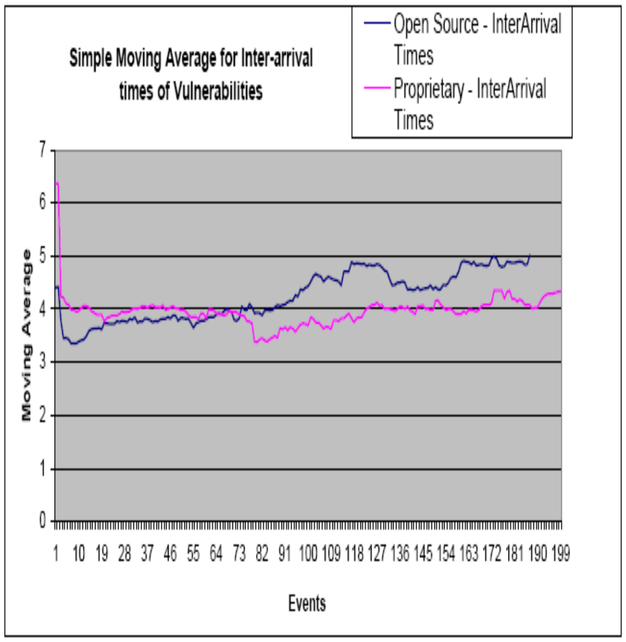
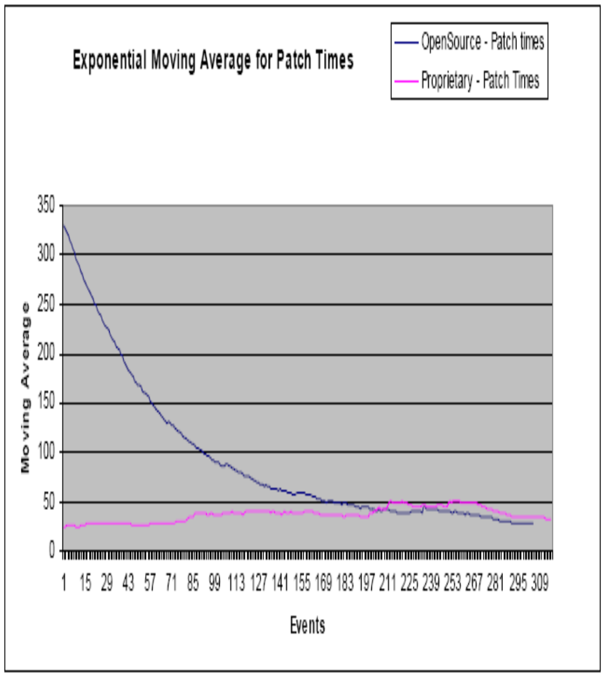


Fig. 5. Simple Moving Average for patch-times and vulnerability inter-arrival times for 120-events interval.



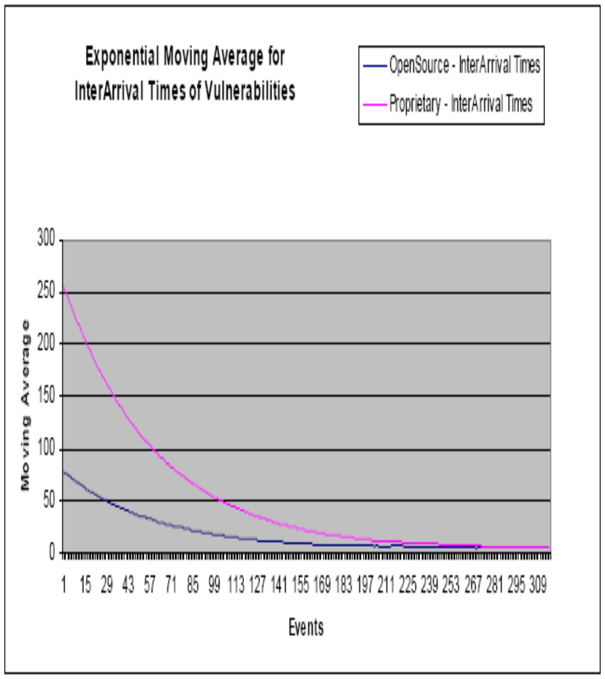


Fig. 6. Exponential Moving Average for patch-times and vulnerability inter-arrival times for 120-events interval.

Summarizing, the results provide some perspective into the ongoing debate of security between open source and proprietary software systems. The paper makes a contribution to this growing literature on software security in two ways. First, the analysis reveals yet again that the security issue is still open. Critics who argue in favor of the "more critical eyes" theory may do well to look at the observations again. Though time to patch or vendor-responsiveness, is not the only measure of software quality, in the minds of the user, it is definitely one of the proxies for software security. The faster the patch is available, the more confident users feel towards the software's security. Again, research (Rescorla, 2002) does show that securing a system does not end with making a patch available. Most users are found to be less responsive (call it user-responsiveness) to apply the patch that is available to them. Yet, restricting our study to purely technical concerns, and to just the vulnerabilities found in operating system applications, the results are not conclusive.

As mentioned earlier, given the limited data available to us, we do not differentiate our data sources based on the different disclosure policies they follow. Incorporating them would ensure a more complete framework is in place. Going back to the argument of proprietary software being more targeted (due to their wide market share) and hence less secure, our results show that this is not the case. Both kinds of software contain almost the same number of vulnerabilities and further, the yearly data reveals no trends indicating any one holding a clear advantage over the other, from a security standpoint.

6. Conclusion and Future Research

Our study contributes to the literature on software security. The key motivation remains to carry the software reliability model forward. Quite a few data points had to be imputed, since the information was incomplete. We seek to further examine this data through an analytical framework from the perspective of security as reliability. The insights available from the software reliability literature will be applied accordingly. Another issue worth pursuing is that of staffing questions for software development. Some critics state that open source software has too many developers than is efficient, and thus wastes resources. Others purport that perhaps open source software has naturally evolved to rely on the relatively large numbers of programmers used to manage the software. We hope to eventually shed light on this issue as well.

Our analysis serves as a good starting point to compare open source and proprietary software systems from a security perspective. However, the study is not complete. We hope to obtain similar data on server applications as well. Finally, incorporating the information on vendor disclosure policies for our different data sources and also the user patterns in applying a patch once it is available, will help us build on the framework we are trying to establish through this study. How good a patch is, or whether frequent patching is cost-effective are still questions open to research. An interesting extension of our analysis would be to analyze the quality of a patch, in terms of the number of new vulnerabilities it introduces into the system. Though data might be difficult to obtain, an analytical birth-and-death model could capture the mechanics of the vulnerability-patch lifecycle adequately.

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