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When less can be more ? Setting technology levels in complementary goods markets

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Abstract
In most markets, higher technological quality directly translates into higher consumer utility. However, many new products do not work standalone but require the availability of a complementary product. In these markets, pushing a product closer to the technological frontier can have detrimental effects as this excludes increasing numbers of consumers whose complementary products no longer function with the focal product. Firms therefore have to balance product quality against market size. Technological change brings a dynamic perspective to this tradeoff as it renders existing technology obsolete but also increases performance of the complementary products, therefore increasing market potential. We study these mechanisms in the empirical context of computer games. In line with our expectations, we find an inverted U-shaped relationship between closeness to the frontier and sales revenues as well as differential effects of technological change depending on initial technological quality.

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Keywords: Technological Frontier, Technological Change, Computer Games Industry

JEL Classification: tbd

1. Introduction

Finding the right distance to the technological frontier is not only a highly important task for managers of innovations but a difficult one as well (Cooper & Kleinschmidt 1987; Paulson Gjerde et al. 2002). This is even more complicated if the frontier is constantly pushed due to technological change (Bhattacharya et al. 1998; MacCormack et al. 2001). What the firm is developing right now might be obsolete by the time the product is introduced to the market. With rapid technological change it might therefore make sense to place your product close to the frontier (Paulson Gjerde et al. 2002). Generally, products close to the frontier have been found to be commercially more successful (Cooper & Kleinschmidt 1987; Rindova & Petkova 2007). Consumers are attracted by innovative products which increases the odds of buying it. However, what if a position close to the technological frontier would be detrimental to product success?

We argue that being at the edge of the technological frontier is particularly harmful for products requiring a complement. While usual complements, as long as they fit together like razors and blades, do not have to meet particular requirements, we find cases where the complement is expected to provide a certain performance. As an example of the intellectual puzzle, consider the computer games industry. A game that is close to the frontier needs a computer close to the frontier itself. Developing this game might prove to be relatively unprofitable as the high requirements on the complement, the computer, limit the potential market of gamers.

Complements unable to provide the required performance cannot support the focal product. Hence, individuals using low-performance complements are unable to use high-performance focal products. Managers involved with developing innovative products have to consider a close position to the technological frontier to reduce market potential. On the other hand, high-performance products are more appealing which increases the chance of consumers buying it.

While a position closer to the technological frontier diminishes market potential, it increases product attractiveness. This trade-off becomes clear considering the extremes. First, a product that is technology-wise outdated could be supported by almost any complement. Consequently anyone could use it but no one would as the weak performance is not appealing. On the other hand, market potential is low for a cutting edge product. That is because the closeness to the technological frontier translates into high requirements on the complement which only few can provide. Therefore, while most consumers would like to buy it, the least could actually do so. We therefore expect closeness to the technological frontier (henceforth CTF) and revenues to have an inverted U-shaped relationship.

Further, changing product characteristics is unfeasible after market introduction; i.e. the absolute level of performance remains flat for the rest of the product life cycle. Technological change pushes the frontier which has two implications: On the one hand, the distance to the frontier increases. New product releases closer to the frontier increase competitive pressure which ultimately lead to its obsolescence. On the other hand technological change increases performance on the complements side. Consequently, more consumers have a complement able to support the focal product. While the first effect decreases attractiveness, the latter increases market potential.

With the goal of generating insights for the relationship of closeness to the frontier, technological change and product success, we ask three specific questions that we address in this paper: (1) Is there an inverted U-shaped relationship for closeness to the technological frontier and revenues? (2) How is revenue driven by technological change? (3) Does technological change influence the effect of CTF on revenues?

The empirical context of our study is the computer games industry, which is well-suited for the analysis for several reasons. First, system requirements are a fair measure of closeness to the technological frontier. Second, computer games require a complement, the PC, and have specific requirements on its performance. Third, the computer games industry is subject to rapid technological change.

We draw our data from four different sources. First, we use a dataset from Futuremark, with roughly 1.5 million benchmark results between 2002 and 2010. This yields a time-series of monthly hardware availability and indicates the pace of technological change. In addition, the NPD group provides a panel with monthly revenue and sales data for computer games, and we use MobyGames to match it with game-specific information like genre and release date. Additionally, GameSpot provides system requirements for games which, compared to the benchmark scores, yield a measure of CTF.

Our first major result is that games closer to the technological frontier are more successful. While higher system requirements reduce market potential, they make the game more attractive. However, our results show a decreasing marginal effect suggesting an inverted U-shaped relationship for revenue and CTF. Second, our findings indicate that the effect of technological change is negative which captures the effect of increasing distance to the frontier eventually leading to obsolescence. Third, the effect of technological change turns positive if a game is closer to the technological frontier. In this case, the market potential increasing effect outweighs the negative effect of obsolescence.

2. Theoretical Mechanism

Systems of complements are well known. A DVD requires a DVD-Player, a razor needs blades and the printer will not print without a cartridge. All of these examples, however, work once combined with an adequate complementary product. They do not have particular requirements on the performance of their complement. For standardized products like the DVD consumers can use any DVD-Player. Moreover, the performance of the DVD is the same regardless of the DVD player’s age, functions or features.

However, there are cases where this does not hold. That is because the focal product still requires a complement to work but its own performance is tightly linked to the characteristics of the complement. Computer games serve as a good example. Here, the focal product, the computer game, requires a complement, the computer. Obviously, the benefit from playing depends on the performance of its computer. If the hardware does not meet the minimum system requirements, the computer game will probably not even start. However, more powerful systems allow for more advanced graphical settings, more realistic physical effects and a smoother gameplay.

Performance of the focal product is causally determined by complement performance. However, a minimum performance is required as complements below this threshold cannot support the focal product. For computer games, this is commonly referred to as the minimum system requirements specifying the hardware of the computer. Any system configuration weaker than this lower threshold cannot support the game. Accordingly, all individuals owning a computer unable to provide the minimum system requirements are excluded from the consumption of the product.

Products close to the technological frontier appeal to consumers. At the same time, such products suffer from a small market potential. This implies two trade-offs regarding how close the product should be to the frontier. Both are discussed in more detail below.

2.1. Distance to the frontier

The question of where to position the new product is critical. Closeness to the technological frontier contributes to the product's attractiveness which in turn has an effect on the commercial success. Cooper & Kleinschmidt (1987) and Jain & Ramdas (2005) argue that superior performance is key for the success for the product whereas inferior technology suffers from a significant reduction in revenues. On the other hand, a position close to the frontier requires increased costs for research and development. High R&D expenses make an innovation unlikely to be at the cutting edge (Paulson Gjerde et al. 2002).

Although various studies found a position closer to the technological frontier to be beneficial ((Bartelsman et al. 2008; Iacovone & Crespi 2010; Cantner et al. 2012), we argue for a non-linear relationship in industries where the focal product makes requirements on its complement.

The non-linearity follows from the fact that closeness to the frontier excludes consumers. That is because unless a consumer's complementary item provides the required performance, it cannot support the focal product. These requirements are basically a function of the characteristics of the focal product. The closer the focal product is to the technological frontier, the closer the complement has to be to the frontier itself.

That creates a trade-off for the firm concerned with positioning its innovation. With the distribution of complements performance being exogenously given for the firm decreasing distance to the frontier reduces market potential. That is because the CTF of the focal product defines the threshold for the complementary item. All individuals with complements weaker than the threshold are excluded from consumption.

At the same time, products close to the frontier are more appealing to consumers (Jain & Ramdas 2005). Individuals have a preference for innovative products and the likelihood of purchase increases as distance to the frontier decreases. Hence, products closer to the frontier are expected to reach a larger share of consumers whose complementary product can provide the required performance.

We argue that the relationship for product success and CTF is inverted U-shaped. That is because a technology-wise outdated product would address the whole market but no one would bother to buy it. Its far distance to the technological frontier is not appealing to the consumers. By reducing the distance to the frontier, the product slightly loses market potential but gains attractiveness. At some particular level of closeness to the frontier the sales-enhancing effect of increased attractiveness will equal the sales-reducing effect of decreased market potential. Decreasing distance to the frontier further would make the product less successful as the negative effect of decreased market potential dominates the effect of increased attractiveness.

2.2. Technological Change

Dynamic environments with fast pace of technological advancement present an additional challenge to the firm concerned with developing new products (Bhattacharya et al. 1998; Bstieler 2005; MacCormack et al. 2001). Considering technological progress, matters for at least two reasons. First, technological change pushes the frontier. Failing to adapt to these changes will increase the gap to environmental demands over time. That is distance to the frontier increases and technological change inevitably leads to obsolescence. This has been investigated in the context of firms and its technologies (Sørensen & Stuart 2000) and oftentimes inertia is mentioned as a reason for firms failing to adapt to external changes (Hannan & Freeman 1984; Amburgey et al. 1993). Additionally, the introduction of substitutes closer to the frontier increases competitive pressure. Adner & Snow (2010) discussed several strategies how old technologies can handle the threat of substitution by new products. However, often firms and products fail (or even cannot) react to new competition.

Usually, products are perfectly inert as the absolute technological sophistication is fixed after it is introduced to the market. This means that product characteristics cannot be changed after the release. New rival product introductions are technology-wise more sophisticated and push the frontier. Therefore, the relative level of technological sophistication of the focal product decreases as the technological frontier moves further.

Similar to the argument of Hannan & Freeman (1984) products cannot adapt to this external change, its distance to the technological frontier increases over time and keeping up with market demands becomes harder. This eventually leads to the product's obsolescence.

At the same time, technological change has a positive aspect. Not only rival products move closer to the frontier but also the complements. This means that better complements are introduced to the market and replace older hardware. Consumers unable to use the focal product before might be after upgrading their complement thus increasing the group of consumers potentially able to use the focal product. In the presence of technological change, market potential increases automatically over time.

This results in an interesting trade-off when it comes to choosing CTF for the product. In a world without technological change, the firm trades off product attractiveness with market potential. Considering technological change, increasing competitive pressure, especially for less developed products, has to be taken into account. As the technological frontier is constantly moving, the initial performance needs to be high enough to withstand competition. Once the focal product falls too far behind the technological frontier, it becomes obsolete and drops out of the market and henceforth generates no more revenues. The profit maximizing firm chooses a shorter initial distance to the frontier than in a setting without technological change. This is consistent with the findings of Paulson Gjerde et al. (2002) which suggest faster technological change to result in closer to the frontier innovations. The initial market potential might be low due to the short distance to the frontier but the product will survive longer on the market. As time progresses, average performance of complements rises thus increasing market potential for the focal product.

3. Empirical Context

We use the computer games industry as the empirical context of our study. This industry is well suited for the analysis, as gamers need a complement, the PC, which additionally has to fulfill minimum system requirements. We argue that hardware requirements are a fair indicator for closeness to the technological frontier. Consumers generally prefer games with realistic and detailed graphics and convincing game physics; both resulting in higher requirements on the computing power.

We identified two main trade-offs for firms choosing CTF. First, shorter distance to the frontier diminishes market potential but, on the other hand, increases attractiveness. Second, developers have to take two contrary effects of technological change into account; the introduction of better substitutes has a negative effect while, on the other hand, the availability of better computers increases market potential. Both trade-offs are discussed in more detail in the following subsections.

3.1. Closeness to the Frontier

Recent developments in the computer industry give game producers room for powerful and detailed graphics and more realistic game physics. However, all of that requires increased computing power which results in higher system requirements. While realistic graphics and game physics increase the attractiveness for the gamer, it limits the amount of consumers which can use it. That is because the higher system requirements exclude consumers if their PC cannot provide the required performance.

The developer makes a strategic decision of whether she prefers to sell a less developed product to a larger market or, vice versa, a cutting-edge game to a smaller market. The relevant question in this case is whether the sales-enhancing effect of increased product attractiveness through shorter distance to the frontier can exceed the sales-reducing effect of lower market potential.

Here, we expect to find an inverted U-shaped relationship for CTF and revenue. That is because a technology-wise outdated product would address the whole market but its far distance to the technological frontier is not appealing to gamers. By incorporating better graphics, the product slightly loses market potential (due to higher system requirements) but gains attractiveness. At some particular level of closeness to the frontier the sales-enhancing effect of increased attractiveness will equal the sales-reducing effect of decreased market potential. Decreasing distance to the frontier further would make the product less successful as the negative effect of decreased market potential exceeds the effect of increased attractiveness.

3.2. Technological Change

In 1965, Gordon Moore made a prediction (which today is commonly known as Moore's Law) that transistor density of integrated circuits would double about every two years

(Moore 1965). Time should prove him correct. Figure 1 gives a striking overview of the data that we draw from our Futuremark dataset. Futuremark is the leading company in 3D, PC and mobile performance benchmarks which not only sells 3D benchmarks, but also provides a free version for measuring the 3D graphics performance of gaming PCs. The diagram reveals that computing power increased drastically over a 9-year period.

INSERT FIGURE 1 HERE

During this time span, the average benchmark score (lower graphic) skyrocketed from roughly 2,318 in January 2001 to almost 53,000 in January 2010, which equals an increase by a factor of 22.8.

This rapid technological change has two implications. First, computer games that were cutting-edge at the date of launch might be surpassed by better substitutes only 12 months later. With product characteristics remaining constant, distance to the frontier increases over time because higher-performance products are introduced. Figure 3 shows how a computer game moves further from the frontier as time progresses. While GTA3 was close to the technological frontier at the time of its release, its distance to the frontier increases rapidly.

INSERT FIGURE 3 HERE

On the other hand, average hardware availability improves due to the diffusion of more powerful PCs. This implies that a larger share of computers can run the game which increases market potential. Put differently, market potential increases while product attractiveness decreases.

4. Data

4.1. Sources of Data

Our empirical analysis combines several sources of data. First, we use a dataset from MobyGames, the world's largest video game documentation project, providing detailed information on genre and release date. It further indicates if a game uses licensed content (e.g. James Bond 007), is part of a series (e.g. the FIFA series), or utilizes a third party graphics engine.

We match this with data from the NPD Group, a leading organization collecting and providing information on this industry. The NPD data provides monthly unit and dollar sales and covers the period 1995-2008[1]. The sales numbers are based on a sample of 17 leading U.S. retail chains that account for 65 percent of the U.S. market (Clements & Ohashi 2005).

We supplement these data with game-specific characteristics such as minimum and recommended hardware requirements. This information is drawn from Gamespot, an online gaming community primarily providing reviews and previews of video game related issues.

Additionally, the Futuremark dataset provides roughly 1.5 million benchmark results from four different benchmark generations[2]. This information not only includes the benchmark score and the date, but also system specifications such as CPU speed, processor type, graphic card and graphic memory, as well as operating system. We use this dataset to calculate a time-series of monthly average hardware availability between March 2001 and March 2010. The differences between months yield a clear indication of technological change.

Futuremark released four different benchmarking products between 2001 and 2006, all of them using slightly different methodologies to evaluate system performance. This causes a problem when combining the observations from the four datasets. The same hardware configuration would generate different benchmark values depending on the version of the benchmarking software.

[1] The NPD database has already been used for several other studies (Shankar & Bayus 2003; Clements & Ohashi 2005; Corts & Lederman 2009).
[2] These are 3DMark2001, 3DMark2003, 3DMark2005 and 3DMark2006

We therefore standardize the values, i.e. “deflate” all benchmark scores to a 3DMark2001-level. Using the 3DMark2001 dataset, we investigate how the particular system components drive the benchmark score. The OLS regression with 3DMark2001 benchmark score as our dependent variable uses processor speed (measured in MHz), graphic card vendor and graphic card memory as the explanatory variables. Additionally, we control for a squared term of processor speed to capture a potentially non-linear relationship.

Although the regression already explains almost 76% of the variation, one might argue that other omitted factors like the exact graphic card type or operating system also influence the benchmark score. While this is certainly true, we have to use the least common denominator between the information provided by the benchmark datasets and the game-specific data on system requirements. For the most part, the latter only include processor speed, hard disk space, graphics memory and RAM.

These coefficients are then used to predict the benchmark scores of the three remaining benchmark datasets on a 2001 basis, yielding a time-consistent dataset with comparable benchmark values. In a second step, the coefficients are used to translate the minimum system requirements into a required benchmark score for the computer games[3]. To identify a game’s closeness to the frontier we need to know where the frontier is. The latter is calculated as the average benchmark scores of computers benchmarked within the last 12 months[4]. With benchmark data starting in March 2001, we can compute CTF for all games released since February 2002.

4.2. Variables and Descriptive Statistics

4.2.1 Revenue (ln)

Our dependent variable is the success of the computer game, measured as the natural logarithm of a game's revenue. Using the natural logarithm, we can reduce the skewness of the revenue data.

[3] The coefficient "ATI graphic card" is used for the calculation of the required benchmark score.
[4] We only kept one observation per user per month in order to avoid unsystematic biases.

4.2.2 Closeness to the Technological Frontier

The closeness to the technological frontier $\boldsymbol{CTF_{i,t}}$ of a game is calculated as follows:

$$\mathrm{CTF_i} = \frac{\mathrm{SYSTEM\_REQUIREMENTS_i}}{\mathrm{mean(SYSTEM\_AVAILABILITY_t)}}$$

The Futuremark dataset provides benchmark scores by dates, which are then used to calculate a measure for the mean system availability by month[5] which we use as an indicator for the technological frontier. Dividing the game's system requirements, expressed as a 3DMark2001 benchmark score, by the average benchmark score, yields a percentage indicating how much of the available system potential is used by the game in the release month. Since the game requirements do not vary over time, closeness to the frontier decreases as the benchmarked hardware gets more powerful. An example of the development path can be found in Figure 3. The translation of minimum system requirements into a corresponding 3DMark 2001 benchmark score, however, is based upon assumptions. To show that this does not drive our results, we provide a robustness check with a different operationalization in section 6.2.

4.2.3 Control Variables

While using game-fixed effects already captures all time-constant game-specific effects in our panel regression we additionally control for time-variant variables.

Evidently, a tremendous part of sales development can be explained through the time a game is on the market. In our sample, the average game makes more than 80% of its entire revenue within the first 12 months after release with sales declining steeply afterwards. Therefore, we control for the time a game is available on the market ($\boldsymbol{age_i}$), defined as the number of months since the date of launch.

Using 12 dummies we can identify the effect of the respective calendar month (***dm***). With sales peaking during the holiday seasons, it is important to control for the impact of a particular calendar month on sales.

[5]We use a rolling window of 12 months, considering all users who ran the benchmark within that time span a potential consumer in the respective month.

As argued above, we expect technological change $\boldsymbol{TC_t}$ to drive sales significantly. Using benchmark data, we calculate the change of the average benchmark score from one to the following month. However, this variable is subject to a strong time trend which is highly correlated with our variable $\boldsymbol{age_{it}}$. To detrend this measure, we subtract the average of score changes. This yields a measure indicating if technological change is particularly strong or weak in the respective month.

In the cross-section regression, we have to control for several time-constant covariates which were otherwise captured in the game-fixed effect. We control for genre[6], as these might be inherently differently successful. Also, development budget could be an indicator for commercial success. Although we do not observe actual budgets, we approximate this by controlling for the count of developers, the team size $\boldsymbol{TS_i}$, engaged in the creation of the computer game. In addition, we control for a vector of dummies including whether the game is part of a series, uses licensed content, employs a 3D-graphic-engine or includes special technology in the programming process.

4.2.4 Descriptive Statistics

Table 1 gives descriptive statistics of the main variables of interest[7] and Table 2 reports the respective correlations.

The total logarithmized revenue ranges between 2.485 and 17.89, which equals roughly \$58.8 million (World of Warcraft – The Burning Crusade released in 2007). The average game in our sample generates roughly \$1,635 a month and was created by 136 developers.

INSERT TABLE 1 HERE

INSERT TABLE 2 HERE

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[6] The list of genres consists of Action, Adventure, Driving, Puzzle, Role-Playing, Simulation, Sports and Strategy.

[7] Here, only first-month CTF is reported because ongoing technological change would otherwise cause a downward bias.

Looking at the statistics of $\boldsymbol{CTF_{i,t}}$, it is noticeable that the average game uses only 32.5% of the available hardware on the market at the time of release. However, this might be the result of two contrary biases. First, we use the minimum hardware requirements for the calculation of $\boldsymbol{CTF_{i,t}}$. Recommended hardware requirements are significantly higher but not consistently available in our sample. Second, graphic benchmarks are most intensively used by hardcore gamers or, put differently, at least not by the standard PC user, resulting in a considerable upward bias. However, with both biases being systematic, they do not falsify our results.

5. Estimation and Results

5.1. Empirical Models and Estimation Methods

5.1.1 Closeness to the Frontier and Product Success

In our first regression we identify the effect of closeness to the frontier on the total success of a game using cross-sectional data. Calculating the sum of revenues of the first 12 months yields the indicator of the game's total success. The average game in our dataset made 83.7% of its total revenue within the first year. To show that the arbitrary cut-off does not drive our results, we perform robustness checks in section 6.1 using different time spans for the calculation.

We use the following standard OLS regression model with robust standard errors:

$$Log(Total_{Rev})_i = \alpha_0 + \alpha_1 CTF_i + \alpha_2 CTF^2{}_i + \alpha_3 X_i + \sum_{g=1}^{6} \beta_g dg + \sum_{k=1}^{12} \gamma_m dm + u_i$$

The variable $\boldsymbol{X_i}$ is a vector of multiple control variables that are expected to drive the success of the game. Besides the linear effect for closeness to the frontier, we also control for the squared term to check for a potentially non-linear relationship. Further we employ dummies to control for potential effects of genre (***dg***) and introduction-month (***dm***).

5.1.2 Closeness to the Frontier and Technological Change

In a second step, we exploit the panel structure of our data to identify the effect of technological change and its interaction with closeness to the frontier on monthly revenues[8].

We use the following specification

$$Log(Rev_{i,t}) = \alpha_0 + \alpha_1 age_{i,t} + \alpha_2 TC_t + \alpha_3 TC_t * CTF_i + \sum_{m=1}^{12} \beta_m dm + u_i + \varepsilon_{i,t}$$

with game-fixed effects. However, the game-fixed effect might not be constant over time which would mean that observations are dependent within clusters. Our estimation therefore uses clustered standard errors on the game-level.

The interaction term reveals how the effect of closeness to the frontier is moderated by technological change. The main effect for CTF drops as it is captured by the game-fixed effect. Again, we control for calendar months to account for the seasonality of sales. In addition to the standard error term $\varepsilon_{i,t}$, the use of game-fixed effects includes a game-specific time-constant heterogeneity term u_i.

5.2. Results

5.2.1 Technological Frontier and Product Success

Model 1 of Table 3 presents the OLS estimation results of the control variables on the total logarithmized revenue.

INSERT TABLE 3 HERE

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[8] We start with the second month as first month-revenues are not comparable due to different introduction times.

Here, we find positive and highly significant coefficients for team size and the series dummy (not reported).

In model 2, we add the measure of closeness to the technological frontier. The effect of the variable is positive and significant. In the third model, we add a quadratic term of CTF. The coefficient of the quadratic term is negative and significant, indicating a decreasing marginal effect of closeness to the frontier on the success of a computer game.

The results indicate that games closer to the technological frontier are more successful in terms of generated revenue. Clearly, this sounds fairly intuitive. It, however, misses the fact that shorter distance to the frontier automatically translates into higher requirements on the complement. This way, a position closer to the technological frontier excludes consumers whose complement is not powerful enough to support the focal product.

In the computer game industry, developers need to consider two contrary effects when choosing closeness to the frontier. First, shorter distance to the frontier leads to increased product attractiveness and, second, reduces market potential. This is because more realistic graphical effects imply higher system requirements, which exclude consumers whose hardware configuration does not meet the requirements. Our results suggest that, in the case of this particular industry, the sales-enhancing effect of product attractiveness exceeds the negative effect of reduced market potential; however, only up to a particular level. As expected, we find a decreasing marginal effect of closeness suggesting an inverted U-shaped relationship for closeness to the frontier and revenue. This inverted U-shape is confirmed by a U-Test ($p<0.05$) and illustrated in Figure 2.

INSERT FIGURE 2 HERE

5.2.2 Technological Change and Product Obsolescence

Table 4 contains the results for our fixed-effects panel regression. Here, we find several interesting results: First, not surprisingly, the effect of age is significant and negative, meaning that games sell less the longer they are on the market. Second, the effect of technological change is negative and significant. That is because, as technology advances, better products are released. As distance to the frontier increases, it becomes more difficult to attract consumers, which eventually leads to obsolescence.

INSERT TABLE 4 HERE

On the other hand, our results show that technological change can also have a positive effect as it increases market potential. The positive and significant coefficient of the interaction term suggests a moderating influence of closeness to the frontier on the effect of technological change. That is because games close to the frontier address only a small market potential. They therefore benefit the most from technological change which improves the average complements performance. The further a game is from the frontier, the less it benefits from the market potential increasing effect. The results show that games using more than 27% of average hardware power (mean is 32.5%) benefit from technological change. Below this threshold, the net effect of technological change turns negative.

6. Robustness Checks

In this section we perform several alternative regressions to confirm that the relationship between the closeness to the technological frontier, technological change and product success is robust. To be specific, we show results to be insensitive to choices of cut-off values, calculation of the closeness measure and alternative specifications.

6.1. Cut-off Values

In our cross-section regression, we aggregated revenues for the first 12 months. To make sure that this cut-off does not drive our results, we perform four additional estimations, each of them using revenue data of the first six, 24 and 36 months. The fourth model uses the full revenue information.

Results are reported in Table 6 and show results to be qualitatively similar. The linear term for CTF is throughout positive and significant while the squared term remains negative and significant which indicates the inverted U-shaped relationship.

6.2. Alternative Measure of Distance to the Frontier

As mentioned in section 4, we translate the game's system requirements into a 3DMark2001 benchmark score using the regression coefficients. However, making the game's requirements comparable to the benchmark scores is based on several assumptions.

To show that results are not driven by the operationalization of closeness to the frontier, we propose a second way of measurement. System requirements as well as benchmark data include CPU speed, graphic memory and RAM. Instead of using predicted benchmark values, we calculate how many individuals would have been able to play a particular game in a given month. A gamer can play it if its computer's CPU speed, graphic memory and RAM each exceed or at least equal the requirements of the game. This yields a time-series of market potentials for each game.

However, this as well comes with two drawbacks. First, 3DMark2001 does not include data on RAM. Comparing on only two dimensions (CPU speed and Graphic Memory) would yield highly upwardly biased results. Therefore, we concentrated on the remaining data from later benchmarking versions. As a consequence we omit the time before the introduction of 3DMark2003 which ultimately results in a loss of 233 games. Second, the minimum system requirements are satisfied by almost every computer in the benchmark dataset. With a mean market potential around 0.98, the linear and the squared term are almost perfectly correlated.

We therefore use the games in our dataset which provide both minimum and recommended system requirements to calculate the difference between the two specifications. This allows us to extrapolate the recommended requirements for games which reported minimum system requirements only. For RAM and graphic memory we used a factor of 2 and 0.4 for CPU speed. That is to use the full potential of the game, the computer needs to provide 40 percent more computing power than indicated by the minimum requirements.

We estimate both regressions presented in section 5.1 with the alternative measure which is denoted $\boldsymbol{MP_i}$. It indicates the share of individuals in the benchmark dataset able to play the respective game. Here, lower values indicate a shorter distance to the frontier. The results are reported in Table 7 for the cross section and in Table 8 for the panel analysis.

The results in Table 7 suggest that market potential has a positive and significant effect. However, the squared term is negative and significant indicating a decreasing marginal effect of market potential. A U-Test confirms the inverted U-shaped relationship ($p<0.05$) which lends support to the findings from our preferred regression.

Similarly, we find support for the results of our preferred panel estimation. Table 8 shows that technological change is beneficial unless the game already addresses a large market potential. In this case the negative effect of competitive pressure outweighs the positive effect of increased market potential. Although the interpretation is the other way round, it confirms the results of Table 4.

6.3. Alternative Specification

To show that the results are stable even under alternative specifications, we estimate a regression using a log-log specification. However, we can only test the linear relationship as the logarithm of the squared term is too close to the log of the linear term. The variable is consequently dropped due to multicollinearity.

Table 9 shows that as well in a log-log-specification, the relationship between closeness to the frontier and product success remains positive and significant.

7. Conclusion

In this paper we investigate the effect of closeness to the technological frontier and technological change on the success of computer games, using data from 571 games over a 2002-2008 time period. Our regressions have uncovered a number of interesting findings. First, we find that computer games closer to the technological frontier generate more revenue. However, the decreasing marginal effect suggests an inverted U-shaped relationship for CTF and revenues. Second, technological change has two effects on sales: First, a negative one because better substitutes are introduced which make the focal product obsolete. Secondly, a positive one as average performance of complements increases, which leads to a larger market potential. The results show that if the product is close enough to the technological frontier (i.e. uses more than 27% of average hardware power), the market potential increasing effect of technological change outweighs the negative effect of obsolescence.

However, it should be pointed out that more research is needed on the relationship of closeness to the frontier and product success for industries where a complement is required. While our first study yields first results on this relationship, insight into different industries would be interesting. Especially because the computer game industry does not provide such a strict exclusion like, as an example, a golf course with handicap requirements. This means that gamers, if willing to accept some stuttering, can play a game even if their hardware provides less computing power as required. Therefore, whether our results hold in general can only be explored by further research, which we hope to have inspired with our paper. More work on this topic would help to provide firmer conclusions.

Our paper has a number of limitations. The point estimate for closeness to the frontier might be overstated. That is due to two contrary biases. On the games side, we have a downward bias because for the vast majority of games in our dataset only provides information on minimum system requirements. Clearly, more powerful hardware is recommended for an enjoyable gameplay. At the same time we assume an upward bias in our benchmark data. Benchmarking computer systems is especially common in the gaming community where computer power is above average. The standard personal computer, which might also be used for casual gaming, is underrepresented in the benchmark dataset. Indicators for the upward bias are observations of CPUs with 22 GHz, which is an unmistakable sign for overclocking and, again, an idiosyncrasy of the gaming community. However, since these biases are systematic they do not invalidate our findings.

Moreover, although game revenues are a first indicator, a game's profits would be a far more reliable sign of product success. However, our dataset lacks information on development costs or, at least, development time, which in combination with team size could be used as a proxy. This would be a promising topic for further research.

Another idiosyncrasy of the computer games industry is the release of patches. A quick way for the developers to fix small bugs even after the game is released. One might argue that patches could postpone the inevitable obsolescence of the game or improve its closeness to the frontier. Both effects are, in our opinion, too small to really affect consumer choices and hence impact our revenue data.

Also, detailed graphics and realistic physics are only one part of the gaming experience. Funny characters and a good story as well contribute to game quality which determines its success. Although these effects are not captured by the measure of CTF, we do not believe it to bias our results. First, in the panel regression it is effectively accounted for by the game-fixed effect as it does not vary over time. Second, since it is uncorrelated with CTF, omitting these variables in the cross-sectional analysis has no effect on consistency.

Using system requirements as a measure of closeness to the frontier might have a down side in this context. As the development process of the game is unobserved, we do not know if the programmers delivered sloppy work. Ineffective programming would unnecessarily increase system requirements. We would therefore infer that the game is closer to the technological frontier while it is really just poorly programmed.

Despite these shortcomings, we believe that our paper provides useful insight on the relationship between the closeness to the technological frontier, technological change and product success, thus lending some empirical support to development strategies of computer game developers.

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Figures and tables

Table 1: Summary Statistics

Variable	**Mean**	**Std. Dev**	**Min**	**Max**	**N**
Total Revenue (ln) $\boldsymbol{Total\_Rev_i}$	13.35	1.970	2.485	17.89	633
Monthly Revenue (ln) $\boldsymbol{Rev_{i,t}}$	7.400	3.103	0	17.60	33,378
Closeness to Frontier $\boldsymbol{CTF_i}$	0.325	0.134	0.066	1.285	633
Detrended Technological Change $\boldsymbol{TC_t}$	0.000	0.013	-0.019	0.040	95
Teamsize $\boldsymbol{TS_i}$	136.4	121.6	1	905	633

Table 2: Pairwise-correlations

Variable	**(1)**	**(2)**	**(3)**	**(4)**
(1) $\boldsymbol{Total\_Rev_i}$ / $\boldsymbol{Rev_{i,t}}$	1.000			
(2) Closeness to Frontier $\boldsymbol{CTF_i}$	0.140	1.000		
(3) Technological Change $\boldsymbol{TC_t}$	0.499	0.179	1.000	
(4) Teamsize $\boldsymbol{TS_i}$	0.463	0.014	-0.014	1.000

Table 3: How does closeness to the frontier influence revenues?

	(1)	(2)	(3)
	Dependent variable: ln(total revenue)		
Closeness to Frontier $\boldsymbol{CTF_i}$		2.114***	5.514***
		(0.654)	(1.511)
Closeness to Frontier sq. $\boldsymbol{CTF^2_i}$			-3.977**
			(1.586)
Teamsize $\boldsymbol{TS_i}$	0.004***	0.004***	0.005***
	(0.001)	(0.001)	(0.001)
Series Dummy	0.835***	0.629***	0.638***
	(0.157)	(0.189)	(0.189)
Licensed Content Dummy	0.587**	0.503	0.553
	(0.284)	(0.353)	(0.341)
Special Technology Dummy	1.100***	1.420***	1.450***
	(0.191)	(0.218)	(0.221)
3D-Engine Dummy	0.333*	0.304	0.374*
	(0.180)	(0.209)	(0.213)
Number of Games	571	571	571
R^2	0.347	0.368	0.374

Notes: OLS point estimates. Robust standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). Dependent variable is the logarithmized sum of first 12 months revenues. All specifications control for fixed effects on the level of the genre and the release month. The constant is not reported.

Table 4: How does technological change influence revenues?

	(1) Dependent variable: ln(monthly revenue)
Tech. Change $\boldsymbol{TC_t}$	-18.916***
	(4.282)
$\boldsymbol{TC_t}$ * $\boldsymbol{CTF_i}$	69.853***
	(11.895)
Months since release $\boldsymbol{age_{i,t}}$	-0.124***
	(0.002)
R^2	0.764
Observations	32,743
Number of Games	632

*Notes: Fixed-effect OLS point estimates. Standard errors are clustered at the game level. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). All specifications control for fixed effects on the level of the game, the age of the game in month and the calendar month. The constant is not reported.*

Table 5: How do hardware characteristics influence the 3DMark2001 benchmark score?

	(1)
	Dependent Variable: 3DMark2001 Benchmark Score
Processor Speed	-2.607 ***
	(0.020)
Processor Speed squared	0.001***
	(0.000)
NVIDIA Graphic Card	687.309**
	(14.80)
ATI Graphic Card	1247.45***
	(15.62)
Graphics Memory	41.355***
	(0.046)
Constant	1840.562**
	(25.67)
R^2	.758
Number of Observations	1,155,142

Notes: Robust standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1).

Table 6: Robustness Check "Revenue Cut-off"

	(1) full sample	(2) 36 months	(3) 24 months	(4) 12 months	(5) 6 months
	Dependent variable: ln(total revenue)				
Closeness to Frontier $\boldsymbol{CTF_i}$	5.624***	5.473***	5.458***	5.514***	5.377***
	(1.546)	(1.562)	(1.555)	(1.511)	(1.522)
Closeness to Frontier sq. $\boldsymbol{CTF^2_i}$	-4.134**	-4.000**	-3.963**	-3.977**	-3.796**
	(1.645)	(1.673)	(1.661)	(1.586)	(1.622)
Teamsize $\boldsymbol{TS_i}$	0.005***	0.005***	0.005***	0.005***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Series Dummy	0.805***	0.802***	0.814***	0.836***	0.786***
	(0.144)	(0.144)	(0.144)	(0.142)	(0.150)
Licensed Content Dummy	0.613***	0.614***	0.616***	0.615**	0.377
	(0.236)	(0.236)	(0.238)	(0.239)	(0.351)
Special Technology Dummy	1.140***	1.143***	1.139***	1.067***	0.964***
	(0.178)	(0.178)	(0.177)	(0.188)	(0.241)
3D-Engine Dummy	0.429***	0.428***	0.426***	0.347**	0.428**
	(0.160)	(0.160)	(0.159)	(0.166)	(0.179)
Observations	571	571	571	571	571
R^2	0.383	0.382	0.383	0.374	0.358

Notes: OLS point estimates. Robust standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). Dependent variable is the logarithmized sum of revenues for different time spans. All specifications control for genre, release month and game characteristics. The constant is not reported.

Table 7: Robustness Checks "Closeness Measurement"

	(1)
	Dependent variable: ln(total revenue)
Market Potential ***MP_i***	3.239**
	(1.403)
Market Potential sq. ***MP^2_i***	-2.456**
	(1.176)
Teamsize ***TS_i***	0.638***
	(0.189)
Series Dummy	0.638***
	(0.189)
Licensed Content Dummy	0.553
	(0.341)
Special Technology Dummy	1.450***
	(0.221)
3D-Engine Dummy	0.374*
	(0.213)
Observations	338
R^2	0.445

Notes: OLS point estimates. Robust standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). Dependent variable is the logarithmized sum of first 12 months revenues. All specifications control for genre, release month and game characteristics. The constant is not reported.

Table 8: Robustness Check "Closeness Measurement"

	(1)
	Dependent variable: ln(monthly revenue)
$age_{i,t}$	-0.132***
	(0.003)
Tech. Change ***TC_t***	14.970***
	(4.718)
TC_t * ***MP_i***	-24.102***
	(5.914)
Observations	17,249
Number of Games	377
R^2	0.774

Notes: OLS point estimates. Clustered (on the game level) standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). Dependent variable is the logarithmized monthly revenues. The specification controls for game fixed effects. The constant is not reported.

Table 9: Robustness Check "Log-Log-Specification"

	(1)
	Dependent variable: ln(total revenue)
Closeness to Frontier (ln) CTF_i	0.760***
	(0.182)
Closeness to Frontier sq. CTF^2_i	
Teamsize TS_i	0.004***
	(0.001)
Series Dummy	0.839***
	(0.142)
Licensed Content Dummy	0.623***
	(0.237)
Special Technology Dummy	1.059***
	(0.186)
3D-Engine Dummy	0.346**
	(0.166)
Observations	571
R^2	0.371

Notes: OLS point estimates. Robust standard errors in parentheses. Asterisks denote significance levels (*** p<0.01, ** p<0.05, * p<0.1). Dependent variable is the logarithmized sum of revenues for different time spans. All specifications control for genre, release month and game characteristics. The constant is not reported.

Figure 1: Development of Graphics Memory and Benchmark Scores 2001-2010

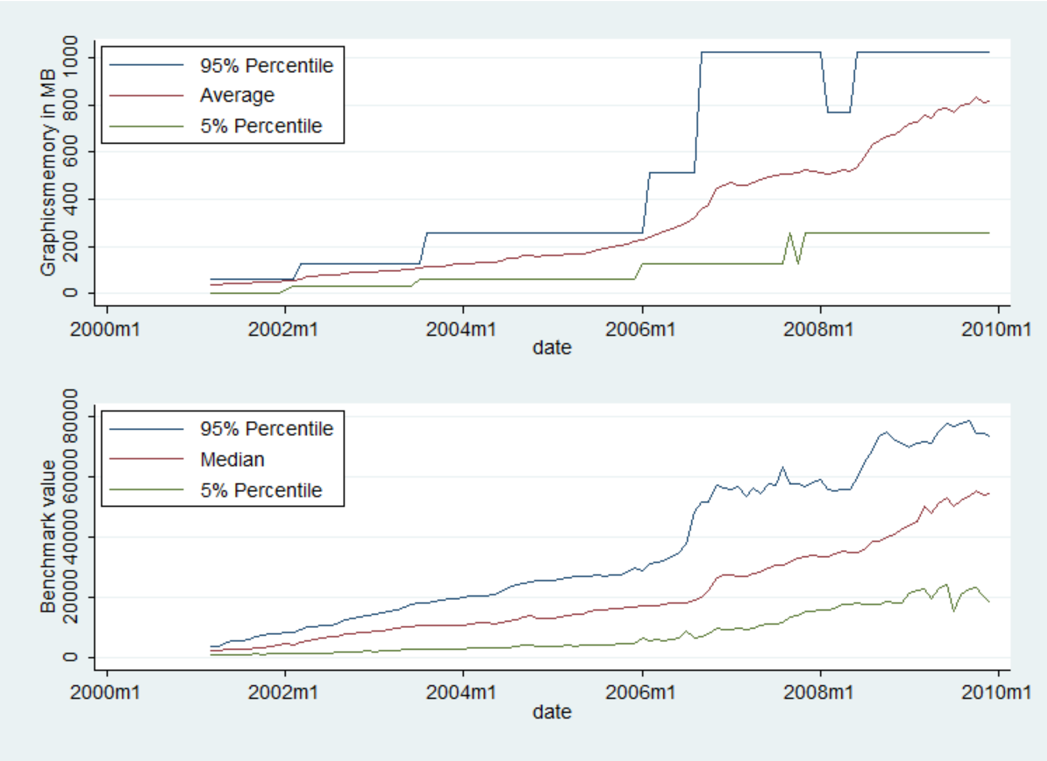

Figure 2: Relationship Revenue and Closeness to the Technological Frontier

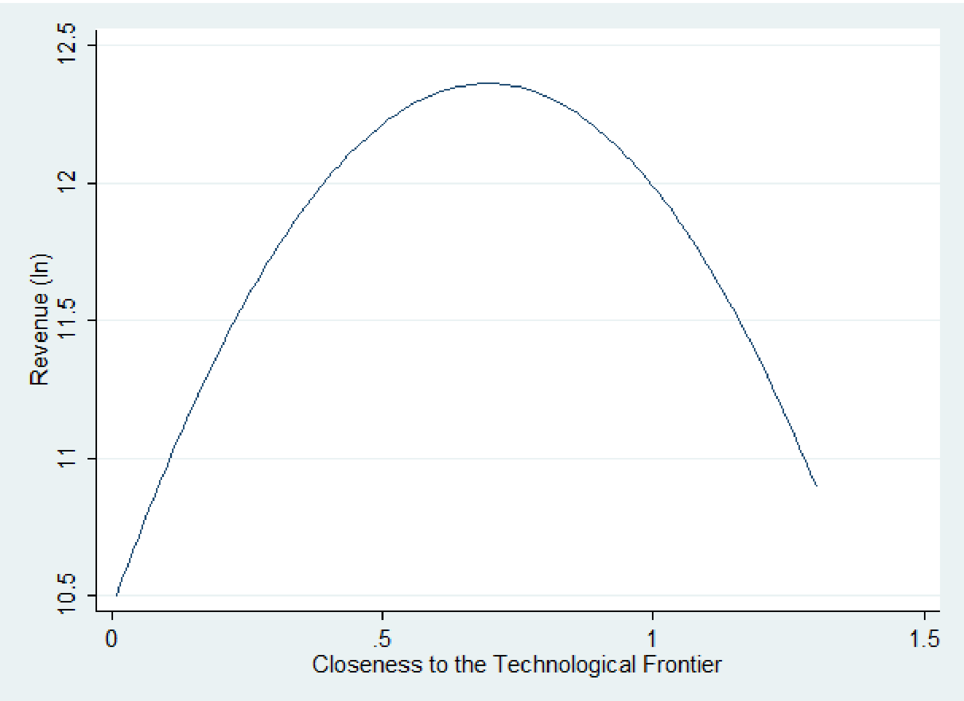

Figure 3: Obsolescence of Computer Games