Product Upgrading Decisions under Uncertainty in a Durable Goods Market *

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Abstract

This paper studies investment behavior of firms deciding when to introduce an upgrade in a durable goods monopoly. The firm chooses both the investment timing and the price of the upgrade while facing the risk of the upgrade experiencing a serious malfunction and requiring a complete recall. More specifically, the paper aims to show what incentives a firm may have to introduce an upgrade early and accept the higher malfunction risk. The firm can reduce this risk by performing product tests of uncertain duration. We show that the willingness to introduce an upgrade early with significant malfunction risk is larger when (*i*) the demand for the existing version has weakened, (*ii*) the quality and stock of potential customers for the upgrade is high or (*iii*) the testing process is slow.

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1 Introduction

Samsung introduced Note 7, the annual upgrade of the Samsung Galaxy Note smartphone series, in the fall of 2016. Customers immediately reported incidents of the battery overheating, causing the Note 7 to catch fire or even explode. Samsung ended up recalling all sold Note 7 units and refunding the customers, essentially losing all revenue from the smartphone[1]. The example of Samsung is only the most recent among the many product upgrades that have been recalled as a result of serious malfunctions. Typically, these products are durable goods. Durable goods are consumer goods that do not wear out fast or have to be repurchased for several years[2]. In general, product upgrades are critical for producers of durable goods to be successful. Failing to deliver innovative upgrades may lead to a substantial loss in demand and market share, as evident by Nokia's drop from 50% to under 5% market share since the introduction of the iPhone in 2007 [3]. This paper investigates the incentives that drive producers of durable goods to introduce a product upgrade with the risk of malfunction.

Although durable goods expenditure accounted for roughly $1.3 trillion in the USA alone in 2016[4], the research on investment decisions for producers in durable goods markets has gained limited attention in the literature. Interestingly, most of the durable goods literature ignores the concept of product upgrades although durable goods markets are typically characterized by products that improve over time. Levinthal and Purohit (1989) were the first to address the upgrading problem and studied the decision of a monopolist in a two-period model under the case of both separate production and joint-production. They found that the profits from separate production, meaning that the existing version is phased out when the upgrade is introduced, gives unambiguously higher profits than joint-production. Furthermore, they found that a buy-back policy can make joint-production most profitable when there is a substantial difference in quality between the two versions. We consider a separate production model like the one presented in Levinthal and Purohit (1989) and extend it by introducing a testing phase of uncertain duration and a possibility of product malfunction for the upgraded version.

Fudenberg and Tirole (1998) presents a more thorough analysis of the upgrading problem, focusing on what happens in the presence of a second-hand market. They assume that new and used products are imperfect substitutes because the quality of the products deteriorate over time. Consequently, the monopolist has incentive to lower the durability to make used products less competitive to the upgrade. Contrary to Fudenberg and Tirole (1998), we will ignore second-hand markets to more accurately evaluate the effects of a testing phase and a risk of product malfunction requiring a total recall.

[1] http://www.samsung.com/us/note7recall/
[2] http://www.investopedia.com/terms/d/durables.asp
[3] https://www.statista.com/statistics/263438/market-share-held-by-nokia-smartphones-since-2007/
[4] http://www.investopedia.com/terms/d/durables.asp

A topic that has received significant attention in the durable goods literature is the time inconsistency problem. This problem was first addressed in Coase (1972) and it arises because durable goods sold in the future will affect the future value of units sold today. Coase (1972) argued that unless a monopolist is able to pre-commit to a price, the consumer's expectations on future price reductions will instantly lower the price of the durable good to marginal cost. He also argued that leasing would avoid the problem, which was later confirmed in Bulow (1982). Common topics in subsequent durable goods literature include the robustness of Coase's time inconsistency problem and the ways to overcome it. A more recent contribution on the latter is Hahn (2006) who found that introducing a stripped-down version of a durable good would in fact mitigate the time inconsistency problem. Waldman (1996) analyzed a model for the upgrading problem similar to Fudenberg and Tirole (1998) and showed that product upgrade introductions are subject to a time inconsistency problem like the one presented in Coase (1972). They found that this gives the firm an incentive to make the existing version obsolete upon introduction of the upgrade. Unlike Coase (1972) and Waldman (1996), this paper assumes that firms are able to pre-commit to a price. In reality, this is true for many firms. Consider for instance Apple's credible reputation for not reducing the price of existing products until a new version is introduced.

Several papers considering investment under uncertainty use examples from the durable goods industry to motivate their research, without taking the specific features of durable goods into account in their models. A recent example of this is Lavrutich *et al.* (2016) which considers a market entry decision of two competitive firms that are well aware of each other. In addition, a third, hidden firm can enter the market at an unknown point in time. To motivate the concept of hidden competition, Lavrutich *et al.* (2016) refers to the car industry and uses Apple as an example of a hidden competitor now that they are developing their own electric car. Although the market for electric cars is clearly a durable goods market, the model presented does not account for this in the demand function.

The contribution of this paper is two-fold. First, it extends the literature on investment decisions for durable goods by including a testing phase and a risk of having to recall a malfunctioning product. Second, it extends the literature on investment under uncertainty by developing a model that accounts for the specific features of durable goods. We find that a firm's incentive to introduce a risky upgrade in the market may be explained by three reasons. First, an incentive to release a risky upgrade arises when the profits from selling the existing version has dropped low. Second, if the upgrade is of good quality and has a high expected initial stock of potential customers, the expected value of the investment is high. This gives incentive to invest early even if significant malfunction risks are present. Finally, a slow testing process may drive the firm to gamble on a risky upgrade rather than waiting for more sub-tests to complete.

The rest of the paper is organized as follows. In section 1 we solve the upgrading problem when there is no uncertainty in the duration of the testing phase and the firm refrains from introducing the upgrade until testing is completed. In the second section we relax the assumption of deterministic duration of the testing phase. In section 3 we allow the firm to introduce an upgrade before the testing phase is completed, at the risk of the upgrade malfunctioning. Section 4 summarizes the findings and concludes. The proofs of all propositions can be found in the appendix.

2 Model

In the basic model a monopolistic firm producing a single durable good makes a decision on when, or if, it should introduce an upgraded version of the good. Here, we assume the technology for the upgrade needs to go through an exogenous testing phase to avoid the risk of malfunction. The fist assume that duration of the testing phase is deterministic and finish at time t_n[5]. In the basic model firm does not invest before the testing phase is completed, but can then adopt the technology and introduce the upgrade by paying a fixed investment cost I. Later, we relax this assumption and allow the firm to introduce the upgrade before testing is completed. Upon introduction of the upgrade a stock of potential customers, hereafter referred to as customer potential, for the new version arises and is expected to be Q_2^0.

The firm is currently selling the existing version at the price P_1. Since we do not consider the decision to introduce the existing version, P_1 is treated as a fixed parameter. In other words, P_1 is the price the firm committed to when the existing version was introduced. Furthermore, we let $Q_i(t)$ denote the remaining customer potential for version i. Subscript 1 represents the existing version, while subscript 2 represents the upgrade to be introduced. Each customer can at most buy one unit of each version of the product. In reality this is often true for durable goods. For instance, a single person would rarely purchase more than one iPhone 7. The stock of potential customers therefore reduces over time as more units are sold, and the dynamics is given by equation (1):

$$dQ_i(t) = -q_i(t)dt, i = 1, 2, \tag{1}$$

where $dQ_i(t)$ denotes the instantaneous change in the customer potential for version i over time period dt and $q_i(t)$ denotes the instantaneous demand for version i. As stated in the introduction we also assume that the existing version becomes completely obsolete upon introduction of the upgrade, implying that Q_1 drops to 0. This allows us to investigate the effects of a testing phase and product malfunction risk on the investment decision in more detail.

The instantaneous demand is a linear function as given in equation (2):

$$q_i(t) = Q_i - \eta_i P_i, i = 1, 2, \tag{2}$$

[5]The time-lag from technology adoption to market release is included in t_n.

where η_i in the demand function is a price penalty factor determined by the quality of the product. Typically, one would expect the upgrade to be of better quality than the existing version and therefore the relation $\eta_1 > \eta_2$ to hold.

As the example with the Samsung Galaxy Note 7 in the introduction illustrated, producers of durable goods may choose to introduce a product before it is thoroughly tested for malfunction risks. We therefore relax the assumption that the firm refrains from undertaking the investment until testing is completed. Instead, we introduce a test level θ to describe the amount of testing that has been completed. The test level θ is modeled as a Poisson jump process with arrival rate λ and jump size u, as presented in equation (3) below.

$$d\theta = \begin{cases} u & Prob = \lambda dt, \\ 0 & Prob = 1 - \lambda dt. \end{cases} \tag{3}$$

The overall product testing is often considered a series of independent sub-tests; a smartphone test could for instance consist of battery testing, CPU testing and screen responsiveness testing. Hence, a Poisson jump process is a suitable modeling approach to describe the development in the testing phase. The jump size u defines the impact of a single sub-test, while λ determines the expected duration of each sub-test by $\mathbb{E}[duration] = \frac{1}{\lambda}$.

Samsung ended up recalling all sold units of their Galaxy Note 7 and essentially lost the entire revenue from the project. We introduce a disaster probability p_d to capture the probability of experiencing a malfunction that requires all units to be recalled. The disaster probability depends on the test level by the relation $p_d = \mathrm{e}^{-\theta}$. One important characteristic of this modeling assumption is that the marginal effect of testing is diminishing, as presented in Figure 1. In reality, firms often test the most vital parts of the product first to fix the most damaging flaws early. Therefore, it makes sense that the completion of a sub-test in the beginning of the testing phase, when θ is low, has a greater impact on the disaster probability. Another aspect of the disaster probability is that it will never hit 0. This captures the real world fact that no matter how thorough a product is tested, it will never be completely free of malfunction risks.

The expected present value of the revenue from the upgrade, denoted by $V_2(\theta)$, is then given by

$$\mathbb{E}[V_2(\theta)] = p_d \mathbb{E}[V_2(\theta)|\ disaster] + (1 - p_d)\, \mathbb{E}[V_2(\theta)|\ no\ disaster]. \tag{4}$$

When we assume that a malfunction requires all sold units to be recalled, the expected revenue in the event of a disaster is equal to 0. Recall from section 2 that the present value of the revenue from the upgrade when there is no malfunction risk is given by $\frac{Q_2^{0\,2}}{4\eta_2(1+\rho)}$. Equation (4) is therefore equal to

$$\mathbb{E}[V_2(\theta)] = \frac{Q_2^{0\,2}}{4\eta_2(1+\rho)} \left(1 - \mathrm{e}^{-\theta}\right). \tag{5}$$

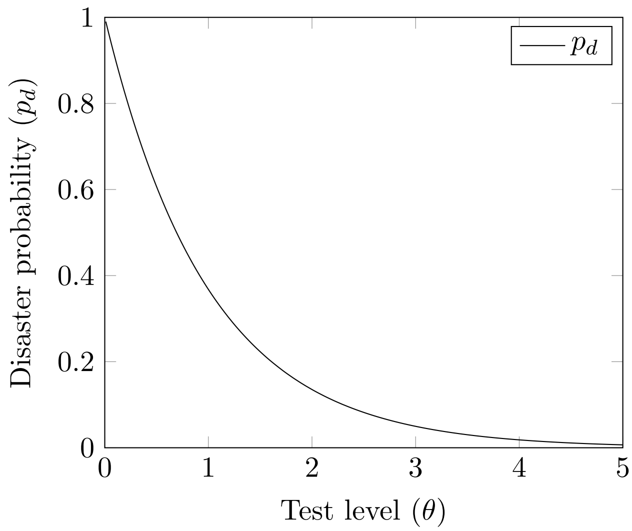

Figure 1: The marginal effect of testing on the disaster probability.

The optimal investment strategy depends on both the test level and the remaining customer potential for the existing model. A high test level allows the firm to invest in a safer technology, increasing the expected revenue from the upgrade. A high remaining customer potential would on the other hand imply that the firm gives up a large profit from the existing model by introducing the upgrade. For a given stock of potential customers Q_1, we find the optimal timing of the investment by deriving the technology test threshold $\theta^*(Q_1)$. For θ below the threshold the firm prefers to delay the investment until either more testing is completed or more units of the existing version are sold, while for θ above the threshold the firm prefers to introduce the upgrade immediately.

To find the threshold function we need to determine the firm value in the continuation region and the stopping region, meaning the regions where it is optimal for the firm to wait and invest respectively.

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